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SSTDMA in the INTELSAT VI System

Editorial Note

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S. B. BENNETT, Associate Guest Editor, INTELSAT

This is the fifth and final issue of the *COMSAT Technical Review* (CTR) series dedicated to the INTELSAT VI satellite and system.* Because of the importance and complexity of INTELSAT VI and its associated system operation, three issues of CTR were needed to fully document the process leading to its successful implementation. These issues cover the subject from concept, through design and test, to in-orbit operation. Related fourth and fifth issues address system applications and the implementation of satellite-switched time-division multiple access (SSTDMA) system, respectively. Compilation of this series has been a joint effort of COMSAT and INTELSAT, including co-editors from each organization.

The first issue in the series described the overall development of INTELSAT VI, including system planning, specification of the spacecraft bus and communications payload, and the designs for SSTDMA and frequency-division multiple access (FDMA) services. The second issue focused on the design of the INTELSAT VI spacecraft and its communications payload, including the design of the spacecraft bus; the attitude and payload control system; a design overview and description of the communications payload; the design, implementation, and testing of the antenna system; and the design and implementation of the onboard SSTDMA package. The third issue in the INTELSAT VI series covered a wide range of topics, including measures taken to ensure a reliable satellite; the launch, deployment, and in-orbit testing phases; and operation of the satellite in orbit. Various topics of concern to the system user were addressed in the fourth issue, including earth station considerations and the advantages of using digital circuit multiplication equipment (DCME) and video signal processing. A summary coverage of the successful mission to reboost INTELSAT 603 was also given.

This fifth and last issue in the CTR INTELSAT VI series contains eight papers devoted to all aspects of the SSTDMA system, which was first used commercially on INTELSAT VI. The first paper presents an overview of the SSTDMA system, relating each major facet of SSTDMA to the subjects discussed in the other papers in the issue, as well as to relevant papers in the previous special

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* Refer to pages 559 through 563 of this issue for a listing of the papers published in this series.

issues on INTELSAT VI. The design, function, and operation of the SSTDMA reference and monitoring stations are addressed in the second paper, which describes the development of the SSTDMA reference terminal equipment based on the reference terminals used by INTELSAT for the fixed TDMA system on INTELSAT V. The third paper covers the development of new BTP generation methods applicable to the SSTDMA system environment, focusing mainly on practical implementation, algorithms, and an example. The INTELSAT Headquarters Subsystem (HQS) is the subject of the fourth paper, which describes the INTELSAT Operations Center TDMA Facility (IOCTF) and elements of the INTELSAT Satellite Control Center (ISCC), and how the HQS controls the three SSTDMA networks.

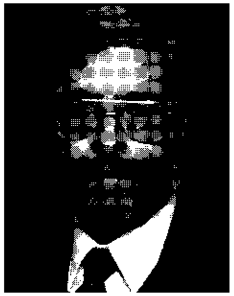
The fifth paper in this current issue is devoted to the design, development, and testing of the onboard timing source oscillator control system, which is necessary to keep the onboard SSTDMA package synchronized with the reference terminals of a particular SSTDMA network. The complexities of the INTELSAT SSTDMA networks require an expert system for near-real-time diagnosis of network operation and performance, as described in paper six. The major topics addressed in the seventh paper are the overall role of the ISCC, the Repeater Command Assistance Program (RCAP6) and its role in command preparation and execution, and the role of the ISCC in supporting SSTDMA system operation. The last paper describes the deployment, testing, and transition to operation of the SSTDMA networks in the INTELSAT VI system, from implementation plan to service initiation.

This issue concludes the CTR INTELSAT VI series. The editors trust that this comprehensive treatment of the INTELSAT VI system will prove useful to future system planners. The papers in this series were the result of a major effort by a large group of authors from COMSAT, INTELSAT, Hughes Aircraft Corporation, and elsewhere. They are all to be congratulated on their substantial achievement.

Geoffrey Hyde received a BASc in engineering physics and an MASc in electrical engineering from the University of Toronto in 1953 and 1959, respectively, and a PhD in electrical engineering from the University of Pennsylvania, Philadelphia, in 1967. Prior to joining COMSAT Laboratories in July 1968, he worked on antennas, microwaves, and propagation at RCA, Moorestown, NJ, and at Avro Aircraft Company and Sinclair Radio Labs in Canada.

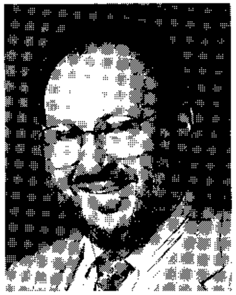
At COMSAT prior to 1974, Dr. Hyde was concerned with the development of the torus antenna, a general antenna analysis computer program (GAP), and related areas of endeavor. In February 1974 he became Manager of the Propagation Studies Department, where his work included a wide variety of efforts in propagation measurement and analysis. In 1980 he joined the staff of the Director, COMSAT Laboratories, and in 1984 became Assistant to the Director. His duties included coordination of the COMSAT R&D programs, coordination of ITU activities at COMSAT Laboratories, and editorship of the COMSAT Technical Review. *In June 1989 he retired, and is currently a consultant to COMSAT Laboratories.*

Dr. Hyde is a member of URSI Commissions B and F, and the AIAA, and is a Registered Professional Engineer in Ontario, Canada. His honors include David Sarnoff Fellowships (1965 and 1966), Fellow of the IEEE (1987), and the IEEE G-AP award for best paper, 1968 (jointly with Dr. Roy C. Spencer).



John A. Lunsford received a BSEE from the University of Maryland in 1973 and an MSEE from the University of Pennsylvania in 1980. From 1973 to 1980, he worked on advanced radar signal processing equipment development projects for the RCA Missile and Surface Radar Division (MSRD), including the AEGIS Advanced Radar Signal Processor for the U.S. Navy's AEGIS shipboard radar system. He joined COMSAT Laboratories in 1980, where he participated in a number of TDMA system specification and equipment development efforts, including the system specifications for the INTELSAT TDMA/DSI system. From 1985 to 1989, Mr. Lunsford worked as an independent contractor for INTELSAT, where he made major contributions to the SSTDMA system design and specification, as well as the specifications for the INTELSAT Operation Center TDMA Facility, Satellite Control Center, and SSTDMA burst time plan generation software system. In addition, he had a principal role in the implementation, installation, testing, and documentation of all elements of the SSTDMA system.

Mr. Lunsford rejoined COMSAT Laboratories in 1990 as manager of the Network Systems department in the Network Technology Division, where he led an engineering team performing research and development in the areas of onboard processing, ISDN, *TDMA, network control, and system architectures for advanced satellite communications systems. He is currently manager of the Network Engineering and Development department, where he is responsible for hardware development for various satellite communications projects.*



Simon B. Bennett received a BEE from City College of New York in 1959 and an MEE from New York University in 1961. His career, which spans the entire history of communications satellites, began with work on the first TELSTAR satellite program at Bell Telephone Laboratories from 1959 to 1963. He continued in this field from 1961 to 1974 at COMSAT, where he contributed to the success of satellite programs from Early Bird to INTELSAT IV.

In 1974, Mr. Bennett joined INTELSAT as Manager of Engineering, where he was engaged in the formulation and application of INTELSAT's intersystem coordination process. Subsequently, as Manager of Space Segment Programs, he was responsible for all technical and programmatic aspects of satellites and launch vehicles encompassing the INTELSAT V and VI series of satellites. This was followed by one year as Director of System Planning. From 1986 to 1990, he was in charge of the operation of INTELSAT's fleet of 15 to 18 satellites and associated tracking, telemetry, command, and monitoring facilities. From early 1990 until his retirement from INTELSAT in July 1992, he was assistant to the Vice President for Engineering and Research. He is currently President of Bennett Consultancy, Alexandria, Virginia.

Index: communication satellites, INTELSAT, networks, time division multiple access, system control

The INTELSAT SSTDMA system design

J. A. LUNSFORD, J. F. PHIEL, R. BEDFORD, AND S. P. TAMBOLI

(Manuscript received January 8, 1991)

Abstract

The INTELSAT satellite-switched time-division multiple access (SSTDMA) system introduced with the INTELSAT VI satellite series is the most advanced commercial communications system ever implemented. Because it provides dynamic beam switching on board the satellite, its implementation required considerable changes to the network control system used for INTELSAT V fixed TDMA, while minimizing the impact on existing traffic terminals. In order to control the onboard switch in synchronism with the TDMA system, the INTELSAT Operations Center TDMA Facility and the INTELSAT Satellite Control Center were incorporated as active control elements in the SSTDMA system. This paper provides an overview of the SSTDMA system, including a general description of the major control system elements, modifications to the TDMA frame architecture design, allocation of bursts in the frame to provide network control, and network control procedures such as those for onboard oscillator control and burst time plan change.

Introduction

Operating over INTELSAT V satellites, the INTELSAT 120-Mbit/s time-division multiple access (TDMA) system, first began carrying traffic on the Atlantic Ocean Region (AOR) 341.5°E longitude satellite in October 1986. Because of its fixed-beam connectivity, this system is referred to as fixed TDMA. For complete flexibility in applying fourfold frequency reuse, the fixed TDMA system employs four reference terminals per network—two in each overlapping zone/hemispheric coverage beam (east and west) of the INTELSAT V satellite [1]–[2].

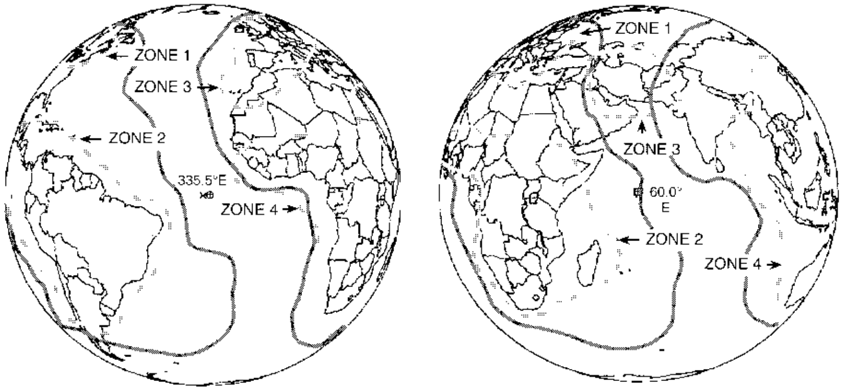
The advantage of the fixed TDMA system has been its ability to use the full power and bandwidth of a transponder for highly efficient multiple access. Satellite bearer channel capacities of approximately 1,500 64-kbit/s channels (not including digital speech interpolation [DSI] gain) have been achieved in actual time plans, with forward error correction (FEC) for all traffic bursts. The bit error rate performance of this system, even for worst-case links, is better than 1 in 10^{12} for more than 95 percent of the worst months.

The INTELSAT VI satellite, with its two satellite-switched TDMA (SSTDMA) transmission channels comprising 12 C-band transponders, provides a number of major advantages over fixed TDMA. These include improved connectivity, reduction in traffic station uplink and downlink equipment, more even distribution of traffic in beams, reduction in the number of reference terminals needed to control the network, and increased availability due to interference immunity and recovery capabilities. Implementation of the SSTDMA system involved a major redesign of the system control elements and inclusion of the INTELSAT Satellite Control Center (ISCC) and the satellite as active elements in the system. These changes were accomplished without affecting existing traffic terminals.

The implementation, deployment, and testing of the system was a massive effort which was completed in a little more than 2 years, with very few problems. The first INTELSAT SSTDMA system went into operation on May 19, 1990, with SSTDMA reference terminal equipment (SSRTE) installed at the Tanum earth station in Sweden and the Etam earth station in West Virginia, U.S.A. Testing of the second SSTDMA system began in late 1991, in the Indian Ocean Region (IOR), using the INTELSAT VI satellite at 60°E longitude with SSRTEs located at the Beijing earth station in China and the Reisting earth station in Germany. This system was put into operation on January 31, 1992.

Advantages of SSTDMA

The SSTDMA system employs two C-band hemi beams and four C-band zone beams provided by the INTELSAT VI spacecraft. Figures 1a and 1b show the INTELSAT VI beam coverages for the AOR and IOR, respectively. Transition to SSTDMA offers a number of advantages beyond those of fixed TDMA. For example, a switch on board INTELSAT VI provides the capability to regain the connectivity lost by multibeam bent-pipe satellites [3]. In addition, the SSTDMA system conserves earth station uplink and downlink equipment by providing access to destinations in multiple beams from a single upbeam and downbeam. With fixed connections, the greater coverage of the hemi beams, coupled with the desire to minimize the amount of up- and down-conversion equipment, produces a tendency for these beams to be more heavily loaded and to reach saturation more quickly. The beam-switching ability of the SSTDMA system makes it possible for a terminal having single-beam access to correspond with any terminal in any other beam. Thus, since the smaller traffic-bearing terminals will no longer prefer one beam over another, traffic can be scheduled more uniformly in all transponders, resulting in more efficient use of satellite resources. However, in practice, this potential is limited by the fact that all zone beams do not currently have a significant population of TDMA users.



(a) Atlantic Ocean Region (b) Indian Ocean Region

Figure 1. *Three-Ocean C-Band Coverage Patterns for INTELSAT VI*

The broadcast and semibroadcast features of the INTELSAT VI onboard switch make it possible to distribute reference bursts from two reference terminals in different coverage areas to all downbeams, and to distribute a single principal burst from each traffic terminal simultaneously to both reference terminals. With this capability, the number of reference terminals needed to reliably control a network can be reduced from the four required for the fixed TDMA system to two for SSTDMA.

The SSTDMA system architecture permits the use of "interference-immune" configurations (using four transponders) in which network control is assured unless an interferer originates from two uplink beams simultaneously. For cases where operational requirements do not permit the use of immune configurations, the SSTDMA reference terminals have been modified to automatically restart the network upon removal of the interferer. While these measures do not protect traffic terminals, they do protect the provision of the network control functions, and thus are expected to benefit continuity of service by eliminating the need for manual intervention by reference terminal operators to restart the network.

Network architecture

Transition to SSTDMA operation on the sixfold frequency reuse beams of INTELSAT VI was planned from the outset [3],[4]; details on INTELSAT VI payload performance are provided in Reference 5. In 1985, INTELSAT determined that the satellite switch, which provides greater flexibility for distributing control within the network, could be used effectively to reduce the number of reference terminals to two, without loss of system reliability [3]. This modification to the SSTDMA system, together with a number of other system considerations, made it necessary to adopt a different approach to network control than that used in the fixed TDMA system [6].

This new approach involved changes in architecture, network configuration, and control scheduling which resulted in the need for new RTE, modification of many system procedures, and in particular, introduction of a new disciplined frame structure. These changes were engineered to be transparent to existing traffic terminal equipment and are implemented entirely within the control elements of the network [7],[8]. Some of the more important architectural features of the SSTDMA system are described below.

The major functional element of the SSTDMA subsystem on board the INTELSAT VI satellite [9],[10] is the microwave switch matrix (MSM), which can dynamically switch six upbeams to six downbeams during a frame period. The onboard SSTDMA subsystem also includes timing source oscillators (TSOs), switch state memory and digital control logic, and an array of redundancy and bypass switches.

A new frame structure provides dedicated regions of the frame for system control, management, monitoring, and traffic distribution. Further, a new approach for selecting network configuration and control facilitates interference-immune configurations in which network control can be maintained from at least one reference terminal if interference does not occur on more than one uplink beam simultaneously [6].

The fixed-TDMA RTE and its software were modified to support SSTDMA operation [7],[11]. The most significant change was the addition of an acquisition and synchronization unit (ASU), which synchronizes TDMA frame timing to the switch frame timing on the satellite.

A new SSTDMA burst time plan (SSBTP) generation software system [12],[13] includes a much more complex traffic scheduling algorithm that accommodates the beam switching capability of the INTELSAT VI satellite. The software also contains rule-driven algorithms for scheduling network control.

The INTELSAT Operations Center TDMA Facility (IOCTF) was designated as the hub for all network communications and control, necessitating a complete redesign of the IOCTF hardware and software to provide the reliability demanded by such a central role [14]. The IOCTF and ISCC functions were integrated to support SSTDMA, while retaining the capability to support fixed TDMA [14]–[16]. A central monitoring and control facility called the Headquarters Subsystem (HQS) was formed by aggregating the IOCTF and ISCC to support both fixed TDMA and SSTDMA.

A knowledge-based (expert system) diagnostic system analyzes burst detection and status data gathered by the reference and traffic monitoring elements of the network [14],[17]. The expert system resides in the IOCTF, where it can access various databases and other status data from the reference terminals and the ISCC. Nonreference diagnostic equipment (NRDE) monitors traffic in the nonreference beams in support of the diagnostic system. This equipment is located at designated host traffic terminals in zone beams that do not illuminate reference terminals [17].

This paper offers an overview of the SSTDMA system design, beginning with a brief description of the overall SSTDMA system architecture which highlights modifications made to the fixed TDMA system elements to implement SSTDMA. The SSTDMA frame architecture and underlying design considerations are then discussed. A synopsis of network control selection for SSTDMA is also provided, followed by a description of two system procedures—onboard TSO control [18] and BTP change—which involve multiple system elements.

SSTDMA system elements

The major elements of the SSTDMA system, and their interconnectivities, are illustrated in Figure 2. For one SSTDMA network, these elements include:

- The INTELSAT VI SSTDMA subsystem
- Two SSTDMA reference terminals (SSRTEs)
- The IOCTF
- The ISCC
- Two sets of nonreference diagnostic equipment (NRDEs)
- User traffic terminals.

The telemetry, tracking, command, and monitoring (TTC&M) site and the IBM mainframe computer are support facilities. Traffic terminals operating in the SSTDMA system are identical to those operating in the fixed TDMA systems.

An SSRTE is located in either the north or south zone beam—one in the east and one in the west. An NRDE is located at a host traffic terminal in each of the remaining zone beams that do not illuminate the reference stations. The ISCC, IOCTF, and IBM mainframe computer are all located at INTELSAT Headquarters in Washington, D.C. The INTELSAT constellation of satellites employs a system of six strategically placed TTC&M sites for monitoring and control [19]. The SSRTEs are connected to the IOCTF by dedicated data links for the

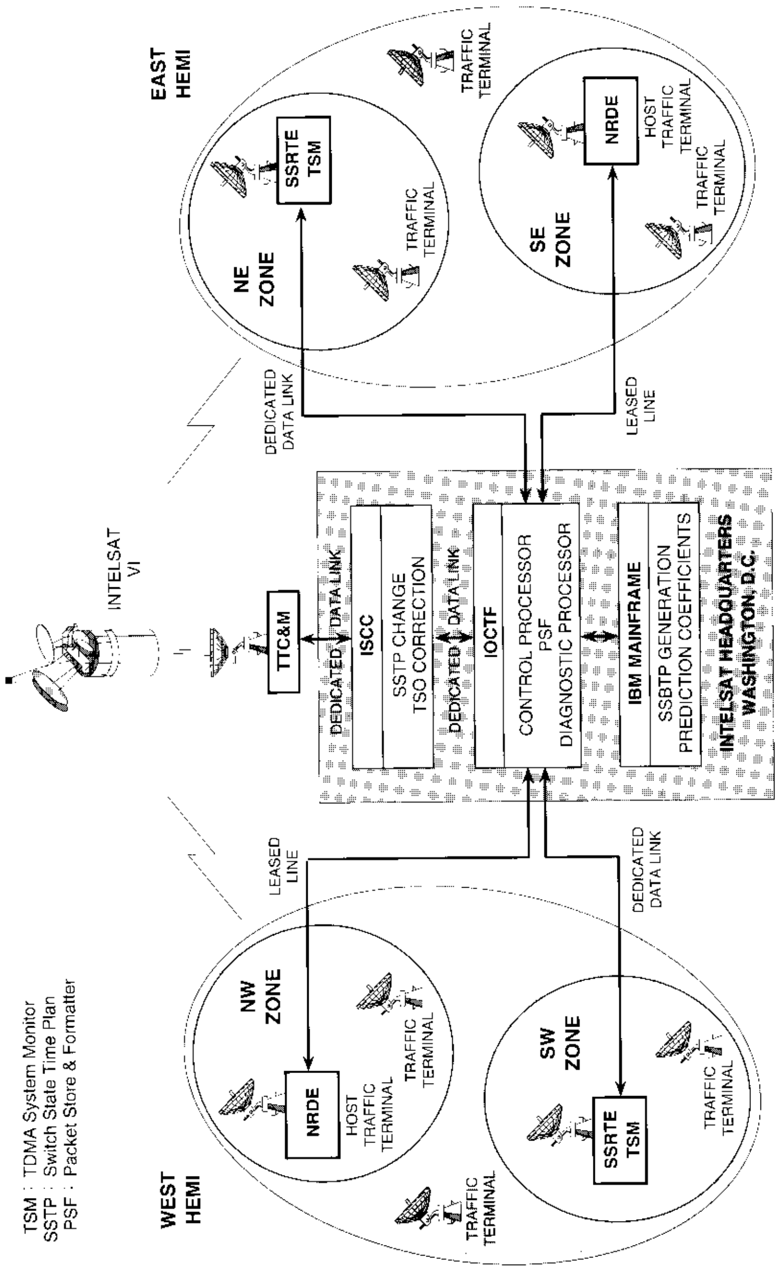


Figure 2. *Major Elements of the INTELSAT SSTDMA System*

communication of all system operational, monitoring, and status data. The NRDEs are connected to the IOCTF via leased circuits to transmit monitoring data to the IOCTF. Dedicated data links also connect the ISCC with the IOCTF, and with the TTC&M sites. The subsections that follow provide a brief overview of the major SSTDMA system elements.

INTELSAT VI SSTDMA subsystem

The INTELSAT VI SSTDMA subsystem (Figure 3) is the heart of the SSTDMA system. This onboard subsystem consists of two identical switching units for dynamic interconnection of upbeams to downbeams in two transmission channels, according to a programmable sequence stored on board the satellite. There is no possibility of beams in one transmission channel being connected with those in the other channel. Each switching unit comprises a 10 × 6 dynamic MSM with associated digital input logic, an input ring redundancy switch network, redundant distribution control units (DCUs) with internally redundant memories, redundant power supplies, and a static bypass switch matrix. The DCUs and input logic can be cross-strapped to avoid single-point failures.

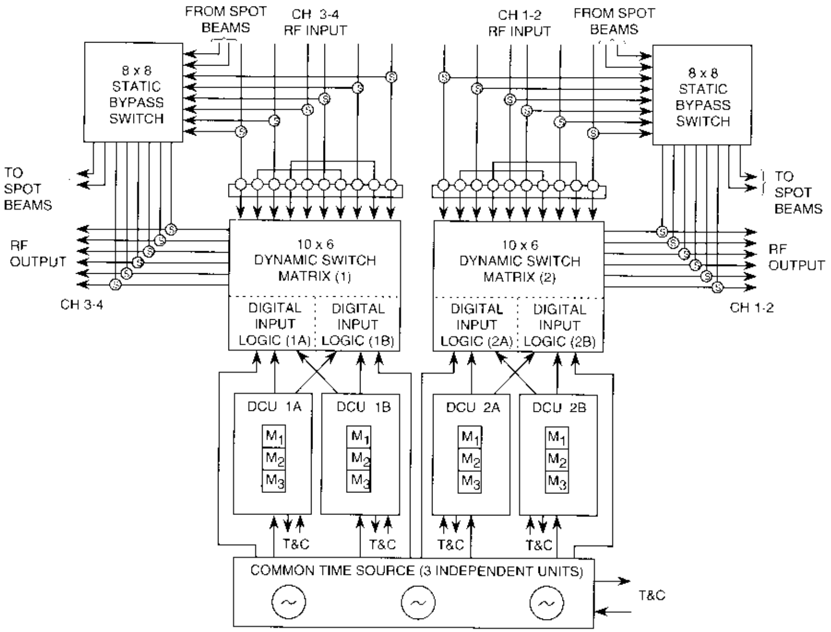


Figure 3. *INTELSAT VI SSTDMA Subsystem*

Both switching units share a common timing source to ensure switching phase coherence between the two TDMA transmission channels. Each switching unit can access one of three identical timing sources through ground command. The timing source comprises a frequency-commandable, voltage-controlled crystal oscillator (the TSO) and associated digital circuitry.

The six input channels to a switching unit are connected to six of the 10 MSM input lines through a ring-redundancy switch network constructed of coaxial R-switches. This network provides central symmetry, allowing flexible routing of input paths through the network. The R-switch network, along with the 10 rows in the MSM, provides four redundant rows in the event of failure of a diode switch in an active row.

Each switching unit establishes interconnections cyclically between the six active input lines and the six output lines. The interconnection pattern for each switch state and the duration of the state are contained in the switch state data stored in DCU memory. These data are fed serially to the digital input logic, which decodes the data and activates diode bias control signals corresponding to one of the 10 rows in each column of the matrix. When biased ON at the programmed switch state transition time, a diode connects the corresponding row and column.

The DCU stores and cyclically executes a sequence of switch configuration words to control the 60 switch elements in the 10 × 6 MSM. The duration of any state defined by a switch configuration word is controlled by its starting position in the frame, and can vary from 1.0593 μs to 2 ms. Each DCU memory can store 64 switch states. Through telemetry commands, three memories can function interchangeably as on-line, off-line, or standby memory. The contents of each memory can be verified independently, and the contents of the off-line memory can be modified through telemetry commands.

For network synchronization, a special mode is provided whereby a designated switch state anywhere in the normal switching sequence can be replaced by a special switch state during the first frame of each switch masterframe (16.384 s). This special switch state, called the substitution switch state, normally extends the associated switch state and is used to synchronize the TDMA superframe to the switch masterframe. The DCU operational mode designating the usage of each memory, the timing source employed, and the activation of the substitution switch state is commanded through the DCU mode status word via telemetry.

Further details concerning the design, operation, and testing of the INTELSAT SSTDMA subsystem are provided by Nakamura *et al.* [9] and Gupta *et al.* [10].

SSTDMA reference terminal equipment

System architectural changes arising from inclusion of the satellite switch as an active element in the network have resulted in many changes to the TDMA RTE. All of these changes affect the way the SSRTE performs network timing synchronization, network control, and monitoring. The changes were designed to be completely transparent to the operational requirements of traffic terminals accessing the network. The fixed TDMA RTE design was modified to produce the SSRTE design depicted in Figure 4.

The most significant modification to the RTE is the addition of the ASU, which is responsible for the new functions necessitated by the system architecture changes. These functions include:

- Acquiring and synchronizing the satellite switch frame and switch masterframe to the TDMA frame and superframe
- Monitoring the frequency drift of the onboard TSO and periodically communicating this information to the IOCTF

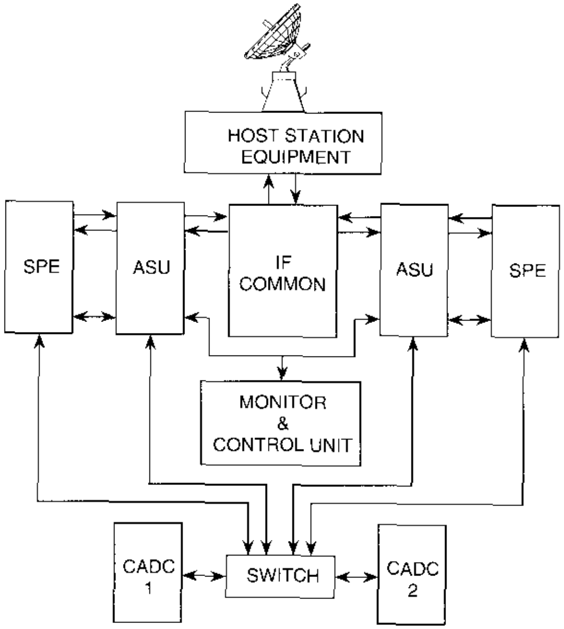


Figure 4. *SSTDMA Reference Terminal Major Subsystem*

- Monitoring the unique word (UW) detections of all reference and traffic bursts present in the transponders that illuminate the reference terminal, and providing this information to the IOCTF periodically for space segment or terrestrial segment failure analysis. This function is performed by the diagnostic receiver in the ASU.

The signal processing equipment (SPE) consists of the reference terminal element, which performs all network control and synchronization functions via the transmission of reference bursts. A number of modifications to the SPE were necessitated by SSTDMA system architecture changes. The most significant of these were:

- Modification of the terminal acquisition and synchronization (TAS) support procedure to implement sequential acquisition for all terminals. The parallel method of acquisition was deleted.
- Modifications to the BTP change procedures to coordinate changing of the switch state time plan (SSTP) in the satellite with the BTP change in the terrestrial network. Changes to the procedures were also necessary to account for the existence of only two reference terminals instead of four.
- Modifications to the inter-reference station procedures to reflect the presence of only two reference terminals in the network.
- Modifications to network startup procedures to account for the ASU function.
- Addition of a "survival mode" to maintain timing and automatic network startup in an interference environment under certain network configurations.

One SPE and one ASU are paired as a redundant pair. If a failure occurs in the online SPE/ASU pair, a redundancy switch will activate the other SPE/ASU pair, if it is in normal standby mode.

The control and display console (CADC) performs all data logging, operator display functions, database management (including reference terminal condensed time plan [RCTP] and reference terminal operational parameters [ROP] handling), and all data communications via the digital data link to the IOCTF. A number of hardware and software modifications were made to the CADC to reflect new functional requirements, procedure changes, and database changes.

The SSRTE also contains the TDMA system monitor (TSM) equipment for the SSTDMA system. Numerous changes were implemented in the TSM to accommodate the new SSTDMA frame structure and the multiple uses of the test region of the frame. A detailed description of the SSRTE and the SSTSM is provided in a companion paper by Bedford *et al.* [11].

INTELSAT Headquarters Subsystem

Due to the static nature of fixed TDMA, the IOCTF and ISCC can operate under this system as independent control centers, with no interaction. However, because the onboard SSTDMA subsystem is an active element in the SSTDMA system, a control center integrating the IOCTF and ISCC is necessary to coordinate operation of the onboard SSTDMA subsystem with the rest of the SSTDMA system. This integrated control center is the SSTDMA HQS. Some of the major functions performed by the HQS include onboard TSO frequency correction, distribution of BTP data to both the SSTDMA subsystem on board the satellite and to the terrestrial elements, and synchronization of BTP change events between the satellite and the terrestrial segment. These requirements heightened the importance of the IOCTF as the central facility for all network communications and control, and led to a complete redesign of the IOCTF hardware and software to provide a more reliable system. The new system requirements necessitated careful integration of IOCTF and ISCC functions to support SSTDMA, while retaining the capability to support fixed TDMA as well.

INTELSAT Operations Center TDMA Facility

Figure 5 illustrates the IOCTF architecture. At the core of the IOCTF are two fully redundant, interconnected computer systems: the IOCTF control processor (ICP) system and the packet store and formatter (PSF) system. In addition, the IOCTF contains a nonredundant Sun workstation that hosts the SSTDMA expert-system-based diagnostics function. An Ethernet local area network (LAN) conforming to IEEE Standard 802.3 links the ICP and PSF, connects the ICPs with two operator station clusters, and links the nonredundant SSTDMA diagnostics subsystem with the ICP and PSF.

The ICP system serves as central processor for all control and monitoring activities and supports the operator interface. All operational functions can be performed on either of the two redundant ICPs. The ICP system comprises a pair of VAX/11-780 processors closely coupled in a homogeneous VAX cluster. This architecture eliminates single points of failure and enables the system to detect, isolate, and recover from processor and disk failures. Up to eight operator stations provide the interface for all IOCTF functions.

The PSF system incorporates the functions of the network packet recirculator/concentrator processors, now retired from service. It serves as the data communications gateway between the IOCTF system and the TDMA reference and monitoring stations (TRMSs), between the IOCTF system and the ISCC portion of the HQS, and as a switching point for communications between TRMSs. DS-1000 data links connect the PSF with the TRMS and ISCC. The PSF system is based on a pair of Hewlett-Packard (HP) A900 computers, which can

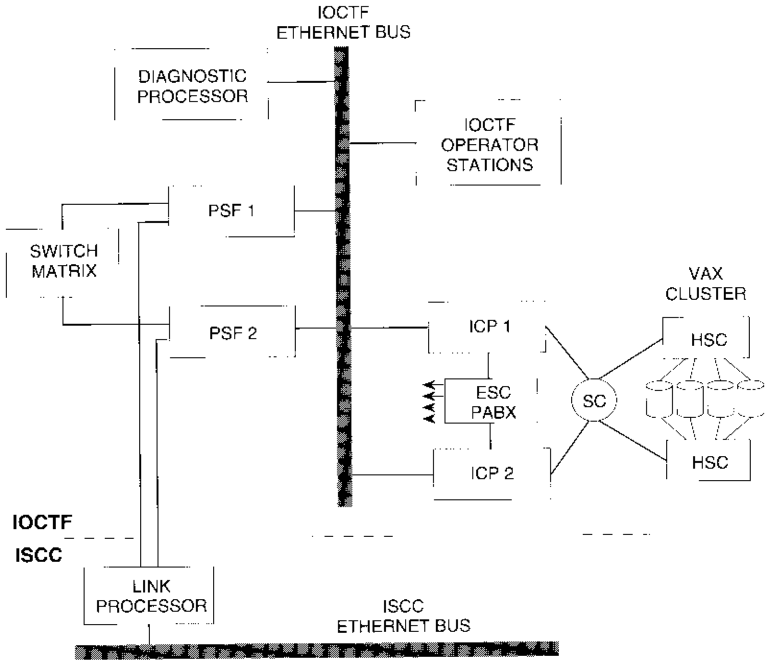


Figure 5. *INTELSAT Operations Center TDMA Facility*

be operationally configured in on-line, standby, or test mode. During normal operation, automatic switchover from the on-line to the standby processor will take place within 2 minutes if the on-line PSF fails.

The diagnostic system provides limited fault isolation capabilities for the SSTDMA network. It receives near-real-time data from the SSRTEs and NRDEs via the PSF and ICP, performs data reduction, and conducts a knowledge-based analysis.

A detailed description of the SSTDMA IOCTF is provided in a companion paper by Luz *et al.* [15]. The SSTDMA diagnostic system is discussed in detail in another companion paper by Tamboli *et al.* [17].

INTELSAT Satellite Control Center

The ISCC is part of the Integrated Satellite Control System (ISCS) used by INTELSAT for the telemetry processing, tracking, commanding, and ranging of four different series of spacecraft: INTELSAT V, VI, K, and VII. The ISCS is a worldwide star network, with the ISCC as its hub, where data and control mechanisms are centralized.

The ISCC is implemented as a distributed system with an Ethernet backbone, and the required functions are distributed logically over different processors, as shown in Figure 6. The processors consist of HP A900 computers organized to support both common support functions and spacecraft-specific functions. The common support processors include:

- *Historical Retrieval Processor.* The HRP stores data and provides satellite engineers with tools for inspecting and analyzing past and current spacecraft activities.
- *Network Concentrators and Link Processors.* These units provide application-level links between the ISCC, TTC&M sites, and the IOCTF.
- *Command Coordination System.* The CCS serves as the focal point for spacecraft commanding activities for all satellites. Common commanding mechanisms and resources are used to effectively integrate the control of all spacecraft.
- *Alarm and Control Consolidation System.* The ACC system provides a centralized operator interface to the various processors at the ISCC. Events and alarms pertaining to spacecraft health and the processing network are received and managed in a central database.
- *Communications and Control Processor.* The CCP serves as a control and management processor for the ISCS network. In addition to maintaining the operational status of the Ethernet processors, the CCP performs a wide variety of functions, including network initialization, processor time synchronization, global file management, network configuration control, event and alarm processing, telemetry line management, activity scheduling, and display configuration.

Spacecraft-specific functions are organized according to the particular requirements of each spacecraft series. These functions basically relate to telemetry processing and display processing, and for INTELSAT VI include:

- *Telemetry Processors,* which perform functions such as telemetry capture and validation, telemetry line monitoring, multicast of validated telemetry frames onto the ISCC LAN, transmission of telemetry frames with bad checksums to the HRP, limit and status checking, command detection and verification, spacecraft ID and mode stuffing, bit stuffing, and override of telemetry validation errors.
- *Display Processors,* which provide real-time telemetry displays, strip charts, and hard copies of telemetry displays. Strip charts are provided for normal telemetry only, while displays and display hard copies are provided for both normal and dwell telemetry.

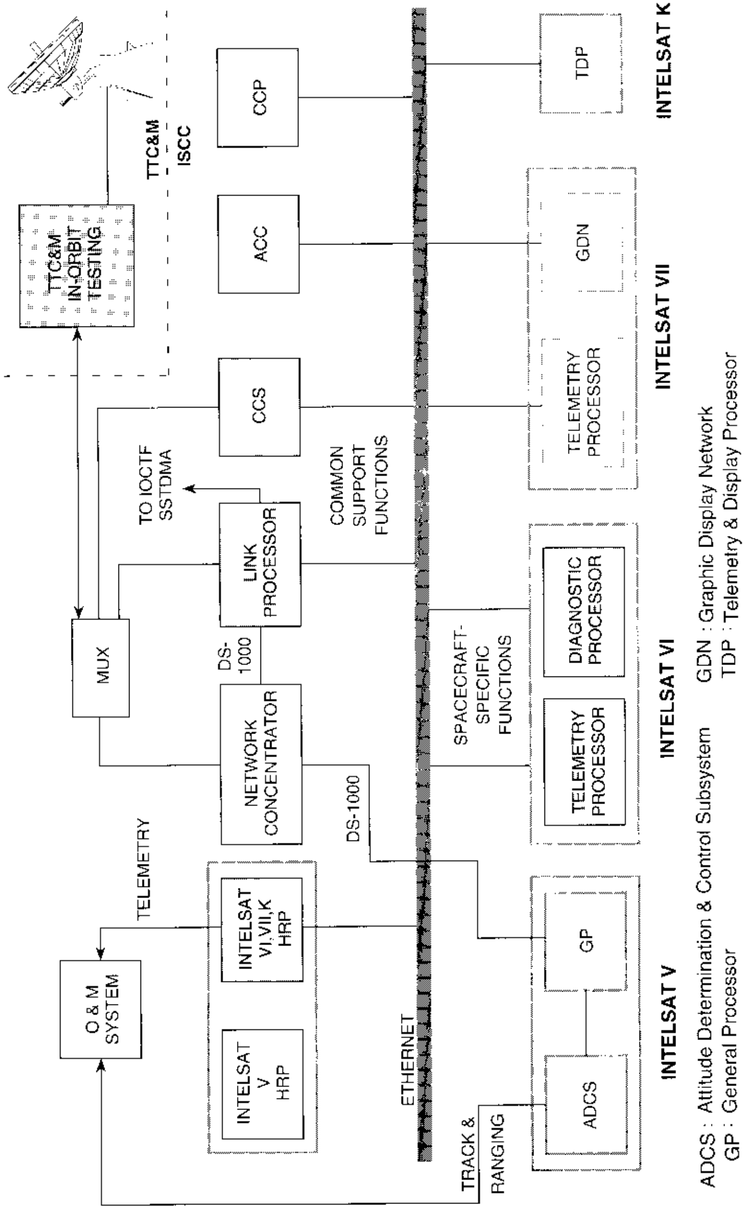


Figure 6. *INTELSAT Integrated Satellite Control System*

A number of major SSTDMA operations require support from both ISCC and TTC&M sites. These include onboard TSO correction, SSTP loading, and SSBTP change. In order for the ISCC to provide spacecraft commanding capabilities to SSTDMA, various databases are transferred from the IOCTF to the CCS—in particular, the SSTP and SSBTP. This information is then passed to PC-based command assistance processors, which build the command queues needed to implement the changes on the spacecraft. The queues are loaded to the CCS, which oversees the execution of the commands. The ISCC also receives and logs the satellite TSO frequency error data computed by the IOCTF and generates command queues for correcting the onboard oscillator frequency. In addition, the ISCC provides the IOCTF with alarm and monitoring information pertinent to spacecraft performance and SSTDMA operation.

Further details on the ISCC SSTDMA subsystem and its role in testing and operating the SSTDMA subsystem on board INTELSAT VI are provided in a companion paper by Pettersson *et al.* [16].

Nonreference diagnostic receiver

Diagnostic receiver equipment in the SSRTE ASUs monitors all bursts in the hemi and zone beams that illuminate the reference terminals; however, the receivers cannot provide information concerning bursts in beams not received by SSRTEs. Consequently, NRDEs containing similar diagnostic equipment are installed in host traffic terminals located in nonreference zone beams to provide the diagnostic system with the necessary burst detection information for these beams.

SSTDMA frame architecture

In the fixed TDMA/DSI system, a fixed frame hierarchy and flexible frame format have been defined [1],[2],[5]. While the terrestrial segment of the SSTDMA system maintains the same frame hierarchy as fixed TDMA, a much more rigid frame format is required [8]. The reference and traffic burst formats established for fixed TDMA are also maintained for SSTDMA; however, the reference burst service channel message repertoire has been modified and additional burst types added to support various SSTDMA functional requirements. The SSTDMA subsystem on board INTELSAT VI spacecraft maintains its own frame hierarchy, with timing intervals of the same duration as corresponding intervals in the TDMA frame hierarchy. The timing intervals in the two hierarchies are synchronized by the ASU in the master primary SSRTE (MPRT). Details of the synchronization procedures are provided in Bedford *et al.* [11].

The INTELSAT VI SSTDMA subsystem frame hierarchy

In describing the INTELSAT VI SSTDMA subsystem frame hierarchy, two terms must be introduced relating to the operation of the MSM: connectivity and switch state. A connectivity is defined as the upbeam-to-downbeam connection within a single transponder, which remains unchanged over a period of time. A switch state is an interval of time over which the set of all connectivities in the SSTDMA transponders associated with one transmission channel remains unchanged.

Figure 7 depicts the INTELSAT VI SSTDMA subsystem frame hierarchy. The fundamental timing unit is the frame unit, which has a duration of 64 symbols, or 1.0593 µs. The minimum duration of a switch state is 4 frame units, due to the time required by the DCU and input logic circuits in the SSTDMA subsystem to access, decode, and set up the next switch state. Switch states can be defined to be from 4 to 1,888 frame units, in increments of 1 frame unit.

The next timing interval in the hierarchy is the switch frame. This unit defines the interval over which the sequence of switch states in each transmission channel repetitively cycles. The switch frame may contain up to 64 switch states, which is the limit of the switch state memory capacity in the DCU. The switch frame has a duration of 1,888 frame units (2 ms). This matches the duration of the TDMA frame, since the repetitive cycle of bursts in each upbeam in the TDMA frame must be routed to the proper downbeams by the cyclic sequence of switch states in the switch frame. The TDMA frame is synchronized by the ASU in the MPRT such that it coincides with the switch frame at the satellite.

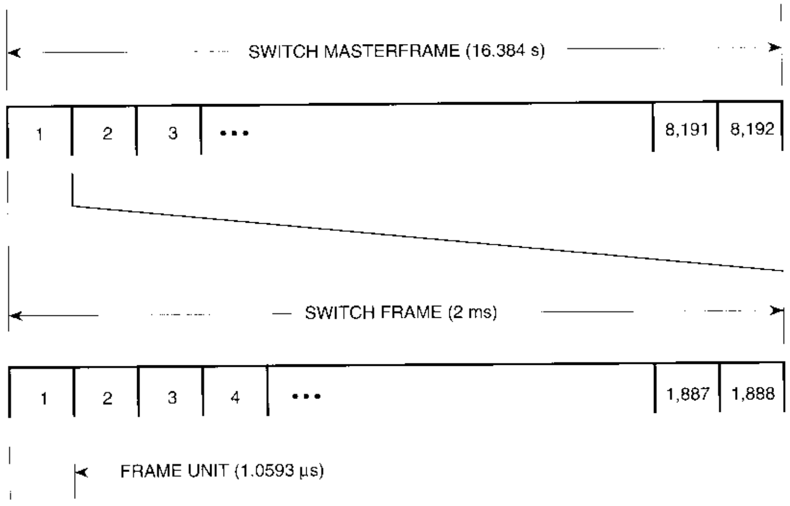


Figure 7. *SSTDMA Subsystem Frame Hierarchy*

There are two independent transmission channels in the SSTDMA subsystem, each corresponding to a separate MSM. The switch frames in each transmission channel are synchronized, while the sequence of switch states in each channel is normally quite different.

The highest level in the SSTDMA subsystem frame hierarchy is the switch masterframe, which has a duration of 8,192 switch frames, or 16.384 s. The switch masterframe defines the timing used by the DCU to implement a switch state memory rotation. When a rotation is commanded, the new memory is placed on line at the start of the first switch frame of the masterframe. The timing of a synchronous BTP change event in the TDMA system is synchronized to the superframe, which also has a duration of 16.384 s. Thus it is necessary for the TDMA superframe to be synchronized with the switch masterframe in the SSTDMA subsystem. As with the synchronization of a TDMA frame to a switch frame, this function is performed by the ASU in the MPRT.

The frame timing hierarchy in the SSTDMA subsystem is provided by the timing source digital electronics. This unit receives a 5.664-MHz signal from the TSO and divides it by six to provide the 944-kHz frame unit signal. It then divides the frame unit signal by 1,888 to provide the 500-Hz switch frame signal, and finally, it divides the switch frame signal by 8,192 to provide the 0.061-Hz switch masterframe signal.

SSTDMA frame design

To maintain coordination and ensure the optimum performance of the functional elements (*i.e.*, reference and traffic terminals) in a TDMA network, various control, administrative, test, and measurement functions must be performed. In general terms, the frame format of a TDMA system defines the partitioning of the TDMA frame into divisions or regions. It also defines the placement of system entities such as bursts or windows within these regions to facilitate the implementation of one or more of the above functions [1],[2],[5].

The dynamic routing capability of the MSM on board INTELSAT VI has had a major impact on the frame format design for SSTDMA. As illustrated in Figure 8, the SSTDMA frame is divided into seven regions:

- *Metric Region.* The metric region initiates with the frame. It comprises three switch states that are controlled by the DCU on the satellite and used by the ASU to synchronize the TDMA frame and SSTDMA subsystem frame hierarchies.
- *Reference Burst Distribution Region.* The RBD region immediately follows the metric region. It consists of two switch states which route the two reference bursts (RB1 and RB2) from their respective upbeams to the downbeams containing the RBD region.

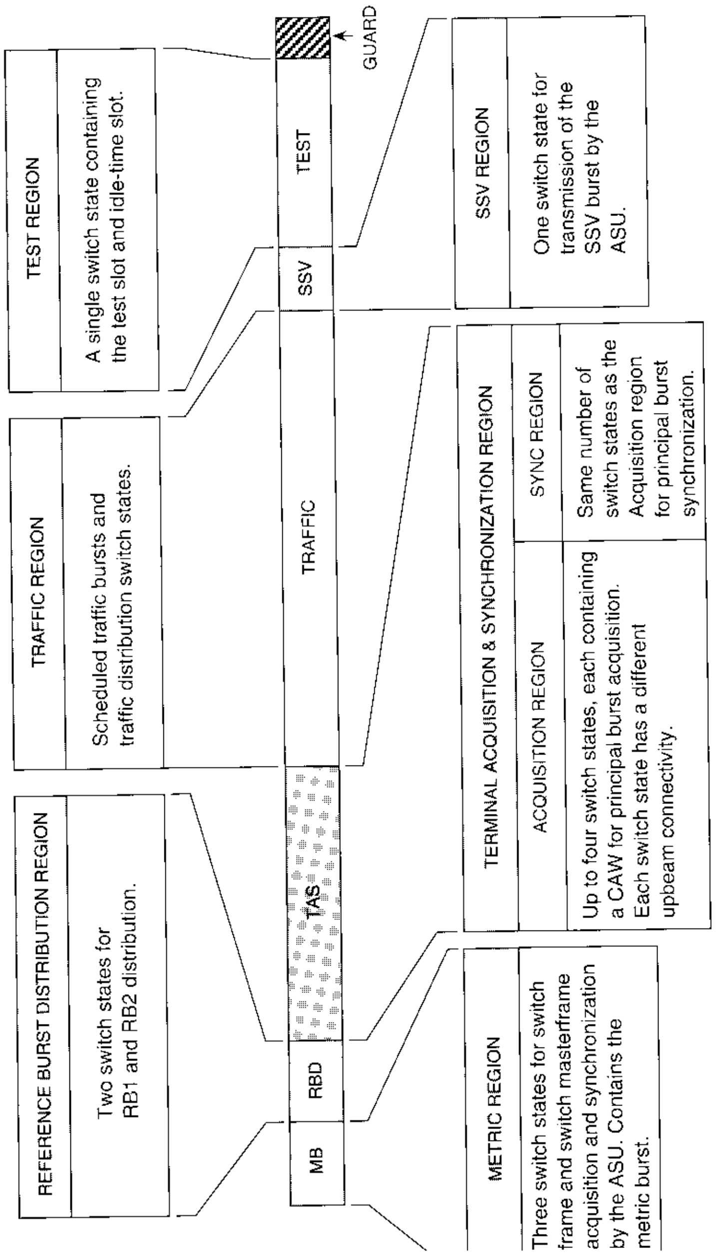


Figure 8. *SSTDMA Frame Structure*

- *Terminal Acquisition and Synchronization Region.* The TAS region always follows the RBD region in the frame. It contains two subregions: the acquisition region containing the common acquisition window (CAW), and the synchronization region into which terminals transmit their principal bursts.
- *Traffic Region.* This is the region into which terminals transmit their traffic bursts. It may be split into subregions, depending on the requirements for the overhead regions (MB, RBD, TAS, SSV, and test) in the downbeam. The switch state connectivities in this region depend on traffic distribution requirements.
- *Switch State Verification Region.* The SSV region always precedes the test region in the frame. It consists of one minimum-duration loopback switch state into which the ASU transmits the SSV burst. It is utilized by the MPRT during coordinated BTP changes.
- *Test Region.* This region always precedes the guard region in the frame. It consists of one switch state containing the test slot and idletime slot. The connectivity of this switch state is initially set to a default value, but may be changed by the database management system in the IOCTF.
- *Guard Region.* This is a minimum-duration, no-connection (NC) switch state. It is always the last switch state in the frame and protects the metric region from being preceded by a loopback connectivity, which would extend the duration of the metric loopback connectivity.

Not all of the above regions appear in every downbeam. Figure 9 shows the three possible types of frame structures, only one of which will appear in any given downbeam. The frame structure for metric transponders will appear in one east and one west downbeam only. These downbeams will contain a metric region and SSV region, as well as RBD and TAS regions. The second type of frame structure contains RBD and TAS regions, but no metric or SSV region. This type of frame will only occur in downbeams that illuminate reference terminals. The third type of frame contains RBD and traffic regions. All frame types contain a guard region and, optionally, a test region.

In general, except for the location of the metric burst and the principal burst spacing, the rules regarding burst spacing for fixed TDMA have been retained for SSTDMA. Switch state boundaries are constrained to occur on 64-symbol boundaries because the smallest interval of time in the onboard SSTDMA subsystem is the frame unit. The following subsections describe in detail the seven regions of the SSTDMA frame.

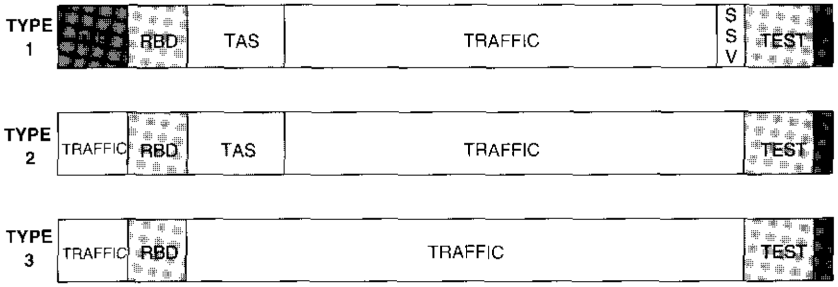


Figure 9. *SSTDMA Frame Types*

METRIC REGION

In order for a transmitted burst to arrive at the satellite at the same time that the SSTDMA subsystem establishes the connectivity to route the burst to its destination downbeam, the frame (timing) hierarchy in the TDMA system must be synchronized to that in the SSTDMA subsystem. The ASUs in both the MPRT and the SRTs maintain phase synchronization between the SSTDMA frame hierarchy and the INTELSAT VI SSTDMA subsystem frame hierarchy. Specifically, each ASU independently transmits a special burst, called the metric burst, into a special loopback switch state called the metric loopback switch state. The metric loopback switch state is always followed by an NC switch state, which prevents any burst from passing through the transponder for the duration of the switch state. The portion of the frame containing both the metric loopback and NC switch states is called the metric region.

The transponder from which an ASU receives it own metric burst is called its metric transponder. This transponder is also the reference control transponder of the associated SSRTE. If two transmission channels are supporting SSTDMA, the metric transponders may be in different transmission channels.

While the metric region comprises two switch states in any given frame, three DCU memory locations are needed to define the switch states for all frames. DCU memory locations 0 and 1 define the metric loopback and NC switch states for normal frames, while locations 0 and 2 define the metric loopback and NC switch states for the switch masterframe. The switch state defined by DCU memory location 2 is called the substitution switch state. Figure 10 illustrates the use of these switch states.

Figure 10 also shows how the ASU maintains synchronization between the TDMA frame and the switch frame on the satellite. The ASU transmits a metric burst into the metric transponder each frame interval. This burst propagates to the satellite and arrives in the metric loopback connectivity such that the

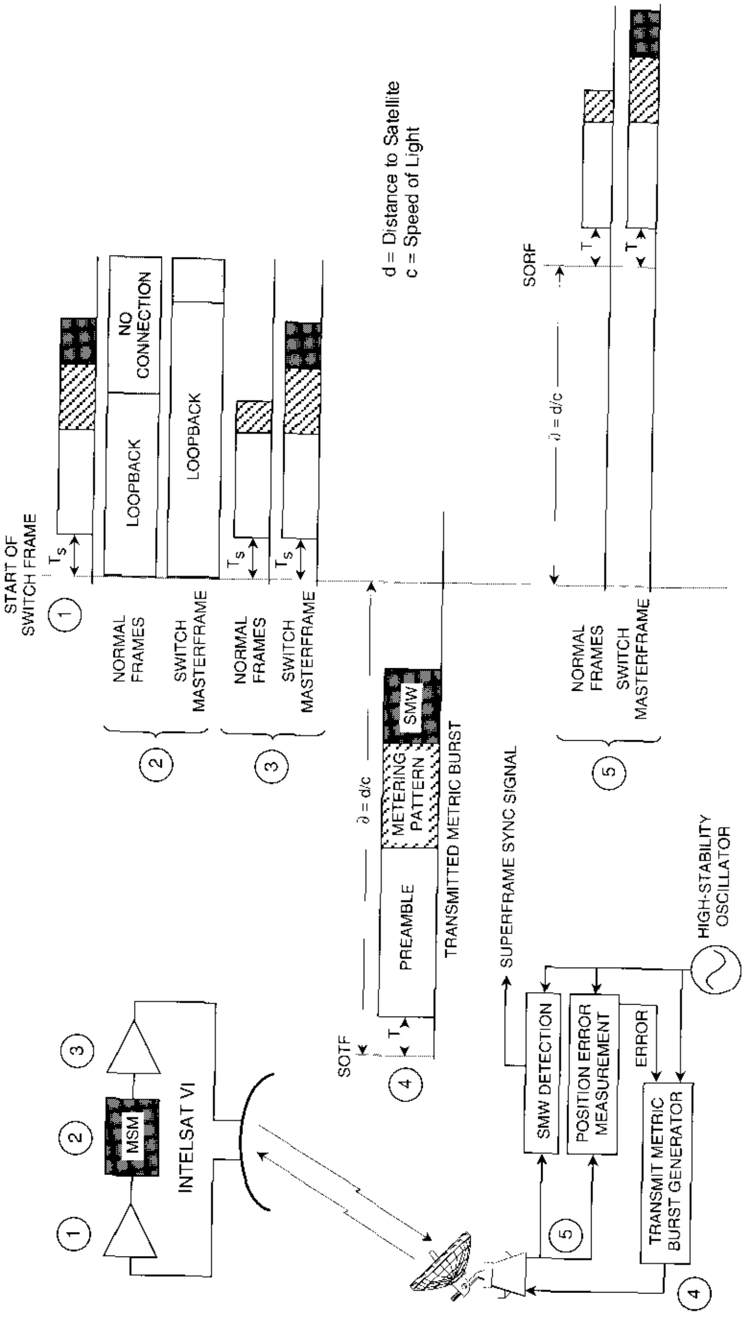


Figure 10. *Switch Frame and Switch Masterframe Synchronization*

connectivity terminates at a predefined point in the metric portion of the burst. The truncated metric burst then propagates back to the ASU in the metric transponder, where it is received. The ASU measures the number of symbols of error between the received metric pattern and the target cutoff point and adjusts its transmit metric burst position to compensate for the measured error. By continuously adjusting its transmit timing to eliminate metric position error, the ASU ensures that its start of transmit frame (SOTF) always tracks the start of frame (SOF) defined by the switch frame timing in the satellite.

In one frame during every switch masterframe interval, the metric loopback switch state is extended by including in the DCU a special switch state called the substitution switch state. During this switch state, the switch masterframe synchronization word (SMW) at the trailing end of the metric burst is allowed to pass through the MSM and be received by the ASU. The ASU synchronizes the SSTDMA superframe to the reception of the SMW. Since this event occurs only once each switch masterframe, the above process effectively synchronizes the TDMA superframe to the switch masterframe.

The location and duration of the metric region were important design considerations. Locating the metric region at the beginning of the switch frame and limiting the metric loopback switch state to 512 symbols provided a number of advantages to the system design. Locating the metric region at the beginning of the frame eliminated the need for the ASU to have a BTP, since the ASU would always expect the metric region to be found at the beginning of the frame. This simplified the BTP generation software, IOCTF database management, the time plan management software of the CADC, as well as the ASU itself. Eliminating the need for the ASU to have a time plan also eliminated the need for it to participate in coordinated BTP changes, again greatly simplifying the ASU design. Finally, limiting the duration of the metric loopback switch state minimized the impact on frame overhead, and at the same time enabled unambiguous metric acquisition and synchronization by the ASU.

In any given frame, the metric region comprises two switch states and one metric burst. Figure 11 shows the format of the metric region and metric burst. The metric loopback switch state begins at the first symbol of the switch frame (the SOF). This switch state is defined in switch state memory location 0. The next switch state will be either the substitution switch state or the metering switch state, depending on whether it is the first frame of the switch masterframe or a normal frame. Both the metering and substitution switch states are NC states only in the reference control transponders. The difference between these two switch states is the position in the frame at which they begin. The metering switch state begins 512 symbols after the SOF and is stored in DCU memory location 1; the substitution switch state begins 576 symbols after the SOF and is stored in DCU memory location 2. The DCU

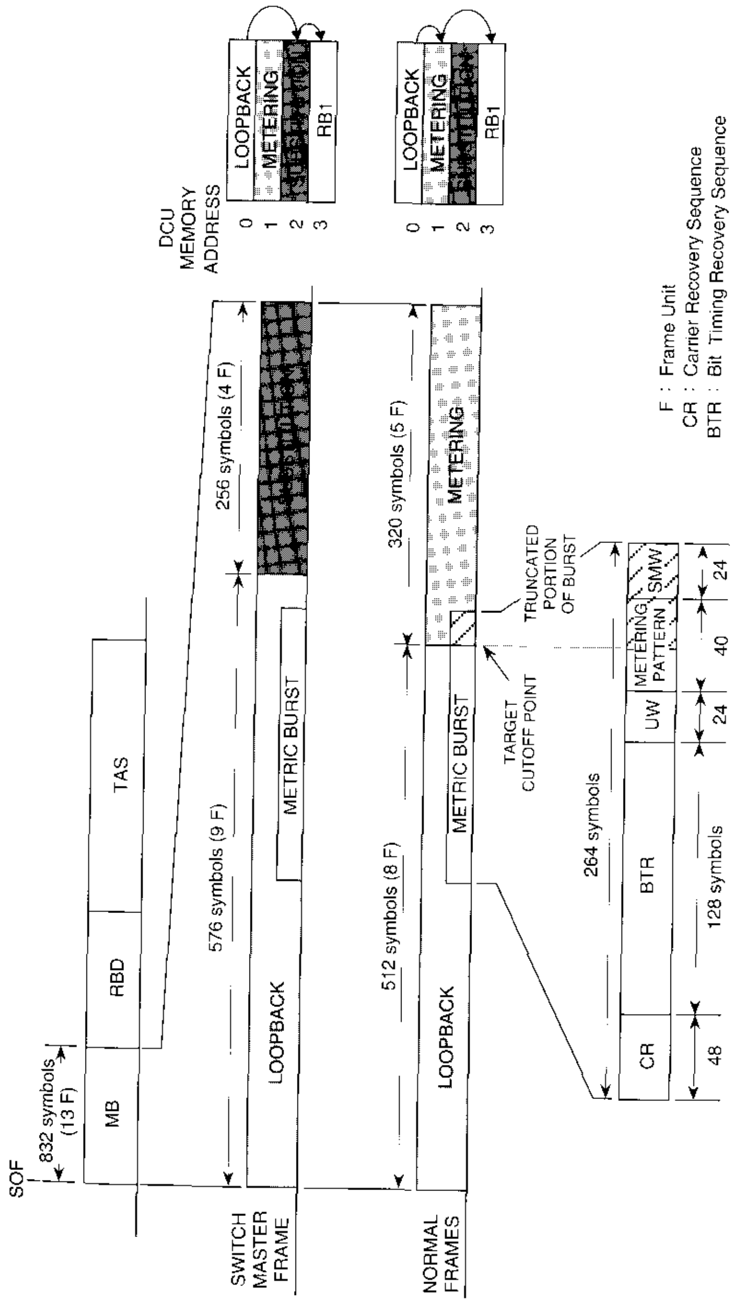


Figure 11. *Metric Region Structure*

reads memory location 1 and skips memory location 2 in every frame except the first frame of the switch masterframe, where it skips memory location 1 and reads memory location 2.

In addition to the normal metric burst, the MPRT ASU transmits a special acquisition burst during network startup. The format and use of this burst are described in Reference 11.

RBD REGION

In the fixed TDMA system, reference terminals access all transponders in their respective coverage areas. Thus, if a transponder has a west-to-east connectivity, the west reference terminal pair will transmit an RB1 and RB2 that can be received by the terminals in the east. Each reference burst pair will carry one of two possible control and delay channels (CDCs), each of which addresses control to a different set of terminals [1],[2],[5]. As in fixed TDMA, each reference terminal in the SSTDMA system can transmit into one to four upbeams. However, since there can be as many as 12 transponders in an SSTDMA network, the reference burst transmitted by a reference terminal in one upbeam may be switched by the MSM into a number of downbeams. The decisions concerning the upbeams into which a reference terminal should transmit reference bursts, which of the two CDCs the reference bursts should be associated with, and the downbeams into which the reference bursts should be switched are complex issues that are inextricably linked to other concerns such as interference immunity and future network growth. This complexity has necessitated development of the network configuration and control selection concepts discussed later in this paper.

Another design consideration for reference burst distribution is the location of reference bursts within the frame. In fixed TDMA, the two reference bursts transmitted by reference terminals in the same transponder are separated by approximately half a frame to prevent a misplaced burst transmitted by another terminal from interfering with both reference bursts in that transponder. Since reference bursts are transmitted in spatially isolated upbeams in SSTDMA, both reference bursts can be located adjacent to one another in the frame, to minimize fragmentation of the traffic portion of the frame.

The portion of the frame reserved for the distribution of reference bursts is called the RBD region. This region comprises two switch states: one defining the upbeam from which RB1 is received, and the other the upbeam from which RB2 is received. The duration of each switch state has been set to 512 symbols, which is just long enough to allow passage of a complete reference burst with guard space, thus minimizing the impact on overhead.

Since the metric transponder is also the reference control transponder, it may contain two loopback connectivities with durations of 512 symbols. Such a transponder is said to have two loopback appearances. The ASU must be aware of this condition in order to properly perform metric switch state acquisition [11]. Locating the RBD region immediately after the metric region eliminates any possibility of ambiguity for the ASU during metric switch state acquisition, and minimizes the impact of traffic region fragmentation. It also simplifies the burst location procedures in the BTP generation software because RB1 and RB2 are always located in the same place in the frame.

The onboard SSTDMA subsystem supports two transmission channels designated 1-2 and 3-4. During SSBTP generation, these channels are identified as transmission channel A or transmission channel B. If two channels are used in a time plan, one will be A and the other B. All reference bursts transmitted by an SSRTE in the same transmission channel are transmitted simultaneously. Reference bursts in transmission channel B are transmitted 512 symbols later than those in channel A to prevent simultaneous transmission of reference bursts in the same polarization. It should be noted that, while it may not be necessary to schedule reference bursts in every downbeam, every traffic terminal in the network must receive the reference bursts in its controlling transponder at the same location in the frame. Thus no traffic may be scheduled in any other transponder coincident with the RBD region.

Figure 12 depicts the structure of the RBD region and shows the location of the reference bursts. The reference burst format is identical to that for fixed TDMA; however, a number of modifications have been made to the reference service channel message repertoire. The Start of Plan Change and Notification of Plan Change messages used in fixed TDMA to coordinate a BTP change between the MPRT and PRT are no longer needed for SSTDMA. These messages have been deleted and a new message, called the Acquisition Cycle Interval Assignment message, has been added to the reference burst service channel repertoire [11].

TAS REGION

Redundancy between the MPRT and the SRT is dependent on both being able to control the same set of terminals. In fixed TDMA, both RTEs are located in the same coverage area, guaranteeing reception of the same downbeams. Locating both SSRTEs in the same coverage area would have unacceptable reliability and system monitoring penalties for the SSTDMA system. For this reason, the SSRTEs are located in opposite hemispheric coverage areas.

In the fixed TDMA system, one traffic burst (typically the largest) from each traffic terminal is designated as the principal burst and is used for control purposes by the controlling RTEs. However, in the SSTDMA system, there is no guarantee that each traffic terminal will transmit traffic bursts to both coverage areas. To ensure that both reference terminals receive a burst to be used

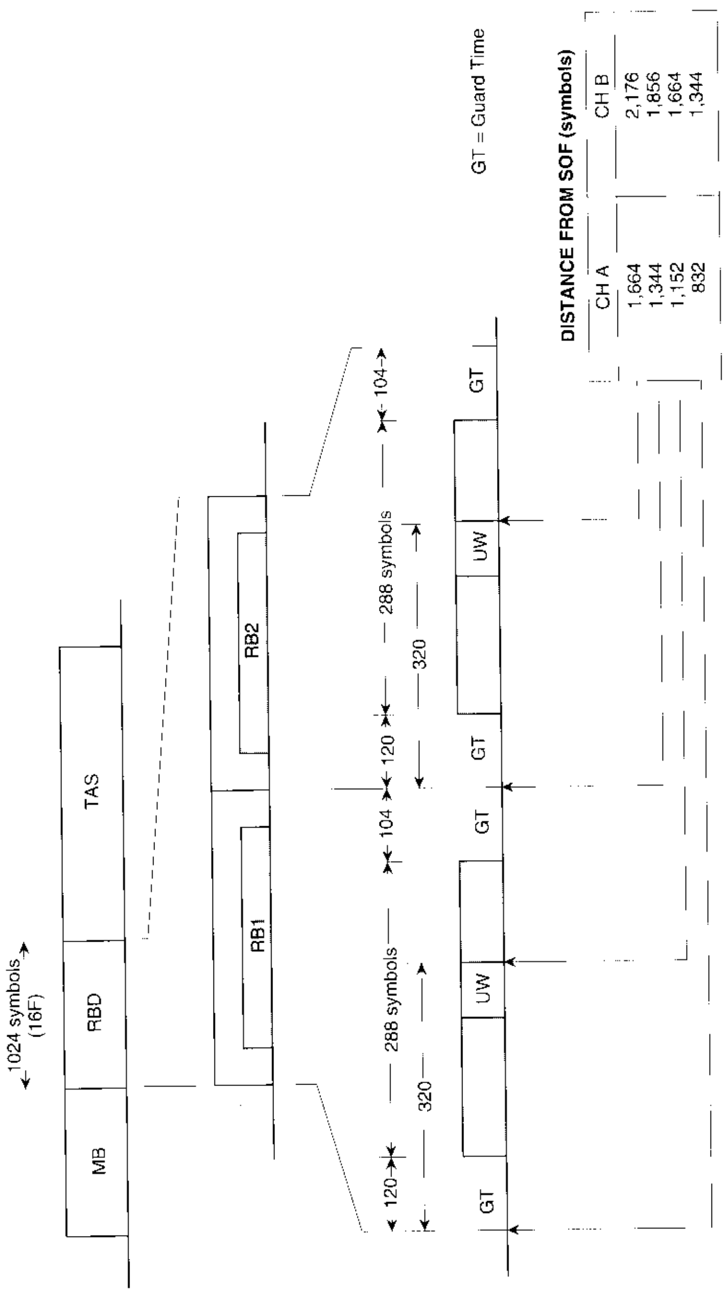


Figure 12. *RBD Region Structure*

for terminal control, a burst from each terminal would have to be semibroadcast to both coverage areas. Doing this with full traffic bursts would waste frame capacity and lead to scheduling difficulties.

The approach adopted was to set aside a frame region in the transponders that can be received by the SSRTEs (reference transponders), into which traffic terminals would transmit small principal bursts that carry no traffic. These principal bursts are semibroadcast to both SSRTEs. The portion of the frame set aside for this purpose is called the TAS region. One result of this approach is that the parallel method of acquisition can no longer be used, since the principal bursts are not sufficiently long to accommodate acquisition uncertainty. To allow all bursts to be acquired sequentially, each TAS region is separated into a CAW region and a synchronization region. Both of these regions are further subdivided into subacquisition windows (SAWs) and subsynchronization regions. During acquisition, a principal burst of the terminal is moved from its respective SAW to its subsync region. The duration of the SAW is a function of the worst-case acquisition uncertainty for any terminal acquiring in the SAW. The duration of a subsync region is a function of the number of principal bursts that the region must accommodate.

To minimize the impact of the TAS regions on the number of switch states in a time plan, the CAW region is placed before the sync region. Further, to minimize fragmentation of the traffic region, the TAS region is placed after the RBD region in the frame. The TAS region may comprise up to four connectivities, depending on the number of control upbeams assigned to the associated TAS group by the BTP generation program. Figure 13 depicts the TAS regions for the four possible connectivities. Two rules govern the ordering of connectivities within the TAS region. The first rule states that, if possible, the first connectivity in the CAW region should not be the same as the RB2 loopback connectivity in the RBD region, if the TAS region appears in the RB2 metric transponder. This rule was established to prevent destruction of the second loopback appearance required by the ASU for switch frame acquisition. However, it may not always be possible to generate a BTP in accordance with this rule. Such a case would occur when the RB2 loopback connectivity is the only connectivity in the TAS region. Consequently, provisions have been made in the ASU to perform switch frame acquisition using a single loopback appearance [11].

The second rule governing connectivity order is that the first connectivity of the sync region must be the same as the last connectivity of the CAW region. This rule is part of an overall attempt to minimize the number of switch states consumed by the overhead regions. Figure 14 shows the location of entities within the TAS region for a typical three-connectivity configuration. The CAW region contains one CAW that spans three different connectivities. The portion of the CAW in each connectivity corresponds to a SAW. Partitioning the CAW in

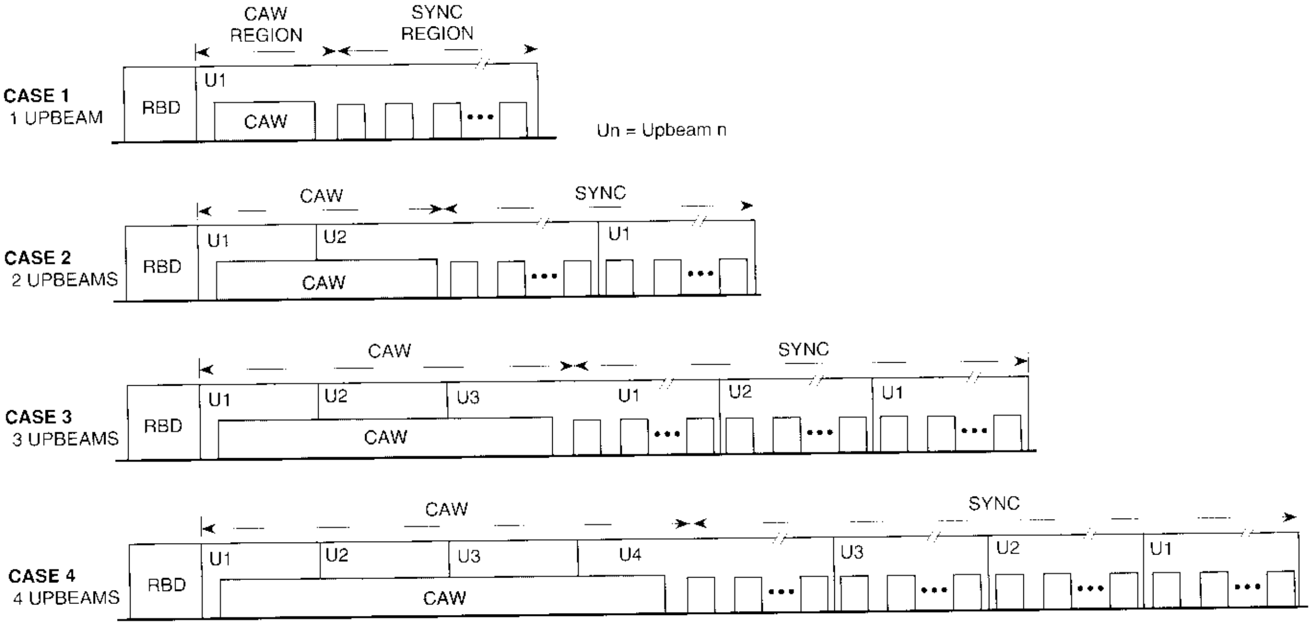


Figure 13. *Possible TAS Region Structures*

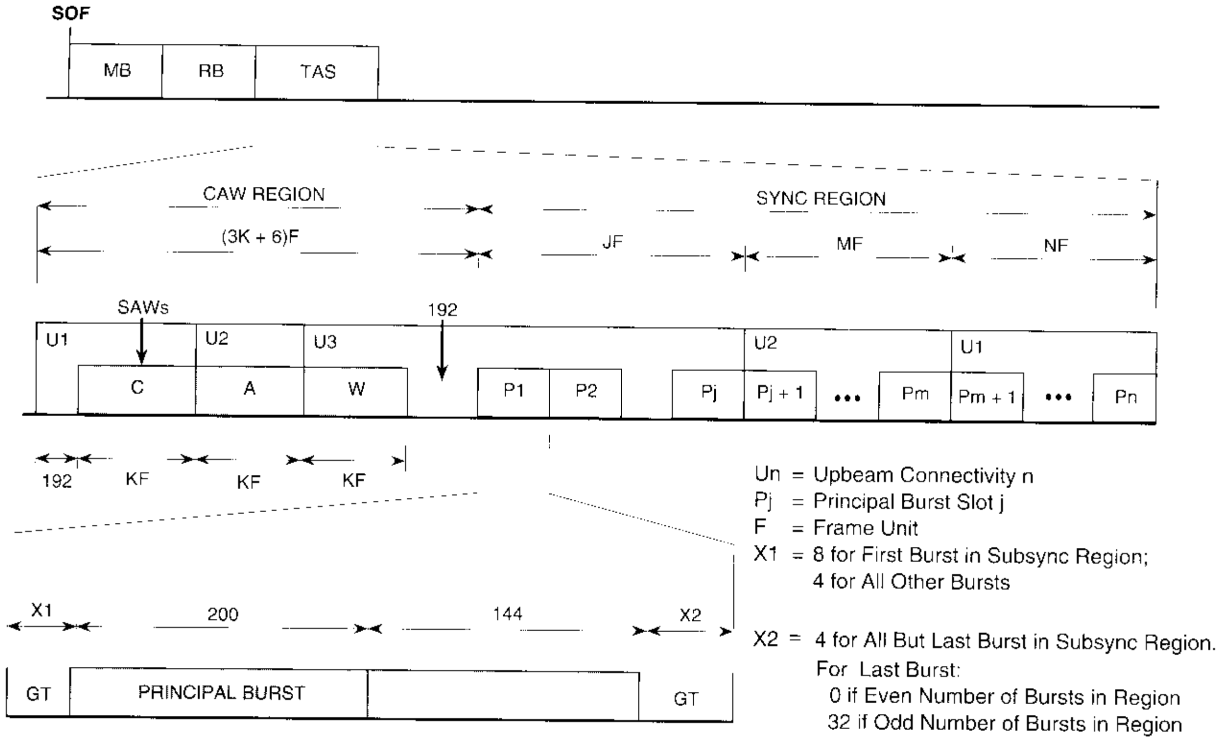


Figure 14. *Typical TAS Region Structure*

this way, instead of implementing different CAWs in each connectivity, eliminated the need for significant hardware and software redesign of the SPE. Maintaining the fixed TDMA design with one CAW, but changing the expected location of a burst within the CAW, resulted in a relatively minor firmware change.

Each SAW is nominally 2,048 symbols long. All terminals transmitting their principal bursts into the same upbeam will transmit their short burst into the corresponding SAW. The SSRTE computes the offset from the center of the CAW to the center of a terminal's SAW and subtracts this distance from the terminal's acquisition value of transmit delay.

There are as many subsync regions in a TAS region as there are SAWs, and each subsync region has a connectivity corresponding to one of the SAWs. Upon receiving a SYNC code from the SSRTE, each terminal will transmit its principal burst at the designated location in the subsync region corresponding to the SAW. Experience with existing fixed TDMA systems has shown that there is very little variation in principal burst position error from control frame to control frame. Therefore, to conserve frame overhead, it was decided to schedule only eight symbols of guard time between principal bursts. This can be done without affecting the 64-symbol guard space that traffic terminals expect to encounter between transmitted bursts. The principal burst, which comprises a normal preamble and an optional traffic channel, is defined in the condensed time plan (CTP) for each traffic terminal by code blocks 30 and 31. One subburst is defined to have a duration of 64 symbols, and no FEC is applied to this burst. Actual transmission of the subburst is optional; if transmitted, it need not be connected to a terrestrial interface module. Scrambling will be applied to the principal burst following the UW. The voice and teletype orderwires carried in the principal burst will always be the REF1/ISCC and REF2/ISCC orderwires.

TRAFFIC REGION

The traffic region consists of that portion of the frame in a transponder that does not contain overhead regions. Traffic terminals transmit their bursts into this region. In any transponder, the frame is partitioned into a number of connectivities, each carrying traffic bursts from a particular upbeam to that transponder. Bursts are spaced at least 64 symbols apart. The last symbol of the UW of any traffic burst is located on a symbol number of the frame that is divisible by 16. When transponder-hopping occurs on the transmit side, an additional 16 symbols of guard space are added between bursts transmitted from the same terminal. This situation might occur if one or more bursts from a terminal are scheduled in one upbeam coincident with a CAW region in another transponder, and the terminal must hop to an upbeam in the CAW region to transmit its principal burst. The normal traffic burst format is identical to the fixed TDMA traffic burst format specified in Section 4 of *INTELSAT Earth Station Standard* (IESS) 307 [20].

SSV REGION

An SSV burst is transmitted by the ASU to assist in determining the satellite SSTP status during a synchronous BTP change. The burst is transmitted into a minimum-duration loopback connectivity in the metric transponder. The loopback connectivity associated with the SSV burst is called the blind slot, and this region of the frame is called the SSV region. The use of the SSV burst and the blind slot switch state are explained later.

There is one SSV region in the metric transponder for each SSRTE. The region immediately precedes the test region, as illustrated in Figure 15, and has the same connectivity as the metric loopback connectivity. The SSV burst consists of a preamble only and is transmitted and received by the ASU. Each SSV region begins 117,312 symbols after the SOF and has a duration of 256 symbols (4 frame units). The last symbol of the UW of the SSV burst occurs 117,536 symbols after the SOF.

TEST REGION

As in fixed TDMA, the capability to perform burst mode link analysis (BMLA) and TSM noise floor measurements has to be provided in the SSTDMA

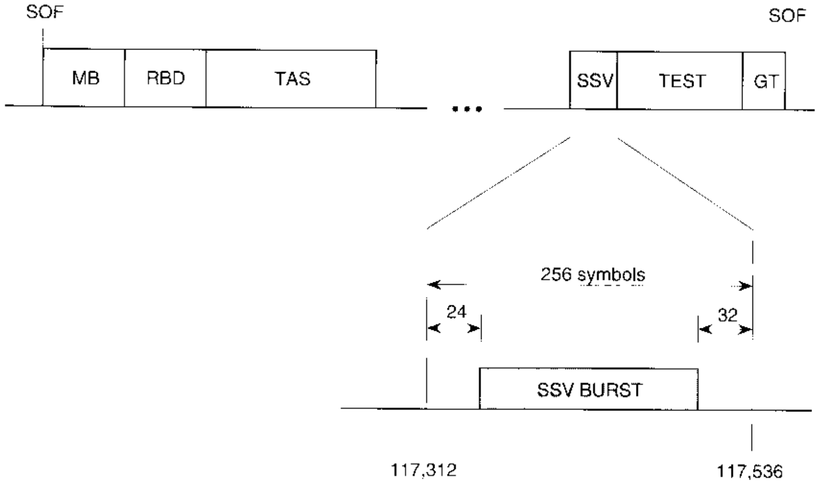


Figure 15. *SSV Region Structure*

system. BMLA testing requires that a test slot be provided somewhere in the frame, while TSM noise measurement requires an idletime slot somewhere in the frame. Both slots are connectivity-dependent.

Because of the dynamic switching capability of the INTELSAT VI satellite, a traffic terminal can correspond in one beam with terminals that transmit and receive in a number of other beams. In order for any single terminal to of perform BMLA testing with any other terminal in the network, every transponder would need to contain as many as six test slots, each with a different upbeam connectivity. Such a design would consume 15 percent of the total capacity of the system and is clearly an untenable solution. An alternative approach, adopted for SSTDMA, is to include one test slot in each transponder, but to allow the system to change the connectivity of this slot to accommodate a specific terminal-to-terminal connectivity. The SSTP Manager software in the HQS has been designed to perform this function under operator control; however, the test slot must occupy a single switch state and be easy to locate in the SSTP. Considering these requirements, along with the need to minimize fragmentation of the traffic region, the test region was specified as a single switch state that is time-aligned in all transponders and is located at the end of the frame, just prior to the guard region.

In fixed TDMA, the idletime slot is a 288-symbol region of the frame which contains no burst. The TSM uses this slot to determine the noise floor, in order to measure the carrier-to-noise ratio, *C/N*, of bursts in the frame. An idletime slot with a fixed connectivity is included in every transponder in the fixed TDMA system. As with the test slot, as many as six idletime slots, each with a different connectivity, would be needed to measure the noise for any given connectivity in the SSTDMA system. That is, every reference transponder would need to have 30 frame units allocated to accommodate this requirement. This, of course, is also untenable. The approach taken was to locate the idletime slot concurrent with the test slot. Default test slot connectivities are identified by the BTP generation system for each transponder, and reflect the connectivity most likely to be required by the TSM. Whenever a test slot connectivity is changed so that traffic terminals can perform BMLA testing, the TSM is notified by the HQS that the slot is busy and should not be used for idletime measurements. When the slot is no longer needed by the traffic terminals, the HQS operator can return the slot to the default connectivity.

Figure 16 shows the structure of the test region, which begins 117,568 symbols after the SOF. The 288-symbol idletime slot begins 16 symbols after the beginning of the test slot. The TSM measures receive signal power in this interval. Since there is no carrier present, this measurement represents the noise power in the transponder.

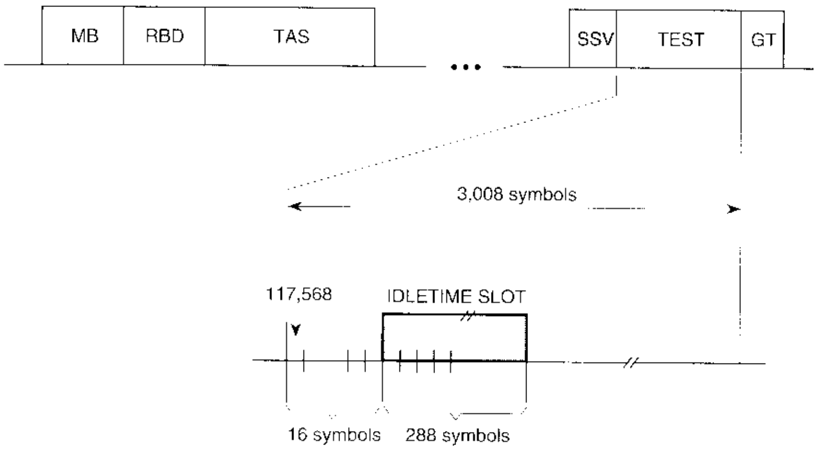


Figure 16. *Test Region Structure*

GUARD REGION

The guard region is the last switch state in the frame and immediately precedes the SOF for the next frame. The SOF guard switch state has NC in all transponders. Its purpose is to prevent extension of the metric loopback switch state due to occurrence of a loopback connectivity in the test region or traffic region which precedes it.

Network control selection

The previous section addressed the structure of the SSTDMA frame and the system design concepts affecting it. This section discusses the interrelationship of the various regions of the frame, and the way in which control elements are assigned within these regions to define an optimum network configuration. While the concepts discussed here are intrinsic to the SSTDMA network architecture, they are embodied in the SSBTP generation software discussed in a companion paper by Mizuike *et al.* [12].

Network control selection involves two processes: control assignment and control scheduling. Control assignment is the process of associating reference bursts and CDCs with RBD regions, and principal bursts with TAS regions. It is further subdivided into traffic control assignment and reference control assignment. Minimizing terminal equipment is important in the former, while interference and failure immunity are important in the latter. Control scheduling is the process of locating control bursts and connectivities within the SSTDMA frame.

Assignment of control in the SSTDMA system results in scheduling of frame overhead (reference bursts, principal bursts, and CAWs) in downbeams. For a given downbeam, the amount of control overhead reduces the frame space in which traffic can be scheduled. With high overhead and heavy traffic loading, it may be impossible to schedule all the available traffic. Thus, the two major considerations in control assignment are to minimize the amount of control overhead and to equalize its distribution among downbeams.

Traffic control assignment

Three functions are associated with traffic control assignment:

- *Control Group Assignment* assigns a pair of reference bursts for carrying control and timing information to groups of terminals called communities of controlled terminals.
- *CDC Assignment* assigns reference bursts to CDC-A or CDC-B and assigns a CDC address for the terminal within each CDC.
- *TAS Group Assignment* assigns a principal burst for each terminal in a community of controlled terminals to an upbeam that will be switched into a pair of downbeams received by both reference terminals.

CONTROL GROUP ASSIGNMENT

The control group assignment function is illustrated in Figure 17. For the case shown, the east reference terminal transmits a reference burst into one upbeam, and the west reference terminal into another. The bursts are skewed in time relative to the SOF so that there is no overlap and they arrive in the proper switch state. The pair of bursts is switched at the satellite into a number of downbeams, called control downbeams, which are received by a community of controlled terminals. A terminal can belong to only one community, and each terminal in a community takes control from only one control downbeam. The pair of beams into which the reference terminals transmit a given pair of reference bursts is called a reference beam pair. The group of control downbeams into which the reference bursts are switched is called a control group. Thus, all downbeams in a control group will have the same upbeam connectivity in the RBD region of the frame.

Because reference terminals can transmit into four upbeams, up to four reference beam pairs, control groups, and associated communities can be defined. The reference beam pairs are selected from the set of beams illuminating the reference terminals (reference beams) that carry SSTDMA traffic. The control downbeam for each traffic terminal may be defined as the priority downbeam for that terminal. Alternatively, the control downbeam may be forced to be a specific downbeam. A control loading factor is defined for each control downbeam and is the total number of terminals accessing that beam. Any downbeam assigned as a control downbeam is a constrained downbeam, while the remaining downbeams are unconstrained.

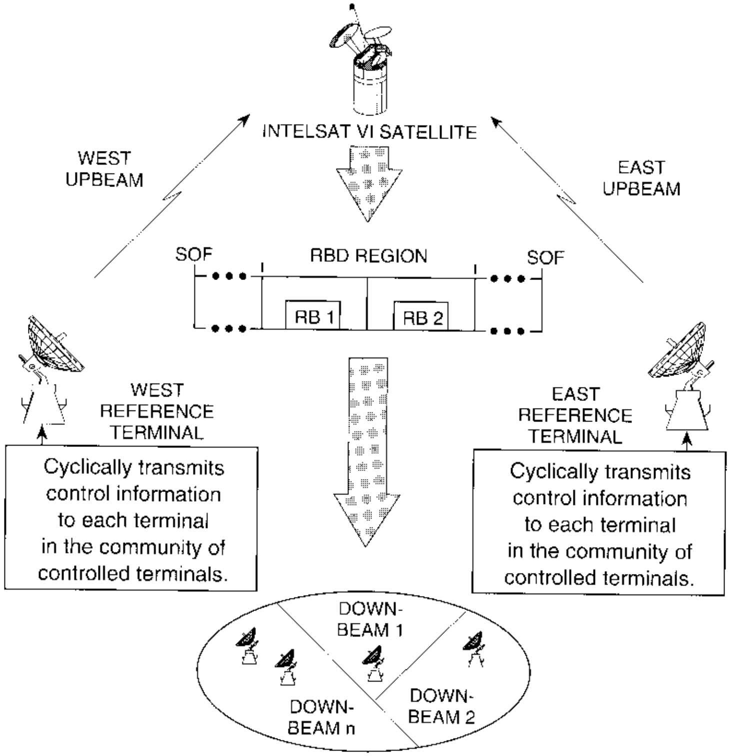


Figure 17. *Control Group Concept*

A control group is defined for each reference beam pair, and each constrained downbeam is assigned to a single control group such that the difference in the loading factor for each group is minimal. The control group loading factor is the sum of the control loading factors of the member downbeams. Equalizing the loading on each CDC in this way reduces the probability of one CDC being overloaded as the network grows.

The set of terminals accessing the control downbeams in a control group defines the community, and the number of terminals in the community is the same as the control group loading factor. Since control downbeams from one transmission channel cannot be assigned to a control group in the other channel, there can be a maximum of six beams assigned to any one control group. Consequently, if both an east and west reference beam do not exist in a transmission channel, then no beams in that channel can be used for terminal acquisition and control, since each control group must contain two reference beams. This guarantees that both reference terminals will have at least one control downbeam from which to receive control.

CDC ASSIGNMENT

CDC assignment refers to the association of either CDC-A or CDC-B with a reference beam pair, and the assignment of terminals to CDC addresses within each CDC cycle. In the SSTDMA system, CDC assignment follows a few simple rules. If two or more control groups are defined, there will normally be two CDCs. CDC-A or CDC-B is assigned to a control group such that the total number of terminals being controlled in each CDC is as nearly equal as possible. The sum of the control group loading factors for a CDC is called the CDC loading factor. By equalizing the CDC loading factors in this way, the possibility of overloading one CDC with more than 27 terminals is reduced and greater freedom is provided for future expansion of the network.

Each terminal is assigned a CDC address in the CDC associated with the control group it accesses. Terminals with the greatest amount of traffic are assigned the lowest CDC addresses. During network startup, terminals are acquired sequentially in increasing CDC address order.

TAS GROUP ASSIGNMENT

The TAS group assignment function is illustrated in Figure 18. Each terminal in a community must transmit its principal burst into an upbeam called a control upbeam. The group of control upbeams associated with a community of controlled terminals is called a TAS group. Each upbeam in a TAS group is consecutively switched into the TAS region in the downbeams of the reference beam pair associated with the community. Thus, the principal bursts of the terminals in a community will return to the reference terminals in the downbeams of the reference beam pair which contains the reference bursts controlling that community. From the perspective of a reference terminal, each community is controlled independently.

The control upbeam for each terminal is defined to be the priority upbeam designated for that terminal. Alternatively, the control upbeam may be forced to be a specific upbeam. Any upbeam assigned as a control upbeam is a constrained upbeam, while remaining upbeams are unconstrained. In addition, the upbeams corresponding to the control downbeams for the reference terminals are constrained, even though they might not be assigned as control upbeams. This guarantees that a subacquisition region is scheduled for each referenced terminal.

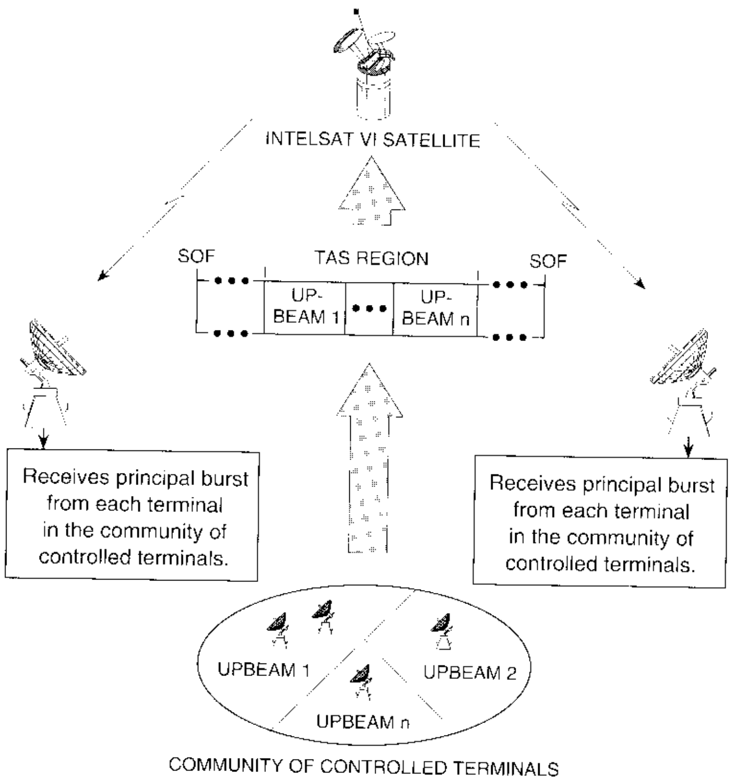


Figure 18. *TAS Group Concept*

As with the control group, a TAS group will be defined for each reference beam pair and will consist of one or more control upbeams. A TAS group can contain a maximum of four upbeams. This limitation is designed to prevent the scheduling of excessive overhead in a reference beam pair, which may limit traffic scheduling capability. After all TAS groups are assigned for constrained terminals, beams are constrained and assigned to existing TAS groups to ensure that every unconstrained terminal can transmit its principal burst into at least one TAS region. As a result, some unconstrained terminals may be able to access control upbeams in more than one TAS region, or multiple upbeams in the same TAS region.

Reference control assignment

Overlaying the assignment of reference beam pairs, control groups, and TAS groups is the assignment of control upbeams and downbeams for the two reference terminals. The control downbeam has special significance for an

SSTDMA reference terminal. Besides being the downbeam in which the reference terminal receives control, it designates the loopback connectivity for the metric and SSV bursts. A reference control downbeam must have loopback connectivity in the RBD region so that, if the partner reference burst disappears, the reference terminal will still receive its own reference burst.

Each reference terminal contains a front-end screening device that allows only the RBD and TAS regions to be received by the SPE. A necessary condition for interference immunity is that the connectivities contained in the RBD and TAS regions in each reference control downbeam are different. An interference immunity configuration will most likely occur if the reference control downbeams are chosen from control groups that have different CDC associations. If these groups are in different transmission channels, the configuration will definitely be immune, regardless of the immunity configuration within either channel. Such a configuration also affords an extra level of failure protection in that a row or column failure in either MSM, or a double bit-flip in a DCU memory, will not affect the control transponders of both reference terminals.

Interference protection

Although the MSM offers many advantages to the SSTDMA system, it also increases the distribution of interfering signals to a greater portion of the network. In many SSBTPs, every upbeam connectivity may appear in every transponder. Thus, a continuous interferer, such as a swept CW signal in one upbeam, will appear in all downbeams containing a switch state that has the upbeam connectivity of the interferer.

While the SSTDMA frame format cannot be arranged to eliminate the effects of an interferer on traffic terminals, steps have been taken in the design of the SSRTE and the assignment of connectivities to the RBD and TAS regions to prevent complete failure of the network. Two IF screening switches have been included on the SSRTE receive side. One switch connects the ASU demodulator to the metric down-chain only during the time slots occupied by the metric and SSV regions. Thus, the ASU demodulator will only be exposed to an interferer in the metric loopback connectivity. The second screening switch connects the SPE demodulators to their respective down-chains only during the RBD and TAS regions. Consequently, an SPE demodulator will only be exposed to an interferer in one of the upbeam connectivities in the RBD and TAS regions.

Judicious selection of the connectivities in the RBD and TAS regions under certain network configuration conditions can result in what is termed an interference-immune configuration [6]. In such a configuration, while some or all traffic terminals will be affected by the interferer, at least one SSRTE will be totally unaffected and will be automatically available to reacquire failed terminals as soon as the interference ceases.

In addition to screening and interference immunity control selection, a mode of operation called the interference survival mode has been designed into the SSRTE. This allows the SSRTE to automatically enter network startup in an interference-nonimmune configuration in which the interferer does not appear in the metric loopback connectivity and causes only the SPE to fail. Details of the interference survival mode are discussed in Reference 11.

Network procedures

Most new procedures defined for the SSTDMA system involve only one physical element in the system, such as the SSRTE, IOCTF, or ISCC. These procedures are discussed in companion papers addressing the specific elements [11],[12],[15],[18]. There are, however, two procedures which involve every element in the system: TSO correction and BTP change. The interaction of the various system elements involved in implementing these two procedures is discussed here.

Onboard clock (TSO) correction

Plesiochronous (nearly synchronous) operation of international digital circuits requires highly accurate and stable clocks on both sides of the international connection. As defined in International Telephone and Telegraph Consultative Committee (CCITT) Recommendation G.811 [21], these clocks must have a long-term accuracy of 1 part in 10^{11}. In TDMA, the clock on the terrestrial side is supplied by the national network. On the satellite side, the clock is supplied by the common TDMA terminal equipment and is synchronized to the 2-ms TDMA frame.

The SSTDMA frame is synchronized to the SSTDMA subsystem switch frame, which is generated from the satellite TSO. The TSO has a specified worst-case drift of 5 parts in 10^{11} per day. To comply with CCITT Rec. G.811, the TSO frequency must be controlled relative to the high-stability local timing source (LTS) at the reference terminals. The LTS is a cesium oscillator with a long-term accuracy of 1 part in 10^{11}. Figure 19 is a block diagram of the overall TSO correction system, and a brief system overview is provided here. Details of the TSO correction system are given in a companion paper by Maranon *et al.* [18].

TSO correction involves the following three functions, which are performed in various elements of the network:

- *Oscillator phase error measurement* is performed at the ASUs in each reference terminal. The phase error is periodically transmitted to the IOCTF.

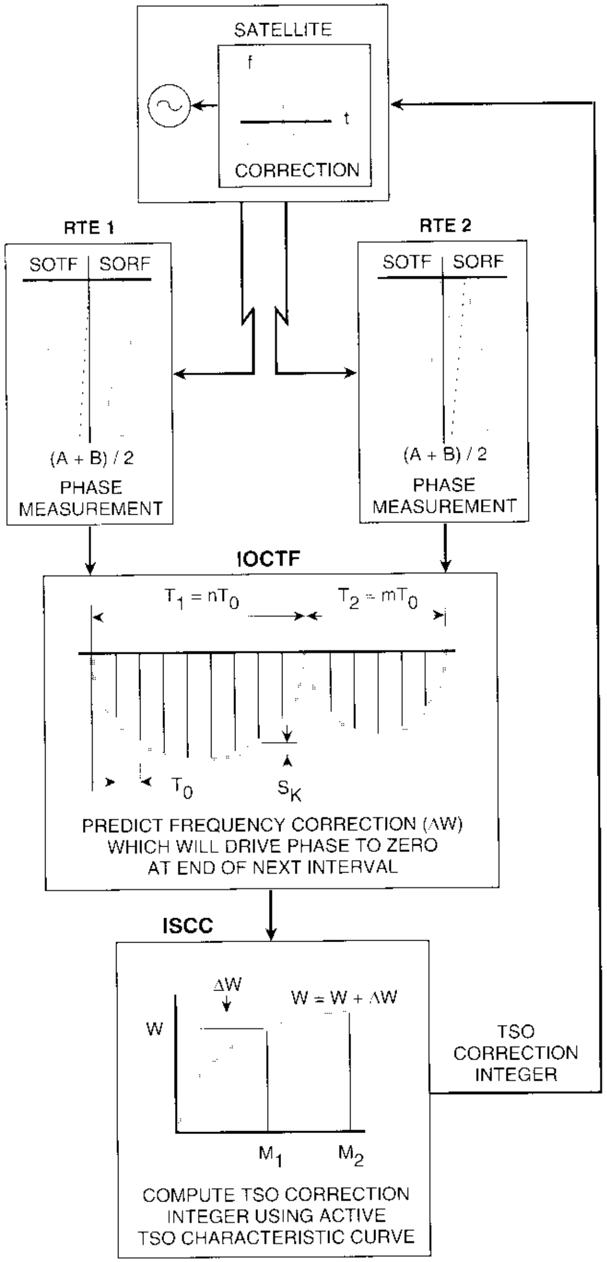


Figure 19. *Overall TSO Control System*

- *Clock correction prediction* is performed at the IOCTF using the phase error reported from the reference terminals. The prediction algorithm operates over a relatively long interval (typically 15 to 30 days) and predicts how much frequency correction must be applied to the oscillator on the satellite to cause the accumulated phase error to return to near zero over the next correction interval.
- *Oscillator correction* is performed at the ISCC. The oscillator control integer to be transmitted to the satellite is computed based on the cumulative value of frequency corrections and the characteristic curve for the on-line oscillator. Once computed, the value is transmitted via telemetry to the spacecraft.

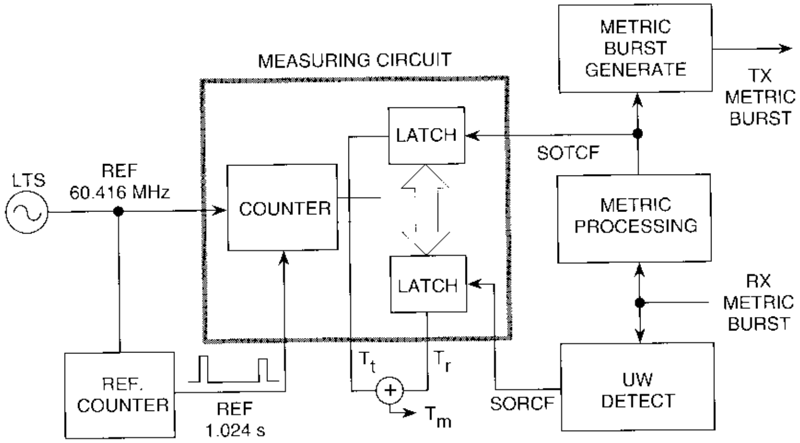
PHASE DIFFERENCE MEASUREMENT

The ASUs at the MPRT and SRT periodically measure the phase of the switch frame relative to the SSRTE LTS, using an innovative technique developed by NEC which automatically eliminates Doppler effect from the measurement. Figure 20 illustrates this method. First, the 60.416-MHz symbol clock derived from the LTS oscillator is provided to the phase measurement circuitry. A flywheel counter provides a reference pulse having a periodicity of one control frame (1.024 s). A measuring circuit then computes the midpoint between the start of transmit control frame (SOTCF) and the start of receive control frame (SORCF) at each superframe boundary, and measures the (initially arbitrary) position of this point relative to the reference pulse. The movement of the SOTCF due to path length variation is equal to (but in the opposite direction from) that of the SORCF [14],[18]. Thus the midpoint is unaffected by satellite movement. However, due to a frequency difference between the TSO and LTS, movement of the SOTCF and SORCF relative to the reference pulse will be equal and in the same direction. Thus the midpoint will move relative to the reference pulse in proportion to the TSO frequency inaccuracy.

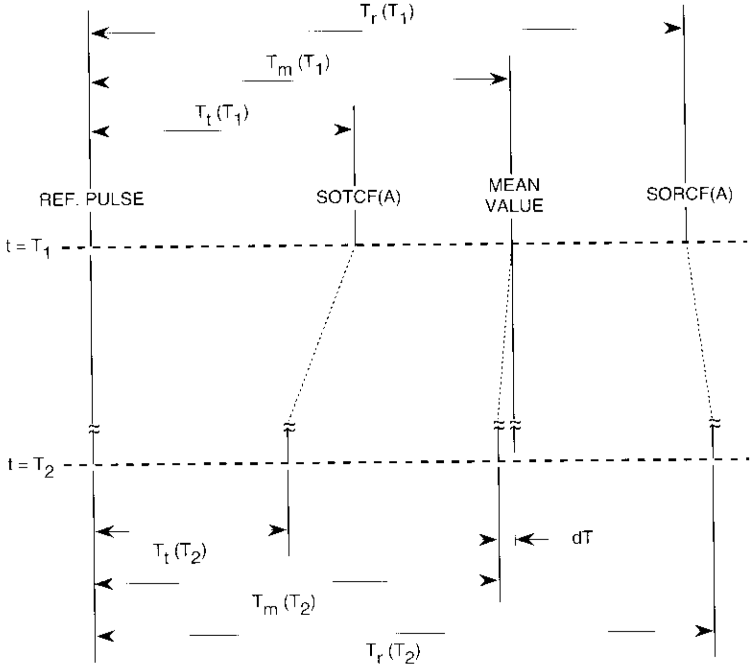
Once during each control frame, both the on-line and standby ASUs in an SSRTE report the phase (the number of symbols between the reference and the midpoint), and the phase change from the last control frame, to the CADC. The CADC then calculates a local cumulative phase term based on the values reported by the on-line ASU and reports this value to the IOCTF once each clock phase reporting interval.

CLOCK CORRECTION PREDICTION

At the IOCTF, cumulative phase difference for the system is computed using data from either the MPRT or SRT (if MPRT data are unavailable). The IOCTF receives periodic phase error measurements (relative to a terrestrial cesium



(a) Measurement Circuit



(b) Measuring Principle

Figure 20. *Phase Difference Measurement Method*

reference) from each SSTDMA reference terminal and computes a local cumulative phase error for the system using the phase reported from the MPRT or SRT. The current phase, oscillator frequency, and drift performance are computed and logged each reporting interval, and an unscheduled frequency correction is requested if the phase exceeds a preset threshold. The IOCTF also computes a TSO correction interval consistent with TSO drift performance and INTELSAT operational requirements. The amount of frequency correction required to drive the cumulative phase error to zero over the next correction interval is then predicted and reported to the ISCC at the end of the current correction interval.

FREQUENCY CORRECTION

When a correction is requested by the IOCTF, the ISCC computes the new TSO control integer for the on-line TSO in the spacecraft by adding the incremental correction requested to the sum of all previous corrections since startup. This value is then added to the nominal oscillator frequency of 5.664 MHz. The characteristic curve for the specific TSO is used to determine the value of control integer that will result in the smallest quantization error. The computed TSO control integer is then sent to the TTC&M station for transmission to the spacecraft.

SSBTP change

Changing a BTP in an INTELSAT TDMA or SSTDMA system is a multiphase process involving generation of the BTP, distribution of the BTP to the network elements, and coordinated execution of the BTP change. SSBTP generation is covered in detail in Reference 12; distribution and execution are discussed here.

SSBTP DISTRIBUTION

In fixed TDMA, only traffic and reference terminals require BTPs. The coordinated execution of a BTP change involves only these terminals, and the IOCTF participates in the process only by distributing and verifying the BTP to the reference and traffic terminals. Distribution is more complex for SSTDMA; Figure 21 illustrates the overall SSBTP distribution process. New elements requiring a BTP in the SSTDMA system include the INTELSAT VI satellite, diagnostic receiver, NRDE, and diagnostic processor. The SSBTP database manager is responsible for distributing the time plans to these elements. Coordinated execution of an SSBTP change involves the SSRTE, traffic terminals, and the satellite; other elements change time plans asynchronously.

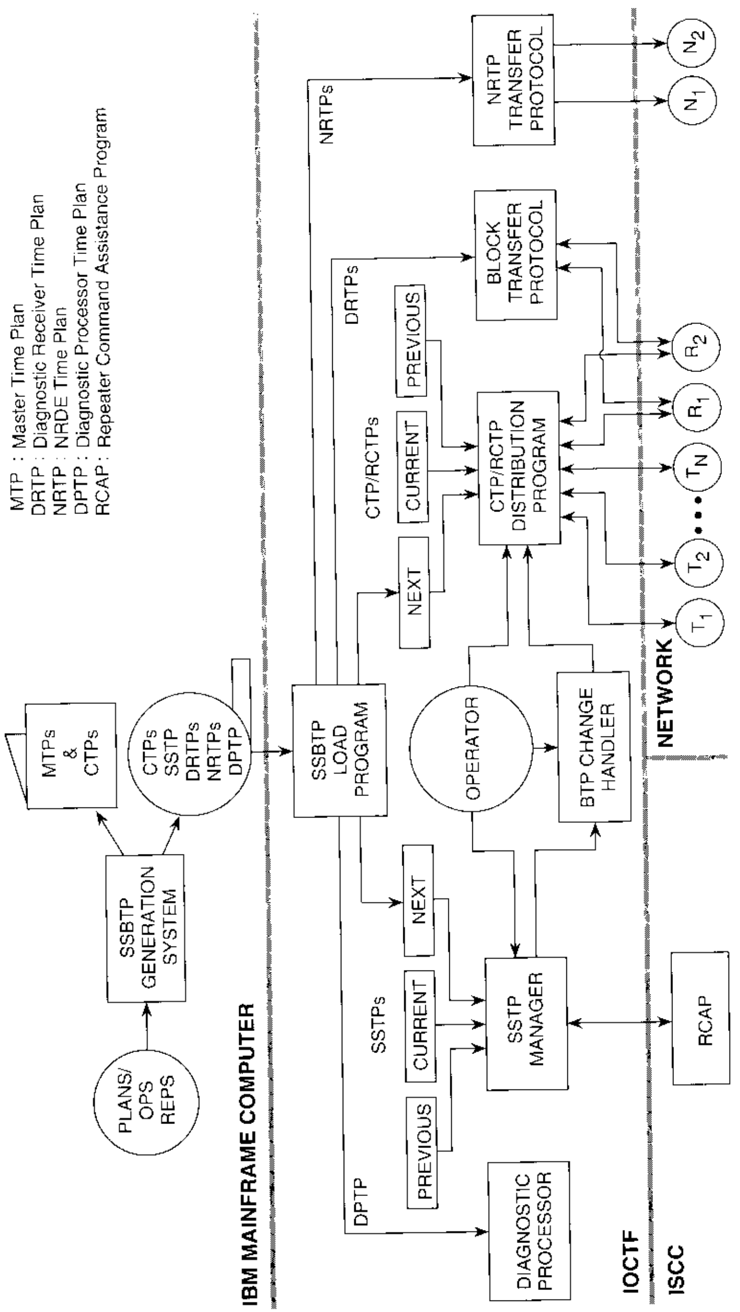


Figure 21. *SSBTP Distribution*

Since the INTELSAT VI satellite is involved in the coordinated SSBTP change, the HQS must also be actively involved. In its role as the hub for all data communications within the SSTDMA system, the IOCTF coordinates events between the SSRTEs and the ISCC. The IOCTF software that performs this function is called the SSBTP change manager (SSBTP CM).

The ISCC commands the satellite so that the satellite SSTP changes at the proper instant relative to the SSBTP change at the SSRTEs and traffic terminals. This function is performed by the SSTP change manager (SSTP CM) software in the ISCC. The SSTP CM receives SSTPs from the ISCC, loads these plans into the DCU memories of the satellite, and manages the on-line, off-line, and standby status of these memories in accordance with the type of SSTP change required. Four types of SSTP changes are identified in the SSTDMA system:

- *Type 1 Change* facilitates implementation of a non-TDMA connectivity change via the MSM, instead of through the normal static bypass switch. Type 1 changes are implemented asynchronously under manual control at the ISCC.
- *Type 2 Change* facilitates a specific SSTDMA connectivity change such as test slot connectivity reassignment. Type 2 changes are implemented asynchronously under manual control at the ISCC.
- *Type 3 Change* facilitates changing the SSTP in coordination with the BTP in the SSTDMA system. Type 3 changes are implemented under semi-automatic control, requiring only operator sanction of automatically generated command sequences.
- *Type 4 Change* facilitates changing the blind slot SSTP prior to the execution of a coordinated SSBTP change. Type 4 changes are implemented under manual control prior to the execution of a Type 3 change.

Under normal conditions, the content of the on-line and off-line DCU memories in the spacecraft will be the same. This SSTP is referred to as the current normal (CN) SSTP. The off-line memory is continuously monitored for accuracy via telemetry. When a Type 1 or 2 SSTP change is requested, the SSTP CM in the ISCC loads the required SSTP under operator control, either by accessing the SSTP data file in the ISCC, or from magnetic tape. This usually takes place several days prior to the required time of change. The new SSTP is referred to as the new normal (NN) SSTP. After the NN SSTP is loaded and its validity checked, the command sequence is generated for loading the NN SSTP into the off-line DCU memories. Transmission of the command sequence is initiated under operator control. Once loaded, the content of the off-line memories is verified via telemetry. Upon verification, the command sequence to switch the off-line memories to on-line is generated and transmitted to the spacecraft under operator control. This action activates the new SSTP. Further details concerning Type 1 and 2 SSTP changes are provided in References 12 and 13. Any time the content or status of a DCU memory is modified, the SSTP CM in the ISCC transmits the DCU Memory SSTP Status message to the ISCC via the ISCC data link.

When a Type 3 SSTP change is requested, the SSTP CM will actually execute a Type 4 change, followed by a Type 3 change. The SSTP CM will load two SSTPs under operator control, either by accessing the SSTP data files in the ISCC, or from magnetic tape. One of these SSTPs is the NN SSTP and the other is the blind slot (BS) SSTP. The BS SSTP is used to change the SSV switch state to NC, thus blocking the SSV burst and causing the SSRTE to declare BS Active. Since coordinated (Type 3) BTP changes are planned well in advance, the above actions take place several days to a week prior to the required time of change. After both time plans are loaded and their validity checked, the command sequences for loading both the BS and NN SSTPs into the off-line DCU memories are generated. Transmission of the command sequence to load the BS SSTP to the off-line memories is initiated under operator control at least 1 hr (and normally 2 to 24 hr) prior to the expected time of change. The off-line memories containing the BS SSTP are switched on-line by operator command at least 30 minutes prior to the expected time of change, and the NN SSTP is then loaded to the off-line memories. The ISCC continuously monitors the SSTP in the off-line memory via telemetry until the plan is ultimately switched on-line during the synchronous SSBTP change.

SSBTP CHANGE PROCEDURE

The SSBTP change procedure differs from that for fixed TDMA in two major respects. First, the entire procedure must now include commanding of the satellite in order to synchronize the change of the satellite SSTP with the change in CTPs in the ground segment terminals. Second, since there is no primary RTE in SSTDMA, the MPRT has complete control of the procedure.

The fixed TDMA BTP change procedure was designed to achieve a changeover of foreground and background CTPs synchronized to the transmit and receive superframes at all terminals, in recognition of the eventual migration of the system to SSTDMA operation. To synchronize the satellite commanding with the SSBTP change procedure in the MPRT, the following approach is taken. The overall procedure is illustrated in Figure 22.

The commanding necessary to rotate on-line and off-line memories in the DCU consists of setup commands, followed by an execute signal. The memory rotation takes place on the next superframe boundary after reception of the execute signal. To ensure that the execute signal is transmitted at the correct

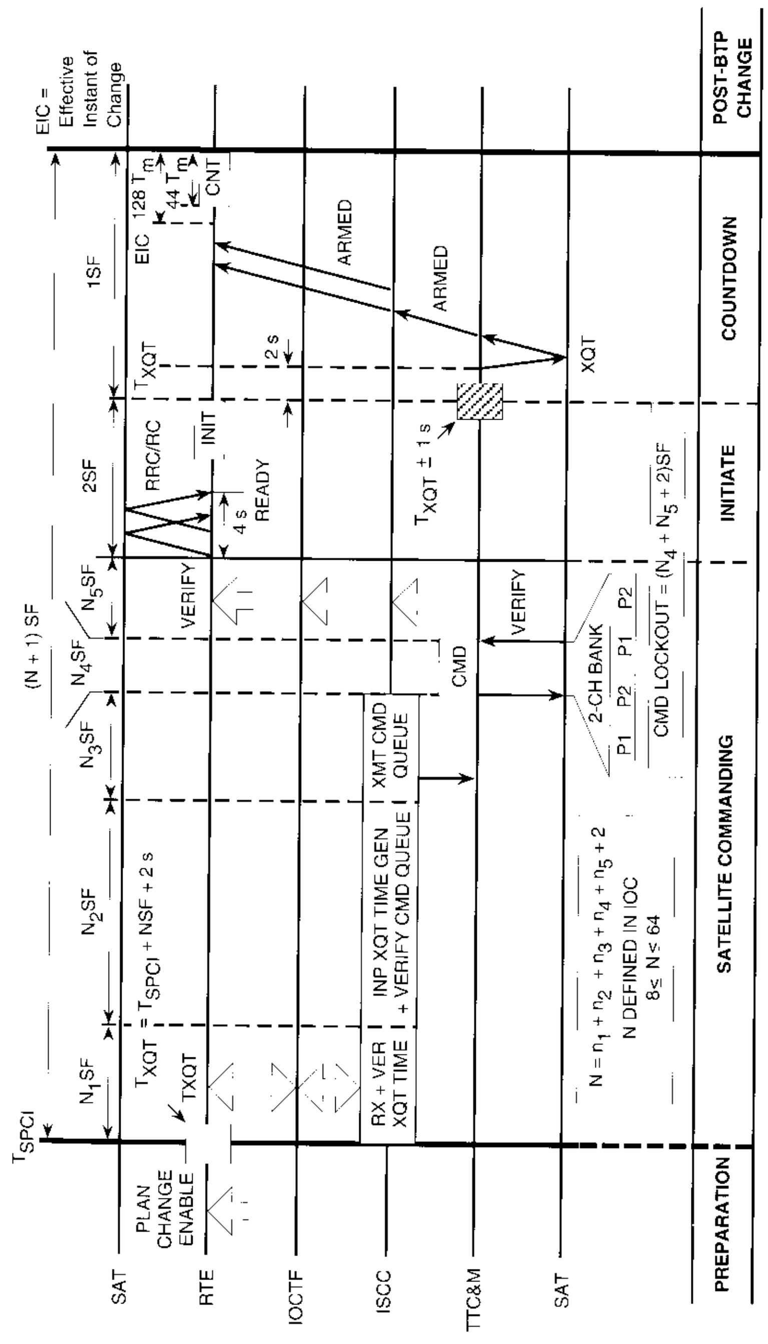


Figure 22. SSBTP Change Procedure

time relative to the SSBTP change procedure, the MPRT calculates the Universal Time Coordinated (UTC) time at which the execute command should be transmitted. This calculation is based on local knowledge of the time of occurrence of the start of transmit superframe relative to UTC time at the MPRT. The UTC time at the MPRT is synchronized to the UTC time at the ISCC, based on reception at the SSRTE of an international time standard signal such as the Global Positioning System signal. The calculation accuracy for the execute time is ±1 s. The execute time can be calculated by the MPRT up to 18 minutes in advance of the actual time, to allow for manual setup of the command sequence if necessary.

After satellite commanding (including the execute signal) has been transmitted, the HQS will detect from telemetry that the satellite has received the execute signal. The HQS then sends the SSTP Change Armed message to the MPRT. Reception of this message at the MPRT allows the BTP change to proceed. If the SSTP Change Armed message is not received, the MPRT will suspend the procedure and attempt to recover from the situation.

This recovery process, known as fail-safe recovery, will be used when it is uncertain whether the satellite memory roles will be rotated at the superframe boundary. To perform fail-safe recovery, the MPRT uses the SSV burst. Long before a BTP change is to take place, an SSTP change is performed in which the SSV switch state is changed from loopback to NC. When this occurs, both SSRTEs lose reception of the SSV burst, which results in declaration of the Blind Slot Active condition. It is a requirement of the reference terminals that a BTP change cannot be initiated unless Blind Slot Active is declared.

When the MPRT suspends the BTP change procedure, it waits until the superframe boundary on which memory rotation should have occurred. If the rotation took place, then the Blind Slot Active condition will no longer be declared, and the MPRT will immediately continue with the BTP change procedure. On the other hand, if the rotation did not occur, the Blind Slot Active condition will continue to be declared. In this case, the MPRT will declare BTP Change Failed and the network will continue as before.

The impact on the network of asynchronously executing the BTP change will be a 1- to 2-s loss of traffic for terminals whose burst positions and lengths are either modified or occur in switch states that are modified. Further details regarding the SSBTP change procedure as it pertains to the IOCTF, ISCC, and SSRTE are provided in References 12, 13, and 14, respectively.

Implementation, testing, and transition to operation

Implementation of the first SSTDMA system in the AOR on the 335.5° INTELSAT VI satellite was a massive endeavor involving the design, testing, and installation of the SSRTEs, the IOCTF (including the diagnostics subsystem), the ISCC SSTDMA subsystem, and the SSBTP generation software. This effort took place between the end of 1987 and mid-1989. In mid-1989, two SSRTEs were installed, one at Tanum earth station in Sweden, and the other at Etam earth station in West Virginia, U.S.A. System testing over the first INTELSAT VI satellite (INTELSAT 602) took place in late 1989 and early 1990. The first INTELSAT SSTDMA system, on INTELSAT 602, went into operation on May 19, 1990. Testing of the second SSTDMA system using the IOR 60.0° INTELSAT VI satellite began in late 1991, with SSRTEs located at the new Beijing earth station in China and at Reisting earth station in Germany. This system began operation on January 31, 1992. A companion paper by Kullman *et al.* [22] gives a detailed description of the deployment, testing, and transition to service of these SSTDMA systems.

Conclusions

The INTELSAT SSTDMA system represents the most advanced commercial communications system ever implemented. The INTELSAT VI satellite, with its two SSTDMA transmission channels, provides a number of major advantages over fixed TDMA, including improved connectivity, reduction in traffic station uplink and downlink equipment, more even distribution of traffic in beams, a reduction in the number of reference terminals needed to control the network, and an increase in availability due to interference immunity and recovery procedures. Implementation of the SSTDMA system involved major redesign of the system control elements and inclusion of the ISCC and the satellite as active elements in the system. The implementation, deployment, and testing of the system were completed in a little more than 2 years, with very few problems.

The inclusion of the satellite switch, and the reduction in the number of reference terminals, along with a number of other system considerations, have resulted in a network control approach for SSTDMA which is different than that used in the fixed TDMA system. The new approach involved architectural, network configuration, and control scheduling changes resulting in the need for new reference terminal equipment, modification of many system procedures, and in particular, the introduction of a new, disciplined frame structure. These changes were engineered to be transparent to existing traffic terminal equipment and are implemented entirely within the control elements of the network. The changes were extensive, involving the satellite, frame structure, reference terminal modifications, new BTP generation software, revised network configuration and control concepts, the HQS, and a new knowledge-based diagnostics subsystem.

Acknowledgments

The INTELSAT SSTDMA system represents a major milestone in the history of satellite communications, and was made possible only through the *dedication of a great many people in many disciplines. While it is impossible to mention everyone, the authors wish to acknowledge S. J. Campanella, B. Pontano, F. Assal, and W. Schmidt of COMSAT, and G. Forcina and R. Colby of INTELSAT, for the early work that provided the technical foundation for the SSTDMA system. They further acknowledge the outstanding efforts of R. Parthasarathy, R. Kochhar, R. Scott, R. Williams, C. Kullman, A. Lunsford, and M. McKenzie of INTELSAT who spent countless hours providing program management and administration.*

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The HQS would not have been successful without the outstanding efforts of the staff of Century Computing, the prime contractor for the IOCTF, and the staffs of CSC and Contel, prime contractors for the ISCC. Finally, thanks are due to J. Dicks, O. Shimbo, and E. Magnusson of INTELSAT for their support throughout the program.

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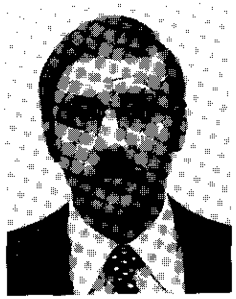
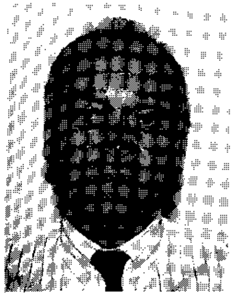
John A. Lunsford received a BSEE from the University of Maryland in 1973 and an MSEE from the University of Pennsylvania in 1980. From 1973 to 1980, he worked on advanced radar signal processing equipment development projects for the RCA Missile and Surface Radar Division (MSRD), including the AEGIS Advanced Radar Signal Processor for the U.S. Navy's AEGIS shipboard radar system. He joined COMSAT Laboratories in 1980, where he participated in a number of TDMA system specification and equipment development efforts, including the system specifications for the INTELSAT TDMA/DSI system. From 1985 to 1989, Mr. Lunsford worked as an independent contractor for INTELSAT, where he made major contributions to the SSTDMA system design and specification, as well as the specifications for the INTELSAT Operation Center TDMA Facility, Satellite Control Center, and SSTDMA burst time plan generation software system. In addition, he had a principal role in the implementation, installation, testing, and documentation of all elements of the SSTDMA system.

Mr. Lunsford rejoined COMSAT Laboratories in 1990 as manager of the Network Systems department in the Network Technology Division, where he led an engineering team performing research and development in the areas of onboard processing, ISDN, TDMA, network control, and system architectures for advanced satellite communications systems. He is currently manager of the Network Engineering department, where he is responsible for hardware development for various satellite communications projects.



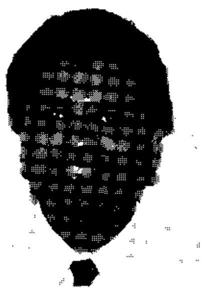
John F. Phiel, Jr. received a BSEE and MSEE from Drexel University in 1963 and 1965, respectively. From 1965 to 1967 he was with the U.S. Army SATCOM Agency, where he worked on the Initial Defense Communications Satellite Program. He joined COMSAT in 1967, and was involved with transmission system engineering and earth station implementation. As a Senior Communications Engineer in the Space and Information System Office of COMSAT General Corporation, he was engaged in studies of new business activities and COMSTAR communications performance analysis.

In 1978, Mr. Phiel joined INTELSAT, where his activities have focused on the design and implementation of the 120-Mbit/s TDMA system and the development of the IESS-501 DCME specification. He is currently Department Manager of Communications Engineering at INTELSAT.



Roger Bedford received a BSc in electronic engineering from Bolton Institute of Technology, England, in 1974; and a MSc in telecommunications from Essex University, England, in 1975. From 1975 to 1977 he worked on satellite system analysis and earth station design for the Marconi Company. In 1977, he joined Bell-Northern Research Laboratories in Canada, where he was involved in the integration of Canadian domestic satellites into the trans-Canada telephone network. He subsequently joined Miller Communications Systems, where he was responsible for system and hardware design of a 3-Mbit/s TDMA system.

Mr. Bedford joined INTELSAT in 1981, and took major responsibility for the design evaluation, installation, and testing of the reference terminals for the INTELSAT 120-Mbit/s fixed TDMA system. In 1986, he became Principal Project Engineer for the design and development of the INTELSAT 120-Mbit/s SSTDMA system. Since 1990, he has been Project Manager for the INTELSAT SSTDMA implementation program.



Satish P. Tamboli received a BSc in electrical engineering and computer science from George Washington University in 1977, and an MSc in operations research from Stanford University in 1979. He is currently a Senior Engineer in the Communications Engineering Department at INTELSAT, where his principal interests are INTELSAT network evolution and integration in the global ISDN/BISDN. He is also leading the effort to develop SDH transport capability within the INTELSAT system. In addition, at INTELSAT he has been involved in testing the fixed TDMA system, and in design and development of the SSTDMA system. Prior to joining INTELSAT, Mr. Tamboli was with Texas Instruments, where he was responsible for fabricating 4K and 16K static RAM integrated circuits.

Index: INTELSAT, synchronization, systems monitoring, time division multiple access (satellite-switched), reference stations

The INTELSAT SSTDMA reference and monitoring station

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Abstract

The equipment installed at each INTELSAT 120-Mbit/s satellite-switched time-division multiple access (SSTDMA) reference and monitoring station is described. The equipment consists of an acquisition and synchronization unit (ASU), responsible for acquiring and maintaining synchronization with the onboard satellite switching sequence; signal processing equipment for real-time digital signal processing to execute network control functions; a control and display console, responsible for interfaces with the operator and the INTELSAT Operations Center TDMA Facility; and the TDMA system monitor, responsible for real-time analog burst signal measurements. This equipment is based on modification of the fixed TDMA reference terminal equipment, with the addition of the ASU subsystem. The major functional differences between fixed TDMA and SSTDMA are described for each subsystem.

Introduction

The INTELSAT satellite-switched time-division multiple access (SSTDMA) reference and monitoring station equipment consists of the SSTDMA reference terminal equipment (SSRTE) and the SSTDMA system monitor (SSTSM), which are interconnected and interfaced to host station equipment. The SSRTE and SSTSM are modified and expanded forms of the fixed TDMA [1] RTE and TSM.

The SSRTE was designed to maintain or improve the overall reliability, operability, and ease of maintenance of the original equipment, while containing the conversion process as much as possible. The original RTE [2] consisted of three main subsystems: the signal processing equipment (SPE) subsystem, the control and display console (CADC) subsystem, and the engineering service circuit (ESC) subsystem. For the SSRTE, a completely new subsystem—the acquisition and synchronization unit (ASU)—was added, and the SPE and CADC subsystems were modified.

Modifying the TSM for operation in an SSTDMA environment required changes to the application software only. These changes affected the operator interface, time plan processing, measurement display and processing, the database editor, and the interface with the INTELSAT Operations Center TDMA Facility (IOCTF).

Overall architecture

Figure 1 is a block diagram of the SSRTE and SSTSM system. Critical components are provided in a redundant configuration. For example, the SPE subsystem contains two identical SPE basic racks, normally in an on-line and standby relationship. Consistent with this philosophy, the new ASU subsystem contains two redundant ASU basic racks which interface to both the SPE and CADC subsystems. To simplify the high-speed 60-Mbit/s interface with the SPE, the ASU and SPE basic racks are paired and located side by side to give two redundant ASU/SPE units. Figure 2 shows the rack front panel elevation of the SSRTE for the ASU and SPE subsystems.

All modifications to the SPE subsystem (with the majority being changes in firmware) were confined to the SPE basic racks. The IF common rack contains transmit and receive satellite equalizers, level detectors, and redundancy switchover logic to establish the correct IF signal paths, depending on which ASU/SPE is on line. The SPE subsystem also contains the local timing source (LTS) rack which houses triply redundant, high-stability cesium beam oscillators used to supply long-term network timing.

The CADC subsystem consists of two processors (sometimes housed in the same rack); two visual display units (VDUs), with associated touch-panel controls and printers, in two racks; the RTE control panel (RCP) and Greenwich mean time (GMT) clock in one rack; and two desktop system consoles with keyboards. Physical modifications to the CADC subsystem consisted of the addition of two switches and labeling changes on the RCP, replacement of the GMT clock with the Global Positioning System (GPS)[*] synchronized time code

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[*] A constellation of satellites managed by the U.S. Department of Defense and available for commercial use as an international time standard.

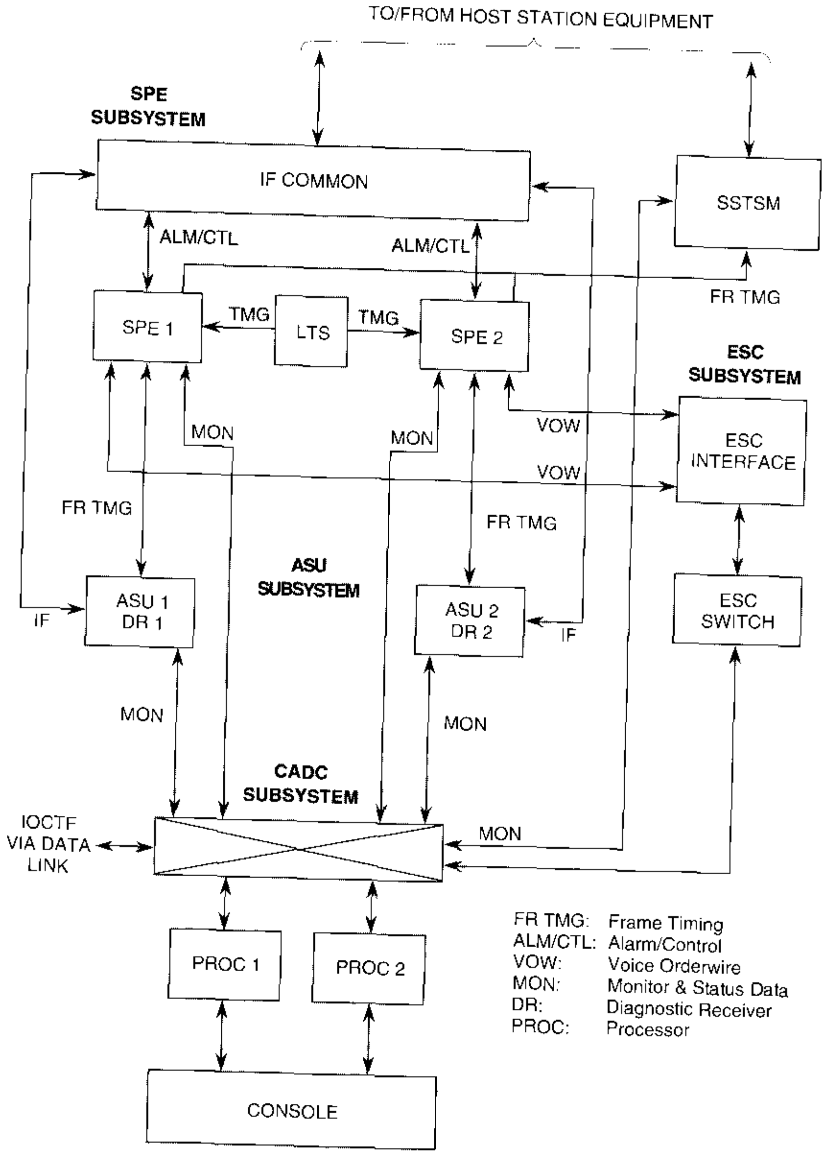
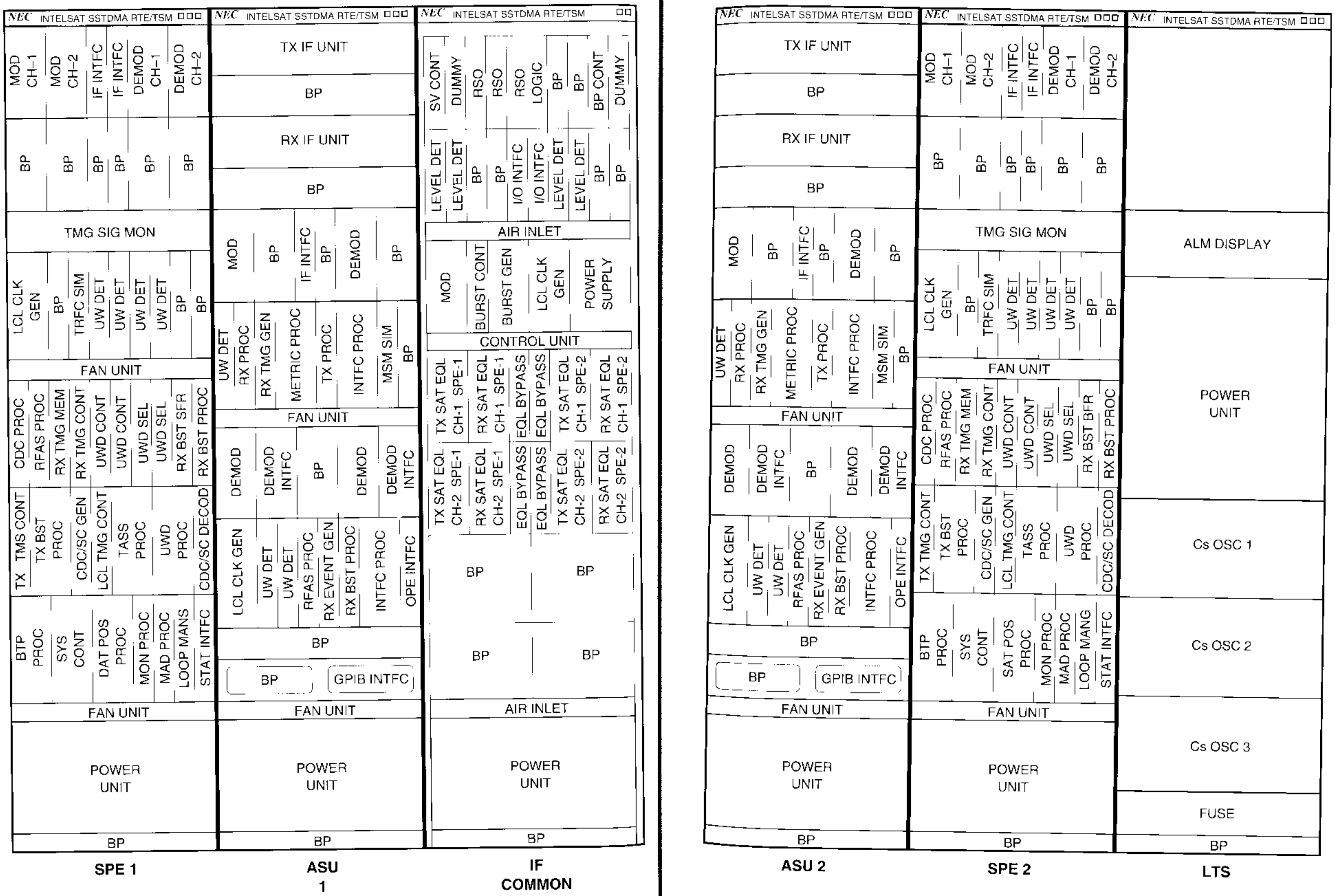


Figure 1. *SSRTE Block Diagram*



BP: Blank Panel

Figure 2. *ASU and SPE Rack: Face View*

generator, and addition of an IEEE-488 Standard general-purpose interface bus (GPIB) interface for the new ASU subsystem. All software in the CADC was extensively changed.

The ESC subsystem and the TSM hardware were not modified. The TSM interfaces, shown in greater detail in Figure 3, are as follows:

- 140-MHz IF interfaces on both the transmit and receive sides via the IF common rack.
- 6/4-GHz interfaces with the low-noise amplifier (LNA) and high-power amplifier (HPA) subsystems of the host station, used to inject calibration signals prior to the LNA and to monitor the HPA output level.
- Status and timing signal interfaces with both SPE basic racks.
- A data link interface with the IOCTF via the CADC subsystem.

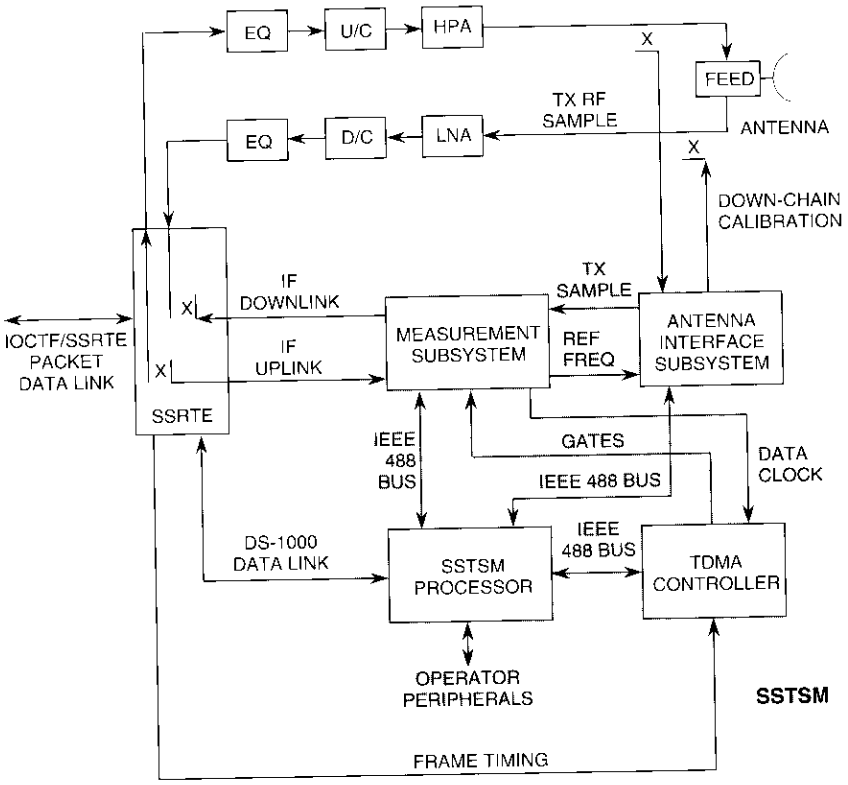


Figure 3. *TSM Block Diagram*

The ASU subsystem

Each of the two redundant ASU basic racks contains a transmit IF unit, receive IF unit, ASU modem shelf, ASU basic shelf, diagnostic receiver demodulator shelf, and diagnostic receiver shelf. The ASU rack face elevation is shown in Figure 4.

The primary task of the ASU is to acquire and synchronize to the switching sequence generated on board the satellite. Consequently, the ASU is capable of measuring the phase difference between a timing reference derived from the LTS and a timing reference derived from the onboard satellite oscillator that is generating the switching sequence. These data are transmitted via data link to the IOCTF for use in measuring and correcting the onboard oscillator frequency, as described by Maranon *et al.* [3]. Two additional functions of the ASU are the transmission and reception of the switch state verification (SSV) burst, which is used in the burst time plan (BTP) change procedure, and operation of the screening switch, which is a key feature of the SSTDMA system's improved immunity to interference. The formats of all bursts transmitted by the ASU are depicted in Figure 5.

The diagnostic receiver, which is separate from the ASU function, detects the presence or absence of individual bursts in all transponders received by the SSRTE. These data are transmitted via data link to the diagnostics subsystem in the IOCTF, as described in Tamboli *et al.* [4].

Overview of ASU operation

As described by Lunsford *et al.* [5], the ASU uses a special loopback region of the frame in a designated transponder to transmit and receive the metric burst. This special region is known as the metric region and appears in each metric transponder. The two SSRTEs use the two metric transponders in the network to transmit and receive their respective metric bursts.

The task of the ASU is to measure the time of cutoff or truncation of a portion of this metric burst by the satellite switch. The metric burst (Figure 5c) contains a 40-symbol metering pattern which, during normal operation, is positioned such that the trailing edge of the special connectivity truncates the metering pattern at a designated (target) symbol position. When the ASU receives its own metric burst back from the satellite, it measures the symbol position within the metering pattern at which truncation occurred, and adjusts the transmit timing of the metric burst so that truncation will occur at the target position. One such adjustment cycle is illustrated in Figure 6, where the onboard (switch frame) timing, and hence the occurrence of the special loopback connectivity, is shown occurring progressively later relative to the

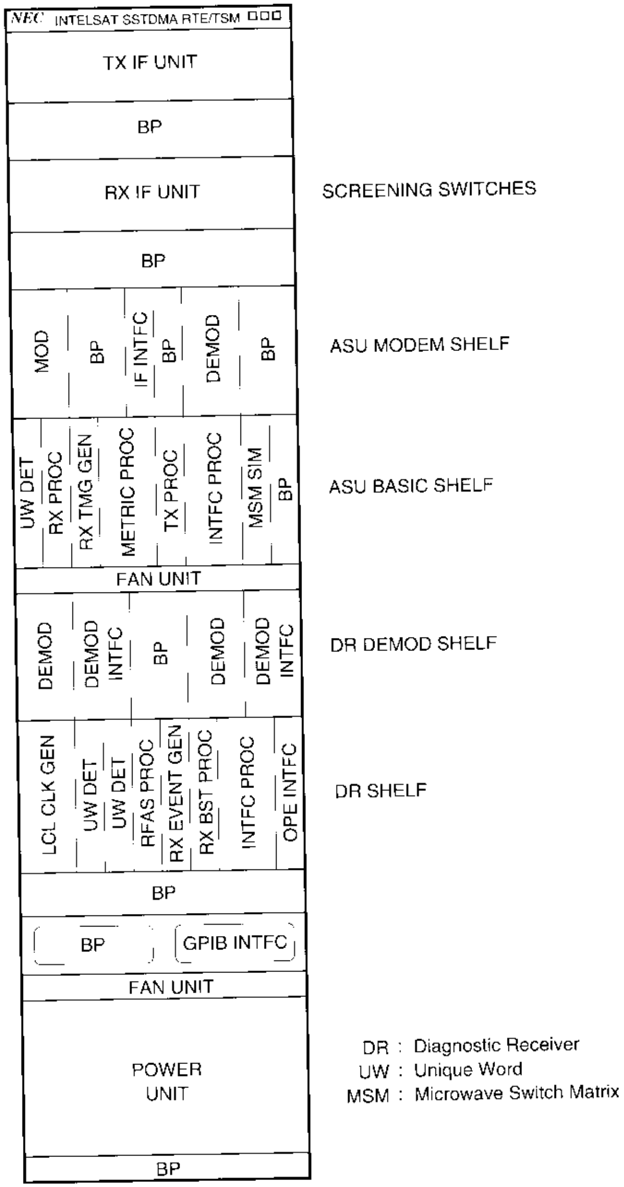


Figure 4. *ASU Rack Face Elevation*

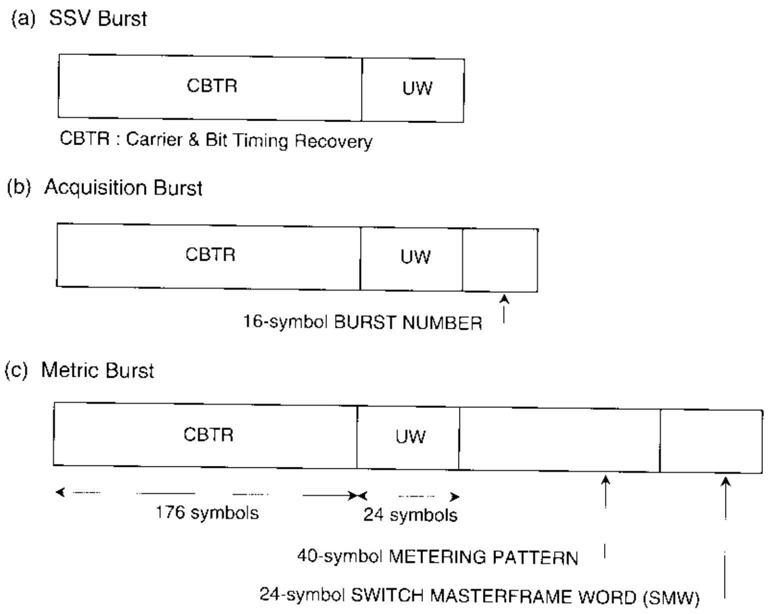
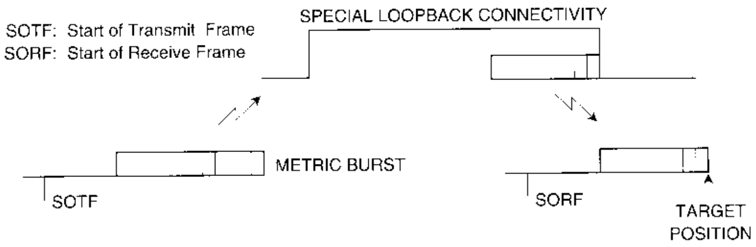


Figure 5. *Formats of all ASU Bursts*

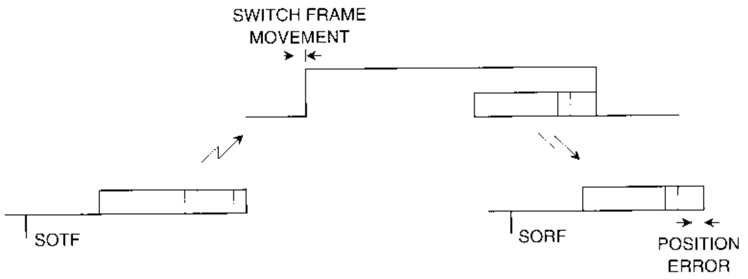
arrival of the metric burst at the satellite. This could be due to the satellite moving closer to the ASU, or to the onboard clock running slower than the ASU transmit timing, which is derived from the LTS. After adjustment, the transmit timing of the ASU is synchronized to the switch frame timing at the satellite. This timing may then be used by the paired SPE, and ultimately by the rest of the network.

The superframe can be synchronized with the switch masterframe by using the metric burst, which has a 24-symbol switch masterframe word (SMW) following the metering pattern. Normally, the SMW is not received by the ASU (as depicted in Figure 6); however the onboard switch subsystem [5]–[7] is provided with a mechanism for extending the special loopback connectivity by 64 symbols in the first frame of each switch masterframe. This enables the ASU to receive the SMW, and thus derive the switch masterframe timing from the SMW detections.

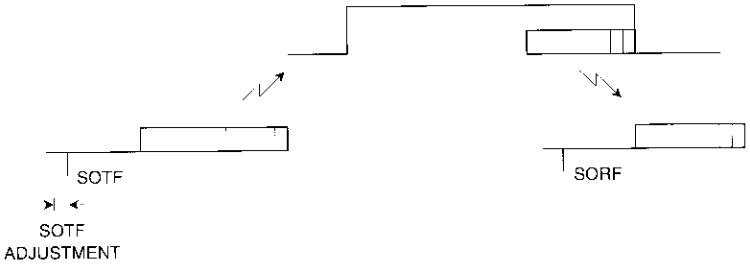
The structure of the metric region is shown in Figure 7 for metric and nonmetric transponders. The metric region always contains two switch states: the metric loopback switch state and metric switch state during normal frames, and the metric loopback switch state and masterframe switch state during the



(a) T_1 Metric Pattern Truncation at Target Position



(b) T_2 Switch Frame Moved Relative to Metric Burst Timing—Truncation Not at Target Position



(c) Metric Burst Timing Corrected —Truncation Again at Target Position

Figure 6. *Metric Burst Synchronization Example*

first frame of the switch masterframe. This latter switch state extends the loopback period of the metric region by 64 symbols, or approximately 1 μs.

The metric region is followed by the reference burst distribution (RBD) region, which must also contain a loopback switch state. These two loopback switch states (metric and reference) are always 512 symbols in duration, and are the only loopback states in the frame that are less than 1,024 symbols long. Normally, 512-symbol loopback connectivities will appear twice in the metric transponder.

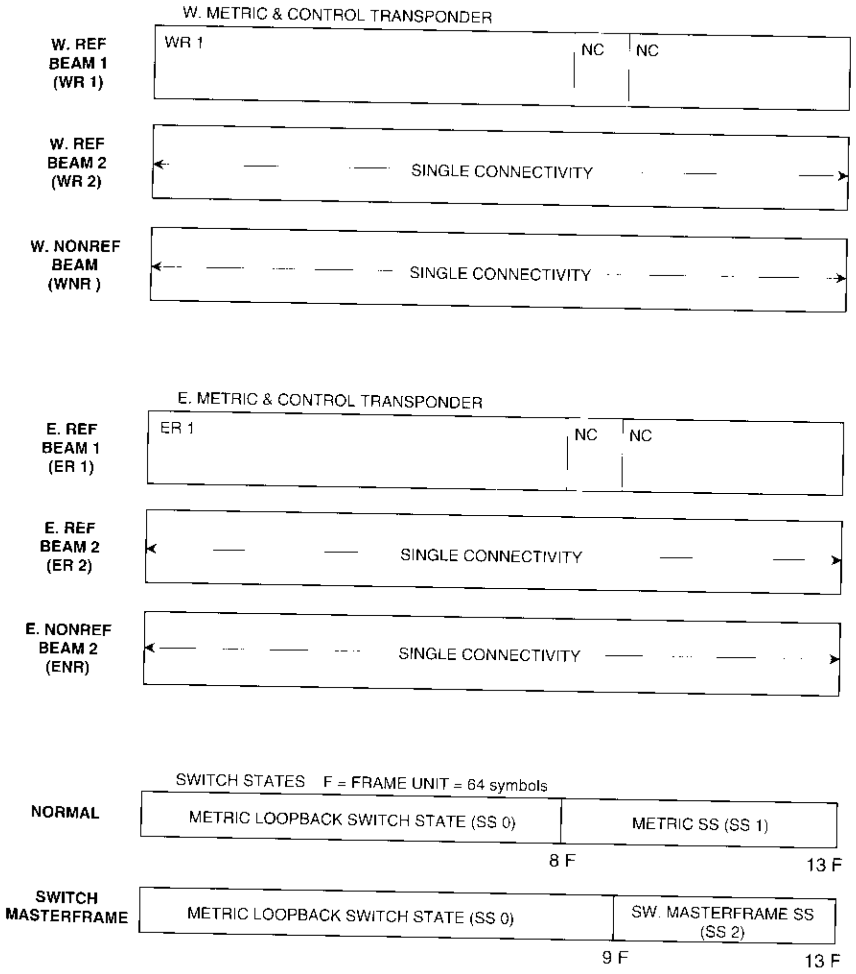


Figure 7. *Structure of the Metric Region*

The RBD region is followed by the terminal acquisition and synchronization (TAS) region, which also contains loopback connectivities. In the special case where the first connectivity in the TAS region is a loopback, the reference burst 2 (RB2) distribution loopback will be extended and the SSRTE transmitting RB2 will thus observe only one 512-symbol loopback in the metric transponder.

During acquisition of the metric loopback connectivity, the ASU searches the metric transponder for all loopback connectivities that are 512 symbols long. To define the number of these loopbacks, the ASU receives from the IOCTF a loopback appearances parameter which is set to either 1 or 2. Acquisition is accomplished by transmitting a series of full-power short bursts (the acquisition bursts), and searching the received burst pattern for these short loopback appearances. Since the BTP rules forbid traffic loopback connectivities of less than 1,024 symbols, the pattern of received bursts can be processed to unambiguously identify the metric loopback connectivity. After coarse transmit timing (about 256 symbols) is established based on acquisition burst transmission into this connectivity, the metric burst is transmitted and acquired with progressively finer timing (metric burst acquisition phase 1: eight symbols; phase 2: one symbol) until the burst is declared synchronized. At this stage, switch masterframe acquisition and synchronization are performed, and the ASU startup procedure is complete.

ASU variable parameters

The ASU was designed so that several parameters which control its operation can be changed, through either programmable read-only memory (PROM) replacement or a GPIB connection to an external IBM PS/2 computer known as the monitor and control unit (MCU). The MCU is not intended as an operational part of the SSRTE, but as a test and debugging tool. In this discussion, when a parameter controls the execution of a procedure, the parameter's name, variable range, and operational value are indicated in square brackets; for example [D_{co}, 0–2, 1.25]. A list of these parameters is provided for reference in Table 1.

As described by Lunsford *et al.* [5], the ASU does not participate in synchronized BTP changes, since dedicated positions in the frame are allocated for its bursts. These data are also stored in PROM and can be modified by the MCU. Table 2 lists the ASU time plan data.

Metric loopback acquisition

The ASU transmits a series of full-power acquisition bursts, each 216 symbols long, at a spacing of 256 symbols (*i.e.*, 40-symbol separation) and 472 bursts per frame. According to the format shown in Figure 8, each acquisition burst contains a burst number between 0 and 471. The bursts are transmitted and received by the ASU in the metric transponder, and are received only during loopback switch states. As illustrated in the figure, the ASU burst transmission sequence begins with an arbitrary start of transmit frame (SOTF), and transmits acquisition burst 0 at the position normally assigned for the metric burst (T_a symbols in Table 2).

TABLE 1. ASU SOFT VARIABLES

NAME	DESCRIPTION	RANGE
W_{tx}	Frames to wait after transmit timing adjustment	128–256
F_{br}	Frames to declare Burst Received	16–64
F_{bl}	Frames to declare Burst Lost	16–64
T_{br}	Timeout for burst received	32–128
N_a	0110 accumulation period	64–256
D_{11}	0110 detection threshold	0.5–0.9
M_{11}	0110 misdetection threshold	0.1–0.5
F_{bn}	Frames for Burst Number Valid	2–16
S	SMW pattern	24 symbols
F_{sr}	Frames for SMW Received	16–64
F_{sl}	Frames for SMW Lost	16–64
E_{sync}	Metric burst position error limit	0–16
P_{fail}	Failed metric sampling periods	2–16
M	Metric pattern	40 symbols
N_s	Metric sampling period	64–511
T	Target for metric cutoff	0–40
E_{cz}	Error variation of cutoff zone	0–40
S_{min}	Minimum metric sample size	0.5–1.0
D_{co}	Threshold for cutoff decision	0–2
F_{sbr}	Frames for SSV Burst Received	16–512
F_{sbnr}	Frames for SSV Burst Not Received	16–512

TABLE 2. ASU TIME PLAN VARIABLES

NAME	DESCRIPTION	RANGE	CURRENT VALUE
T_a	Position of metric burst (symbols)	0–120,400	486
T_s	Position of SSV burst (symbols)	0–120,400	117,536
d_1	Displacement between metric burst and RBD regions for RB1 in bank A	0–120,400	768
d_2	Displacment for RB2 in bank A	0–120,400	1,280
d_3	Displacement for RB1 in bank B	0–120,400	1,280
d_4	Displacement for RB2 in bank B	0–120,400	1,792

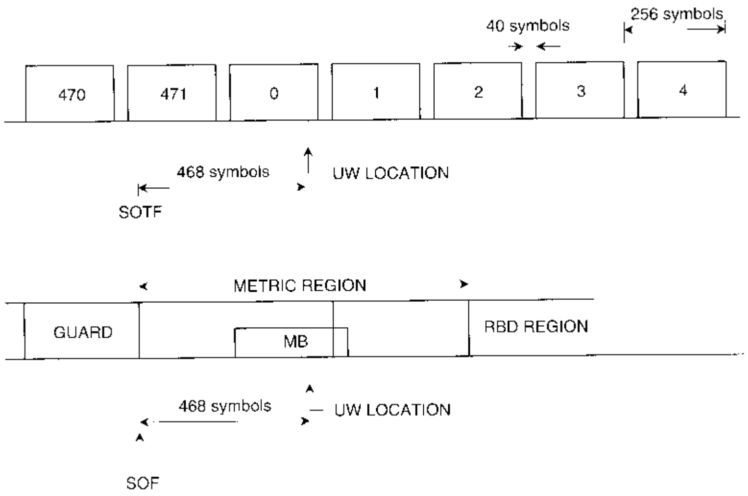


Figure 8. *Transmitted Acquisition Bursts*

MULTIPLE-WINDOW MODE

After transmission of the acquisition bursts, the first unique word (UW) detected with zero errors sets the position for the receive synchronization window (Rx Sync window), which is a 64-symbol predicted window (see Reference 8 for a description of windows). Relative to the Rx Sync window, the ASU places a series of smaller 32-symbol windows at 256-symbol intervals throughout the receive frame, as shown in Figure 9. This is known as the multiple-window mode. At the same time, an arbitrary start of receive frame (SORF) is set up relative to the position of the Rx Sync window, as if the metric burst were received in this window.

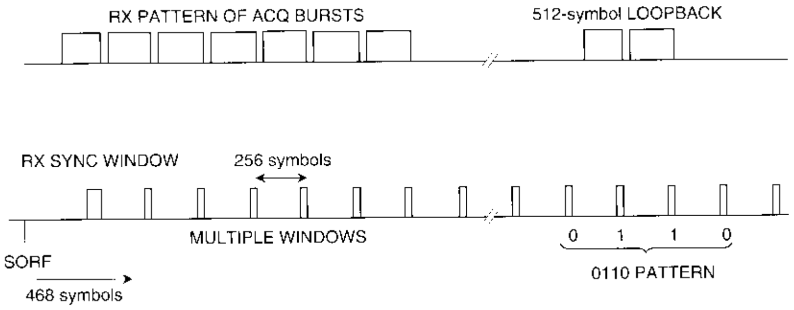


Figure 9. *Multiple-Window Mode and the "0110" Pattern*

The sequence of UW detections generated by these windows is recorded over a complete frame, and examined for occurrences of the "0110" pattern. This is a pattern of detections in two consecutive windows, with no detections in the adjacent windows. If found, this pattern signifies the possible presence of a 512-symbol loopback connectivity, as depicted in Figure 9. If the pattern is not found, ASU transmit timing is retarded by 8 symbols, the windows previously used are cleared, and the entire process is restarted.

When one or more occurrences of the 0110 pattern are found, the detection data from the multiple windows are recorded over [N_a, 64–256, 64] frames. In these data, the position of each pattern relative to the current SORF, and the number of occurrences at this position, are determined. This gives the number and position of the possible 512-symbol loopbacks that have been found, as shown in Figure 10.

Normally, the loopback appearances parameter is 2, and the ASU expects to find two 512-symbol loopbacks in the metric transponder, corresponding to

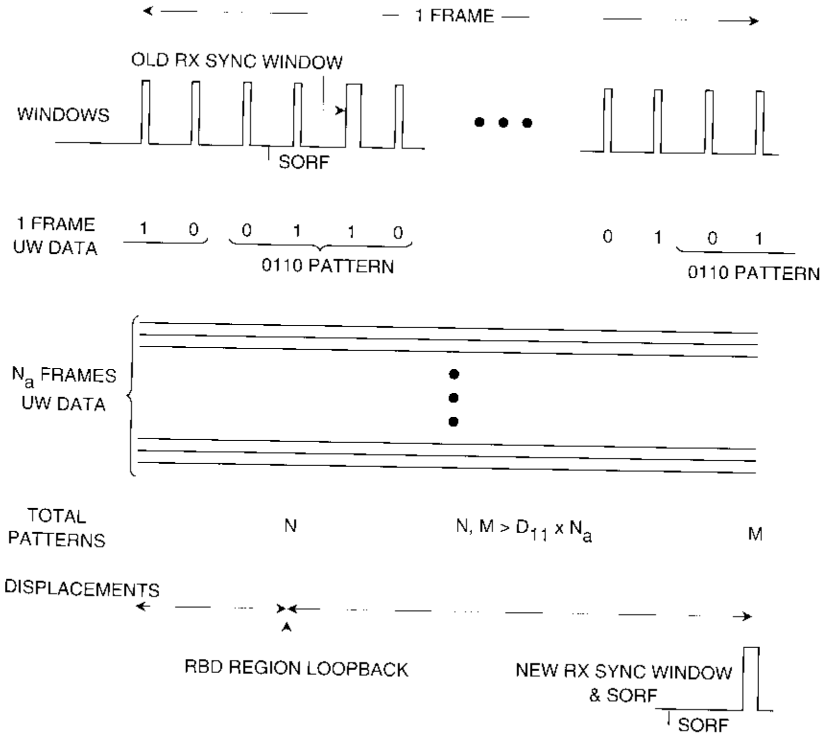


Figure 10. *Metric Loopback Acquisition*

the metric loopback switch state and one of the RBD region switch states. In this case, at least two 0110 pattern positions must be found, and the number of occurrences at each position must be greater than $[D_{11}, 0.5\text{–}0.9, 0.9] \times N_a$. Also, any additional patterns at other positions must be less than $[M_{11}, 0.1\text{–}0.5, 0.1] \times N_a$. If these two conditions are satisfied, the ASU checks the time displacement between the two pattern positions against the displacement expected for the current time plan. This displacement is a fixed quantity and will change according to the reference burst (RB) type (RB1 or RB2) and the bank (A or B) that is in use for the metric transponder (parameters d_1 through d_4 from Table 2). If all conditions are satisfied, the Rx Sync window is relocated to the position of the first detected UW in the 0110 pattern which corresponds to the metric loopback switch state. This is determined based on the relative positions of the detected loopbacks.

If the loopback appearances parameter is 1, the ASU will expect to find only one pattern position that meets the $D_{11} \times N_a$ criterion, and will select this position as the metric loopback switch state, if it is found. If the metric loopback switch state is not found, then ASU transmit timing is retarded by 8 symbols, and the entire procedure is restarted.

SINGLE-WINDOW MODE

When the Rx Sync window is relocated, the SORF is also relocated and the multiple windows are cleared, leaving only the Rx Sync window to detect the first acquisition burst UW in the selected 0110 pattern. This is the single-window mode.

The burst number of the acquisition burst being received is now decoded. If the same burst number is decoded in $[F_{bn}, 2\text{–}16, 4]$ consecutive frames, the number is considered valid. The decoded burst number is then used to retard the ASU transmit timing by $256B_d$ symbols, where B_d is the number decoded. Referring to Figure 11, it can be seen that this strategy places acquisition burst 0 in the Rx Sync window. When a burst number of zero is decoded, no further transmit timing adjustment is done and transmission of the acquisition bursts ceases. At that time, transmission of the metric burst starts at the same position as acquisition burst 0, and phase 1 of metric burst acquisition begins.

Metric burst acquisition

Acquisition and synchronization of the metric burst with the switch frame timing takes place in two phases. At the start of the procedure, the metric burst is received in the Rx Sync window and placed in the forward part of the detected 512-symbol loopback, in the same position as acquisition burst 0, as shown in Figure 12. Thus, the entire metric burst, including the SMW, will be received. At the start of phase 1, the ASU begins detecting the SMW. When the SMW is detected, the ASU retards the SOTF by 8 symbols and waits $[W_{tx}, 128\text{–}256, 148]$ frames to again detect the SMW. This moves the metric burst up to the closing edge of the switch state, and finally truncates the SMW. When the ASU no longer detects the SMW, phase 2 begins.

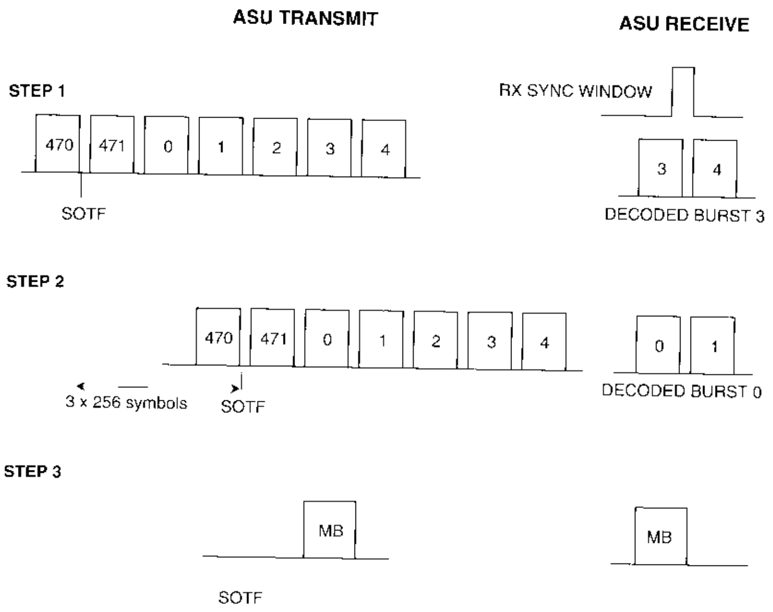


Figure 11. *Metric Burst Transmission Process*

At the start of phase 2, the metric burst is positioned with a number of SMW symbols being truncated by the trailing edge of the metric loopback switch state. However, the entire 40-symbol metering pattern is intact. During phase 2, the contents of the received metering pattern are employed to make an initial estimate of position error, using the position measurement procedure described later. Since the entire pattern is still being received, this will result in a measurement of $T - 40$ symbols $[T, 0\text{–}40, 26]$, which is negative because the burst is being received early. This measurement will produce a forward movement of $T - 40$ symbols, which may result in metering pattern cutoff. As soon as metering pattern cutoff occurs, the position error can be measured and the transmit timing adjusted accordingly. Phase 2 terminates and metric burst synchronization is declared when the measured position error drops below $[E_{sync}, 0\text{–}16, 5]$ symbols.

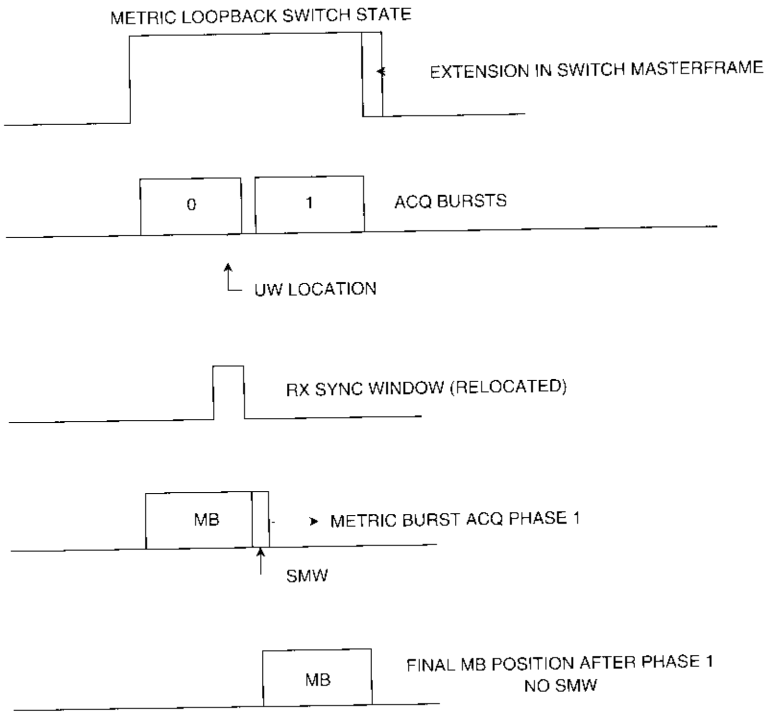


Figure 12. *Metric Burst Acquisition Phase 1*

Upon completion of phase 2, the switch masterframe acquisition procedure and the metric burst position error measurement procedure begin.

Switch masterframe acquisition and synchronization

At the start of each transmit superframe (SOTSF), the UW transmitted in the metric burst is changed from UW0 to UW3. Initially, the SOTSF will be arbitrary. At the satellite, the loopback connectivity in the metric region will be extended by 64 symbols on the first frame of each switch masterframe. This exposes the SMW at the end of the metric burst in this frame.

The switch masterframe acquisition procedure detects the occurrence of UW3 in the received metric burst and starts a frame count that is stopped by reception of the SMW, as shown in Figure 13, step 1. The next occurrence of the SOTSF is then retarded by this number of frames (step 2), which causes coincident (in the same frame) detection of UW3 and the SMW. When the ASU detects this condition, switch masterframe synchronization is declared. If the condition is not detected for 10 consecutive superframes, the ASU generates a warning message: Metric Burst or Switch Masterframe (SMF) Acquisition Failed. Achieving switch masterframe synchronization terminates the ASU startup procedure. The SSV burst is then transmitted, and the screening switches begin to operate.

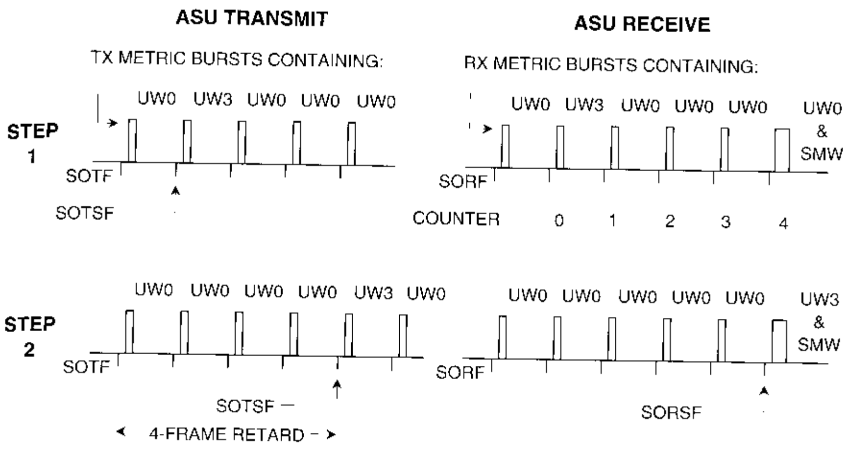


Figure 13. *Switch Masterframe Acquisition*

Switch masterframe synchronization consists of monitoring the displacement between UW3 and the SMW. If the SMW is detected and the displacement is not equal to zero in two consecutive measurements, an alarm condition occurs which produces a request for switchover to the redundant ASU/SPE. If the SMW is not detected for four consecutive superframes, a warning message is generated but no alarm condition is declared.

Metric burst synchronization

The metric burst is kept in synchronization with the switch frame by measuring the position error of the burst relative to the metric switch state, once every control frame. This measurement is based on keeping the closing edge of the metric switch state at a specific symbol position [T, 0–40, 26] within the metering pattern contained in the metric burst. The transmit timing of the metric burst is then adjusted based on the measured position error. If a valid position error is not measured in [P_{fail}, 2–16, 4] consecutive control frames, an alarm condition and request for switchover are generated.

Metric position error measurement

The symbol position within the metering pattern at which cutoff (closing of the switch state) occurs is measured by statistical correlation over a sampling period of [N_s, 64–511, 128] frames. Each sampling period begins on the second frame of a control frame because in the first frame of each superframe the metric loopback is extended by 64 symbols.

The metering pattern data received in each frame of the sampling period are compared to the transmitted metering pattern to determine two vectors, B_p and B_q, that contain the bit correlations between transmitted bits (T_p, T_q) and received bits (R_p, R_q) for both the P and Q channels, as follows:

$$B_p(j) = \text{NOT}\ [T_p(j)\ \text{XOR}\ R_p(j)] \qquad j = 0, 1, 2, \ldots, 38, 39 \tag{1a}$$

$$B_q(j) = \text{NOT}\ [T_q(j)\ \text{XOR}\ R_q(j)] \tag{1b}$$

The number of symbol correlations, S, in the received pattern is also determined:

$$S = \sum_{j=0}^{39} \left[B_p(j)\ \text{AND}\ B_q(j)\right] \tag{2}$$

If the difference between the number of symbol correlations, S, and the target symbol cutoff value, T, is less than [E_{cz}, 0–40, 26], the metering pattern data collected for the frame are considered valid and are accumulated; otherwise, they are discarded. Each time a valid frame of data is accumulated, a variable, N_v, is incremented.

The two vectors of bit correlations in each channel are added to give a single correlation vector whose elements can be 0, 1, or 2, as

$$A(j) = B_p(j) + B_q(j) \qquad j = 0, 1, 2, \ldots, 38, 39 \tag{3}$$

For the mth received valid frame, the values of $A(j)$ are stored in the correlation matrix, $C(j, m)$.

At the conclusion of the N_s-frame sampling period, if the number of valid frames, N_v, exceeds [$S_{\min}$, 0.5–1.0, 0.5] × N_s, the bit correlations for each symbol position of the metering pattern are arithmetically summed to form the decision vector, $D(j)$, as

$$D(j) = \sum_{m=1}^{N_v} C(j,m) \qquad j = 0, 1, 2, \ldots, 38, 39 \tag{4}$$

Starting at symbol position zero ($j = 0$), $D(j)$ is compared to [D_{co}, 0–2, 1.25] × N_v. The first symbol position at which $D(j)$ drops below this threshold is defined as the symbol position of metering pattern cutoff.

The metric burst position error is defined as

$$\text{Error} = T - (J + 1) \tag{5}$$

where J is the index of the first element of $D(j)$ whose value is below $D_{co} \times N_v$. This process is illustrated in Figure 14.

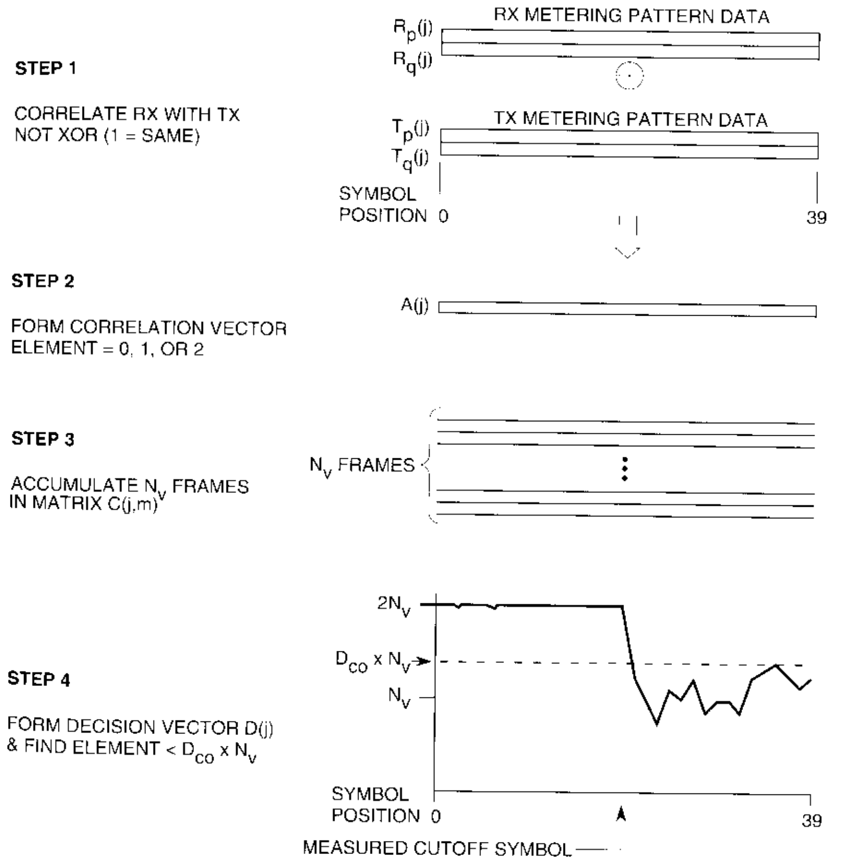


Figure 14. *Metric Burst Position Error Measurement Processing*

Direct synchronization from SPE timing

For all standby ASUs, as well as for the on-line ASU in a newly acquired inoperative SSRTE, the paired SPE establishes receive and transmit timing prior to the ASU. In this situation, the ASU will synchronize metric burst transmit and receive timing directly, based on the timing signals from the paired SPE. When the metric burst has been received and a valid position error measurement obtained, the normal cycle of metric cutoff measurement and transmit position adjustment will begin. For standby ASUs, the transmit timing will be taken from the paired SPE.

SSV burst transmission and reception

SSV burst transmission and reception begins after switch masterframe synchronization is achieved. If the ASU declares SSV Burst Received, then the Blind Slot Not Active condition is declared and passed to the paired SPE. If SSV Burst Not Received is declared, the Blind Slot Active condition is declared. The blind slot declaration is used for fail-safe recovery from the BTP change procedure, as explained later.

Screening switch operation

The receive IF unit housed in the ASU rack accepts four down-chain signals from the IF common rack. The signals are then distributed to the paired SPE, the diagnostic receiver housed in the same ASU rack, and the single ASU demodulator. The down-chain for the ASU demodulator is selected manually, using a front panel switch. Four screening switches are provided for the down-chain signals fed to the SPE, and one screening switch is provided for the ASU demodulator signal. These switches are controlled by data provided by the CADC, which are derived from the contents of the reference terminal condensed time plan (RCTP). Screening switch operation begins after the ASU declares switch masterframe synchronization. The switches prevent certain regions of the frame from being received by the ASU and SPE, and are a key element in the strategies used to resist interference, as described later.

Onboard oscillator phase measurement

The ASU employs a special technique, originally used experimentally by NTT [9], to measure the phase change between timing derived from the onboard oscillator and timing derived from the LTS, independent of the effects of satellite motion. The technique is based on the relative motion of the ASU SOTF, the ASU SORF, and a timing reference derived from the LTS. It was developed to prevent the satellite Doppler effect from corrupting the measurement, as would occur if the period between the SORFs were compared to the period between the LTS reference pulses. In this case, the diurnal expansion and contraction of the frame length would be impressed upon the long-term difference in frame length, and measurements would be extremely difficult.

To explain the application of the above technique, two situations can be described:

- *No Satellite Motion With Clock Offset.* This case (Figure 15) assumes that the satellite is stationary (no Doppler) and the onboard clock is running slower than the LTS; hence the satellite switch frame is longer than the LTS frame, and the start of frame at the satellite moves forward (*i.e.*, occurs progressively later) relative to the LTS frame. Since there is no satellite motion, the SORF will also move forward relative to the LTS frame and, to maintain synchronization, the SOTF must move forward by the same amount.

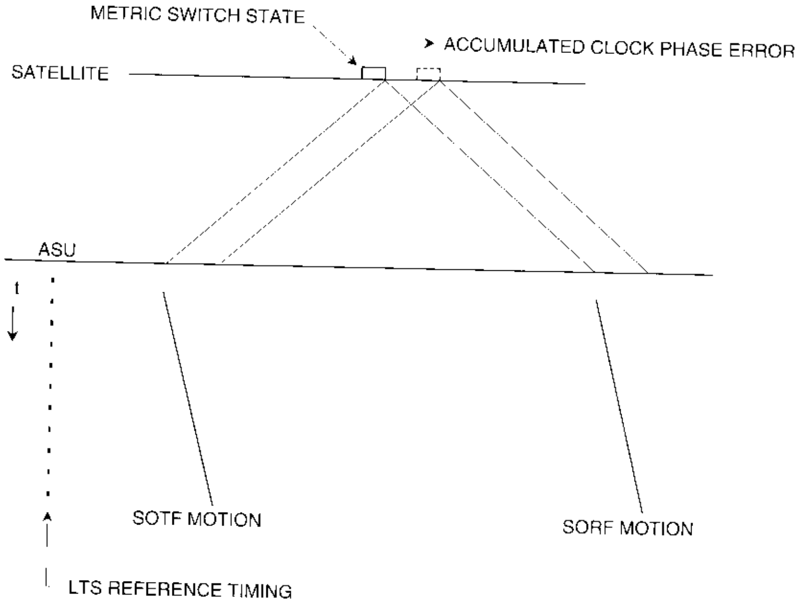


Figure 15. *Effect of Clock Offset*

- *Satellite Motion Without Clock Offset.* This case (Figure 16) assumes that there is satellite motion, but there is no onboard clock drift relative to the LTS. Consequently, the start of frame at the satellite will continue to occur at the same time relative to the LTS frame. As the propagation distance for the metric burst changes due to satellite motion, the SORF arrives earlier or later at the ASU, producing the same effect as above. However, to maintain synchronization, the SOTF must now occur later or earlier to compensate for the change in distance; and in fact the SOTF will advance/retard by the same amount that the SORF retards/advances.

Combining these two observations by measuring the amount by which the SOTF and SORF move relative to each other gives an accurate assessment of the satellite range variation independent of clock offset. Conversely, clock offset may be measured by observing the movement of the midpoint of the SOTF/SORF relative to the LTS frame.

In practice, the ASU maintains two counters, each of which is reset by a reference pulse from the LTS. One counter measures the time, in symbols, between the reference pulse and the start of transmit control frame (SOTCF); the other counter measures the time, in symbols, between the reference pulse and the start of receive control frame (SORCF). The results of these two counters are summed to form the periodic phase measurement known as $T(M)$, which is reported to the CADC each superframe. Figure 17 depicts the situation combining satellite motion and clock offset, along with the values of $T(M)$ and the constituent counters. As shown, half of the difference in two successive values of $T(M)$ is the phase accumulation, in symbols, over the period between the two values, due to clock frequency difference between the LTS and the onboard oscillator. This accumulation can be either positive or negative. If it is positive, the onboard clock is slower than the LTS, resulting in a longer frame and successively later SORFs/SOTFs. The use of this information to correct the onboard clocks is discussed by Maranon *et al.* [3] and Lunsford *et al.* [5].

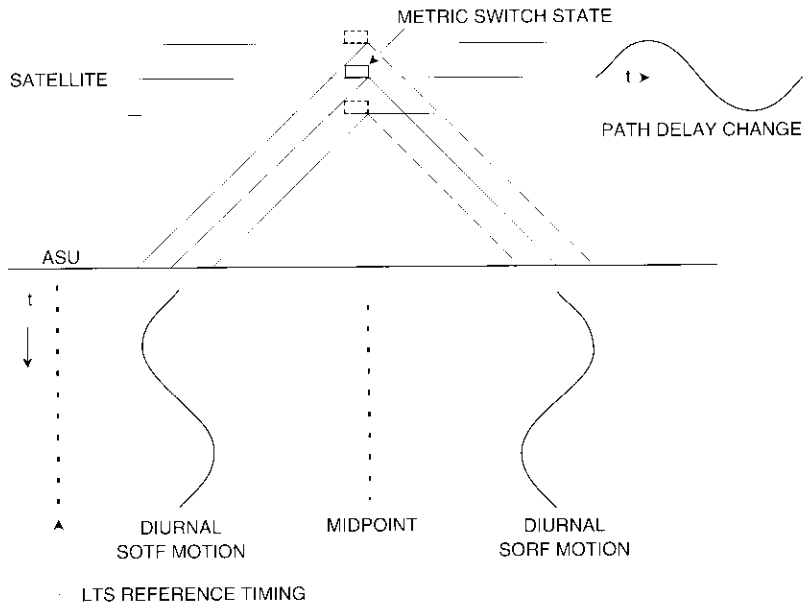


Figure 16. *Effect of Satellite Motion*

The diagnostic receiver

The diagnostic receiver provides an independent means of monitoring the presence or absence of all bursts in the transponders received by the SSRTE, to report back to the diagnostics subsystem in the IOCTF, as detailed by

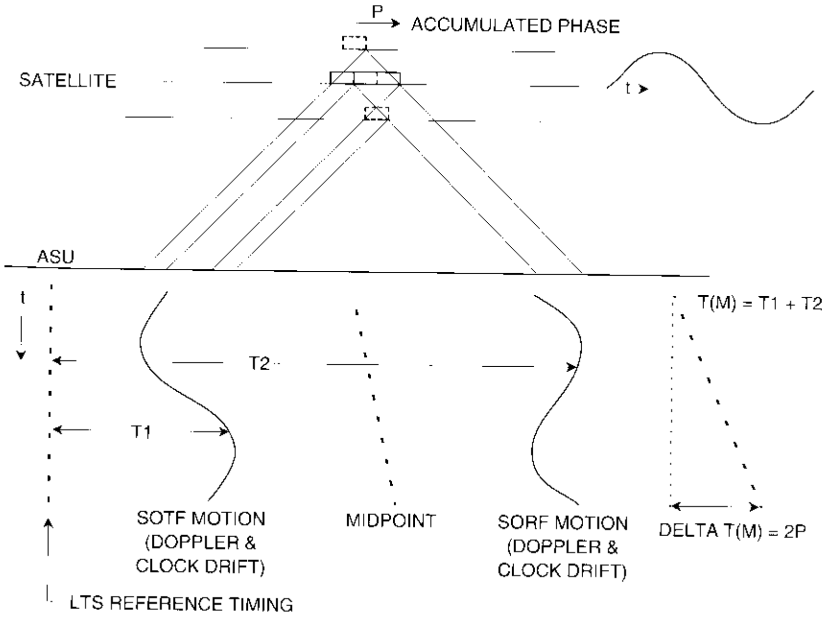


Figure 17. *Combined Effects of Satellite Motion and Clock Offset*

Tamboli *et al.* [4]. This is necessary because the inclusion of screening switches in the SSRTE design prevents the SPE from receiving the traffic portions of the frame. Since the diagnostic receiver has no active role in the network, the inputs are left unscreened and all bursts can be monitored.

Each diagnostic receiver contains two demodulators and is mounted in an ASU basic rack. With the two diagnostic receivers in the two ASU racks, the SSRTE can receiving and monitoring the bursts in up to four transponders. The diagnostic receivers have no on-line or standby status. Transponders are selected by means of front-panel switches, and selection is monitored by the CADC.

Each diagnostic receiver derives receive timing independently from the reference bursts in the transponders being monitored. All bursts are detected within 64-symbol windows located in the frame relative to the receive timing derived by the diagnostic receiver. Bursts are defined by the diagnostic receiver time plan (DRTP), which is transmitted from the IOCTF via data link and defines only the position and UW type of each burst. The diagnostic receivers maintain a UW detection table for each transponder, in which the status of each burst is represented by a 1 or 0. These tables are transmitted via the CADC to the IOCTF once every superframe, or approximately 16 seconds.

The SPE subsystem

The SPE subsystem routinely handles all of the real-time signal processing necessary for reference and traffic terminal control and monitoring, and executes certain specialized procedures (*e.g.*, BTP change and reference terminal promotion) as needed. The SPE basic rack houses the hardware and firmware that perform this processing. For the SSRTE, the SPE function was modified in the areas discussed below.

Reference terminal control

The format of the RCTP allows the definition of three types of transponders containing reference bursts: those containing controlling reference bursts, from which the RTE takes control; those containing controlled reference bursts, which the RTE controls; and those containing other reference bursts, which the RTE monitors to generate the selective do not transmit (SDNTX) codes that control traffic terminal burst transmission.

In fixed TDMA, one or two transponders are defined as containing controlled reference bursts, depending on whether the connectivity is loop or nonloop. Also, in fixed TDMA there are four reference terminals in the network: the master primary (MPRT), master secondary (MSRT), primary (PRT), and secondary (SRT). In the loopback case, the MPRT and MSRT control themselves in the loop transponder and also control the PRT and SRT in the nonloop transponder, resulting in two controlled reference burst transponders (four controlled reference bursts) being defined in the MPRT and MSRT RCTPs. In the nonloopback case, all RTEs control the opposite-beam RTEs in a single nonloop transponder, resulting in only one controlled reference burst transponder (two controlled reference bursts) being defined in all the RCTPs. In both the loop and nonloop cases, the terminal numbers and burst numbers of all the controlled reference bursts defined in any RCTP will be different, due to the presence of four RTEs in the network.

In SSTDMA, because of the ability to distribute reference bursts to multiple downbeams, all network configurations are loopback. This, together with the provision of only two reference terminals, has the following consequences:

- Eliminates the role of PRT and the concept of the fixed-delay primary.
- Eliminates the concepts of startup pairings and highest role (highest role is always MPRT).
- Introduces the concept of dummy terminal numbers for reference terminal control.
- Introduces the concept of dummy burst numbers for reference terminal SDNTX generation.

ELIMINATION OF THE PRT

The main outward effect of eliminating the PRT is to eliminate code block 131 from the RCTP, which defines the highest role of an RTE, the terminal number of the startup partner, and the type of network connectivity. In SSTDMA, none of these data are needed.

DUMMY TERMINAL NUMBERS

For network configurations in which each SSRTE is controlled in a different control and delay channel (CDC, used to distribute control and acquisition delay data), each SSRTE controls its own reference burst and its partner's reference burst in different transponders. Thus, two controlling reference burst transponders must be defined in the RCTP, giving rise to the definition of four controlled reference bursts. This leads to a duplication of terminal and burst numbers in the RCTP which can potentially corrupt the SPE database. Since this situation will occur only when the two SSRTEs are controlled in different CDCs, the solution adopted is for the SPE to recognize multiple definitions of terminal numbers for controlled reference bursts and to generate dummy terminal numbers for the two reference bursts that are not actually being controlled in each defined transponder. The dummy terminal numbers are formed by inverting the two most significant bits (MSBs) of the 8-bit terminal number, on the basis that all real terminal numbers within a network will have the same two MSBs. This has resulted in a rule that reserves CDC addresses 1 and 2 for the exclusive use of reference terminals in SSTDMA.

DUMMY BURST NUMBERS

For the same reasons described above, in SSTDMA burst numbers are also duplicated in the "other" category of reference burst transponders (*i.e.*, those monitored for SDNTX generation). To distinguish among these bursts, the SPE generates dummy burst numbers that are inserted into the SDNTX message and appear in the logging data. The dummy number is based on the identity of the port on which the SPE receives the burst. This port ID replaces bits 11 and 12 of the 14-bit burst number in the SDNTX message (bit 0 is the least significant bit). In this way, both the local SSRTE operators and the diagnostics subsystem in the IOCTF can determine the transponder for which the SPE generated the SDNTX.

Based on the changes in terminal number and burst number for SDNTX generation, the response of the SPE to reception of SDNTX codes has also changed. The SPE now generates a request for switchover when it receives an SDNTX addressed to either its real terminal number or its dummy terminal number. The 14-bit burst number is its principal burst number, or is coded as "all ones" (*i.e.*, all bursts). All other combinations of terminal and burst number are ignored.

Terminal acquisition and synchronization support

In fixed TDMA, all bursts in the network are controlled by the terminal acquisition and synchronization support (TASS) procedures and the SDNTX generation (SGT) procedures. In SSTDMA, due to the operation of the screening switches in the ASU, nonprincipal traffic bursts cannot be monitored by the SPE, and thus the SGT procedure for these bursts will operate for nonprincipal reference bursts only.

The TASS procedure uses the CDC to provide one of four possible control codes and a value of transmit delay to each controlled terminal, once per control frame (1.024 s). Steady-state synchronization control in SSTDMA is achieved in the same manner as in fixed TDMA [8], by instructing the controlled terminal to advance or retard transmit timing based on a periodic measurement (once per control frame) of the controlled burst position. This control is achieved by changing the value of transmit delay that is used by the controlled terminal to derive transmit timing.

In the initial acquisition and synchronization procedures, the controlling reference terminal first calculates an approximate value for the initial transmit delay, designed to place the acquiring burst in a specific (unused) location in the frame. In fixed TDMA, this unused location is preferably the frame space which will ultimately be occupied by the acquiring terminal's traffic burst, and therefore can be used for acquisition. In SSTDMA, the frame structure is more rigidly defined [5], with specific locations assigned for traffic terminal principal bursts that are closely packed. A separate region of the frame, called the common acquisition window (CAW), is provided to be shared among all acquiring terminals in that transponder during their acquisition attempts. Although the basic procedure of initial acquisition is the same in both fixed and SSTDMA, the way in which terminals are allocated to initial acquisition attempts is different. While the SSTDMA initial acquisition allocation and the fixed TDMA method of sequential acquisition are similar, fixed TDMA allocation is static and SSTDMA allocations are dynamic.

The allocation process operates by assigning nonacquired terminals to subunits of a superframe called acquisition cycle intervals (ACIs), which comprise four consecutive control frames. Within an ACI, a traffic terminal has a maximum of two opportunities (control frames) to respond to an initial acquisition, phase 1 (IAP1) code. If the second IAP1 does not cause a response, the remaining two control codes of the ACI contain a do not transmit (DNTX) code. The possible control code sequences during a single acquisition attempt are depicted in Figure 18.

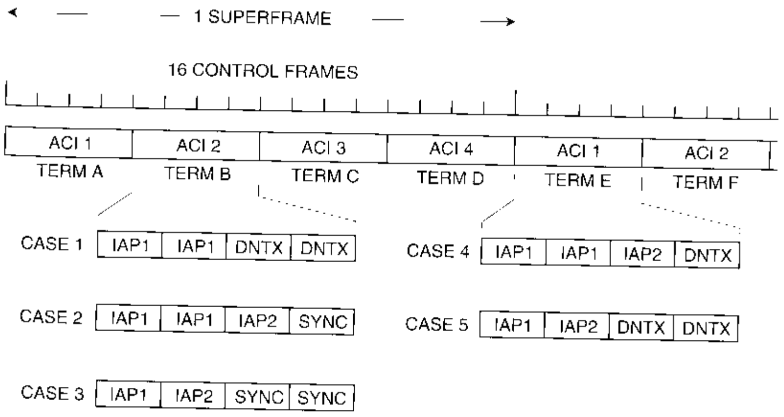


Figure 18. *Possible Control Code Sequences Within a Single ACI*

Terminals are allocated to ACIs based on data in an acquiring terminal (AT) table, which is constructed for each transponder in which the SSRTE receives controlled principal bursts. A maximum of four AT tables can be defined for each SSRTE. Terminal order within an AT table is based on control multiframe and transponder allocation. That is, all terminals controlled in a specific transponder appear in that AT table, in the order in which they are addressed in the CDC. Each terminal is then marked as eligible for acquisition according to its authorization and acquisition status. All terminals eligible for acquisition in each AT table are sequentially allocated to an ACI, and the results of the acquisition attempts are used to update the AT table status. This cycle repeats until no more terminals eligible for acquisition remain in each table.

In such a dynamic allocation scheme, it is necessary to ensure that both the MPRT and SRT are simultaneously acquiring the same terminal. For this purpose, a new service channel message called the ACI assignment message (Figure 19) has been defined. This message is transmitted by both SSRTEs in the first multiframe of the first control frame of every ACI. As shown in the figure, the message contains the control multiframe of the terminal to be allocated for acquisition attempt in the next ACI, for all four AT tables. The ACI assignment message is used to synchronize the inoperative reference terminal (IRT) or SRT ACI assignments to those of the MPRT ACI whenever a mismatch occurs. Also, a warning message is generated at both SSRTEs when there is a mismatch.

The cycle of ACI assignments may be preempted by the need to acquire the partner SSRTE. In this case, the partner will become eligible for an acquisition attempt and will replace the regularly scheduled terminal every fourth ACI. The regularly scheduled terminal will then be given the next ACI. However, if fewer than four traffic terminals are eligible for acquisition in that AT table, no preempting will be done.

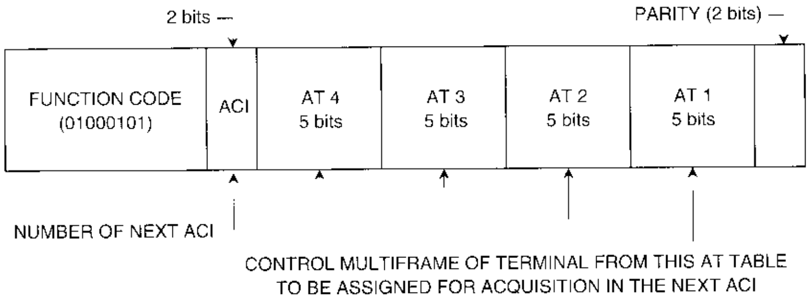


Figure 19. *Format of ACI Assignment Message*

BTP change

Changes in the SSRTE functions to accommodate a BTP change are divided fairly equally between the SPE and CADC subsystems. The major change for SSTDMA [5],[10] is that the satellite command execute time, T_{xqt}, is calculated by the MPRT in order to synchronize the switch-state time plan (SSTP) and BTP change timing between the satellite and ground segments of the network. This calculation is performed by the CADC based on a local measurement of the instant of occurrence of SOTSF relative to Universal Time Coordinated (UTC) time, and on a parameter which defines the number of superframes of lead time before the instant of change. This is known as the BTP Change parameter, and can be between 8 and 64 superframes [5],[11]. In addition, the role of PRT was deleted from the procedure.

BTP change can be enabled either locally at the MPRT or remotely by the IOCTF. If it is enabled remotely, an additional data link message allows the IOCTF to modify the BTP Change parameter. In practice, the IOCTF generates both messages every time a BTP change is performed. It may be necessary to modify the BTP Change parameter if the change is to be coordinated manually, for example, if the data links between the INTELSAT Headquarters Subsystem (HQS) and the telemetry, tracking, command, and monitoring (TTC&M) site are down. (The roles of the HQS and TTC&M systems are detailed in companion papers by Luz *et al.* [11] and by Skroban and Belanger [12].) To provide this manual backup capability, the SSRTE can enable, initiate, and cancel a BTP change locally using switches mounted on the (SS)RTE RCP.

After receiving the Enable command, the CADC samples the time of occurrence of the next SOTSF, using the time code generator. The generator replaces the GMT clock and is synchronized to UTC time via a GPS receiver, also mounted in the SSRTE. Both the CADC and the SPE then begin a superframe countdown from the time of occurrence of the sampled SOTSF, according to the current BTP Change parameter. At the same time, the CADC calculates the UTC time of occurrence of the SOTSF immediately prior to that on which the BTP change will take place. This time, plus 2 seconds, is the satellite command execute time, T_{xqt}, which is shown on the BTP Change Progress display [11] and transmitted back to the IOCTF. The MPRT then waits until the SOTSF—which occurs three superframes (approximately 48 s) before the SOTSF on which the BTP change will take place—to transmit the Request for Ready to Change messages to all authorized terminals. Upon receiving a Ready to Change message from all acquired terminals, the MPRT then declares the Ready to Change condition and illuminates the Ready LED on the RCP.

At the same time, the SRT illuminates the Ready LED on the RCP when it responds Ready to Change, and both the MPRT and SRT inhibit logging of diagnostic receiver data and the transmission of UW detection tables back to the IOCTF. This is necessary because the diagnostic receivers do not take part in a synchronized BTP change, and thus the data immediately following the change are incorrect. Logging and reporting are re-enabled after the new time plan is downloaded to the diagnostic receivers. The SRT also inhibits support of traffic terminal acquisition and transmits DNTX to all nonacquired terminals at this time.

At this point, if the BTP change was enabled locally, the Initiate Plan Change switch mounted on the RCP will become active and, if pressed, will cause Ready to Initiate Countdown to be declared. If the BTP change was enabled by the IOCTF, the Initiate Plan Change switch will remain inactive. In both cases, the MPRT will declare Ready to Initiate Countdown if it receives one or more SSTP Change Armed messages from the IOCTF before the effective instant of change (EIC). The SSTP Change Armed message is generated by the IOCTF based on telemetry data which indicate that the Execute tone was received by the satellite, and this message can be expected within 5 to 6 seconds after transmission of the tone. The EIC is about 4 s (128 multiframes) before the SOTSF on which the BTP change is to occur, and is the decision point for transmission of the countdown sequence. Following declaration of Ready to Initiate Countdown, the Cancel Plan Change switch mounted on the RCP becomes active and, if pressed, will cause the Ready to Initiate Countdown condition to be canceled, irrespective of whether remotely or locally enabled.

At the EIC, the MPRT will decide whether to transmit the countdown sequence, depending on whether Ready to Initiate Countdown is declared. If this condition is not declared, the MPRT will declare Countdown Suspended and enter the fail-safe recovery procedure. This procedure begins on the SOTSF at which the BTP change should have occurred. At this time, the MPRT begins monitoring the blind slot declaration being generated by the ASU subsystem. If at any time during the first control frame of this superframe the Blind Slot Not Active declaration is made, then the countdown sequence will be transmitted immediately. This condition will occur only when the satellite has correctly received and implemented the sequence of commands to rotate memories and so change the SSTP on the correct superframe boundary. In this case, the effect of the ground segment executing the BTP change slightly late will be a 1- or 2-second loss of those bursts affected by the change.

Interference and interference survival mode

One of the advantages of SSTDMA is that control of the traffic terminals may be arranged in what is known as an immune configuration [5],[13]. This refers to immunity from interference, which has proved to be a problem in fixed TDMA. Immunity is achieved by arranging for each SSRTE to be exposed to mutually exclusive sets of uplink appearances in their respective control transponders, while maintaining the ability at each to control all terminals in the network. This scheme ensures that, if an interfering carrier originates from a single uplink, then only one of the SSRTEs will be exposed to interference in its controlling transponder. Thus, the nonexposed SSRTE will continue to control the network. Unfortunately, this type of configuration is possible only when four or more transponders that can be received by the SSRTE are in use.

The immune configuration depends on the operation of the screening switches preventing the SPE from being exposed to any part of the frame other than the RBD and TAS regions. The concept is to use the two available CDCs to control a different set of terminals, with each set including one SSRTE. In the simplest SSTDMA network configuration, only two transponders are used, one each in the east and west. Each SSRTE transmits one reference burst carrying one CDC, which is broadcast to both transponders. Thus, both uplinks appear in the RBD region of both transponders, and also in the TAS region of both transponders (because terminals from both uplinks need to be controlled by both SSRTEs). Assume now that an additional two transponders (one east and one west) are to be added, but the original RBD/TAS regions are not to be disturbed. The simplest approach is to use the other CDC to control the additional terminals and form another (different) RBD/TAS region in the two additional transponders. This results in two distinct RBD/TAS regions in the system, which are mutually exclusive in terms of the uplinks appearing in them. By simply changing the controlling CDC of the SSRTEs (and hence the control transponder), the two SSRTE control transponders now have mutually exclusive uplinks in their RBD/TAS regions. This is the basic immune configuration.

In cases where such a configuration is not possible, the SSRTE has another protection against interference known as the interference survival mode. This too relies on operation of the screening switches, specifically the fact that the ASU is screened from all regions of the frame except the metric region and the SSV region. These regions, by definition, are loopback, and therefore the ASU at each SSRTE is exposed to a different uplink. Thus, interference from a single uplink cannot cause the ASU at both SSRTEs to fail.

The interference survival mode is invoked when the SPE has declared No Timing Available and the ASU still has metric burst synchronization. Two other conditions must be met: the No Input Alarm condition for the controlling transponder must not be declared, and the RCTP must correspond to a nonimmune configuration. In practice, the interference survival mode is identical to the SSRTE startup condition, where the ASU has already acquired metric burst and switch masterframe synchronization and the SPE is transmitting based on ASU timing. After the survival mode is established, the Cancel Startup switch on the RCP can be used to cease transmission. Otherwise, when the interference stops, the SSRTE will continue with the normal startup routine of acquiring the partner SSRTE, followed by the traffic terminals. In this way, the survival mode feature can greatly shorten any traffic outage caused by interference.

Promotion procedures

The procedures governing the operating status of reference terminals (IRTs, SRTs, and MPRTs) in the network were greatly simplified in SSTDMA. There are now only two procedures: the IRT-to-SRT promotion procedure executed by the MPRT, and the SRT-to-MPRT self-promotion procedure.

The IRT-to-SRT promotion, as in fixed TDMA, ensures that the contents of the CDC transmitted by the IRT are nominally the same as the CDC of the MPRT. The introduction of dynamic ACI assignments to acquiring terminals in SSTDMA makes it necessary to check the complete cycle of the ACI assignments over all the AT tables that are being used. Consequently, the procedure operates in two phases. In the first phase, the ACI assignment message content of the MPRT and the IRT is compared; in the second phase, the CDC content for each addressed terminal is compared between the IRT and the MPRT.

The content of the ACI assignment messages must be compared because in some SSTDMA configurations the MPRT is able to check only one of the two CDCs that the IRT may be transmitting. This will occur when one CDC is dedicated to controlling the east beam terminals, and the other to controlling the west beam terminals. Since the ACI assignment message is transmitted in the service channel of every reference burst and contains assignment information for all CDCs, the assignments for the CDC that is not received may be used in the comparison. In this case, it is considered sufficient to compare the content of only the CDC that can be received, since this will reveal any problems with the acquisition delays being generated.

The SRT-to-MPRT self-promotion procedure begins when either an SDNTX code is transmitted to the MPRT, or the MPRT status code is lost, or the SRT enters interference survival mode. If any of these conditions occur, the SRT waits approximately 2 seconds and then samples the current control code for the partner SSRTE. If the control code is SYNC (synchronization), no further action is taken; however, if the control code is DNTX, the SRT assumes the role of MPRT.

Startup procedure

As already stated, the concept of startup pairing has been eliminated, and the highest role of each SSRTE is MPRT. When startup is initiated at either SSRTE, the role of MPRT is immediately assumed, and the on-line ASU executes the metric switch state acquisition procedure, which proceeds through the metric burst and the switch masterframe acquisition and synchronization procedures, terminating in the availability of SOTSF. This SOTSF is then transferred to the on-line (paired) SPE, which initiates transmission of all defined reference bursts based on the paired ASU transmit timing. This transmit timing relationship between the on-line ASU and SPE continues as long as the MPRT role is maintained.

After the on-line SPE begins transmitting its reference bursts, startup proceeds as in fixed TDMA, with two fundamental differences. With SSTDMA, the method of satellite position determination (set during SPE initialization) is always prediction. Also, the partner SSRTE is acquired using the predicted satellite position and the normal CAW, with a continuous IAP1 code transmission. The concept of a startup acquisition (SUA) window is not used, and there is no ranging startup mode. This is because the switching action of the satellite makes it impossible to guarantee that an SUA window can be placed in a sufficiently long continuous connectivity for acquisition using the nominal satellite position.

Both the on-line and standby SPEs receive the SSRTE's reference burst and establish receive timing (SORF, SORMF, and SORSF). This timing is transferred from the standby SPE to the standby ASU, which then synchronizes directly with the received metric burst and enters normal steady-state operation. Although the standby ASU is measuring metric cutoff and obtaining a position error reading, the transmit timing is taken from the paired SPE.

Following successful acquisition of the partner SSRTE, the Become Secondary command is sent concurrently with the SYNC status code, and startup terminates. As in fixed TDMA, startup can be terminated manually if it becomes apparent that the partner SSRTE cannot acquire.

Reference terminal acquisition

The SSRTE normally responds to reception of the IAP1 code by transmitting the short acquiring burst and proceeding through to reception of the SYNC code, at which point all defined bursts are transmitted with the Inoperative (INOP) status code. When the SYNC code is received, the on-line and standby ASUs begin transmitting and receiving the metric burst based on transmit and receive timing from the paired SPE. After establishing metric burst and switch masterframe synchronization, the ASUs begin normal measurement of metric cutoff and adjustment of transmit timing. Thus, the on-line ASU in an inoperative or secondary SSRTE will be independently synchronized to the satellite switch frame. However, the on-line SPE will derive transmit timing in the normal way by receiving control and delay data from the MPRT.

The CADC subsystem

The CADC maintains the operational databases for the SSRTE, controls and monitors the SPE and ASU subsystems, provides the SSRTE operator interface, and manages the data link communications with the IOCTF. The major change to the CADC was the addition of support for the new ASU subsystem.

ASU support

The following ASU support functions are performed by the CADC:

- *Loopback Appearances Parameter*. The CADC maintains this parameter as an additional data item in the reference terminal operational parameters (ROP) database and supplies it to the ASU at initialization.
- *Screening Switch Control*. The CADC extracts these data from the RCTP contents, based on the positions of the reference bursts and principal bursts in each defined transponder, and supplies them to the ASU at initialization.
- *Bank and Reference Burst ID*. The CADC extracts these data from the RCTP contents, based on reference burst position in the metric transponder, and supplies them to the ASU at initialization.
- *ASU Status Display*. A status display VDU is supported for either ASU, showing metric burst acquisition/synchronization status, clock phase measurement status and processed data, and co-installed diagnostic receiver status.
- *ASU Event Logging*. New operator notification messages and system log messages are supported.
- *Maintenance Support*. The existing SPE maintenance support was expanded to include standard loadable databases for the ASU, to be used with the on-site maintenance aids provided.

Clock phase measurement support

Raw phase measurement data are processed by the CADC for local display and transmission to the IOCTF. The CADC maintains a clock phase reporting interval (CPRI) and a phase drift threshold, P_{max}. These parameters can be updated from the IOCTF. The CPRI is the period (in superframes) between reports of the accumulated phase value. The parameter P_{max} is an alarm threshold for average phase drift or short-term frequency offset.

The phase value that the CADC reports to the IOCTF is the previously reported phase value plus the arithmetic sum of the changes in $T(M)$ over all the superframes of the current reporting interval [3]. The CADC processes the $T(M)$ data from both ASUs to determine the correct phase to be reported in the event of a ASU switchover. The phase value reported to the IOCTF is not divided by two.

For alarm and display, the CADC calculates a running average of the real phase drift over the last eight superframes. This is equivalent to a measurement of short-term frequency offset between the LTS and the onboard oscillator. If this value exceeds P_{max}, a local alarm is generated.

Diagnostic receiver support

The CADC maintains the current DRTP, which is received from the IOCTF via data link. The DRTP contains a list of the types of bursts (RB1, RB2, or traffic) and their positions in each transponder. Up to four transponders may be defined. Upon reception of the DRTP from the IOCTF, the CADC downloads the diagnostic receivers immediately if the BTP number matches the foreground BTP number. The CADC receives the UW detection tables from each diagnostic receiver every 512 frames and, based on the current port selections for each demodulator, selects the UW detection tables to be sent to the IOCTF. If duplicate port selection exist among the four demodulators, the CADC will select demodulators in the diagnostic receiver that is associated (co-installed) with the ASU currently on line, and will choose demodulator 1 in preference to demodulator 2. Any change of demodulator port selection will mark UW detection data from that demodulator invalid until the diagnostic receiver is reinitialized and a warning VDU message is generated. During BTP change, the CADC will inhibit logging and transmission of UW detection data until after the change is successful and the new DRTP has been received and downloaded. The CADC also supports loading of a maintenance DRTP for use with the burst simulator.

SPE support

The following additional support functions are provided for the SPE:

- *RCTP Format Changes*. The CADC no longer expects to receive a code 131 block, and sets the appropriate parameters by default at SPE initialization.
- *ROP Format Changes*. The ROP was changed to define only two reference terminals, plus the ASU-specific Loopback Appearances parameter. The display data were changed to include the definition of metric transponder and delete the connectivity description.

- *AT Table Generation*. The CADC generates the AT tables based on RCTP contents.
- *Survival Mode Support*. The CADC determines from the RCTP contents whether the network configuration is immune or nonimmune, to support implementation of the survival mode function.
- *BTP Change Support*. A large number of additional functions are provided to support BTP change, as described previously. Chief among these is the addition of the time code generator to replace the GMT clock, enabling accurate local sampling of the SOTSF time.
- *Monitoring and Logging*. A number of new operator notification messages and events to be logged are supported. In particular, the new "dummy" terminal and burst numbers are supported in the sense that event history flags can be set and will trigger for these bursts. Many of the original fixed TDMA VDU screen formats have changed or have been expanded to accommodate the additional SSTDMA information.

Data link messages and protocols

Additional messages were created between the SSRTE and the IOCTF to support the new SSTDMA functions of BTP change and clock correction. As far as possible, existing messages were not modified, with data fields left unused or converted to other uses. An example is the ROP message, in which the fields previously used for the two nonexistent terminals are now either unused or used to convey the Loopback Appearances parameter.

The data links between the SSRTE and the IOCTF were upgraded for the SSTDMA system to a standard software product operating at speeds up to 9,600 baud [11]. Data flow control for routine data (*e.g.*, CDC message contents, system log contents, and real-time display monitoring) is now centralized at the IOCTF. (These upgrades have also been done for fixed TDMA.)

The TDMA system monitor

All changes to the TSM were confined to the application software. The new TSM software permits operation in either fixed TDMA or SSTDMA mode.

CTP processing

The TSM can now process a TSM CTP (TCTP) for SSTDMA, or for fixed TDMA (for which the format has not changed). In fixed TDMA, the upbeam transponder for a given downbeam transponder is constant. However, in SSTDMA these connectivities may change according to the SSTP, and thus it was necessary to modify TCTP block codes 210 (reference bursts) and 220 (normal traffic bursts) to add the upbeam identification for each burst. Also, two new block codes were added to the TCTP. Block code 260 defines each terminal's principal burst. Block code 270 defines all switch states for all receive transponders that are used to derive the idletime slot (ITS) connectivity map and the spectrum analyzer gate (SAG), which are discussed later.

Measurement processing

In fixed TDMA, the TSM is assigned a receive and transmit ITS for each transponder. However, in SSTDMA, due to frame overhead considerations caused by a potentially large number of different connectivities, the ITSs are placed in the test slots. The test slot connectivity is programmable and may be changed based on operational requirements involving the burst mode link analyzer.

ITS measurements

The TSM performs receive and transmit ITS measurements, depending on the mode selected. The receive ITS is used to measure down-chain gain and down-converter frequency offset, while the transmit ITS is used to measure the gain of the transmit monitor path. In the routine mode, the TSM measures down-chain gain and frequency offset every time a new transponder is entered. In the diagnostic mode, down-chain gain and frequency offset are measured only once, when the measurement is initiated. For set reference power or input backoff, only down-chain gain is measured. If an ITS is not available for a particular downlink transponder, then down-chain gain and frequency offset measurements are inhibited.

When the IOCTF has successfully implemented an SSTP change, a TSM Test Slot Connectivity Change message (number 207) is sent via data link to the TSM. This message contains a TSM test slot status flag for all reference beams. A reference beam is the transponder configuration in which a particular burst (reference or traffic) is used for a set reference power measurement. Once a set reference power measurement has been made for a particular transponder, all other bursts in that transponder are displayed relative to the reference power burst. Message 207 also contains the downbeam ID of all reference beams and the test slot upbeam ID of downbeams having a test slot.

In certain SSBTP configurations, there may be no ITS scheduled for a reference beam. Alternately, although an ITS is scheduled, no reference bursts may be present in a particular downbeam. In this case, a set reference power measurement may be made on a traffic burst. If the ITS Available flag is not set or the ITS Change flag is set for the transponder in question, ITS measurements are inhibited for all parameters other than the set reference power measurement.

TSM routine mode measurements

If receive ITS measurements are not inhibited for a transponder, then down-chain gain and down-converter frequency offset are measured. The measured values are stored in a data file and may be used if ITS measurements are inhibited for a period of time.

In fixed TDMA, the TSM can measure reference and traffic bursts where no distinction is made between principal and nonprincipal bursts. In SSTDMA, the TSM measures reference bursts first, followed by principal bursts, and then normal traffic bursts. If desired, the operator can suppress the principal bursts to speed up the measurement cycle.

An upbeam compensation factor editor is provided which allows the TSM operator to change the compensation factors for bursts which originate in different upbeams. These compensation factors are available for each connectivity and are added to the relative burst power measurement value.

TSM diagnostic mode measurements

Set reference power measurements can be made while the ITS Availability flag is set. A reference burst or a traffic burst may be selected.

Dwell measurements can be made using measured values for down-chain gain and frequency offset, provided that ITS measurements are not inhibited. If ITS measurements are inhibited, stored values are used for down-chain gain and frequency offset, as in the routine mode.

While the ITS Availability flag is not set for a particular transponder, input backoff measurements are also inhibited.

TSM display processing

The display processing software for SSTDMA was changed to include the north and south zone beam designators. Also, in routine mode, bursts and their measurement data are displayed and grouped by transponder, burst type, and upbeam ID. If selected, principal bursts in routine mode are displayed in a different color to differentiate them from other bursts. In both routine and diagnostic modes, when stored values are used for down-chain gain and frequency offset, the displayed data flash on the screen.

In the diagnostic mode, the TSM operator can now control the SAG from the Infotouch display. This is particularly useful when attempting to locate spurious continuous-wave carriers. Using a spectrum analyzer externally triggered on the start of frame, the SAG can be positioned to coincide with a particular switch state, and thereby determine the source of the continuous-wave carrier.

Operator interface modifications

The operator interface in the routine mode was modified to allow the selection of two burst type combinations: "All" refers to reference, principal traffic, and normal traffic bursts; and "RTB" refers to reference and normal traffic bursts.

The diagnostic mode interface was modified to allow either reference bursts or traffic bursts to be selected as the reference power burst. A SAG was also added which can be set from the Infotouch display by specifying either a switch state or the start and stop position in frame units.

Database editor modifications

The system definition file editor was changed to allow three new flags to be set (or reset): a default burst-type flag, a TSM Real-Time Measurement Data Flow Enable flag, and a TCTP Sorting flag.

Changes to the TSM definition data file required removing the fixed TDMA-related transponder identifiers and enabling the operator to enter any alphanumeric data string. New database editors were also added for upbeam compensation factors and the ITS connectivity map.

Acknowledgments

The authors wish to acknowledge the efforts of the staff members of NEC Corporation, too numerous to mention, who contributed to the equipment design; A. Saburi and Y. Yamada of NEC Corporation, who undertook the project management; past staff of INTELSAT, R. Williams, and R. Kochhar, who played key roles in the initial stages of the project; and not least the staff of the Tanum and Etam earth stations, who were hosts and assistants over many months while the INTELSAT and NEC teams worked to finalize the equipment design.

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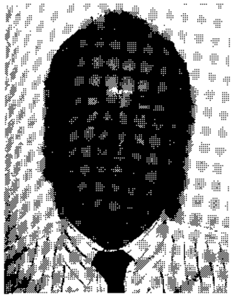
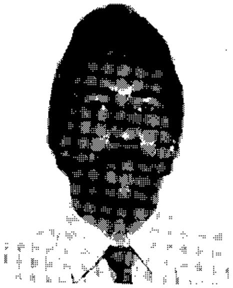


Roger Bedford received a BSc in electronic engineering from Bolton Institute of Technology, England, in 1974; and a MSc in telecommunications from Essex University, England, in 1975. From 1975 to 1977 he worked on satellite system analysis and earth station design for the Marconi Company. In 1977, he joined Bell-Northern Research Laboratories in Canada, where he was involved in the integration of Canadian domestic satellites into the trans-Canada telephone network. He subsequently joined Miller Communications Systems, where he was responsible for system and hardware design of a 3-Mbit/s TDMA system.

Mr. Bedford joined INTELSAT in 1981, and took major responsibility for the design evaluation, installation, and testing of the reference terminals for the INTELSAT 120-Mbit/s fixed TDMA system. In 1986, he became Principal Project Engineer for the design and development of the INTELSAT 120-Mbit/s SSTDMA system. Since 1990, he has been Project Manager for the INTELSAT SSTDMA implementation program.



Anthony Berntzen joined INTELSAT in 1981 as a Member of the Communications Operations Staff. Since 1984, he has been a member of the Fixed-TDMA and SSTDMA project team and participated in the installation and testing of the TRMS equipment. His primary responsibility has involved the integration of hardware and software upgrades for the TDMA System Monitor. From 1969 to 1980, Mr. Berntzen was employed by British Telecom International at Goonhilly Earth Station, where he was involved in all aspects of earth station operations and maintenance, and specialized in cryogenics.

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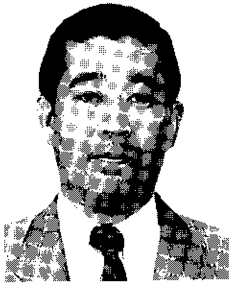
Mr. Lunsford rejoined COMSAT Laboratories in 1990 as manager of the Network Systems department in the Network Technology Division, where he led an engineering team performing research and development in the areas of onboard processing, ISDN, TDMA, network control, and system architectures for advanced satellite communications systems. He is currently manager of the Network Engineering department, where he is responsible for hardware development for various satellite communications projects.



Yuhei Ishi received a BE in applied electronic engineering from the University of Electro-Communications in 1971. He then joined NEC Corporation, and in 1975 became a member of the TDMA system development group, where he developed an experimental TDMA system for domestic satellite communications. His major focus was on microprocessor-based control logic circuit design. He also designed the ASU for COMSAT Laboratories in 1977 as an R&D contractor. In 1982, he designed the INTELSAT TDMA CTTE for a field experiment sponsored by KDD. He subsequently supervised development of RTE for INTELSAT TDMA and participated with INTELSAT engineers in a TDMA system test. In 1987, he was responsible for developing the SSRTE. He is currently Senior Manager of the Network Development Department in the Microwave and Satellite Communication Division at NEC. Mr. Ishi is a member of the Institute of Electronics, Information, and Communication Engineers.

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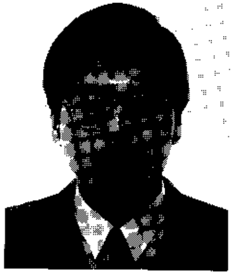

Index: networks, models, software, time-division multiple access, INTELSAT

Generation of burst time plans for the INTELSAT VI SSTDMA system

T. MIZUIKE, L. N. NGUYEN, K. P. CHAUDHRY, J. A. LUNSFORD, AND P. A. TRUSTY

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Abstract

Methods of generating burst time plans (BTPs) for the INTELSAT VI satellite-switched time-division multiple access (SSTDMA) system are presented. Compared with the INTELSAT V fixed TDMA system, SSTDMA requires BTPs of greater complexity. Because of the dynamic beam switching on board INTELSAT VI, the network control scheme was updated significantly and a switching sequence is required. It thus was necessary to develop new methods of generating BTPs for the SSTDMA system. The basic approach to BTP generation is presented first, along with a discussion of operational requirements in the INTELSAT VI SSTDMA system environment. Since a number of purely theoretical papers have already been presented in this field, this paper focuses on the practical implementation of scheduling algorithms. Detailed procedures are described for major scheduling processes such as control assignment, switching-sequence generation, and traffic burst scheduling. The algorithms developed have been implemented in the operational software system, and an example of BTP generation employing actual scheduling software is given.

Introduction

As in the INTELSAT V fixed TDMA system, the INTELSAT VI satellite-switched time-division multiple access (SSTDMA) system functions according to an operational plan called the burst time plan (BTP). The BTP comprises the entire body of timing assignments for a specific SSTDMA network, including the time slot assignments for all transmitted traffic and the control information for all network terminals. The principal difference between SSTDMA and fixed TDMA BTPs is that SSTDMA requires a time plan for dynamic beam switching by the onboard microwave switch matrix (MSM), as well as an updated network control scheme.

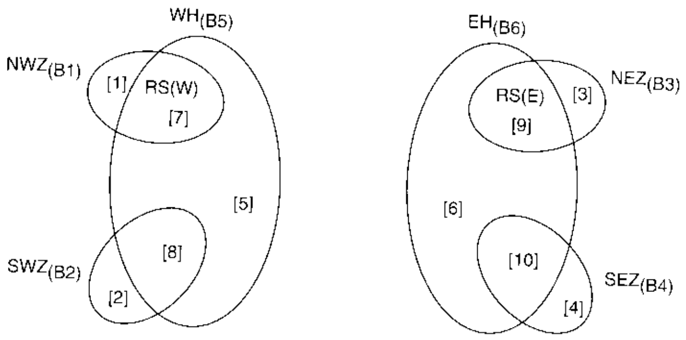
Such BTPs must be generated carefully to ensure efficient utilization of the space segment (SSTDMA frame) while minimizing the earth segment (earth station equipment). Various theoretical studies of SSTDMA system scheduling have been conducted, focusing mainly on switching-sequence generation [1],[2]. Like most commercial networks, the INTELSAT VI SSTDMA system requires efficient BTPs that are both theoretically optimum and practicable. These additional requirements are in response to operational conventions and the need for cost-effective network deployment.

A set of operational computer software has been developed by implementing the methods described here. The software system consists of the NPDGEN/SSBTP (Network Parameters Data Generation/SSTDMA Burst Time Plan) software and the SSMTP/SSCTP (SSTDMA Master Time Plan/SSTDMA Condensed Time Plan) software. The SSTDMA BTP generation software system was developed by Kokusai Denshin Denwa Company, Ltd. (KDD), Japan, R&D Laboratories and COMSAT Laboratories, USA, in close cooperation with INTELSAT. A prototype SSBTP computer program was developed in 1984 and 1985 to demonstrate the feasibility of specific SSTDMA algorithms. As the SSTDMA system specification [3] was developed and finalized during 1987–1988, the prototype software was upgraded to an operational program to incorporate the specification. The SSBTP/NPDGEN software system was developed by KDD during 1987–1989, and the SSMTP/SSCTP software system was developed at COMSAT Laboratories during the same period. The four program modules run on the IBM mainframe computer at INTELSAT Headquarters.

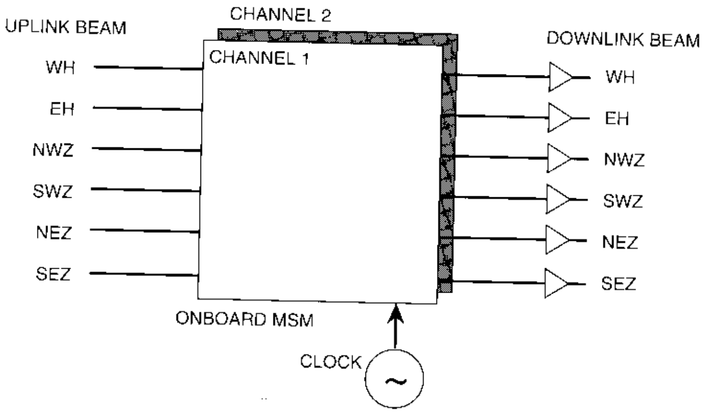
This paper surveys aspects of BTP generation for the INTELSAT VI SSTDMA networks, with a focus on operational requirements. An overview of the BTP in the SSTDMA environment is presented, and detailed requirements and constraints for BTP generation are discussed. The basic strategy for generating BTPs is then presented, along with criteria for each step in the process. Subsequent sections introduce scheduling algorithms for the essential processes of BTP generation and demonstrate an example of BTP generation, with a description of the generation procedure.

Operational aspects of the SSTDMA system

The INTELSAT VI SSTDMA system is configured as shown in Figure 1; its features have been described previously [3]–[6]. The system differs significantly from fixed TDMA in that beams can be switched dynamically by the MSM on board the satellite. This capability has led to a number of changes and refinements in the network operation and system architecture, which have affected the structure of the BTP. One notable difference is the requirement for the satellite to have a switch state time plan (SSTP), or switching sequence.



(a) Beam Coverage



(b) Satellite Transponder

WH: West Hemi
EH: East Hemi
RS: Reference Stations
[n]: Region Number

NWZ: Northwest Zone
SWZ: Southwest Zone
NEZ: Northeast Zone
SEZ: Southeast Zone

Figure 1. *SSTDMA Network Configuration*

In the SSTDMA system, a TDMA frame is divided into a series of switch states stipulated by the SSTP. During each switch state, the MSM maintains a pattern of switch connections between the uplink beams (upbeams) and downlink beams (downbeams) of a multibeam satellite. The MSM can connect one upbeam to one or more downbeams simultaneously. The network control function takes advantage of semibroadcasting beam connections (*i.e.*, an upbeam connected to more than one downbeam in a switch state) to accomplish reference burst distribution, initial acquisition, and steady-state synchronization by a pair of reference stations, resulting in no change in the traffic terminals [7]. Switching of beam connections allows traffic terminals with access to a limited number of transponders to distribute traffic bursts efficiently. The traffic burst configuration remains the same as in fixed TDMA. Therefore, detailed time plans must be developed to establish the burst schedule, in addition to the SSTP, so that transmission among stations within the various beam coverages can be maintained without burst collision or other conflicts.

Operation of the SSTDMA network is characterized by a BTP which specifies precisely the items summarized in Table 1. For each transmission channel, the switching sequence provides the durations and beam connections for a series of switch states. The BTP summarizes the network control scheme, including reference burst distribution and principal burst monitoring assignments. Burst position is assigned for all bursts to route them with an appropriate beam connection. The BTP defines burst and subburst configurations in the same manner as in fixed TDMA. Terminals and terrestrial interface modules (TIMs) are assigned at the transmit and receive earth stations to identify the intended use of the terminal equipment.

Time plans required by various SSTDMA subsystems

The information in a BTP is specified for all terminal and monitoring equipment in an SSTDMA network, in the form of a coordinated set of time plans. Three types of time plans are produced for each BTP. Master time plans (MTPs) provide the information necessary to set up the equipment at each earth station in the network, map the terrestrial channels to the satellite channels, and oversee operations at the stations or at the INTELSAT Operations Center TDMA Facility (IOCTF). International Telegraph Alphabet No. 2 (ITA2)-encoded condensed time plans (CTPs) contain a subset of the MTP information and are loaded to the terminal and system monitoring equipment to provide timing and control information. American National Standard Code for Information Interchange (ASCII)-encoded time plans contain a subset of the MTP information for use in the diagnostic processor at the IOCTF, in the equipment

TABLE 1. SSTDMA NETWORK ITEMS SPECIFIED IN A BTP

NETWORK CONTROL	SWITCHING SEQUENCE	BURST POSITION	BURST CONFIGURATION	TERMINAL USAGE*
• Reference Control Beams • Control Upbeam and Downbeam • Controlling Reference Burst • Principal Burst • CDC Address • Reference Beam Pair, Control Group, and TAS Group Definition	• Frequency channel • Transponders (associated downbeam) • Switch State – Durations – Start timing – Beam connection (upbeam to downbeam[s])	• Frequency channel • Transponder number • Switch state number • Upbeam • Downbeam(s) • Burst length • Start timing	**Burst** - Transmit earth station - Included subburst(s) - Use of FEC indicator (on/off) **Subburst** - Transmit earth station - Subburst type (DSI/DNI/ DDI) - Total no. of bearer and derived channels - Receive earth stations - Traffic of each link - DSI gain and supervisory channel indicator	• CTTE ID no. at transmit earth station • ID no. and type of TIM at transmit earth station • CTTE ID no. at receive earth station • ID no. and type of TIM at receive earth station

* CTTE : Common TDMA Terminal Equipment
ID No. : Identification Number
TIM : Terrestrial Interface Module

that controls the satellite switch at the INTELSAT Satellite Control Center (ISCC), and in the diagnostic receiver equipment. Abridged CTPs (ACTPs) are used during a BTP changeover, and there are several additional test CTPs. In particular, the following time plans are generated:

- *Switch State Time Plans for the MSM.* The switch state MTP consists of a table describing the function and uplink connectivity of switch states for all downbeams in the transmission channel. Each switch state is described by its number, starting position, duration, upbeam switch index, and type. The corresponding CTP (SSTP) is used at the ISCC to provide timing data for switching to the onboard memory through the telemetry, tracking, command, and monitoring (TTC&M) station.
- *Traffic Terminal Time Plans.* The traffic terminal MTP and operational CTP for the SSTDMA system remain unchanged from those for fixed TDMA [8], except for minor modifications to the beam descriptions in the MTP. The MTP and CTP provide the traffic station with controlling reference burst information, principal burst information, burst and subburst configuration information for its transmit and receive traffic bursts, and active orderwire information. In addition, the MTP provides baseband channel assignments, equipment requirements, and a summary of activity at the station. The CTP provides transmit and receive timing information for the terminal.
- *Reference Terminal Time Plans.* The MTP and operational CTP (RCTP) for each reference terminal contain information for all reference bursts transmitted or received by the terminal, as well as for the reference and principal bursts monitored at the terminal. The frame index and reference terminal control and delay channel (CDC) cycle used to address control information to each controlled terminal are provided, along with the terminal's identification numbers and the start and duration of their acquisition windows. The MTP also provides the terminal with metric and switch state verification (SSV) burst information (a summary of transmit, receive, and control activity) and a list of information for all bursts received by the collocated diagnostic receiver equipment. The MTP is used to configure the reference terminal, and the operational CTP is used during normal operation.
- *SSTDMA System Monitor Time Plans.* The system monitor MTP and CTP (TCTP) provide data for all reference, traffic, and principal bursts transmitted or received in each beam accessible to the SSTDMA system monitor (STSM) collocated at a reference terminal. Descriptions of idletime slots and test time slots in the frame are also provided. The TCTP contains beam connectivity maps that give the upbeam connectivity index for each switch state in each accessible downbeam. The SSTDMA system monitor uses these plans to monitor burst transmission status.

- *Diagnostic Receiver Time Plans.* Reference and nonreference diagnostic receivers use diagnostic receiver MTPs and CTPs (DRTPs) to monitor all bursts in the BTP for overall network diagnosis. For nonreference diagnostic receivers, the time plans contain a list of information for all reference, principal, and traffic bursts received from each zone beam monitored by the nonreference diagnostic equipment. The corresponding nonreference receiver CTPs (NRTPs) contain data blocks with the same information.
- *Diagnostic Processor Time Plans.* A diagnostic processor MTP and its corresponding processor CTP (DPTP) contain network identification parameters such as the BTP number and network control assignment data. Terminal control information includes terminal identification numbers, CDC addresses, and controlling beam information. Information is provided for all bursts appearing in all downbeams and includes the entire SSTP. The diagnostic processor at the IOCTF uses these data for overall network diagnosis.
- *Abridged and Test Abridged CTPs.* The ACTP and test ACTP (TACTP) contain only two data blocks, which provide terminals with the BTP identification number. The ACTP is used by the IOCTF to verify that the terminals have the correct CTP in background memory. Upon receiving an ACTP, the terminal substitutes the normal BTP number from the ACTP into the CTP in its background memory and returns the complete CTP to the IOCTF. TACTPs having the modified BTP number are used to support an acquisition test for the terminal during INTELSAT *Satellite System Operating Guide* (SSOG) testing.
- *Test CTPs.* The terminal uses the T1CTP during SSOG testing to verify its response to reference terminal control, and the correct operation of the BTP change procedure. According to the SSOG, the T2CTP is used off line by a traffic terminal to verify the correct functioning of the digital speech interpolation/digital noninterpolation (DSI/DNI) units.

In accommodating the SSTDMA network, every effort was made to minimize modifications to existing fixed TDMA time plans. Very few changes were made to the traffic terminal time plans; however, the time plans generated for the reference terminals and system monitors required more extensive modification for use with the SSTDMA system.

The MTP summarizes transmit and receive activity at each terminal. Corresponding operational and test CTPs are generated in encoded data blocks, as well as in operator-readable form. Each type of CTP block is identified by a specific code block number. An ITA2-encoded CTP is generated by converting the numbers in each block of the CTP to the 5-bit ITA2 code, line by line, and writing each block of these data to a file, which is then transferred from the IOCTF to the terminal or system monitor via the orderwires on the SSTDMA network. Each CTP block ends with a binary five-digit checksum.

Operational requirements of the SSTDMA network

Unlike the fixed TDMA system, the SSTDMA system uses frames that are divided into a series of switch states. Figure 2 shows the SSTDMA frame format for a simple example that includes four beams. Some switch states at the beginning and end of the frame are dedicated to network control functions such as reference burst distribution and principal burst monitoring [4]. The other switch states include traffic bursts. Beam connections can be (one-to-one) uplink-to-downlink, semibroadcasting, or broadcasting. (This is the most significant feature of SSTDMA system operation and its constraints.)

From a number of feasible BTPs, it is desirable to select the most economically efficient plan. The primary goal in generating a BTP for an operational network is to maximize the level of traffic accommodated, while minimizing the number of transponders required. For a given traffic demand, it is also necessary to minimize the amount of equipment required by the traffic terminals. By taking into consideration traffic terminals that may join the SSTDMA community in the future, as well as the capacity for growth of existing links, network expansion can proceed in a planned and systematic manner, and traffic terminal owners can receive advance notice of the need for additional equipment.

Network control requirements

To establish control and monitoring of network performance, and to facilitate traffic scheduling, frames are divided into distinct control, monitoring, and traffic regions. The control region, which includes time slots for all the beam connections required for the network, must be minimized because it is considered to be overhead in terms of net transponder capacity. Semibroadcasting beam connections must be employed effectively so that a

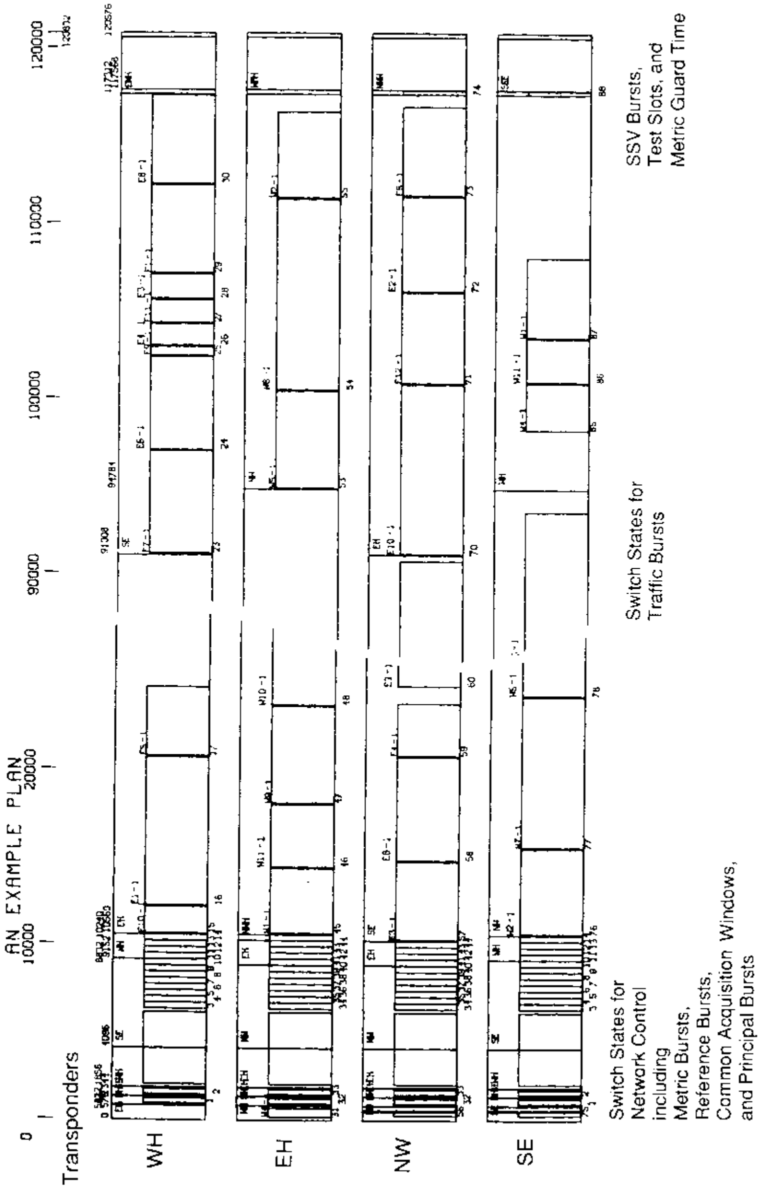


Figure 2. *Frame Format Example*

pair of reference stations can control the network with interference immunity capability [4] and with no change to the controlled traffic terminals. Specifically, controlled terminals should not need an extra beam access solely for network control. Special attention should also be directed toward keeping the control assignment unchanged for existing terminals when a network is expanded into a continuation mode that uses a slightly modified version of the current control assignment plan [6].

Traffic scheduling requirements

The switching sequence must include time slots of sufficient capacity and the necessary beam connectivities to route all traffic demands, while minimizing frame occupancy and thus reserving spare capacity for future system expansion. Since transponder-hopping is available in the SSTDMA system (as in fixed TDMA), the burst schedule must avoid burst collision and overlapping. Burst collision is caused by two or more bursts occupying the same time slot in the transponder, and burst overlapping refers to the simultaneous transmission or reception of two or more bursts at a terminal.

To produce a BTP that is acceptable to TDMA users, it is essential to focus on equipment requirements. A BTP can affect the equipment required at a traffic terminal (common TDMA terminal equipment [CTTE]) in three areas: the number of transponders which the traffic terminal must access; the number of TIMs required; and, under certain circumstances, the amount of CTTE that must be provided. The number of transponders that must be accessed determines the IF/RF equipment required for each up- and down-chain, as well as the need for the CTTE to be equipped for transponder-hopping.

During development of the initial BTPs for SSTDMA networks, users concerns regarding cost and equipment availability dictated that the highest priority should be to minimize the number of TIMs required, which could result in an increase in the number of transponders to be accessed by each traffic terminal. Since a traffic terminal must transmit at least one burst in each up/downbeam connectivity in which it has traffic, and since a dedicated TIM is required for each subburst of each burst, the number of TIMs required can be minimized by limiting the number of subbursts transmitted by each terminal through effective multidestination subburst configuration (*e.g.*, by not splitting traffic that can be accommodated in one subburst into multiple subbursts). To some extent, the satellite's dynamic switching capability permits a tradeoff between the number of transponders accessed by each terminal and the number of TIMs required. Generally, the more a terminal is constrained in the number of transponders it can access, the less flexibility there is in reducing the number of TIMs required, due to congestion in the beams the terminal accesses. Because there is less freedom to aggregate the traffic for the constrained terminal with that for other constrained terminals which access other beams, separate subbursts and TIMs must be formed. Terminals with the ability to both polarization-hop and frequency-hop in the same bank offer the greatest flexibility for reducing the number of TIMs.

Strategy for generating BTPs

Key inputs to BTP generation are the space segment configuration and the traffic requirements of SSTDMA users, together with the equipment and accessible beams available or planned. Traffic demands are given separately for speech-interpolated voice channels, non-interpolated data channels, and multidestination traffic elements associated with digital circuit multiplication equipment (DCME). Numbers of available CTTEs and TIMs (with their types, such as DSI/DNI/direct digital interface [DSI/DNI/DDI]) are specified for each earth station. The network configuration includes the satellite transponders dedicated for the SSTDMA network, SSTDMA reference terminal equipment (SSRTE) locations, and traffic stations.

It is difficult to generate MTPs and CTPs directly from these data, for two reasons. First, the overall scheduling presents an intractable combinatorial problem due to the complexity and magnitude of the mathematical model [9]. Second, since operations planners prefer a comprehensive procedure to incorporate practical constraints in the network, it is realistic to divide the entire process into three phases to ensure that the desired BTP (in the form of MTPs and CTPs) is ultimately generated. The first phase defines the network configuration. The second phase is the actual BTP generation to obtain a comprehensive plan, including control assignment, switching-sequence generation, and traffic burst scheduling. The last phase consists of converting the generated BTP into the formal structure of MTPs and CTPs with error checking.

The second phase, which is the main scheduling process, presents large-scale scheduling problems. A step-by-step approach is employed to make use of efficient mathematical techniques for divided subproblems. In the first step, the network control scheme is determined for the planned network configuration. Taking into account interference immunity [6], the most reliable and efficient control assignment is identified. The second step then generates a switching sequence that makes efficient use of satellite transponders and is also suitable for burst scheduling. In the last step, the burst formation and assignment are determined for the obtained switching sequence. Ultimately, the desired BTP is attained by resolving each subproblem sequentially, following these steps. Figure 3 illustrates a series of these procedures, with input and output data.

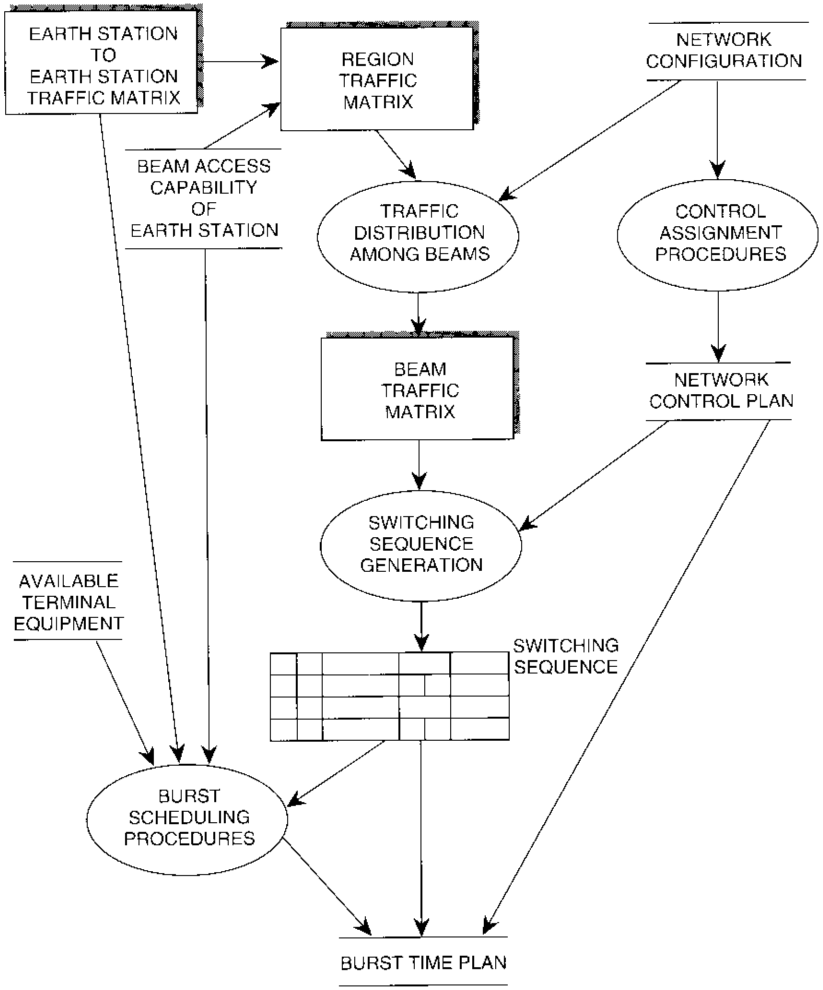


Figure 3. *Overall Procedure for BTP Generation*

The subproblems, discussed below, are formulated as well-studied mathematical models; however, the theoretically optimum solution may have some shortcomings in regard to meeting detailed practical operational requirements. Several editing functions are available to permit slight modification of the automatic scheduling results. These functions allow manual modification of the switching sequence, burst and subburst configuration, and burst positioning.

Software implementation

Based on the strategy described above, a set of computer programs has been developed for BTP generation. This software system is oriented toward the operational planner and the communications engineer. As illustrated in Figure 4, the NPDGEN/SSBTP software comprises the NPDGEN and SSBTP programs, and the SSMTP/SSCTP software consists of the SSMPTDATA and SSGENTP programs.

The NPDGEN program controls the network configuration definition process in the first phase of BTP generation, while the SSBTP program performs a variety of functions in the second phase, including control assignment, switching-sequence derivation, and traffic burst scheduling. In this software system, both automatic algorithms and manual editing functions are

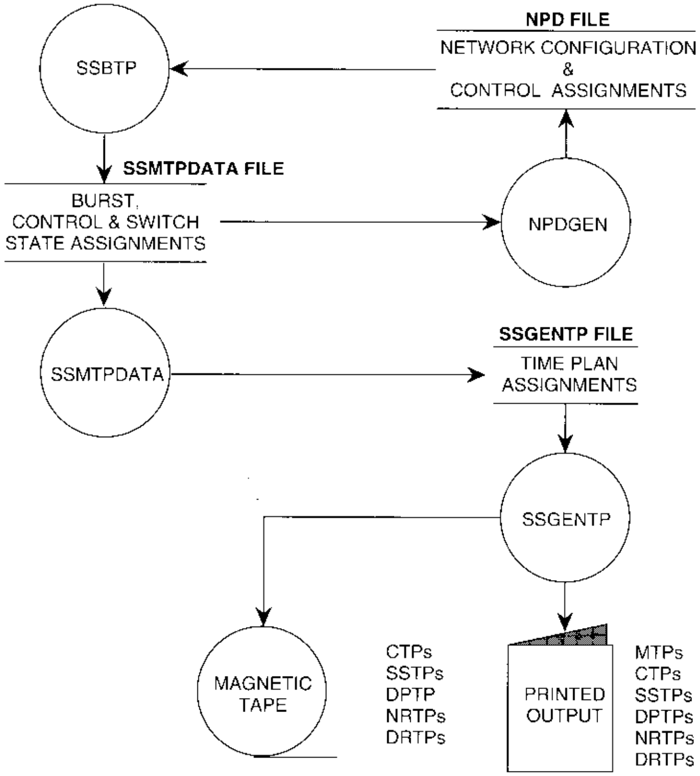


Figure 4. *Software System for BTP Generation*

implemented for the convenience of operational planners. Incorporated into the design is the ability to selectively override the automatic algorithms in order to reconcile a generated BTP with existing operational constraints, or to reduce the changes between successive time plan assignments and the changes in equipment requirements that may occur when the automatic algorithms are used. The NPDGEN/SSBTP also has a plotter output capability to show comprehensive scheduling results.

The SSMTPDATA and SSGENTP programs can convert the generated BTP into the formal format of MTPs and CTPs. The SSMTPDATA program assigns channel numbers and orderwires to the bursts formed in the SSBTP program, assigns uplink connectivities for default test slots, assigns idletime slots, and generates a baseline SSTP. It can also check all of its assignments for any network operating rules violations that may have been produced by manual editing. The SSGENTP program generates MTPs, CTPs, and other time plans from assignments made in the previous three programs. It generates the CTPs and time plans in both an operator-readable format and as an output file that can be transmitted to the IOCTF via magnetic tape or a digital data link. In addition, the SSGENTP program performs error-checking functions. As shown in Figure 4, intermediate data are transferred among these programs via external files. Since these files preserve the BTP for the current network, relevant data can be retrieved to generate BTPs in the continuation mode.

Network control assignment and scheduling

The greater flexibility in beam connectivity in the SSTDMA network results in greater flexibility for the distribution of control. However, it also increases the possibility of distributing interference signals to a larger portion of the network. These factors, together with the reduction in the number of reference terminals in the SSTDMA system, made it necessary for SSTDMA to adopt a network control approach different from that of the fixed TDMA system [4],[6]. In addition, the new frame structure provides dedicated regions of the frame for system control, management, monitoring, and traffic distribution. The control regions are fixed in the SSTDMA frame; however, their size will vary depending on how control is assigned. Thus, it is necessary to assign and schedule control before scheduling traffic.

Requirements for network control assignments

The complexity of SSTDMA control requirements has resulted in network control assignment being a major automatic function of the SSBTP-generation software. This new function consists of a set of procedures driven by rules that incorporate a variety of requirements to enhance cost efficiency and network reliability.

TRAFFIC TERMINAL CONTROL

The prime concern in traffic terminal control assignment is to minimize the need for terminal equipment. The control downbeam should be selected for reference burst reception, and the control upbeam for principal burst transmission, to avoid the need for an extra beam access used only for control.

Another important factor is efficient use of the frame. Since regions dedicated to network control are frame overhead, control assignment should minimize the amount of control overhead and equalize its distribution among downbeams. It is preferable to realize equal CDC address loading and avoid assigning excessive terminal acquisition and synchronization (TAS) regions to a limited set of transponders.

REFERENCE TERMINAL CONTROL AND INTERFERENCE IMMUNITY

The most important factor in reference terminal control is interference and failure immunity. Taking into account interference immunity, control upbeams and downbeams, along with reference beam pairs (RBPs), control groups, and TAS groups, are assigned for the two reference terminals. A configuration is arranged such that one set of SSRTEs controls the other in a different beam connection. If an interfering signal disrupts the operation of only one SSRTE, network operation can still be partially maintained by the other SSRTE, and a total network shutdown resulting in further network outage can be avoided [6].

The control downbeam has special significance for an SSTDMA reference terminal. A reference control downbeam must have a loopback connectivity in the reference burst distribution (RBD) region so that, if the partner reference burst disappears, the terminal will still receive its own reference burst. Further, a necessary condition for interference immunity is that the connectivities in the RBD and TAS regions in each reference control downbeam are different. An interference immunity configuration will most likely occur if the reference control downbeams are chosen from control groups having different CDC associations. If these groups are in different transmission channels, the configuration will definitely be immune, regardless of the immunity configuration in either channel. Such a configuration also affords an extra level of failure protection in that a row or column failure in either MSM, or a double bit-flip in a distribution control unit (DCU) memory, will not affect the control transponders of both reference terminals.

STARTUP AND CONTINUATION MODE OPERATION

Based on the above criteria, control assignment can be determined for a new network in startup mode. As the network grows, new earth stations will join the network and more transponders will be added, coincident with increased traffic demands among existing earth stations. So long as the change is not drastic, it should be possible to update the BTP without affecting the operational plan of the existing station, especially its control assignment. Such a continuation BTP allows new terminals to be included without any network outage, simply by using a BTP change procedure. In the continuation mode, therefore, the control assignment (like control beams and CDC addresses) should remain unchanged for existing terminals. The control assignment for new terminals is determined by adhering to the above criteria as closely as possible. However, the expanded network may not enjoy any additional interference immunity beyond that already present in the initial network.

Control assignment and scheduling procedures

The BTP generation software assigns network control using two processes: control assignment and control scheduling. Control assignment associates reference bursts and CDCs with RBD regions, and principal bursts with TAS regions. Control scheduling is the process by which a particular burst or connectivity is located within the SSTDMA frame.

The control assignment algorithms include a set of heuristic procedures. The overall control assignment procedure, shown in Figure 5, was selected because of its flexibility for various network configurations. The algorithms are implemented in computer software that automatically assigns control. When the heuristic algorithms fail to assign appropriate control, an operator must intervene to slightly change the network configuration or earth station equipment assumption.

CONTROL BEAM SELECTION FOR TRAFFIC TERMINALS

A unique control downbeam and upbeam are selected for each traffic terminal if the terminal has only one downbeam access and one upbeam access, or if its control beams are explicitly specified by input commands. When two or more beams are available for a terminal, its control beams are those designated by the planner as having the highest priority. In such cases, control is assigned by the Constrained Terminal Control Assignment (CTCA) procedure.

For a traffic terminal having multiple-beam access, neither priority nor control beam may be specified in the input command list. Such a terminal is called an unconstrained terminal. If control is arbitrarily assigned in one of the terminal's accessible beams, the terminal could be required to access one beam for control, while all its traffic is scheduled in another beam. This would lead to equipment inefficiencies for that terminal. In this case, control is assigned by the Unconstrained Terminal Control Assignment (UTCA) procedure after traffic is scheduled. To prevent the possibility of a TAS region expanding after traffic is scheduled, space is allocated for the unconstrained terminal's principal burst in all TAS regions that contain upbeams the terminal can access.

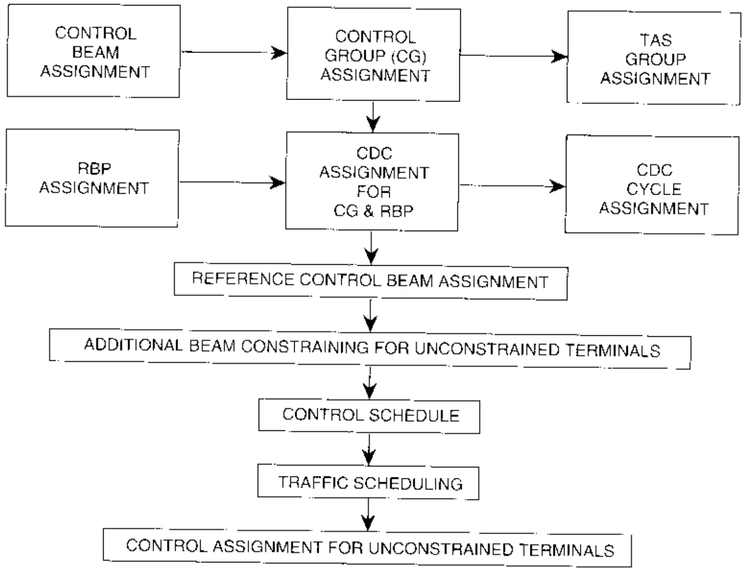


Figure 5. *Control Assignment and Scheduling Procedure*

It may also happen that none of the beams accessible by an unconstrained terminal are available to carry control according to the UTCA procedure. In this case, it is necessary to guarantee that at least one of these beams will be available so that, when control is ultimately assigned, reference bursts in both the downbeam and upbeam will appear in a TAS region. Such extra downbeams or upbeams for the UTCA procedure are added by the Constrained Beam Control Assignment procedure.

REFERENCE BEAM PAIR SELECTION

The RBP is the pair of beams into which the reference terminals transmit a given pair of reference bursts. Since reference terminals are capable of transmitting reference bursts into four upbeams, as many as four RBPs can be defined: two for each of the two frequency channels. The RBPs are selected from the set of beams illuminating the reference terminals (reference beams), and always comprise one west beam and one east beam. At least one RBP is generated for a frequency channel when the channel includes one or more reference beams in both the west and east regions. Two RBPs are created for a frequency channel if it includes four reference beams. In defining an RBP, a zone beam from one region and a hemi beam from the other region are selected if possible.

CONTROL GROUP ASSIGNMENT

This function assigns a pair of reference bursts for carrying control and timing information to groups of terminals called communities of controlled terminals. A control group will be defined for each RBP in a frequency channel. Each group may include a maximum of six downbeams, and must contain two reference beams. This guarantees that both reference terminals will have at least one downbeam from which to receive control. Each downbeam for distributing reference bursts will be assigned to a single control group, such that the difference in the loading factor for each group is minimal. The control group loading factor is the sum of the number of controlled terminals in the member downbeams.

The defined control groups are then assigned to one of two CDC groups: CDC-A or CDC-B. CDC assignment associates either CDC-A or CDC-B with an RBP and assigns terminals to CDC addresses within each CDC cycle. The two control groups in a frequency channel should belong to the different CDC groups if possible. If two or more control groups are defined, there will normally be two CDCs. CDC-A or CDC-B is assigned to a control group such that the total number of terminals being controlled in each CDC is as nearly equal as possible. The sum of the control group loading factors for a CDC is called the CDC loading factor. By equalizing the CDC loading factors in this way, the possibility of overloading one CDC is reduced, and greater freedom is provided for future expansion of the network. Each terminal is assigned an address in the CDC associated with the control group it accesses. Terminals with the greatest amount of traffic are assigned to the lowest CDC addresses.

TAS GROUP ASSIGNMENT

This function assigns a principal burst for each terminal in a community of controlled terminals to an upbeam called the control upbeam, which will be switched into a pair of downbeams received by both reference terminals. There may be as many as four communities of controlled terminals, each with an associated TAS group. Each upbeam to carry principal bursts will be assigned to the TAS group such that the control group of the community contains the downbeam corresponding to that upbeam. Thus, the principal bursts of the terminals in a community will return to the reference terminals in the downbeams of the RBP which contains the reference bursts controlling that community.

As with the control group, a TAS group will be defined for each RBP and will comprise one or more control upbeams, to a maximum of four. This limitation is designed to prevent excessive overhead from being scheduled in an RBP, which may limit traffic scheduling capability.

REFERENCE CONTROL BEAM SELECTION

Besides being the downbeam in which the reference terminal receives control, the reference control downbeam designates the loopback connectivity for the metric and SSV bursts. Each reference control downbeam is selected from a set of candidate control groups that include the loopback connectivity of the reference beam with the associated RBP. The west reference control downbeam is selected first, based on the following rules. The west loopback beam is selected if it is designated by an input command; otherwise, it is selected in channel 1-2 if possible. In this case, higher priority is placed on a beam associated with CDC-A and with a zone beam. The east reference control downbeam is then determined. The east loopback beam is selected if it is specified by an input command; otherwise, it is selected in a different channel from the west reference control beam and from the opposite CDC association, if possible.

CONTROL SCHEDULING

The control region of the switching sequence can now be scheduled based on the control assignment results. The beam connection and duration of each switch state are determined by the frame format [3],[4]. The metric burst and SSV burst are scheduled in the loopback connection of the reference control downbeams, and the RBP region is scheduled based on the RBP and control group definition. In a TAS region, the subacquisition windows and principal bursts are allocated in accordance with the RBP and TAS group definition.

Switching sequence generation algorithms

A number of theoretical studies on switching-sequence generation have addressed only the effective use of the satellite transponder; significant modification would be required for practical application to commercial systems. The SSBTP program, on the other hand, includes the additional functions necessary to generate a switching sequence that conforms completely to the INTELSAT VI SSTDMA system [9]. Since the conventional algorithms for switching-sequence generation assume traffic demand on a beam-to-beam basis, the traffic demands among earth stations are first distributed among the beams, to make efficient use of the satellite transponders. From this beam-to-beam traffic matrix, the switching sequence is generated using well-known algorithms. The switch states are then rearranged to make the generated sequence more suitable for burst scheduling. For a network with two transmission channels, the switching sequence is generated for each channel. Finally, the control and monitoring regions are attached to the traffic region to complete the sequence. These functions are implemented as automatic procedures and are basically executed in this order.

Editing functions are available for manual generation or modification of the sequence. This capability is particularly useful for incorporating practical operational constraints. Especially in the continuation mode, the editing functions are effective for regenerating the sequence whose major portion is to remain unchanged, and for maintaining the major operational schedule unchanged. The editing capability also supplements shortcomings of the automatic algorithm, which cannot guarantee that these requirements will be met, even with a slight change of traffic demands.

Traffic distribution among beams

A linear programming model is applied to distribute the traffic demands, on an earth-station basis, among possible upbeam-to-downbeam pairs. The objective of this process is to minimize the largest fill factor of all the transponders to achieve equal traffic loading. The fill factor is defined as the ratio of traffic actually loaded to transponder capacity. Since distributed beam-to-beam traffic can accomplish equal loading of satellite transponders, the largest margin (*i.e.*, number of unused time slots) can be preserved in the frames. In this way, the net transponder capacity in the total number of accommodated satellite channels assumes an average DSI gain and average requirements for preamble and guard time.

The beam coverage of an INTELSAT VI spacecraft is generally illustrated by the footprints of the six beams, as shown in Figure 1. The numbers 1 through 10 in brackets indicate fictitious disjointed regions which are defined by the footprints of four zone beams and two hemispheric beams. For instance, region 9 is covered by both the northeast zone and the east hemi, whereas region 3 has access to the northeast zone only. An earth station in region 9 may use both the northeast zone and the east hemi, and any ambiguity must be resolved regarding how much traffic will be assigned to each beam. This traffic assignment determines beam traffic distribution and, eventually, transponder traffic loading. To resolve this problem, traffic for each region pair is first defined as a region traffic matrix, $\{r_{ij}\}$. Since every earth station belongs to a unique region, traffic for each region pair is defined simply as the total traffic for all the pairs of earth stations corresponding to the region pair. The amount of traffic to be carried by each beam pair can be defined by a beam matrix, $\{b_{kl}\}$. The objective is to find a matrix $\{b_{kl}\}$ from the given region traffic matrix $\{r_{ij}\}$ based on the above-mentioned criterion of equal transponder loading. This is accomplished by using the linear programming formulation presented in Reference 9.

Generation of the switching sequence

In the conventional algorithms, the criterion for generating the switching sequence is to minimize either the duration of the generated sequence or the number of switchings for the given traffic demand. The former criterion is employed here because the resulting sequence preserves the largest margin of capacity in all the transponders for future traffic growth. The algorithms—called the Greedy algorithm [1] and the Hungarian method [2]—generate the shortest switching sequence from the beam traffic matrix $\{b_{kl}\}$ already obtained. Consequently, these algorithms can be applied directly to the beam traffic matrix to generate the switching sequence.

When the SSTDMA network includes a pair of very lightly loaded transponders, it is advantageous to employ semibroadcasting connection for the pair of downbeams. This reduces the number of TIMs because a transmit earth station can accommodate traffic to destinations in the different downbeams within one subburst. Such semibroadcasting beam connections can be generated, even in the traffic region of the sequence, by the same algorithms using a modified beam traffic matrix. The matrix is modified so that one downbeam includes all traffic to the broadcast beams (*e.g.*, a pair of beams). For the other beam, the same beam connectivity and burst schedule are copied to realize semibroadcasting.

Refining the sequence by rearranging and merging

The switching sequence that the conventional algorithms generate is not always suitable for direct burst scheduling use because the algorithms do not account for various burst scheduling constraints. The algorithms that generate the shortest switching sequence do not minimize the number of switch states;

that is, the same beam connection may appear in two or more switch states which are short and separated from one another. In such a situation, a beam connection may be too short to accommodate a properly formed burst. This can result in a divided subburst, and the need for an extra TIM to accommodate a split portion of the subburst. Since the INTELSAT VI satellite is equipped with a crossbar-type MSM, the same beam connections in adjacent states can be reconnected. To take advantage of this feature, the switching sequence is refined by rearranging the switch states so that those states which include the same beam connections are placed adjacent to each other. This facilitates burst scheduling significantly, while maintaining the shortest sequence [9].

The famous "traveling salesman problem" [10] is employed to optimize the arbitrary ordering of switch states. A perfect graph is first generated such that each switch state corresponds to a distinct node. Every pair of nodes is linked by an arc whose distance is defined by the number of different beam connections between the corresponding switch states. The example sequence shown in Figure 6a is graphed in Figure 6b. Given this perfect graph, the challenge is to find the shortest Hamiltonian circuit that passes through all the nodes only once and minimizes the total distance. In the context of the above-defined graph, the solution indicates the optimum way of rearranging the switch states to minimize the number of times beam connections are switched in one sequence. A well-known heuristic algorithm [11] is employed to solve the problem. The solution is shown in Figure 6b by solid lines, and the rearranged sequence is presented in Figure 6c.

Even after rearranging the switch states, short and isolated beam connections (*e.g.*, B1-to-B1 and B4-to-B4 of state E in Figure 6c) may still exist. In such situations, it is worthwhile to reassign the traffic for the short beam connection to another beam connection if possible. Another switch state will be expanded to include the traffic from the short beam connection. This process, called merging, may help to avoid short beam connection, at the expense of reducing the margin. In Figure 6d, the traffic for B1-to-B1 and B4-to-B4 in state E will be accommodated in the expanded state C, which includes the same beam connections.

Generating the sequence for a two-channel network

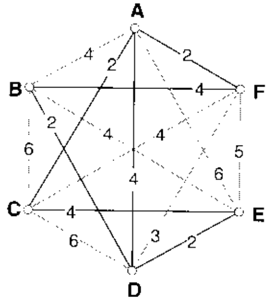
The INTELSAT VI SSTDMA network can generally include two frequency channels. In such a case, two switching sequences are required. The basic strategy for dealing with this network configuration is to generate a long switching sequence of twice the frame length and divide it into two segments to obtain two switching sequences. To generate a long sequence, the doubled transponder capacity is tentatively assumed for the constraints of the linear

	FROM SWITCH STATE						
TO BEAM	A	B	C	D	E	F	
1	4	4	1	4	1	4	M
2	3	6	3	6	6	3	A
3	2	5	2	3	3	2	R
4	1	1	4	1	4	1	G
5	6	3	6	5	5	5	I
6	5	2	5	2	2	6	N

DOWNLINK BEAM OF TRANSPONDERS

Note: Numbers in switch states indicate uplink beams.

(a) Original Sequence



(b) Graph for the Sequence

	FROM SWITCH STATE						
TO BEAM	E	D	B	F	A	C	
1	1	4	4	4	4	1	M
2	6	6	6	3	3	3	A
3	3	3	5	2	2	2	R
4	4	1	1	1	1	4	G
5	5	5	3	5	6	6	I
6	2	2	2	6	5	5	N

(c) Rearranged Sequence

	FROM SWITCH STATE						
TO BEAM	E	D	B	F	A	C	
1	(1)	4	4	4	4	1	M
2	6	6	6	3	3	3	A
3	3	3	5	2	2	2	R
4	(4)	1	1	1	1	4	G
5	5	5	3	5	6	6	I
6	2	2	2	6	5	5	N

(d) Sequence Without Short Beam

Figure 6. *Switching-Sequence Generation Procedure*

programming formulation. The resulting beam traffic matrix $\{b_{kl}\}$ accommodates traffic for both frequency channels. The switching sequence derived from this traffic matrix is about twice as long as one frame. The sequence is divided in two such that each portion of the divided sequence is no longer than one frame.

Some traffic, however, cannot be freely assigned to either channel, due to the beam access limitation of earth stations. For example, link traffic must be assigned to channel 1-2 if either (or both) transmit and receive earth stations have access to channel 1-2 only. Three region traffic matrices are generated separately to guarantee beam connection in a proper channel for such channel-limited traffic. The first matrix, R12, includes traffic that must be routed by channel 1-2 only. The second matrix, R34, includes traffic to be accommodated in channel 3-4 only. The last matrix, R, includes traffic that can be carried by either channel. The dividing process is applied only for the last type of traffic. The sequence derived from matrix R is properly divided in two, and the sequence of each channel is generated from the divided portion plus the portion derived from R12 or R34.

Concatenation of control and monitoring regions

Once the switching sequence is generated for the traffic region of each channel, the control region and the monitoring region for test slots are attached to the beginning and end of the traffic region, respectively. The control region includes the control switch states described previously. It is always guaranteed that the created sequence will be no longer than one frame, because the traffic region is generated by assuming the net transponder capacity, excluding the control and monitoring regions.

Burst scheduling procedures

Burst scheduling for SSTDMA differs from that for fixed TDMA, even though the burst and subburst configurations remain the same. The major difference with SSTDMA is that traffic burst positioning is limited within the time slots of a proper beam connection. Since the network includes a large number of transponders, more terminals will use transponder-hopping and each terminal may have access to more transponders. Consequently, burst overlapping becomes an even greater constraint in scheduling. A new burst scheduling approach was taken to address this situation. Two different procedures are available in the SSBTP program: automatic scheduling and manual scheduling. Manipulation functions have also been provided to allow further refinement of the scheduling results by manual editing.

The overall procedure for automatic burst scheduling consists of iteratively selecting beam connections into which appropriate traffic bursts will be scheduled [12]. Priorities can be placed on the order of beam connection processing (*e.g.*, which beam to process first) and the selection of transmit and/or receive earth stations. Burst scheduling consists of two steps. The first is subburst scheduling, where every traffic burst consists of only one subburst with a preamble. A combinatorial optimization model is applied here to efficiently determine the subburst configuration. A scheduling model, called rescheduling, systematically incorporates burst overlapping constraints. The second step also uses the rescheduling procedure to form traffic bursts that comprise a series of scheduled subbursts.

Manual burst scheduling allows the user to freely determine the burst configuration in advance by input commands. Burst position can be either explicitly specified by the user or sought by the software in a designated beam connection. Priority can be applied to the burst scheduling order (*e.g.*, which burst to schedule first). Due to burst overlapping or collision, the scheduling may fail to assign a position for a burst, which will be canceled and rescheduled later by the automatic procedure, possibly with a different burst configuration. In the continuation mode, manual burst scheduling is especially useful for maintaining the burst and subburst configuration unchanged for the majority of existing traffic, because the automatic procedure cannot guarantee that this requirement will be met.

The SSBTP program provides several editing functions to manually change burst and subburst configuration, burst position, and equipment usage. This process is primarily beneficial for refining the automatically generated burst schedule to reflect detailed practical requirements, and for manipulating the schedule to accommodate "leftover" unscheduled traffic.

Automatic burst scheduling procedures

Since the burst scheduling problem requires a huge combinatorial model, it is realistic to construct an automatic procedure that includes effective optimization algorithms for subprocedures [12]. The heuristic algorithm iteratively selects one beam connection from the predetermined switching sequence, in an order that can be specified by the user. It is generally advantageous to sort the beam connections by priority so that difficult (*e.g.*, heavily loaded) beam connections are processed for burst scheduling first. For each beam connection selected, candidate transmit and receive earth stations are then chosen to route the traffic properly. Higher priority is given to candidate stations that can access the beam connection without transponder-hopping. From these selected links, bursts of one subburst are automatically scheduled where subburst configuration and burst position are simultaneously determined. Finally, for the scheduled burst, appropriate TIMs (DSI/DNI/DDI) are assigned at transmit and receive earth stations such that an outgoing subburst and its return subburst(s) are accommodated in the same module.

SUBBURST SCHEDULING BY BIN-PACKING

The essential subprocedure in overall burst scheduling is subburst scheduling, which is applied for a selected beam connection and candidate transmit and receive earth stations. Given a transmit earth station, the automatic algorithm determines the subburst configuration and simultaneously assigns the burst position. Based on the combinatorial optimization model, the subburst configuration is determined so that the number of subbursts is minimized. A burst position is assigned in which burst collision and overlapping can be avoided.

Subburst Configuration

For each link, a single-destination subburst is formed for traffic that fills the capacity (D channels) of a TIM. For the traffic, C_{tr}, between transmit and receive earth stations, the number of single-destination subbursts is (C_{tr}/D), where (x) indicates the largest integer less than or equal to x. The residual traffic, m_{tr} [= $C_{tr} - (C_{tr}/D) \bullet D$], is the portion to be accommodated in a multidestination subburst. Multidestination traffic, m_{tr}, can be combined with other residual traffic for other destinations to form a multidestination subburst. Configuration of a multidestination subburst must be determined within the capacity of a TIM, and m_{tr} cannot be divided into two or more TIMs for operational convenience. Under these constraints, the subburst configuration should be properly determined with the minimum of multidestination subbursts (or TIMs).

The bin-packing problem [13] is a famous combinatorial method for finding the best way to pack a given number of blocks of different sizes into the minimum number of bins. No block may be divided, and the capacity of the bin cannot be exceeded. Determining the configuration of a multidestination subburst is regarded as a bin-packing problem. A TIM (or subburst) and m_{tr} correspond to a bin and blocks, respectively. An optimum way must be found to pack m_{tr} into the minimum number of bins without splitting m_{tr} and without exceeding the bin capacity. Bin-packing algorithms such as well-known efficient heuristic algorithms [13] are applicable here. In this process, both the voice and nonvoice traffic of a link can be included as different blocks. Subburst length is calculated based on a proper DSI gain if speech-interpolated voice traffic is included.

Burst Position

Determining subburst configuration by bin-packing requires that a feasible time slot be guaranteed for the formed subburst without burst collision and overlapping. For this purpose, a new concept called the link available slot (LAS) is introduced. The LAS is defined for each link by the intersection of three sets of time slots: TS(S) represents vacant time slots in the beam connection, TS(T) represents unused time slots of a transmit terminal, and TS(R) represents unused time slots of a receive terminal. Burst collision is avoided so long as a burst is placed in TS(S). Burst overlap does not occur at transmit and receive terminals if a burst is placed in TS(T) and TS(R). For a multidestination traffic element such as DCME traffic, TS(R) must comprise time slots commonly unused at all the receive terminals. A feasible burst position is also limited within the LAS of the link included in the burst. In case of a multidestination burst, the burst must be at the intersection of the LASs of all links in the burst.

Extended Bin-Packing Algorithm

By integrating the concepts described above, an algorithm called extended bin-packing (EBP) is constructed to determine a desirable subburst configuration with a feasible burst position [12]. As shown in Figure 7, the algorithm attempts to pack blocks (m_{tr}) in descending order of size, and inspects the condition of the LASs every time a new block is packed properly into a bin (TIM or subburst). The new block is accommodated in a bin only when the intersection of the LASs can include both the burst for the new link and the already packed links.

RESCHEDULING ALGORITHM

The other burst scheduling procedure, called rescheduling, schedules a new burst while reassigning burst positions to some previously scheduled bursts. Because it has higher burst scheduling capability, this procedure is applied when the EBP algorithm fails to schedule bursts due to burst collision or overlapping.

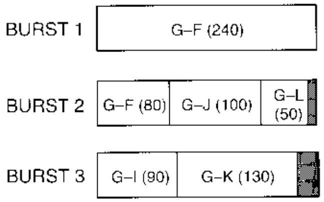
The rescheduling procedure allows the positions of previously scheduled bursts to be reassigned in a beam connection into which a newly created burst is to be scheduled. Positions are kept fixed for all other bursts in other beam connections. The bursts whose positions are reassigned in the target beam connection are referred to as reassignment bursts, while the scheduled bursts that remain fixed are called fixed bursts. To efficiently identify a feasible burst position, the new concept of a burst service slot (BSS) is defined for each reassignment burst and the new burst. All bursts in the objective beam

NWZ TO EH

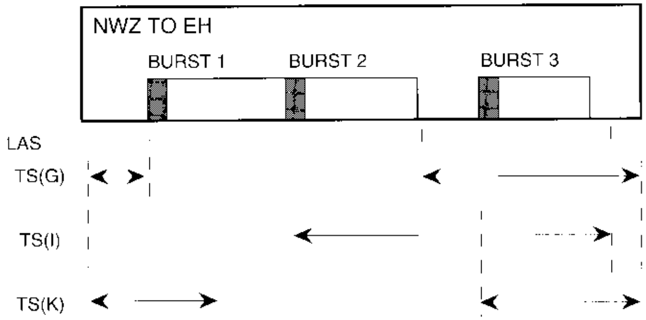
TX EARTH STATION IN UPBEAM NWZ : G
RX EARTH STATIONS IN DOWNBEAM EH : F, I, J, K, L
TRAFFIC OF LINKS FROM TX EARTH STATION G

G to F = 320 = 240 + 80
G to I = 90
G to J = 100
G to K = 130
G to L = 50

(a) Selected Beam Connection



(b) Subburst Configuration Determined by the Bin-Packing Algorithm

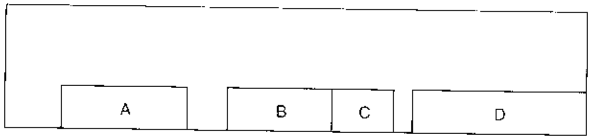


(c) Burst Position Assignment for Burst 3

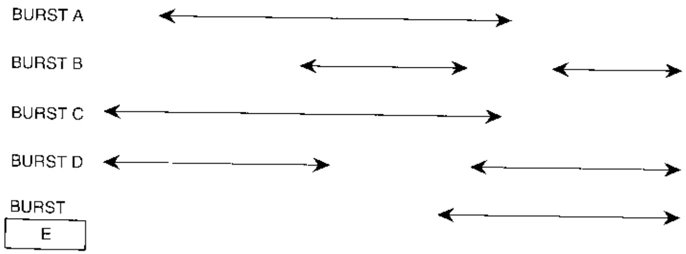
Figure 7. *Subburst Scheduling by EBP Algorithm*

connection are tentatively removed as reassignment bursts, and the available time slots of the beam connection are designated RT. For each reassignment burst and new burst, the unused time slots RTS(T) and RTS(R) are inspected at the transmit and receive terminals, respectively. At the transmit terminal, the unused time slots for transmission of fixed bursts are defined as RTS(T). Similarly, RTS(R) are the time slots that are left unoccupied by the fixed bursts received at the receive terminal. The BSS is defined as the intersection of RT, RTS(T), and RTS(R) for all receive terminals. Bursts can be assigned without overlapping, so long as they are included in their own BSS. Given the BSS for all reassignment bursts and the new burst in the target beam connection, all the bursts can be scheduled successfully by finding feasible positions such that all the bursts are completely included in their own BSS and never collide.

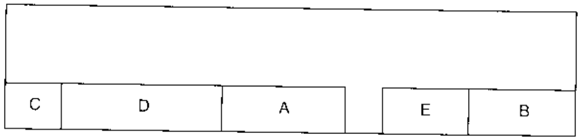
In the rescheduling procedure, the EBP algorithm is applied to form a new burst in which all reassignment bursts are temporarily disregarded. In the example of Figure 8, bursts A, B, C, and D are properly assigned in the beam connection in assignment 1. However, a new burst, E, cannot be scheduled because unoccupied time slots in assignment 1 cannot include burst E without collision. The reassignment bursts in this case are A, B, C, and D. A BSS is now created for these bursts and for the new burst E. For these BSSs, assignment 2 is feasible. A practical solution can also be found for problems of realistic size by using an algorithm that integrates a branch-and-bound method with dynamic programming [12].



(a) Assignment 1



BURST SERVICE SLOT



(b) Assignment 2

Figure 8. *Rescheduling Procedure*

TRAFFIC BURST FORMATION AND RESCHEDULING

Traffic Burst Formation

The traffic bursts scheduled by the EBP and rescheduling algorithms include only one subburst. By combining these scheduled subbursts, traffic bursts comprising multiple subbursts can be generated. The algorithm automatically selects a set of candidate subbursts from each transmit terminal which can be routed by the same beam connection. One traffic burst is then formed by concatenating the set of subbursts. However, at this point in the procedure the target beam connection is generally tightly occupied by the scheduled bursts. In such a situation, rescheduling is again a powerful means of assigning the multiple-subburst traffic burst without collision or overlapping. In this approach, the newly formed traffic burst is regarded as "the new burst," and all other bursts in the target beam connection are considered "the reassignment bursts."

Other Applications of Rescheduling

The rescheduling procedure is further applicable to other manipulation functions for refining scheduling. In some cases, it is effective to move a scheduled traffic burst to another beam connection, into which another burst from leftover traffic may be scheduled. The rescheduling procedure is effective in finding a position for the moved burst in the new beam connection. The moved burst is considered to be the new burst, and all other bursts in the new beam connection are regarded as reassignment bursts.

Another application is to merge two subbursts from the same transmit terminal into one. In certain cases, bin-packing cannot achieve the minimum number of TIMs. For example, a terminal with heavy traffic demand may be requested to receive multidestination bursts whose total duration is longer than one TDMA frame. For a properly formed burst, each vacant time slot preserved in separate switch states may be too short to include the burst, even though the total duration is sufficient. In such situations, the EBP algorithm can allow an extra subburst by splitting a multidestination burst. When a pair of small subbursts is scheduled for this reason, it is advantageous to attempt to merge them from the same terminal in order to reduce the number of TIMs. The new burst formed by the merge will be reassigned in a proper beam connection by rescheduling. The merged burst is regarded as the new burst, and all other bursts in the beam connection are considered reassignment bursts.

ADJUSTMENT OF SWITCHING SEQUENCE

Beam connections in TDMA frames produce extra constraints in SSTDMA burst scheduling. The duration of each beam connection is determined prior to burst scheduling by estimating the average DSI gain and the average overhead requirements for preamble and guard time. Thus, as the result of burst scheduling, some beam connections may have a shortage of time slots while others include unused slots. To improve this situation, a slight adjustment of switch state duration can be effective. When a switch state includes a beam connection that requires additional time slots, it is beneficial to expand the switch state. The switch state is expanded to the right if all the scheduled bursts and switch state boundaries to the right of the switch state can be shifted to the right. The switch state is also expanded to the left in a similar manner. This process is implemented in the SSBTP program such that the scheduling results are shifted without burst collision and overlapping, and the control and monitoring regions are not affected.

BTP generation operational considerations

Once the baseline for traffic requirements, transponders, and available equipment has been established, the process of creating the BTP can begin. The first step in generating the BTP is to run the NPDGEN program, which basically provides the network configuration in terms of the specific parameters associated with the terminals and transponders. The next step is to review the transponder access capabilities of the terminals in the network to determine which terminals are heavily constrained and which have some flexibility in terms of the beams and transponders that can be accessed. In general, terminals are heavily constrained and offer no flexibility if they have access to only one beam in one frequency channel. Terminals will offer some flexibility if they are covered by two or more beams and equipped to access them.

It is important to identify flexible terminals, as these offer the potential to balance transponder loading if the fill factor for any one transponder exceeds 100 percent. Once such terminals have been identified, the switching sequence can be generated using the SSBTP program. If a feasible solution does not exist and the loading in any one transponder exceeds 100 percent, then it is necessary to change the accesses of those terminals that have access flexibility and rerun the SSBTP program to generate the switching sequence. Alternatively, the only options may be to reduce traffic, require terminals to access additional transponders, and/or add transponders.

Once a feasible switching sequence has been generated, it is essential that the user evaluate the switching sequence to determine whether or not it is optimum for the case of interest. It is vital to generate an optimum switching sequence; otherwise the user may waste considerable effort in scheduling traffic. Various options for traffic distribution among beams should be used to compare the different switching sequences. Several criteria are used to evaluate different switching sequences. For example, very short switch states should be avoided; switch states having similar beam connections should not be split; and, in two-bank configurations, the same beam connection should not appear simultaneously in both banks. Often it may be beneficial to modify the length of certain switch states manually, or to create additional switch states using any available margin.

The next phase is to begin scheduling the traffic into the switch states that have been generated. Since a large number of scheduling options and commands are available, a certain level of trial-and-error, combined with experience, is required in order to schedule all the traffic in a congested network. It is essential to identify potential bottlenecks so that such traffic can be scheduled first. Although each case varies, it is a good strategy to schedule heavily constrained traffic first. In some cases, it may be more appropriate to schedule traffic in some heavily congested beam connections first, while in other cases it may be desirable to give priority to traffic in one bank over another.

Traffic scheduling can be performed in three distinct modes. In the first mode, traffic is scheduled using manual commands. This may be required in certain instances when, for example, subbursts must be formed in a particular manner due to user-specified requirements. In the second mode, traffic is scheduled using automatic commands by giving priority to certain traffic terminals, beam connections, or traffic types. The majority of traffic is scheduled in the automatic mode by repeated use of priority and scheduling commands. When most (95 percent or more) of the traffic has been scheduled, the remaining traffic is scheduled on a link-by-link basis by using the available editing commands to manipulate the traffic bursts that have already been scheduled in order to make room for leftover traffic. In this last mode, it is important that the user be able to identify any bottlenecks that prevent the remaining traffic from being scheduled, and find ways of overcoming them. The objective here is to eliminate leftover traffic. In some cases, it may be easier to use a different switching sequence and/or to reduce the traffic in certain links.

As mentioned previously, the burst scheduling algorithms in the SSBTP program are not necessarily limited by the number of available TIMs, but will assume that additional TIMs are available if required to successfully schedule all traffic. Consequently, although all the traffic may be scheduled, the number of TIMs may exceed those available. It is thus necessary to review the number of TIMs required for each TDMA user *vs* the number of TIMs available, and reduce the number of subbursts to an acceptable number where possible. This can be done by employing the various editing capabilities, such as moving traffic from one subburst to another. Other effective options are to merge subbursts by rescheduling, or to move a burst from one position to another.

After all traffic has been scheduled without exceeding the available terminal equipment requirements, the BTP is checked to ensure that it is consistent, with no burst overlap or collision. The final two steps in the process are to run the SSMTPDATA and SSGENTP programs, which perform a number of miscellaneous tasks such as orderwire assignment and channel numbering and then generate the various MTPs and CTPs required by the different elements in the system.

SSTDMA network example

As an example, an SSTDMA network and associated BTP are described for the INTELSAT Indian Ocean Region (IOR) 60°E satellite network. This BTP is one of several scenarios that were analyzed for the IOR SSTDMA network in developing the startup BTP. In all, 25 traffic terminals are active during this time frame. Each user was requested to submit their traffic requirements, the transponder access capabilities of their traffic terminal, and the number of TIMs that would be available. Of the 25 traffic terminals (denoted A through Y), three are covered by only one beam of the INTELSAT VI satellite. These are terminal L (east hemi beam only), terminal S (northeast zone beam only), and terminal E (west hemi beam only). A number of other terminals, which are covered by more than one INTELSAT VI satellite beam, are equipped to access only one transponder.

After reviewing the requirements submitted, it was apparent that seven transponders would be needed to meet the traffic requirements: five in bank 1-2 and two in bank 3-4. Figure 9 shows the transponders assigned to the SSTDMA network, and the loading of each in terms of the number of satellite channels. Because S is the only terminal in this beam during this time frame, the northeast zone transponder experiences very light loading. In all, this BTP accommodates 7,359 satellite channels in 125 links, which translates to over 18,000 one-way voice channels, assuming an average DSI and DCME gain of 2.5. In the given input data, all 25 terminals have access to bank 1-2, but only eight are required to access bank 3-4. Bank 1-2 can be considered to be the

```
                         IOR 60.0E SS/TDMA START-UP PLAN


              <<<  TRANSPONDERS FOR SSTDMA NETWORK  >>>


CHANNEL 1-2

     DOWN BEAM        TRANSPONDER NO.       POLARIZATION     UP LINK FREQUENCY      DOWN LINK FREQUENCY
     5  WH                    11                 A                  5970                   3745
     6  EH                    21                 A                  5970                   3745
     1  NW                    41                 B                  5970                   3745
     3  NE                    51                 B                  5970                   3745
     4  SE                   101                 B                  5970                   3745

 -------------       -------------       -------------       -------------       -------------
 -------------       -------------       -------------       -------------       -------------
|             |     |             |     |             |     |             |     |             |
|    1185     |     |    1170     |     |    1106     |     |     199     |     |    1185     |
|             |     |             |     |             |     |             |     |             |
|          11 |     |          21 |     |          41 |     |          51 |     |         101 |
 -------------       -------------       -------------       -------------       -------------

 A          147      I          175      P          136      S          199      I           83
 B           35      J          230      A          109                           K          133
 C          193      K          140      B          162                           T           89
 D          111      L          235      C           40                           U          151
 E           83      M          168      Q          319                           V          172
 F          385      N          192      R          163                           W          188
 G          112      O           30      D           46                           X          142
 H          119                          F          131                           Y          237


CHANNEL 3-4

     DOWN BEAM        TRANSPONDER NO.       POLARIZATION     UP LINK FREQUENCY      DOWN LINK FREQUENCY

     1  NW                    42                 B                  6050                   3825
     4  SE                   102                 B                  6050                   3825

 -------------       -------------
 -------------       -------------
|             |     |             |
|    1316     |     |    1198     |
|             |     |             |
|          42 |     |         102 |
 -------------       -------------

 A          147      I          219
 B          158      T          211
 Q          267      V          768
 R          158
 D          161
 F          425
```

Figure 9. *Transponders Used in SSTDMA Network Example*

"interconnectivity" bank, which provides connectivity between any two of the 25 traffic terminals in the network, and bank 3-4 can be considered the "thick route" bank, which provides connectivity between the eight largest users.

To reduce the overall frame overhead to accommodate as much traffic as possible, all traffic terminals are controlled in bank 1-2. Thus, there is no TAS region and no reference bursts or principal bursts in bank 3-4. The additional frame space available to the traffic region not only enables more traffic to be accommodated, but also considerably eases the scheduling of traffic, especially for terminals with heavy traffic for which the receive fill factor can be quite high. Figure 10 shows the switching sequence. The burst schedule is determined in a similar format, as depicted in Figure 2.

```
                        IOR 60.0E SS/TDMA START-UP PLAN


                   SS-TDMA  SWITCHING  SEQUENCE  -  BANK 12



                                                           TRANSPONDER NUMBER
                                         41                 51        101        11        21

                                                           DOWN BEAM (TO)
                                         NW                 NE        SE         WH        EH
         START    END    LENGTH
STATE   SYMBOL   SYMBOL  (SYMBOLS)                         UP BEAM (FROM)
  0          0      511      512         NW                 NE        SE         EH        WH
  1        512      575       64                            NE                   EH        WH
  2        576      831      256                            NE                   EH        WH
  3        832     1343      512         NW                 NW        WH         WH        NW
  4       1344     1855      512         EH                 EH        SE         SE        EH
  5       1856     4095     2240         EH                 SE        WH         WH        EH
  6       4096     6143     2048         NE                 WH        SE         SE        NE
  7       6144     9151     3008         NW                 EH        SE         SE        NW
  8       9152     9791      640         NW                 SE        WH         WH        NW
  9       9792    10175      384         NE                 SE        WH         WH        NE
 10      10176    11967     1792         EH                 SE        WH         WH        EH
 11      11968    75711    63744         EH                 NE        WH         SE        NW
 12      75712    80959     5248         SE                 WH        NE         EH        NW
 13      80960    82687     1728         SE                 WH        NW         EH        NE
 14      82688    83391      704         SE                 WH        NW         NE        EH
 15      83392    91327     7936         EH                 SE        NW         NE        WH
 16      91328   116031    24704         SE                 NE        NW         EH        WH
 17     116032   117311     1280         NW                 SE        NE         EH        WH
 18     117312   117567      256         NW                 NE        SE         EH        WH
 19     117568   120575     3008         NW                 NE        SE         WH        EH
 20     120576   120831      256


                   SS-TDMA  SWITCHING  SEQUENCE  -  BANK 34



                                                         TRANSPONDER NUMBER
                                         42                     102

                                                         DOWN BEAM (TO)
                                         NW                     SE
         START    END    LENGTH
STATE   SYMBOL   SYMBOL  (SYMBOLS)                       UP BEAM (FROM)
  0          0     1343     1344         SE                     NW
  1       1344     1855      512         SE                     NW
  2       1856     2367      512         SE                     NW
  3       2368   117311   114944         SE                     NW
  4     117312   117567      256         SE                     NW
  5     117568   120575     3008         NW                     SE
  6     120576   120831      256
```

Figure 10. *Switching Sequence*

The number of subbursts (and TIMs) required in this BTP is 110. The average loading of a TIM in terms of the number of bearer channels is 67 bearers per TIM. The average loading of a TIM in bank 1-2 is 58 bearers, while the average loading in bank 3-4 is 93 bearers, highlighting the fact that bank 3-4 carries the larger links. Figure 11 shows some of the schedule details for burst configuration for one of the SSTDMA transponders.

FOR AC.CE SS/TDMA START-UP PLAN

TDMA BURST CONFIGURATIONS

BST NO.	TX E/S	REL TML NO.	XPDR NO.	UPBEAM	DNBEAM	STATE NO.	SUB-BST NO.	SUB-BST TYP	SUB-BST DSI GAIN	CONFIG. CH V+NB(NB) MD (NB)	SAT CH	UNCODE SYMBOL	RX E/S	REL TML NO.	CHANNELS V+NB(NB) MD (NB)	S. V. CH
49	B	1	21	NW	EH	11-11	1	DSI	2.21	221(15)	109	6976	J L N M O	1 1 1 1 1	68(4) 42(6) 75(3) 32(2) 4(0)	**
50	R	1	21	NW	EH	11-11	1	DSI	2.21	231(7)	109	6976	J M N L K	1 1 1 1 1	33(1) 44(2) 29(1) 43(1) 82(2)	**
51	D	1	21	NW	EH	11-11	1	DSI	2.12	109(5)	55	3520	N J L M	1 1 1 1	31(1) 30(2) 29(1) 19(1)	**
52	R	1	21	NW	EH	11-11	1	DSI	2.00	65(3)	35	2240	I	1	65(3)	**
53	C	1	21	NW	EH	11-11	1	DSI	2.17	152(6)	74	4736	J N M L O	1 1 1 1 1	46(0) 37(1) 38(4) 27(1) 4(0)	**
54	Q	1	21	NW	EH	11-11	1	DSI	2.17	189(19)	98	6272	J M N L O	1 1 1 1 1	73(7) 56(4) 48(2) 5(5) 7(1)	**
55	Q	1	21	NW	EH	11-11	1	DSI	2.00	76(0)	39	2496	L	1	76(0)	**
56	A	1	21	NW	EH	11-11	1	DSI	1.91	51(5)	30	1920	I	1	51(5)	**
57	P	1	21	NW	EH	11-11	1	DSI	2.12	110(6)	56	3584	N J L M K I	1 1 1 1 1 1	13(1) 19(1) 17(1) 13(1) 21(1) 27(1)	**

(** : SUPERVISORY CHANNEL IS ON.)

Figure 11. *Sample of Burst Configurations*

Conclusions

The INTELSAT VI SSTDMA system is a highly sophisticated network, and its operational plan is very complex. Extensive studies were conducted to develop its operational planning methods and computer software. Results from various theoretical studies in this field were utilized, along with experience gained in generating BTPs for the fixed TDMA system. The methods presented here summarize the techniques developed for BTP generation for the INTELSAT VI SSTDMA system, which have already been implemented in the operational software.

This software system serves as an engineering tool for generating BTPs for SSTDMA networks. Its flexibility enables operational planners to override selected assignments, based on requests for modifications from participating administrations, and to analyze these overrides to ensure efficient utilization of the space and earth segments. As SSTDMA networks evolve, the software system will be upgraded to incorporate new operational requirements.

Acknowledgments

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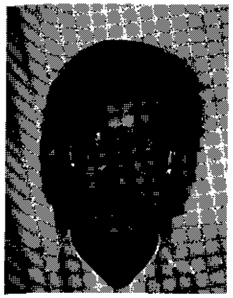

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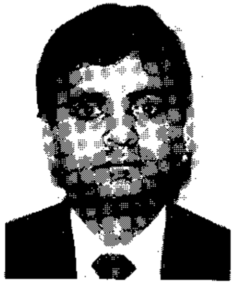

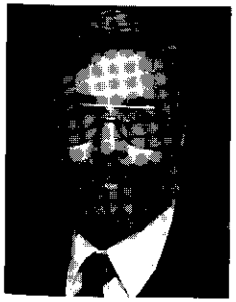

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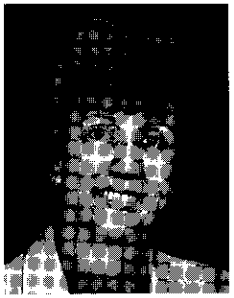

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Index: communication satellites, computer communications, networks, network management

The INTELSAT SSTDMA headquarters subsystem

F. H. LUZ, D. SINKFIELD, AND N. ENGELBERG

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Abstract

The overall system architecture of the INTELSAT satellite-switched time-division multiple access (SSTDMA) headquarters subsystem (HQS) is described. The HQS is the central control and monitoring facility for INTELSAT's three 120-Mbit/s TDMA networks, and was formed by aggregating the INTELSAT Operations Center TDMA Facility (IOCTF) with elements of the INTELSAT Satellite Control Center (ISCC). To support operation in the SSTDMA era, the IOCTF was augmented to become an active, on-line system that performs several critical SSTDMA network functions in close interaction with the ISCC. It also serves as the central data communications hub for computer-to-computer communications between TDMA reference and monitoring station sites; nonreference diagnostic equipment sites; IOCTF; ISCC; and telemetry, tracking, command, and monitoring sites. This paper describes the changes made to the IOCTF system to significantly improve overall system availability by operating the major computer systems in an on-line/standby configuration with either automatic or manual switchover capability. The augmented role of the IOCTF is discussed, and examples are given of how SSTDMA-specific functions are performed, including burst time plan change management, anomaly event handling, central data flow control, and Universal Time Coordinated (UTC) synchronization. Finally, the new IOCTF-based data communications subsystem is described, and the role played by the IOCTF internal Ethernet bus in providing IOCTF inter-subsystem data communications is discussed.

Introduction

INTELSAT currently operates three 120-Mbit/s time-division multiple-access (TDMA) networks: two INTELSAT VI satellite-switched TDMA (SSTDMA) networks at 335.5° and 60.0°, and an INTELSAT V fixed TDMA network at

341.5°. All central control and monitoring activities for the SSTDMA and fixed networks are exercised by the INTELSAT Headquarters Subsystem (HQS), a new facility formed by aggregation of the INTELSAT Operations Center TDMA Facility (IOCTF) and elements of the INTELSAT Satellite Control Center (ISCC). The HQS became operational in May 1990 with the commencement of SSTDMA operation in the 335.5° network. Figure 1 illustrates the network configuration.

In the fixed TDMA era preceding the advent of SSTDMA [1],[2], the IOCTF was a passive element used primarily for network monitoring. The IOCTF and ISCC (a central facility dedicated to the control and monitoring of all INTELSAT satellites) were separate facilities which performed their functions independently, with no computer hardware or software linkage between them. The original IOCTF, designed and built by COMSAT Laboratories, was based on four interconnected system processors: two Digital Equipment Corporation (DEC) VAX 11/780 computer systems and two Hewlett-Packard (HP) A900 computers [3]. The VAX 11/780 computers, known as IOCTF control processors (ICPs), operated as foreground and background processors, performing operational functions and providing the operator interface. The HP A900 computer system, known as the packet store and formatter (PSF) system, together with the Nippon Electric Company (NEC) network packet recirculator and concentrator (NPRC) processors, provided the data communications interface between the IOCTF and the TDMA reference and monitoring station (TRMS) sites.

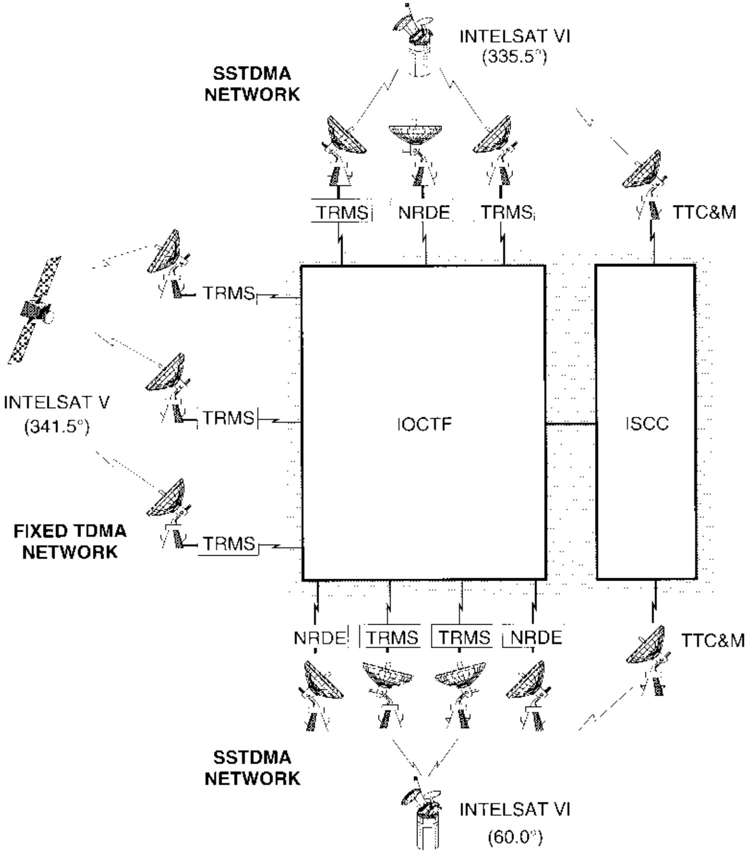


Figure 1. *HQS and the Fixed/SSTDMA System*

The introduction of SSTDMA [4]–[6] changed the operational relationship between the IOCTF, ISCC, and TRMS because the onboard SSTDMA subsystem was included as an active element in the overall SSTDMA system. The role of the IOCTF was elevated to that of an active on-line system which interacts closely with the ISCC [7] to carry out the SSTDMA-specific network control functions of synchronous burst time plan (BTP) changes [8] and periodic onboard timing source oscillator (TSO) frequency corrections [9]. Since the ISCC must command the INTELSAT VI satellite to accomplish these functions, the entire IOCTF, along with those ISCC elements required to support SSTDMA operation, were integrated to form the HQS. The IOCTF and ISCC are now electronically linked to exchange control and other data in support of SSTDMA network operation.

Implementation of the HQS required a redesign of the IOCTF, a complete overhaul of the data communications network, and software modifications to the ISCC. The highlights among the IOCTF architectural changes were as follows:

- Changing of the ICP and PSF system architectures to constitute two fully redundant, interconnected computer systems, both capable of operating in an on-line or standby configuration with either automatic fail-over (PSF only) and/or operator-controlled switchover (PSF and ICP).
- Removal of the proprietary NPRC processors and incorporation of the NPRC functions into the PSF subsystem.
- Addition of a knowledge-based IOCTF diagnostic processor (IDP) system.
- Implementation of an Ethernet-based local area network (LAN) for inter-IOCTF subsystem communications between the ICP, PSF, and IDP.
- Replacement of the aging VAX 11/780 computers with MicroVAX 3800 computers, which share mass storage devices and other peripherals in an Ethernet-based (LAN) VAXcluster.

- Replacement of all obsolete hardware associated with the IOCTF operator interface and implementation of a user interface architecture suitable for distributed processing using standard interfaces and off-the-shelf components.
- Addition of a Global Positioning System (GPS) receiver to provide an international time standard.
- Extension of IOCTF dynamic displays to the ISCC, and vice versa.

A major challenge in implementing the modified IOCTF was to add significant new capabilities to an existing on-line system, while using as much of the existing system as possible and transitioning to the new functions without adversely affecting on-line fixed TDMA operation. Consequently, appropriate test support, together with the reconfiguration capabilities of highly modular design, was considered critical to the successful realization of the HQS. Other important design goals included adequate performance, cost-effectiveness, and a high degree of system maintainability.

SSTDMA Headquarters Subsystem

The HQS comprises a completely redesigned IOCTF and some elements of the ISCC. This section presents an overview of the HQS architecture, with emphasis on the IOCTF, and discusses the IOTCF operator interface architecture and fault tolerance in greater detail.

Overview of HQS architecture

Figure 2 depicts the overall architecture of the TDMA HQS. The IOCTF, the central control and monitoring facility for both fixed TDMA and SSTDMA networks, comprises three subsystems: the ICP, PSF, and IDP. The ICP and PSF subsystems are fully redundant and form the core of the IOCTF. An Ethernet-based LAN serves as the backbone for inter-IOCTF subsystem communications.

The ICP subsystem, based on two DEC MicroVAX 3800 computers, functions as a central processor for all TDMA network monitoring and control activities, and provides the IOCTF operator interface.

The PSF subsystem, based on two HP A900 computers, is the central hub for all TDMA computer-to-computer data communications. As the center of the three TDMA communications networks, the PSF provides the gateway between IOCTF and TRMS sites and Nonreference Diagnostic Equipment (NRDE) sites. In addition, it serves as a switching point for inter-TRMS communications, and interfaces the IOCTF with the ISCC for the exchange of control and other data.

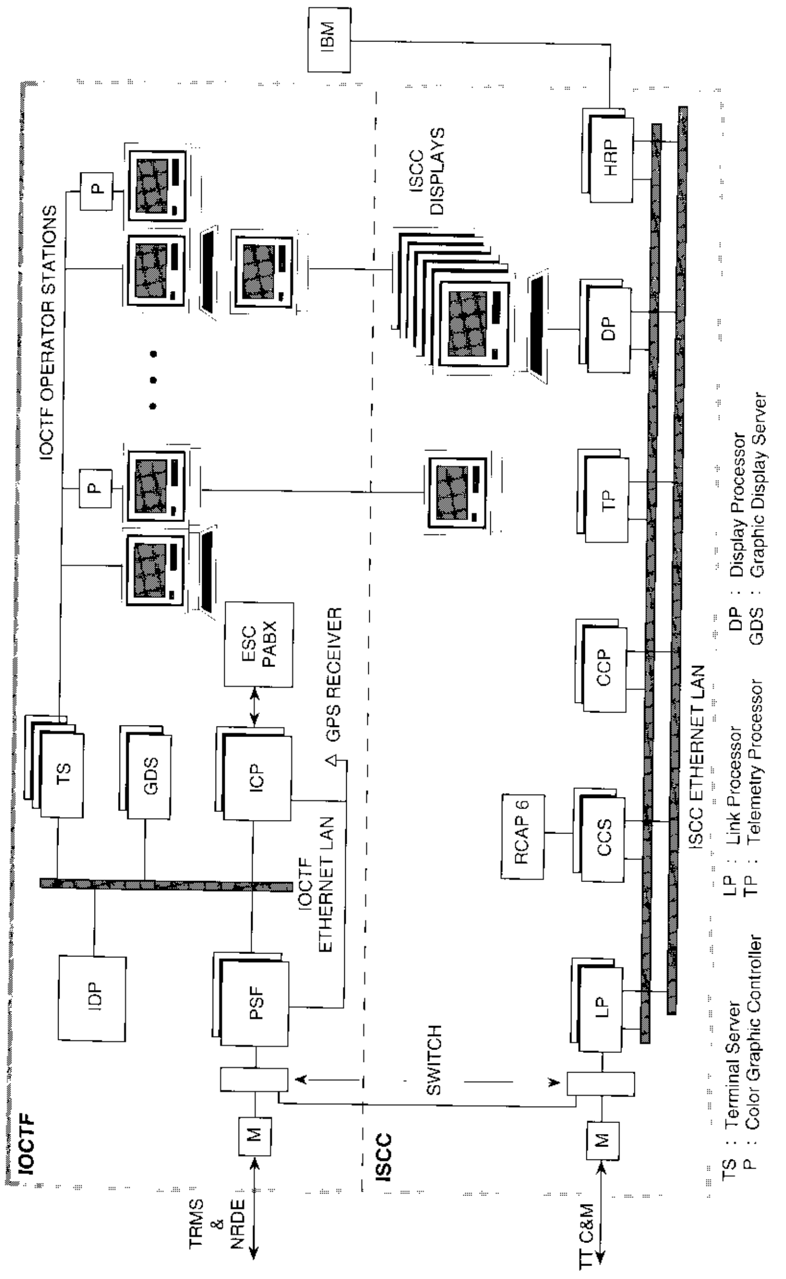


Figure 2. *HQS Architecture Overview*

The IDP subsystem [10] consists of a diagnostic preprocessor (DPP) and a diagnostic expert system (DES). The IDP provides network fault detection and analysis capabilities for all SSTDMA systems by processing near-real-time data from the TRMS and NRDE sites, as well as out-of-limit and alarm data from the ISCC. The DPP and DES are implemented on a Sun workstation Model 330.

The engineering service circuit (ESC) subsystem continues to provide dial-up voice and teletype communications to all TRMS and traffic terminals. The ICP subsystem interfaces with the ESC facility for transmission of condensed time plan (CTP) data to TRMS and traffic terminal sites using the X.25 packet-switched communications protocol. CTP distribution is facilitated through either the TDMA, frequency-division multiple access (FDMA), or single channel per carrier (SCPC) ESC networks, or through the public switched telephone network (PSTN).

The ISCC, INTELSAT's central facility dedicated to the control and monitoring of all INTELSAT satellites, is supported by a network of telemetry, tracking, command, and monitoring (TTC&M) stations [11] located in various parts of the world. The TTC&M stations are linked to the ISCC via dedicated digital data circuits using HP DS-1000 communications software.

The INTELSAT VI network at the ISCC consists of six fully redundant, HP A900 computer-based processor systems: the command coordination system (CCS), the communications and control processor (CCP), the link processor, the telemetry processor, the display processor, and the historical retrieval processor (HRP). An Ethernet LAN conforming to IEEE Standard 802.3 interconnects the various subsystems. SSTDMA-related software modifications were made primarily to the CCS, CCP, and link processor [7].

The CCS is responsible for coordinating the resources used for spacecraft commanding of INTELSAT V, INTELSAT VI, and later satellites. For SSTDMA, the CCS processes all data received from the IOCTF and manages all SSTDMA-related parameters and status data. The PC-based Repeater Command Assistance Program (RCAP) is used to generate the command sequences that control the INTELSAT VI SSTDMA subsystem.

The CCP functions as a central controller that coordinates all network functions and reports network- and spacecraft-related events. In this role, the CCP informs the IOCTF regarding the completion of command sequences relevant to SSTDMA operation.

The link processor serves as a gateway to the TTC&M stations, and interfaces with the IOCTF portion of the HQS. The telemetry and display processors process telemetry data in real time for limit-checking, display telemetry data in various output forms, and perform command verification. The HRP is responsible for telemetry data storage and historical trend analysis.

IOCTF operator interface

At present, six operator stations, each consisting of a video terminal with a keyboard and a color graphic display unit (GDU) provide the user interface. The video terminals serve as the primary operator interface for performing all control and monitoring functions via hierarchical menus. The GDUs, each consisting of a high-resolution red, green, and blue (RGB) monitor and an associated color graphic controller, provide real-time, data-driven dynamic displays for both TDMA network and TRMS site monitoring. Two-color graphic hardcopy units and two serial printers complement the operator interface. Up to four operator stations share one hardcopy unit through a video multiplexer and associated control unit.

The original implementation of the color graphic system was based on Provue, a special software/hardware product developed by DEC [3]. Replacement of the obsolete Provue hardware was necessary to adequately support SSTDMA and ensure long-term maintainability, and was challenging because a complete redesign of the system would have been too costly. Using prototyping, an evolutionary approach was adopted which updated Provue by replacing all existing hardware with off-the-shelf, standard components having standard interfaces. At the same time, the overall Provue software structure was retained, thus avoiding application software changes.

Figure 3 shows the "modern" Provue architecture which is based on a host/slave configuration between the ICP and one or more MicroVAX II-based GDUs. Communication between host and slave relies on the DECnet protocol, which replaced a Provue-specific protocol. The host Provue software forwards the display update data received from the graphic display process associated with each operator station to the slave Provue software. The slave software controls Pericom, the color graphic controller, via a terminal server and RS-232 link using the Tektronix 4107 protocol.

As illustrated in Figure 4, the modern Provue system provides configuration flexibility and growth potential. Each graphic display server (GDS) can independently support up to six GDUs. Normally, the servers are operated in an on-line/standby configuration with an operator-controlled switchover capability; alternatively, they can be operated in an on-line/test configuration. A third option is also provided which allows both GDSs to be configured on line, thereby supporting a total of 12 GDSs.

Communication between the ICP and the operator stations is via the IOCTF Ethernet LAN, which is based on two DEC digital Ethernet LAN interconnect (DELNI) devices. Each DELNI replaces a baseband coaxial cable with eight transceivers ("Ethernet in a box"). In addition to the PSF processors and IDP elements, two MicroVAX II computers and several terminal servers are

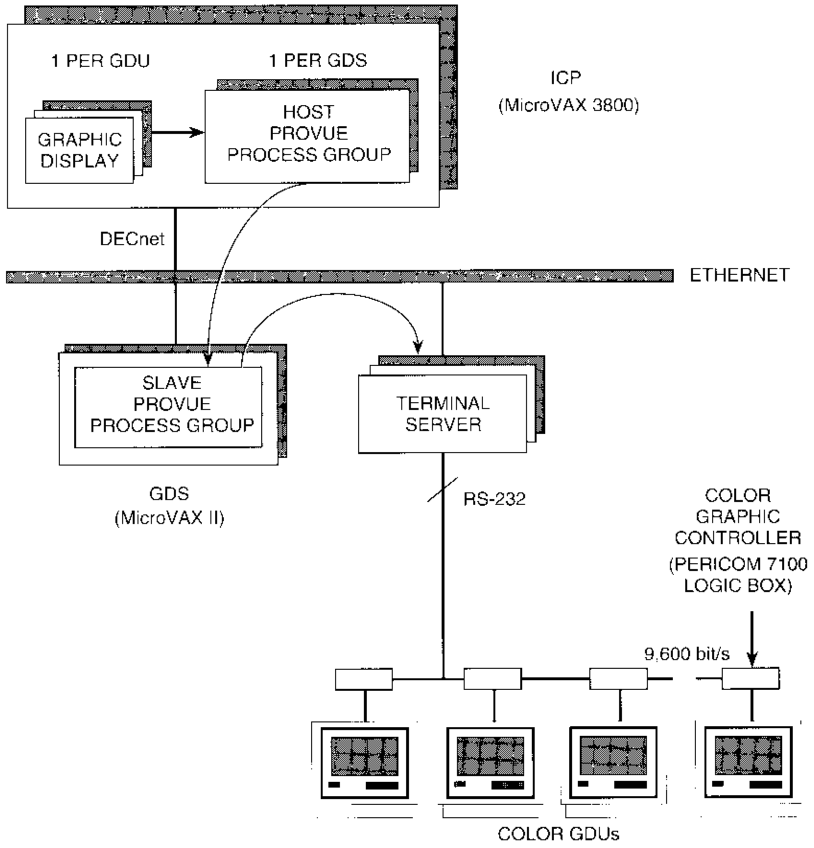


Figure 3. *"Modern" Provue Architecture*

connected to the LAN. Three terminal servers control communications between the host processors and peripherals such as GDUs, video terminals, and printers, while also providing the interface to the external time-of-day source. Figure 5 shows the configuration details.

IOCTF fault-tolerance and test support

One of the major goals for the new IOCTF architecture was to achieve a very high degree of fault tolerance, and at the same time allow for a maximum of configuration flexibility to provide adequate test support. This was accomplished by using redundant components to eliminate single points of failure, using on-line/standby arrangements for all major components, and employing a modular approach so that redundant components could be easily reconfigured to a test bed. Table 1 provides an overview of the impact of component failures on the IOCTF system.

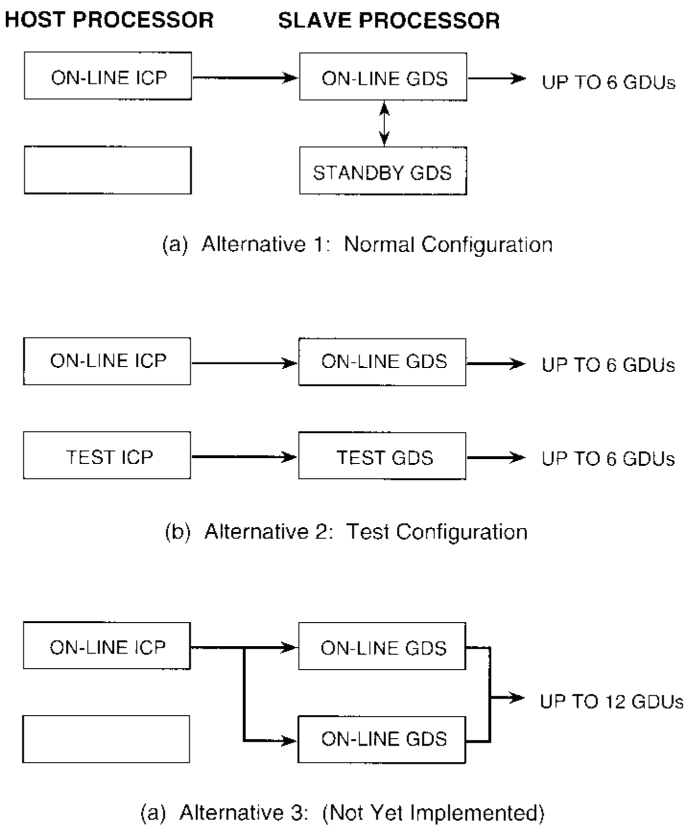


Figure 4. *Provue Configuration Alternatives*

The ICP and PSF are both based on identical computer systems, which are normally operated in an on-line/standby configuration. However, the operational on-line/standby characteristics for PSF and ICP are not the same. While failure of the on-line PSF normally results in an automatic fail-over to the standby processor within 20 s, the ICP operates with a standby available to assume the on-line role within 180 s after an operator-initiated switchover. Although easily possible with the chosen architecture, it was decided not to implement the automatic fail-over feature in the ICP system, but rather to leave the decision to the operator. Similarly, the GDSs normally operate in an on-line/standby configuration with a manual switchover capability.

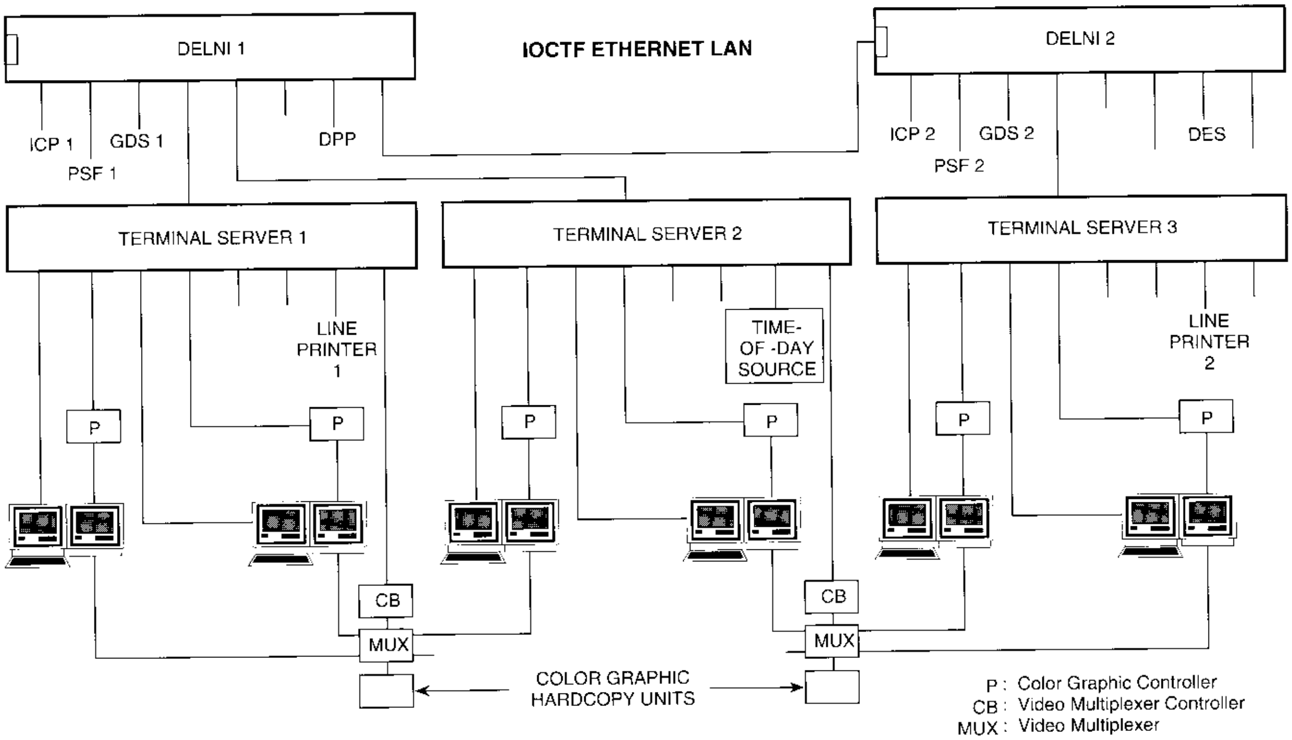


Figure 5. *IOCTF User Interface Architecture*

TABLE 1. OPERATIONAL IMPACT OF IOCTF COMPONENT FAILURE

COMPONENT	QUANTITY	NORMAL OPERATIONAL MODE	RESULT OF FAILURE	IMPACT ON OPERATION/ OPERATOR ACTION
ICP MicroVAX 3800	2	On-line/ standby	ICP failure	Temporary loss of functionality. Operator-controlled switchover to second ICP. Operator must log on again.
ICP System Disk	2	NA*	ICP failure	Temporary loss of functionality. Operator-controlled switchover to second ICP. Operator must log on again.
ICP Data Disk	2	Shadow	Loss of device	None.
Graphic Display Server (GDS)	2	On-line/ standby	Loss of GDS Alarm generated by ICP	Temporary loss of GDUs. Operator-controlled switchover to standby GDS.
Terminal Server (TS)	3	NA	Loss of TS and associated GDUs	None. User interface in degraded mode.
Video Mux, or Video Mux Control Unit, or Hardcopy Unit	2	NA	Loss of device and hardcopy function for GDUs associated with device	None. User interface in degraded mode.
Graphic Display Unit (GDU) or Pericom Logic Device	6	NA	Loss of GDU	None. User interface in degraded mode.
ICP Line Printer	2	NA	Loss of device	None. Operator can select second unit.
ICP Tape Unit	2	NA	Loss of device	None. Operator can select second unit.
Ethernet	2	NA	Loss of Ethernet	Temporary loss of functionality. Operator can easily reconfigure Ethernet using second device.
Packet Store and Formatter (HP A900)	2	On-line/ standby	Automatic fail-over within 20 s	None. Loss of some data.
IOCTF Diagnostic Processor (IDP)	1	On-line	Loss of IDP	Loss of diagnostic capabilities.

* Not applicable.

There are two system disks for the ICP: one on line and the other off line. In addition, two disks serve as data disks containing all operational parameters and data files. One of the data disks is on line and the other serves as a "shadow" disk. Use of the volume-shadowing capability supported by the VAX/VMS operating system ensures maximum data availability and protects against disk failure. Since any data transaction on the on-line disk is duplicated on the shadow disk, at any given time the system will contain an exact copy of the operational data disk. Two spare disks are provided in the ICP for periodic backup of the most critical operational data. All critical data files from the shadow set are copied to the spare disks every 8 hours.

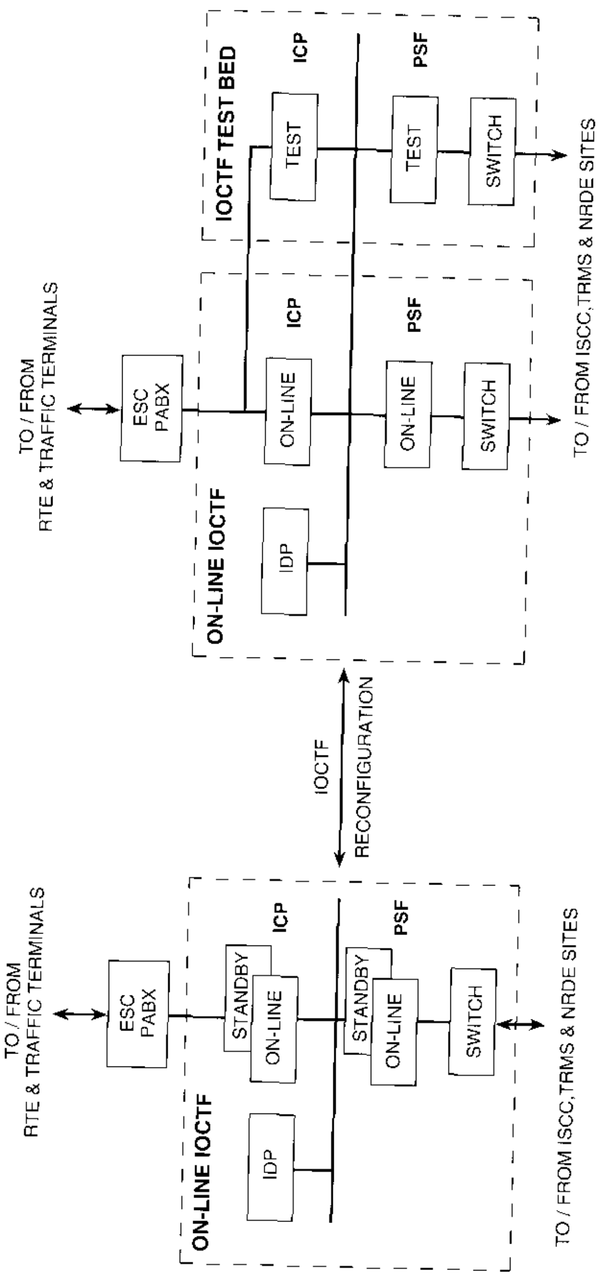
Redundancy for the operator station components is such that a failure of any peripheral device, such as a terminal server, merely results in a degraded mode of operation in which fewer than the maximum number of operator stations are available. The loss of all operator stations would result only from multiple component failures.

As illustrated in Figure 6, a complete test bed can be established by operating the redundant processor components of the ICP and PSF system in "test" mode. In this configuration, there is no interaction between the test mode and the on-line components. This is accomplished by employing a special technique for inter-IOCTF subsystem communications using the Ethernet multicast capabilities for processor-state-dependent group communications (as described in greater detail in a later section). Reconfiguration of the redundant components from standby to test mode, and vice versa, is readily supported by the operator interface so that a complete test bed consisting of a test-mode ICP, GDS, and PSF can be configured in less than 5 minutes.

ICP process architecture

The detailed design for the new IOCTF capabilities was strongly influenced by the existing design, since implementation of the new SSTDMA functions affected all the existing software processes. Figure 7 shows the major processes that handle data flows and graphic displays, and perform operational database management. The boxes in the diagram represent ICP processes. Shading indicates whether a process is new or modified. The lines connecting the processes represent interfaces, and the arrows indicate the direction of data flow. The purpose of each process is listed in Table 2.

Methods used for interprocess communications in the ICP include mailboxes, global common, data files, and global event flags. Mailboxes are used extensively to interface between the Ethernet communications software processes and the ICP application software processes, as well as between ICP



RTE: Reference Terminal Equipment

Figure 6. *IOCTF Test Bed*

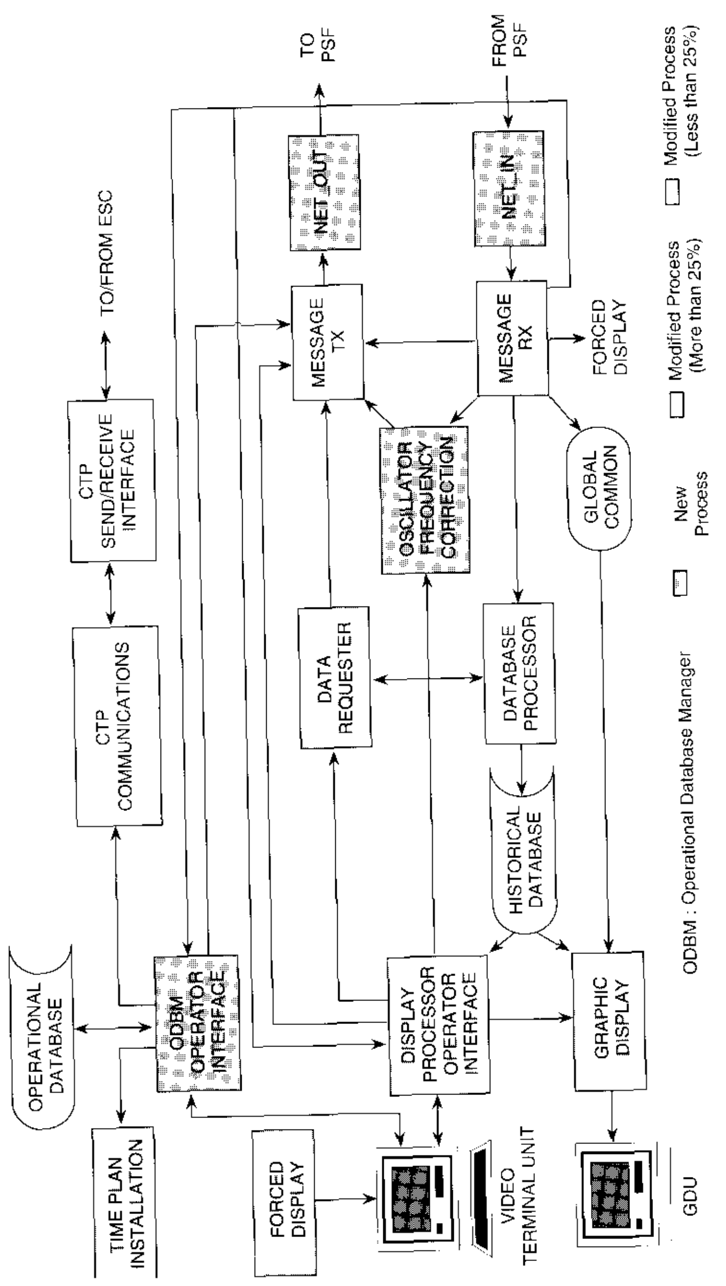


Figure 7. *ICP Process Architecture*

TABLE 2. ICP PROCESSES

PROCESS	PURPOSE
Data Deleter	Deletes data flow and log files aged beyond a user-definable retention period.
Display Processor Operator Interface	Handles the operator interface for all control and monitoring functions, such as display and data flow processing.
Data Requester	Responsible for data flow control.
Database Processor	Handles the storage of TRMS and event data in an historical database.
Forced Display	Performs anomalous event notification.
Graphic Display	Provides the interfaces to the GDS for generating and updating displays.
Message Transmitter	Sends data to the TRMS sites, NRDE sites, and ISCC.
Message Receiver	Receives data from the TRMS sites, NRDE sites, and ISCC.
Oscillator Frequency Correction	Processes phase-data reports and performs periodic TSO frequency corrections.
ODBM Operator Interface	Handles the operator interface for operational database management.
Time Plan Installation	Reads and formats BTPs.
CTP Communications	Front-end processor responsible for CTP distribution to TRMS and traffic terminal sites.
CTP Send-Receive Interface	LAPB process to send and receive CTPs. LAPB process implements the X.25-based communications protocol for CTP distribution.
NET_OUT	Ethernet communications process for outgoing messages from the ICP.
NET_IN	Ethernet communications process for incoming messages to the ICP.

processes. Accordingly, the mailbox message format follows the basic level 6 message format used throughout the TDMA data communications network.

The global common feature provides system and TDMA network configuration data to several processes, as well as timer information for interprocess coordination. Files are used to share the operational database, clock phase data, frequency correction parameters, historical status, and event data among several processes. Global event flags provide interprocess coordination for CTP distribution.

IOCTF functions

The new active role for the IOCTF mandated many changes to the IOCTF application software. The following paragraphs summarize the new features from a network operation viewpoint.

Operational Database Manager. The ODBM integrates the existing fixed TDMA and the new (or modified) SSTDMA operational database functions for handling BTPs, reference terminal operational parameters (ROPs), and satellite position coefficients (SPCs). The ODBM maintains the operational database for both fixed and SSTDMA networks, ensures its integrity, and provides a uniform operator interface.

SSTDMA BTP Change Coordination. As the central TDMA data communications hub, the IOCTF automatically coordinates execution of the BTP change procedure at the master primary reference terminal (MPRT) with the commanding of the satellite by exchanging several messages between the MPRT, IOCTF, and ISCC through the TDMA data communications network. The functions of the MPRT are detailed in a companion paper by Bedford *et al.* [12].

Oscillator Frequency Correction. The IOCTF processes phase data received from both reference terminals to compute a local cumulative phase value, and also maintains a log of the actual TSO frequency error for each clock phase reporting interval (CPRI). If the cumulative phase exceeds a preset threshold value, an unscheduled TSO frequency correction will be requested. Normally, based on operational requirements and actual TSO drift, the IOCTF performs periodic frequency corrections. The amount of frequency correction is predicted such that the cumulative phase error becomes zero at the end of the next correction interval, and this information is forwarded to the ISCC for implementation. Using the cumulative frequency error, the ISCC computes a 12-bit oscillator control integer based on the characteristic curve of the active (on-line) TSO. This number is then transmitted to the satellite via telemetry. Several new functions and one dynamic display were added for control and monitoring purposes. Maranon *et al.* [9] provides an in-depth description of the overall TSO frequency correction system.

Centralized Data Flow Control. Control of all real-time data flows from TRMS and NRDE sites is centralized in the IOCTF.

Alarm System. The alarm system continuously monitors incoming real-time status data from TRMS and future NRDE sites to immediately alert the operator (by optical and acoustical means) to any network or equipment anomaly affecting network operation.

Additional Real-Time Displays. Several new near-real-time displays, including ASU Status, BTP Change Progress, Event Notification, and TDMA Network Status, were added to monitor SSTDMA network operation and enhance existing monitoring capabilities.

IOCTF Diagnostic Processor. Network anomalies are analyzed using real-time data from the TRMS and NRDE sites, along with anomaly event data from the ISCC, to generate a detailed fault report within 3 minutes of any traffic outage. A comprehensive description of the overall SSTDMA diagnostic system is given in a companion paper by Tamboli *et al.* [10].

Operational database manager

The ICP maintains a central database of critical operational parameters. New and existing database management functions have been integrated and now form a group of several software processes commonly referred to as the ODBM. Figure 8 depicts the ODBM, which performs three main functions pertaining to data management of BTPs, SPCs, and ROPs [8].

As illustrated in Figure 8, the SSBTP database contains three different sets of data for each network: next, current, and previous. "Next" indicates the data set that is to be implemented by a time plan change to replace the time plan currently active ("current"). "Previous" indicates the data set that was in use prior to the last BTP change.

The SSBTP database management functions provided by the ODBM allow the operator to install time plan data from magnetic tape, distribute these data to their destinations, perform database housekeeping functions, and (unlike BTP database management for fixed TDMA) actively modify time plan data destined for the INTELSAT VI satellite to accommodate operational requirements.

SPC data enable the TRMSs to compute satellite position in order to determine the initial transmit delay for terminals attempting to acquire the network. The SPC database management provided by the ODBM allows the IOCTF operator to install SPC data from magnetic tape, distribute these data to each TRMS, activate a certain type of SPC data, and review their operational status.

The ROPs are a collection of data used by both SSTDMA and fixed TDMA reference terminal equipment (RTE) [12] to define the network configuration, control the initial acquisition of terminals, and maintain synchronization of terminals. The ROP database management functions provided by the ODBM allow the IOCTF operator to create new ROP data, modify existing ROP data, review (display or print) existing ROP data, distribute ROP data to a selected TRMS, and review ROP status (date/time of last modification and date/time of successful distribution).

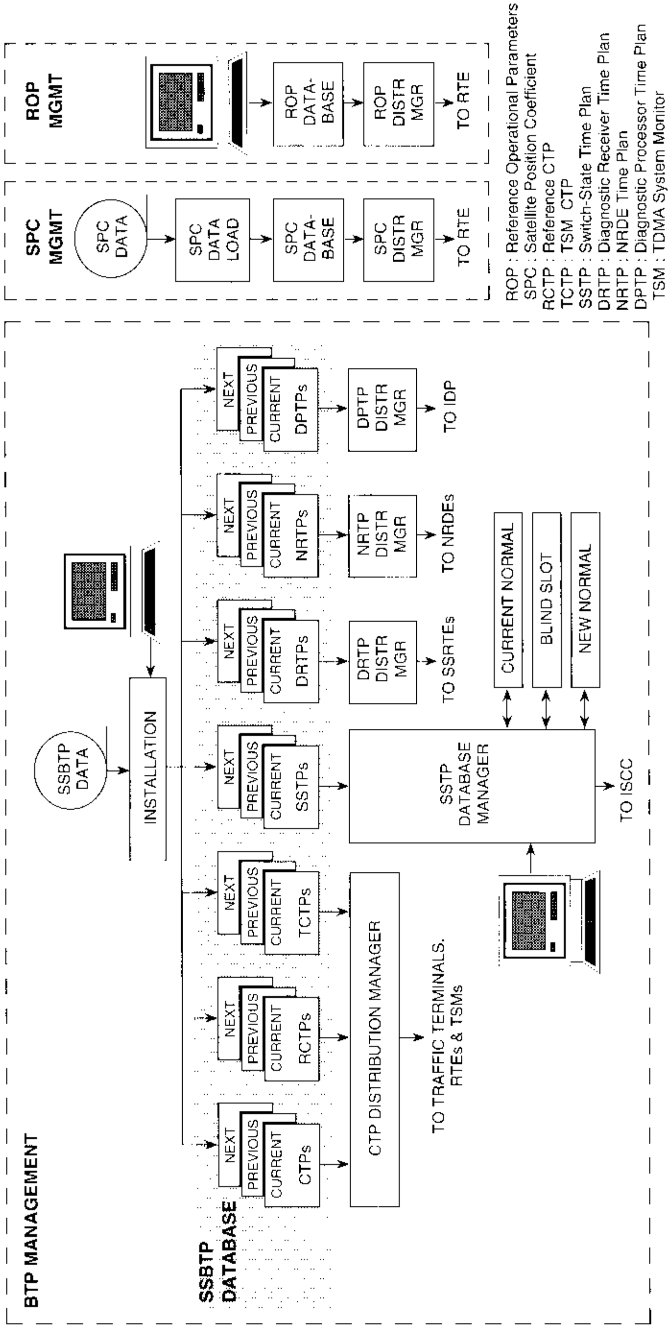


Figure 8. *Operational Database Manager*

Figure 9 illustrates the switch state time plan (SSTP) database functions available for changing the programmed sequence of connectivities in the satellite. The IOCTF is responsible for modifying the SSTPs according to the operational requirements and electronically distributing the modified SSTPs to the ISCC using a custom file transfer protocol. The ISCC implements these SSTPs as either an uncoordinated or coordinated SSTP change.

In addition to the baseline SSTPs, the database contains operational variations referred to as current normal (CN), new normal (NN), or blind slot (BS) to indicate current or intended operational use. With the exception of the BS SSTP, the CN SSTP always reflects the SSTP loaded in the on-line distribution control unit (DCU) memory on board the INTELSAT VI satellite. The ISCC maintains a local copy of the CN, BS, and NN SSTP data. Since this naming convention can be ambiguous, the ODBM uses the SSBTP number, version number, and type to uniquely identify each SSTP.

The ICP also maintains a DCU memory status (DMS) database which contains the characteristics of the SSTP data loaded in the on-line, off-line, and standby DCU memories. This database is automatically updated upon receipt of a DMS Change Notification message from the ISCC. The ISCC sends this message each time an SSTP data upload in any one of the DCU memories, or a DCU memory role change, is verified from telemetry.

SSTDMA operation requires the capability to make operator-controlled or automatic modifications to the operational SSTP. These modifications are limited to connectivity changes not affecting SSTDMA traffic elements and fall into one of the following four categories:

- *Type 1: Non-TDMA Transponder Connectivity Modification.* This function allows the implementation of pseudostatic connectivities between non-TDMA transponders. Normally, such traffic will be implemented via the static bypass switches rather than the microwave switch matrix.
- *Type 2: Test Slot Connectivity Modification.* This function allows the connectivity of one or more selected test slots to be changed, or the connectivities of all test slots to be restored to those of the current baseline SSTP.
- *Type 3: SSTP Connectivity Modification.* The new baseline SSTP is modified to ensure continuity of test slot and non-TDMA transponder connectivities across the time plan change boundary.
- *Type 4: Blind Slot Connectivity Modification.* The CN SSTP is modified to change the connectivity of the switch state verification (SSV) region from loopback to no-connection (BS).

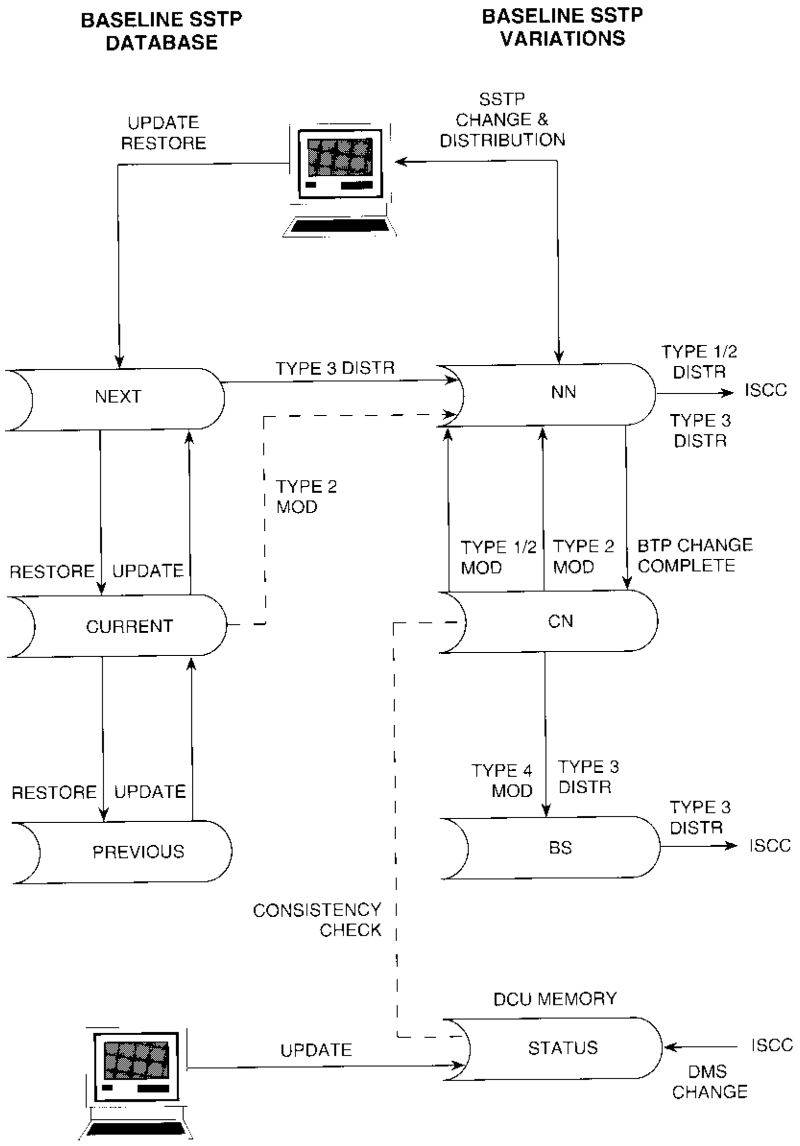


Figure 9. *SSTP Database Management*

Type 1 and type 2 SSTP modifications (and associated SSTP distribution to the ISCC) are implemented as separate functions, while type 3 and type 4 modifications are performed automatically as an integral part of the SSTP type 3 distribution function. Prior to actual SSTP modification, the ODBM performs a consistency check to ensure the integrity of the SSTP database, and immediately aborts any pending function if the characteristics of the on-line DCU memory in the DMS database do not match those of the CN SSTP data file. In such a case, the operator can restore database integrity by manually updating either the DMS database or the CN SSTP data file.

If the type 1 or type 2 SSTP modification function is selected by the operator, the CN SSTP is copied into the NN position, the SSTP data type is updated, and the version number is incremented by 1. The IOCTF operator is then prompted to perform the desired connectivity changes, with the constraint that connectivities between TDMA and non-TDMA transponders are inhibited.

If the operator executes the type 3 distribution function, the BS SSTP is first generated by copying the CN SSTP into the BS position and changing the SSV switch state connectivities to no-connection. The version number and SSBTP number are maintained. The NN SSTP is then generated by copying the next baseline SSTP into the NN position and changing the test slot and non-TDMA transponder connectivities to those of the matching CN connectivities. Should this result in a connectivity between a TDMA and non-TDMA transponder, the violating connectivity will be restored to its original state.

Prior to actual distribution of any SSTP data file, the ODBM verifies that there is no "outstanding" SSTP which has been successfully distributed to the ISCC but never confirmed as being incorporated in the ISCC SSTP database. In such a case, the operator must enable further SSTP distribution.

The ISCC stores SSTP data received from the IOCTF in a temporary file until, under operator control, the data are incorporated into the local SSTP database. An SSTP Database Change message informs the IOCTF of the result of the ISCC SSTP database update attempt.

Following an SSTP upload or a DCU memory role change, the ISCC sends a DMS Change message to the IOCTF to update the IOCTF DMS database. If the content of the on-line DCU memory has changed, the ODBM generates a DCU On-Line Change warning message to inform the operator, and replaces the CN SSTP data file with the NN SSTP data file if the latter has the characteristics of the on-line SSTP indicated in the DMS Change message.

Coordinated SSBTP change

The IOCTF plays a significant role in coordinating an SSBTP change. An overview of the entire SSBTP change procedure is given by Lunsford *et al.* [6].

Details regarding the SSBTP change procedure executed at the MPRT are presented by Bedford *et al.* [12], while SSTP change in the ISCC is described by Pettersson *et al.* [7]. SSBTP generation and implementation are discussed by Mizuike *et al.* [8].

Unlike a fixed TDMA BTP change, an SSBTP change requires the active participation of the HQS. Figure 10 illustrates the overall SSBTP change procedure, which depends on the timely exchange of messages between the MPRT, IOCTF, ISCC, and the TTC&M site via the TDMA and INTELSAT VI data communications networks to simultaneously implement the new SSBTP at the satellite and in the ground segment elements.

The functions performed by the IOCTF include loading and distribution of time plan data, initiation (enabling) of the SSBTP change procedure at the MPRT, routing of messages from the MPRT to the ISCC (and vice versa), and monitoring the SSBTP change sequence. In general, messages exchanged between the MPRT and ISCC are routed via the ICP, which performs the necessary format conversions.

The coordinated SSBTP change sequence normally begins under IOCTF operator control after a new SSBTP has been distributed to the various elements of the network. The new SSBTP rearrangement function prompts the operator for the new SSBTP number and the SSBTP change parameter, N, which defines the amount of time available for commanding the satellite. Upon execution of this function, the ICP sends two messages to the MPRT within a 10-s interval: first, the SSBTP Change Parameter message (M215) containing parameter N, and then the Plan Change Enable message (M201) containing the new SSBTP number. The IOCTF must then intercept the Plan Change Enabled message (M006) received from the MPRT; extract the satellite command execute time [6], T_{xqt}; and forward this time in a separate SSBTP Change Execute Notification message (M250) to the ISCC.

After the ISCC operator verifies that T_{xqt} has been received and tagged correctly onto the command queue for the DCU memory role change, certain setup commands are executed [7]. Upon verification via telemetry that the execute signal has been sent at T_{xqt}, the ISCC automatically sends an SSTP Change Armed message (M072) to the IOCTF. This message is handled differently from all other messages exchanged between the MPRT and ISCC. To expedite transmission, the PSF will intercept the SSTP Change Armed message and route it directly as message M205 to both reference terminals, without involving the ICP. Following reception of this message, the MPRT begins the countdown sequence which ultimately ends with implementation of the new SSBTP in the terrestrial segment at the next superframe boundary.

If, after the start of the satellite commanding phase, the SSBTP change procedure is aborted, the IOCTF will intercept the Cancel Plan Change message

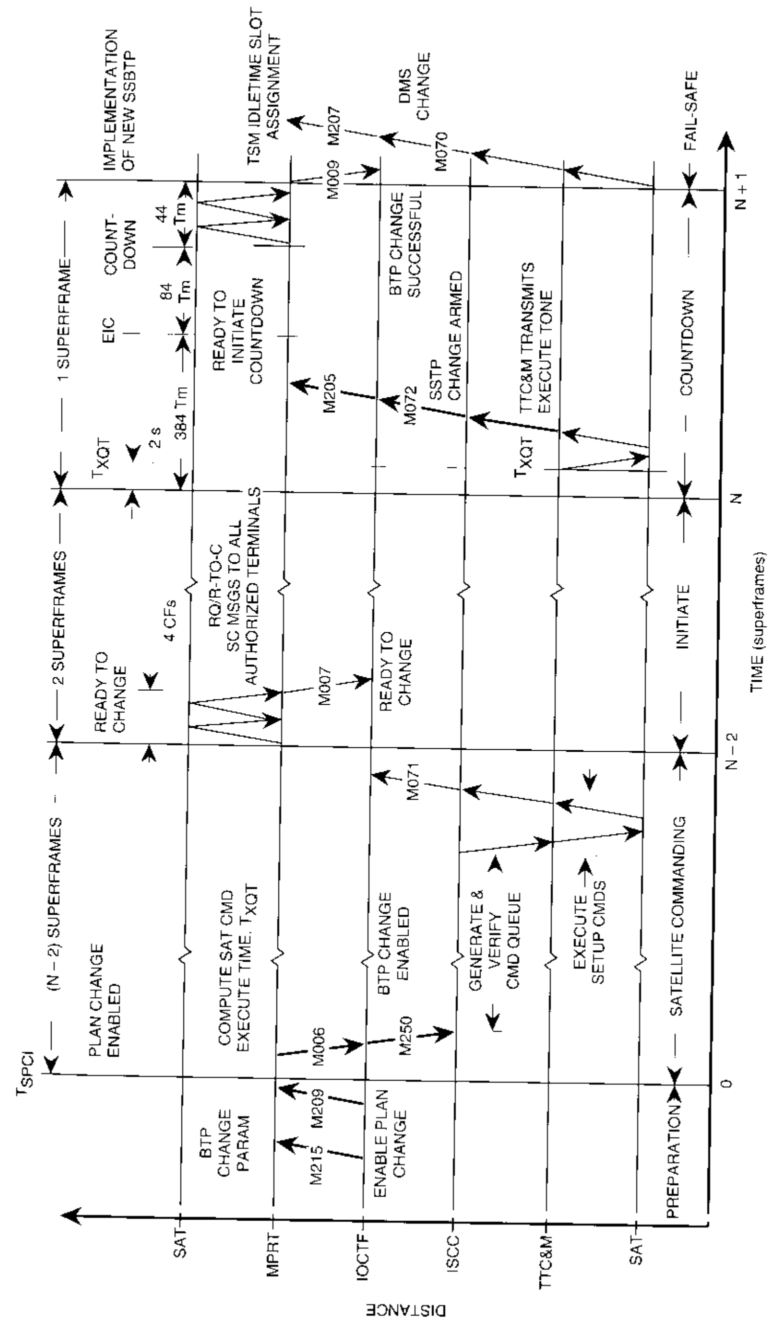
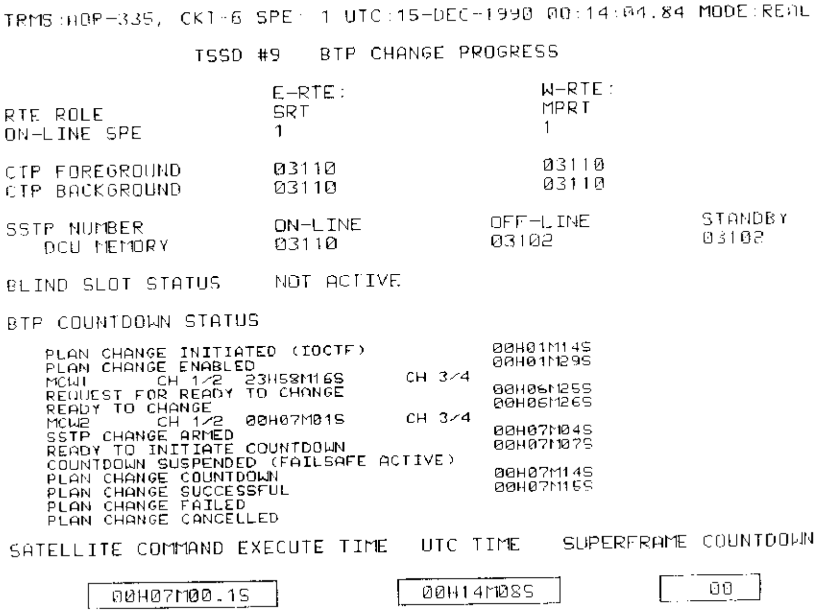


Figure 10. *SSBTP Change Procedure*

(M010) from the MPRT, generate a warning, and forward this information in a separate message (M251) to the ISCC. The ISCC will then automatically instruct the TTC&M site to bypass the pending transmission of the execute tone and instead send a DCU clear command(s) to the spacecraft. This will abort the imminent execution of the SSTP change. Tests have shown that this automatic cancellation is possible up to 5 seconds prior to T_{xqt}.

After reception of the DMS Change message (M070) from the ISCC indicating that the SSTP change has taken place, the ICP automatically updates its local SSTP database and then sends the TDMA System Monitor (TSM) Idletime Slot Assignment message (M207) to the satellite-switched TSMs informing them of potential test slot connectivity changes as a result of the SSBTP change.

Following the Plan Change Enable instant, the ICP processes and logs all SSBTP change-related messages received from the MPRT and the ISCC, and displays this information on the new SSBTP Change Progress display, which allows monitoring of all SSBTP change-related events. The IOCTF also has access to the ISCC display which permits direct monitoring in the IOCTF of the commands sent to the spacecraft. Figure 11 shows a hard copy of the SSBTP Change Progress display, taken after successful completion of the first SSBTP change on December 15, 1990, in the 335.5° network.



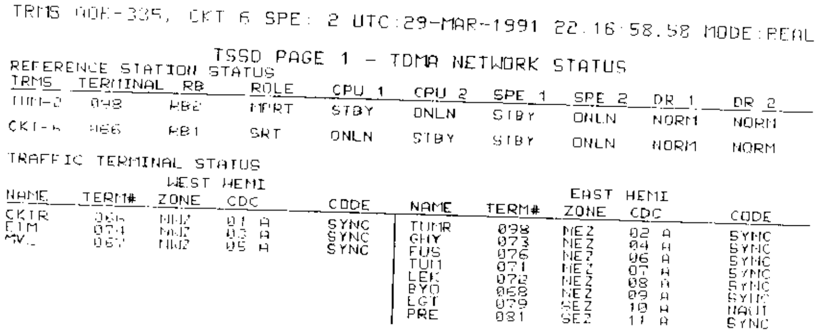
```
TRMS:HQP-335, CKT-6 SPE  1 UTC:15-DEC-1990 00:14:04.84 MODE:REAL

                TSSD #9   BTP CHANGE PROGRESS

                         E-RTE:                  W-RTE:
RTE ROLE                 SRT                     MPRT
ON-LINE SPE              1                       1

CTP FOREGROUND           03110                   03110
CTP BACKGROUND           03110                   03110

SSTP NUMBER              ON-LINE          OFF-LINE           STANDBY
   DCU MEMORY            03110            03102              03102

BLIND SLOT STATUS        NOT ACTIVE

BTP COUNTDOWN STATUS

   PLAN CHANGE INITIATED (IOCTF)                  00H01M14S
   PLAN CHANGE ENABLED                            00H01M29S
   MCW1       CH 1/2  23H58M16S       CH 3/4
   REQUEST FOR READY TO CHANGE                    00H06M25S
   READY TO CHANGE                                00H06M26S
   MCW2       CH 1/2  00H07M01S       CH 3/4
   SSTP CHANGE ARMED                              00H07M04S
   READY TO INITIATE COUNTDOWN                    00H07M07S
   COUNTDOWN SUSPENDED (FAILSAFE ACTIVE)
   PLAN CHANGE COUNTDOWN                          00H07M14S
   PLAN CHANGE SUCCESSFUL                         00H07M15S
   PLAN CHANGE FAILED
   PLAN CHANGE CANCELLED

SATELLITE COMMAND EXECUTE TIME   UTC TIME    SUPERFRAME COUNTDOWN

     00H07M00.1S                00H14M08S              00
```

Figure 11. *SSBTP Change Progress Display*

Network monitoring and system event notification

Existing network monitoring and system event notification capabilities were augmented and improved to adequately support rapid operational decisionmaking. In addition to several new SSTDMA-specific dynamic displays, a new alarm system was implemented to immediately alert the operator to any anomalous condition that requires corrective or preventive action. This capability complements the expert-system-based IDP subsystem, which provides detailed fault analysis within 3 minutes after a network or terminal failure.

The high reliability of the new TDMA data communications network makes it possible to depend on TRMS and NRDE real-time data flows for improved monitoring and alarm functions. An example is the new real-time TDMA Network Status display (Figure 12), which provides the operator with the operational status of all traffic terminals, as well as the equipment status of all TRMS and NRDE sites on a single display. The display is available for both fixed TDMA and SSTDMA network monitoring and uses information contained in the RTE routine data and the control and delay channel (CDC) data from each TRMS.



```
TRMS HQE-335, CKT 6 SPE: 2 UTC:29-MAR-1991 22.16:58.58 MODE:REAL
                     TSSD PAGE 1 - TDMA NETWORK STATUS
REFERENCE STATION STATUS
TRMS   TERMINAL  RB     ROLE   CPU 1  CPU 2  SPE 1  SPE 2  DR 1   DR 2
TUM-2  098       RB2    MPRT   STBY   ONLN   STBY   ONLN   NORM   NORM
CKT-6  066       RB1    SRT    ONLN   STBY   STBY   ONLN   NORM   NORM
TRAFFIC TERMINAL STATUS
               WEST HEMI                                EAST HEMI
NAME   TERM#  ZONE  CDC      CODE | NAME   TERM#  ZONE  CDC      CODE
CKIR    066   NWZ   01 A     SYNC | TUMR    098   NEZ   02 A     SYNC
ETM     074   NWZ   03 A     SYNC | GHY     073   NEZ   04 A     SYNC
MVL     067   NWZ   05 A     SYNC | FUS     076   NEZ   06 A     SYNC
                                  | TUM     071   NEZ   07 A     SYNC
                                  | LEK     072   NEZ   08 A     SYNC
                                  | BYO     068   NEZ   09 A     SYNC
                                  | LGT     079   SEZ   10 A     SYNC
                                  | PRE     081   SEZ   11 A     NAQT
                                  |                              SYNC
```

Figure 12. *SSTDMA Network Status Display*

There are two types of system events: those signaled directly by level 6 messages from the RTEs or the ISCC, and those that are detected within the ICP subsystem (*e.g.*, by continuously examining TRMS and NRDE real-time status data). An example of the first type is the BTP Change Canceled event, which is signaled directly via a special level 6 message from the MPRT. An example of the second type is the TDMA Network Failure condition, about which the ICP informs all TRMS sites pertaining to the same network by sending a special level 6 message. The following rules are used to infer an SSTDMA network failure condition from the RTE routine data flows:

1. IF ("RTE Routine" data flows are on and valid for both SSRTEs) AND (no MPRT and no SRT detection in either data flow) THEN SSTDMA network down.
2. IF (East-SSRTE "RTE Routine" data flow is on AND valid) AND (MPRT or SRT) THEN SSTDMA network up.
3. IF (West-SSRTE "RTE Routine" data flow is on AND valid) AND (MPRT or SRT) THEN SSTDMA network up.
4. IF (other data flow condition) THEN no change in SSTDMA network status.
5. IF (network is down) AND (last network status was up) THEN
   (a) Generate alarm "SSTDMA Network Failure"
   (b) Send level 6 message M206 "SSTDMA Network Failure" to both SSRTEs.
6. IF (network is up) AND (last network status was down) THEN generate general event message "SSTDMA Network Recovery".

From the operator's viewpoint, each system event is classified and prioritized as alarm, warning, or general event. An alarm is usually triggered by an event that could cause, or has already caused, an immediate traffic outage, and normally requires expedited corrective action. An example is a TDMA network failure. A warning is an event that may eventually cause system disruption, for example, the TSO Clock-Phase Data Not Available warning indicating that no phase data have been received during the last CPRI. However, most events, such as operational events and equipment malfunctions, are considered general events. Table 3 provides an overview of the ICP alarm and warning messages, grouped as network and terminal outages, BTP change events, TSO frequency correction events, and miscellaneous problems.

An alarm is immediately signaled to all operator terminals by a message and by terminal bells, and continues to be periodically re-signaled until an operator acknowledges it. A warning is treated similarly, but will not be broadcast if there is an outstanding alarm. Both alarms and warnings are also signaled visually. Through a supervisory menu, the operator may turn off the terminal bells for a particular class of anomaly, and may also elect to have general events brought to the operator's attention.

All system events are now archived for up to 30 days. Event retrieval from the historical database to either an operator screen or a printer can be filtered; that is, system events with a specific combination of severity (alarm, warning, general event), group, source, and time range can be requested.

TABLE 3. OVERVIEW IOCTF ALARMS AND WARNINGS

EVENT NOTIFICATION MESSAGE	TYPE
Network and Terminal Outages	
TDMA Network Failure	Alarm
TDMA Reference Terminal Failure	Alarm
Interference Survival Mode	Alarm
BTP Change Events	
BTP Change Canceled	Warning
Blind Slot Active	Warning
Failsafe Recovery Invoked	Warning
On-Line DCU Memory Update	Warning
TSO Frequency Correction Events	
TSO Clock Phase Data Threshold Exceeded	Alarm
TSO Frequency Correction Alarm Notification	Alarm
Insufficient Valid TSO Clock Phase Data	Warning
TSO Clock Phase Data Not Available	Warning
TSO Correction Warning Notification	Warning
TSO Correction Confirmation	Warning
TSO Correction Confirmation Not Received	Warning
TSO Correction Alarm Notification Error	Warning
TSO Correction Confirmation Identify Mismatch	Warning
Miscellaneous Problems	
Satellite Position Out/Within Limits	Warning
Satellite Position Discontinuity	Warning
Data Link Loss	Warning
UTC Synchronization Errors	Warning
IOCTF Control Processor Failure	Warning
ICP Data Disk Full	Warning
No Valid Unique-Word Data	Alarm

The new real-time Event Notification display allows the operator to view the last 40 system events. Color coding is used to distinguish between alarms, warnings, and general events. Like the TDMA Network Status display, the Event Notification display can be designated as the default display for a particular operator station. The system will automatically invoke the default display if any display other than the selected default display has been continuously active for some period of time. Unacknowledged alarms and warnings are indicated by a blinking color bar at the bottom of either default display.

Data flow control and data storage

One of the major changes made to accommodate SSTDMA was the centralization of all data flow control at the IOCTF. Previously, some data from the TRMS sites (RTE routine and TSM measurement data) were sent unsolicited. Now each data type must be explicitly requested by operator command. The ICP has the capability to manage data flows from up to six TDMA networks. Table 4 lists the real-time and log data flows controlled by the IOCTF.

Once a particular data flow has been activated, the ICP software will ensure data flow continuity by reissuing a request for a data flow that has ceased for some period of time without operator intervention. If re-requests of an active flow are unsuccessful over a longer period of time, the data flow will be canceled automatically.

The ICP stores all data flows, except TSM real-time data, in files containing data collected over a 1-hour interval. A particular data type is automatically deleted after the data have aged beyond an operator-specified retention period. Historical data can be played back at the same rate at which it was captured, or at a different operator-specified rate. Subsample viewing is also possible, where the number of frames being skipped can be specified by the operator. Alternatively, historical data can be analyzed in "change" mode, wherein the data frames are displayed only if they have changed.

UTC synchronization

The requirements for timely execution of coordinated BTP changes and time-stamping of log data for troubleshooting purposes necessitate that the time-of-day clock used at the TRMS sites, TTC&M sites, and HQS be synchronized within ±1 s. At the IOCTF, a Kode Model 325 SatSync GPS receiver provides a Universal Time Coordinated (UTC) signal to the ICP and PSF via a serial RS-232-type interface.

The internal clocks of the ICP and PSF processors are automatically synchronized to UTC each time a mode transition to "on-line" or "test" takes place, and periodically every 24 hours. If the processors' internal clocks are within 1 s of the SatSync time, the clock will not be reset; otherwise it will be corrected. If any attempt to set the internal clock is unsuccessful, another attempt is made automatically 1 hr later. In addition, both the ICP and PSF provide the capability to synchronize their internal clocks upon operator command. Tests have shown that the internal VAX clock and the SatSync never differ by more than 0.16 s immediately following a successful synchronization. Usually, the two clocks agree to within 0.02 s.

TABLE 4. TDMA DATA FLOWS OVERVIEW

DATA FLOW	CONTENT	MSG NO.	SOURCE	MAX MSG SIZE (bytes)	FLOW RATE (s/msg)	DATA FLOW TYPE*
RTE Routine	TRMS and host station operational and equipment status	M042	RTE	554	16.384	C
CDC	Reference and traffic terminal acquisition and control status	M052	RTE	114	2.0	C
CDC/BTP	Same as CDC, but with additional information regarding BTP change events	M051	RTE	198	2.0	C
UW Detection Table	Status (received/not received) of all reference and traffic bursts	M057 M058	RTE NRDE	174 104	16.384	C
TSM Real-Time Measurement	TSM measurement data	M141	TSM	522	3**	C
RTE System Log	RTE system events	M055	RTE	182	1**	D1
NRDE System Log	NRDE system events	M060	NRDE	182	1**	D1
TSM 24-hr Measurement Log	Historical TSM measurement data	M158	TSM	526	3**	D2

* C = Periodic timer-driven data flow.
D = Discrete data flow driven by IOCTF file transfer request.
D1 = Periodic requests.
D2 = Single request.

**Peak flow rate.

TDMA data communications network

The original fixed TDMA data communications network employed X.25 as the protocol for interprocessor communications. The NPRC, a customized hardware and software system located at the IOCTF, served as a switching point between the TRMS computers and concentrated the data circuits dedicated to the TRMS into one single link to the PSF system. The PSF, serving as an intermediate message processor, provided the interface between the TRMS computers and the IOCTF VAX 11/780 computers. The TRMS and PSF computers used HP's DS-1000 communications network and X.25 software. Within the IOCTF, a combination of vendor-supplied (HP and DEC) X.25 software was used for the lower level functions, and a custom communications control software was used for the higher level functions.

While the original TDMA data communications network was adequate for the passive role of the IOCTF in the fixed TDMA networks, it was unacceptable for the active role of the IOCTF in SSTDMA operation. Many problems in the original networks were caused by incompatibilities between different X.25 implementations on the NPRC, PSF, and TRMS computers. In addition, a node or data-circuit failure often required restarting significant portions of the network.

Since SSTDMA depends on extremely reliable data communications for the coordination of SSBTP change events, TSO phase-data reporting, and the provision of real-time data for the new diagnostic and monitoring functions, it was decided to completely redesign the existing data communications system, replace the X.25 protocol between the IOCTF and remote sites with the high-level data link control (HDLC)-based DS-1000 protocol, remove the NPRC processor system altogether and incorporate its functions into the PSN, and implement an Ethernet-based LAN for inter-IOCTF subsystem communications. One of the major challenges for the new TDMA communications system has been to maintain the ICP software interface between the application and the communications interface software. The node numbering scheme has also been maintained, with the addition of new multicast addressing schemes (discussed later) to enhance message exchange options.

Features of the SSTDMA data communications system

Figure 13 shows the topology of the new SSTDMA data communications network, which relies on the PSF central data communications processor. The PSF interconnects the IOCTF Ethernet LAN with three star-type DS-1000-based wide area networks (WANs) encompassing several remote processors in each TDMA network. The PSF also links the IOCTF with the ISCC. The remote computers comprise the control and display console (CADC) and TDMA system

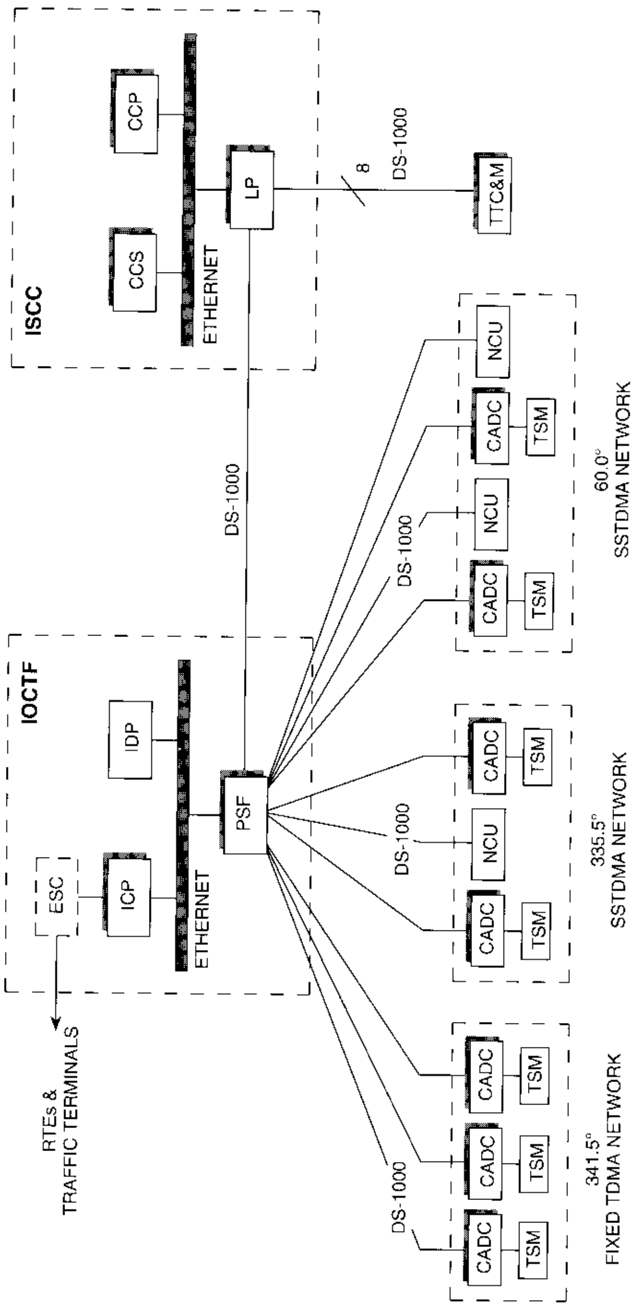


Figure 13. *Topology of the SSTDMA Data Communications Network*

monitor (TSM) processors at each TRMS site, and the NRDE control unit (NCU) processor at the NRDE sites in the SSTDMA networks.

As the central data communications hub for both fixed and SSTDMA operation, the PSF provides interprocessor-computer communications between the IOCTF and all the TRMS and NRDE sites; between TRMS sites in each TDMA network; and between the IOCTF and ISCC. The two identical PSF computers normally operate in an on-line/standby configuration, with automatic switchover to the standby within 20 s should the on-line PSF computer fail. Computer-controlled switching equipment is used to switch the incoming DS-1000 data links between the PSF processors.

The PSF application software provides automatic link recovery from circuit failures and temporary software problems by using available DS-1000 software features, periodically attempting link recovery, and employing link (re)start and reset mechanisms with the Ethernet communications software. A new menu-based operator interface allows DS-1000 network reconfiguration, link status monitoring, PSF switchover, and UTC synchronization.

Figure 14 illustrates the communications interfaces for the new TDMA data communications system. The IOCTF LAN is based on a 10-Mbit/s Ethernet communications link. The IEEE 802.2/802.3 standard is used for communications layers 2 and 3, while a proprietary Ethernet software package provides communications at the higher layers. Implementation of the LAN within the ISCC is similar to that of the Ethernet in the IOCTF.

A custom Ethernet communications software package links the PSF computers with the ICP and IDP computers, and a multidestination routing mechanism allows messages from the remote sites and the ISCC to be received by more than one IOCTF subsystem. The routing mechanism also allows processors on the IOCTF Ethernet LAN to be partitioned into subnetworks so that on-line operations can continue while diagnostics/testing is being conducted simultaneously between processors on the same subnetwork.

HP's DS-1000 communications software package for distributed systems is used to link the computers at the remote sites with the PSF computers, and to link the PSF computers with the ISCC link processor computer. The 9,600-bit/s data links (fixed TDMA currently uses 4,800 bit/s) from the IOCTF (PSF) to the TRMS (CADC, TSM) sites and the ISCC are configured in a star-type network with the IOCTF/PSF as the hub. The HDLC-based DS-1000 software provides peer-to-peer message exchange at levels 1 through 4. For maximum throughput, an HDLC frame size of 1,024 bytes is used. Messages from one TRMS site to another are routed through the PSF without involving the PSF communications application programs, because such communications are handled entirely by the DS-1000 software and firmware.

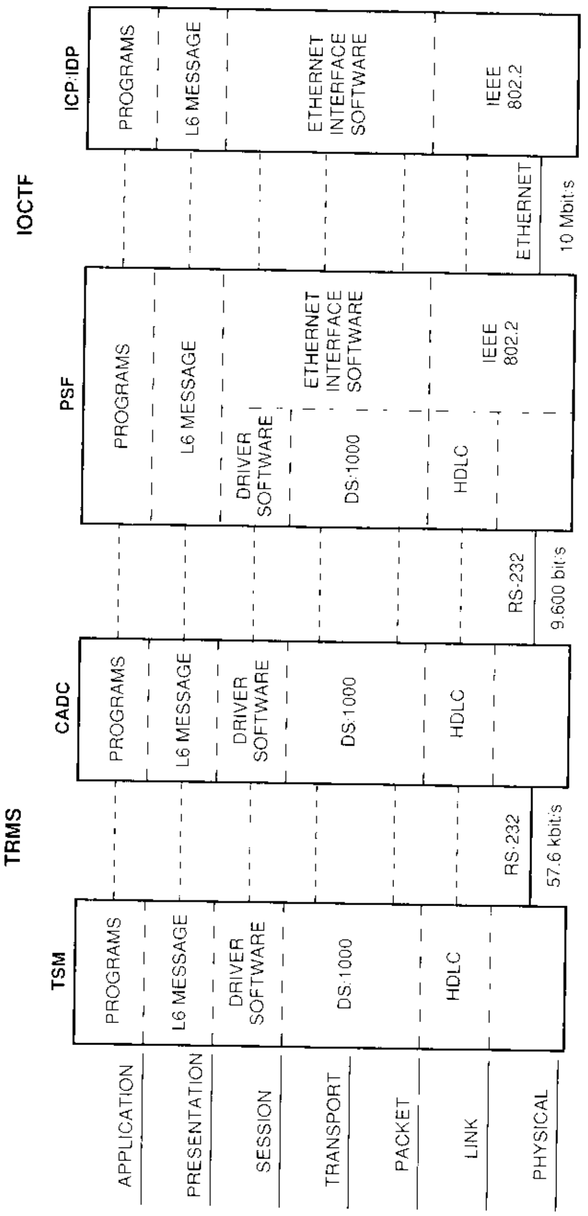


Figure 14. *TDMA Computer Communications Software Interfaces*

Application message formats and packet framing

As messages traverse the network from the Ethernet to DS-1000, and sometimes back again, they go through several protocol/framing translations. Figure 15 illustrates how typical messages are translated as they pass from one link (type) to another on their way to their final destination. The different types of headers and framing information used include a standard 10-byte TDMA level 6 message header, Ethernet framing, and DS-1000 and HDLC headers and framing.

Although chosen to be identical for convenience, level 6 and DS-1000 node numbers within the same subnetwork are independent and serve different purposes. The TDMA level 6 message header is supplied by application programs and contains information such as source node, destination node, message type, and time stamp. The header supplied by HP's DS-1000 communications software package allows routing among the DS-1000 subnetworks, PSF, and ISCC link processors. The Ethernet network header, supplied by the Ethernet interface software, is used to address the nodes within the IOCTF Ethernet LAN. It should be noted that messages traversing the IOCTF Ethernet have been formatted with the same network header as messages traversing the ISCC Ethernet/network. HDLC framing is supplied by the firmware in the Ethernet and DS-1000 interface cards.

Ethernet interface software

Inter-IOCTF processor communications relies on a custom Ethernet protocol which provides for recovery of lost packets. This protocol employs sequence numbers in a fashion similar to that of an HDLC link; however, no control frames (*e.g.*, receiver ready, unnumbered acknowledgments) are used. Instead, each Ethernet node receiving messages checks the sequence number of the message it receives and determines whether it has missed a packet. If a packet has been missed, the node requests it from the sending node and continues processing (after receiving the missing packet) by passing the messages to the TDMA application programs in the proper sequence.

Figure 16 illustrates how the processes of the Ethernet communications interface recover lost packets. Although the figure depicts the PSF Ethernet communications interface in particular, all Ethernet communications processes in all other IOCTF Ethernet nodes are the same. If a packet is received by the Ethernet Incoming Messages process out of sequence, the message is placed into a holding area and a retransmission request is sent to the node to recover the lost packet. (The sending node saves the last five packets placed on the Ethernet.) When the requested packet is received, the Ethernet Incoming

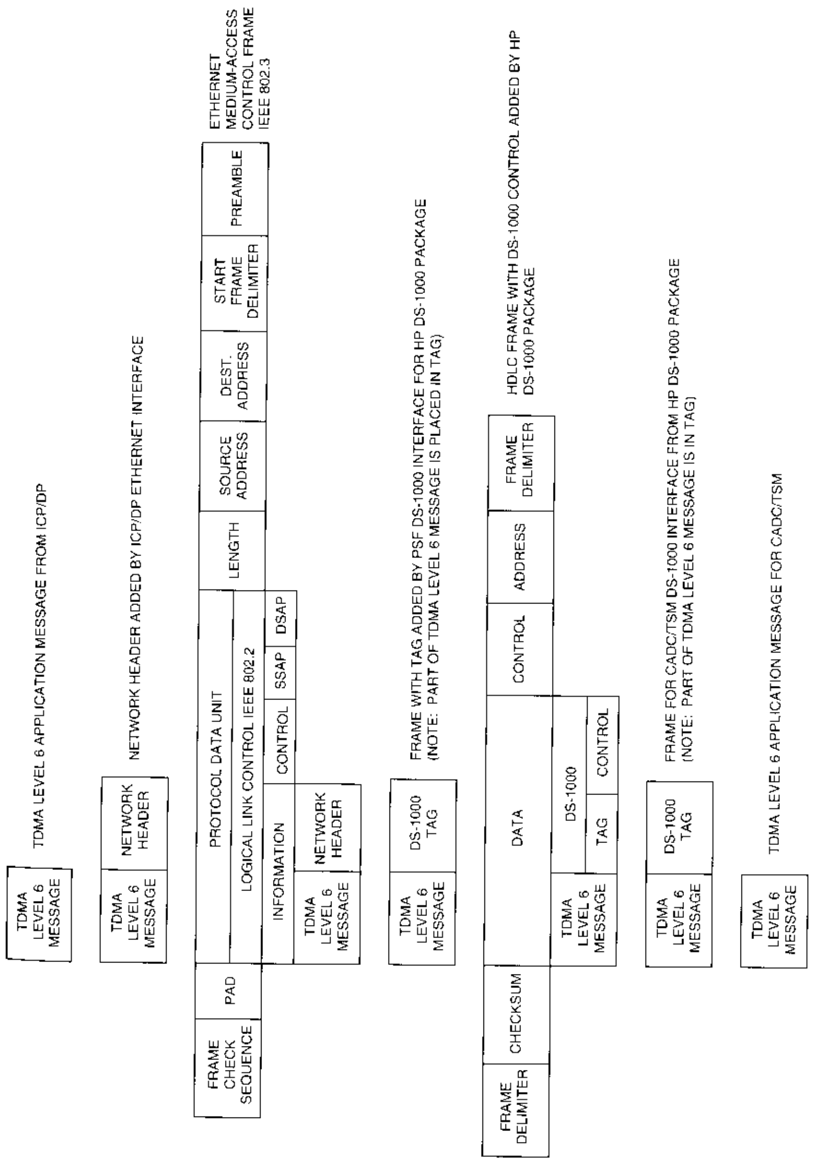


Figure 15. *Packet Framing in the TDMA Data Communications Network*

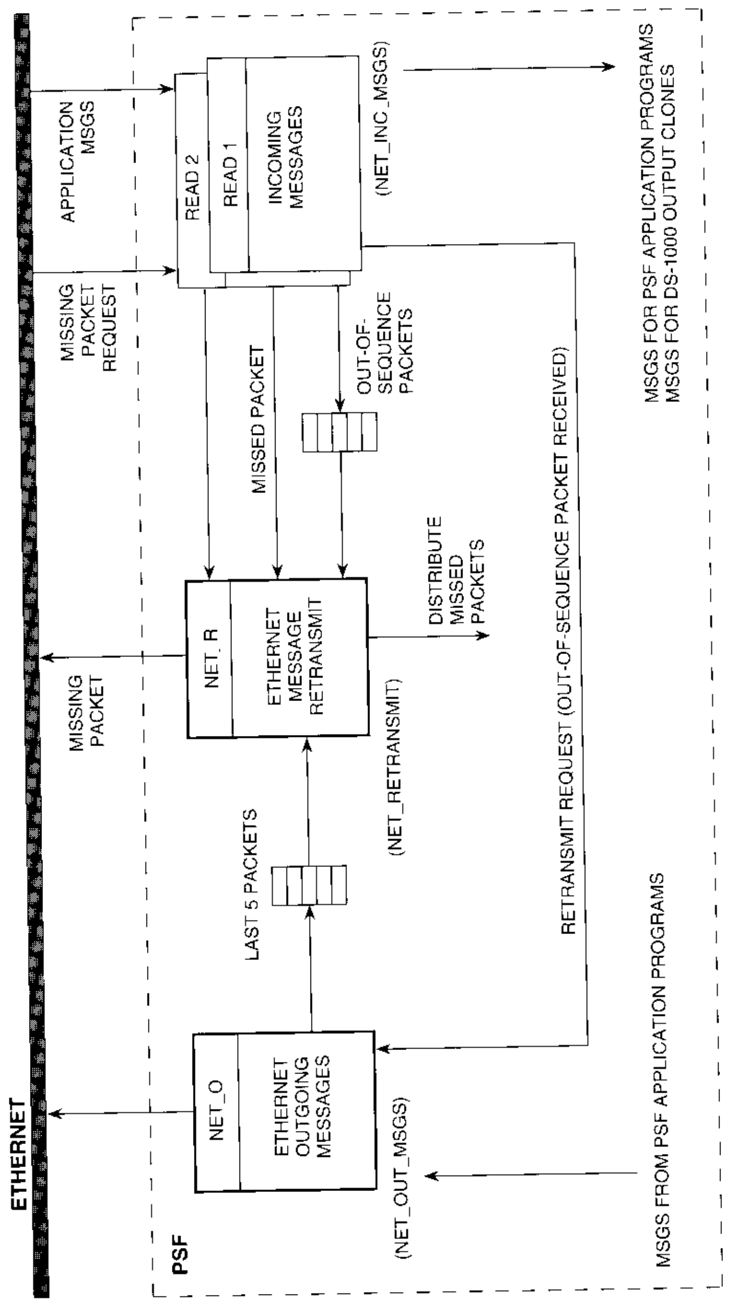


Figure 16. *Ethernet Communications Interface*

Messages process passes this message to the Ethernet Message Retransmission process, which distributes the message to its destination and then proceeds to process the appropriate message from the (out-of-sequence message) holding area.

When a retransmission request for a lost packet is received by an Ethernet node, the Ethernet Incoming Messages process passes the request to the Message Retransmission process, which obtains the requested packet from the area that holds the last five messages placed on the Ethernet, and then sends the packet to the requesting Ethernet node.

Special IOCTF Ethernet group processing

Several novel intercomputer communications capabilities have been incorporated into the new TDMA data communications network to accomplish multidestination message routing within the IOCTF, and to provide an IOCTF test facility. These new capabilities are based on the multicast features of the IOCTF Ethernet bus that interconnects the PSF, ICP, and IDP computers. Multicast is a message transmission mechanism that delivers a message from a single source to a set of destinations, allowing multiple receivers to concurrently process the message. The actual IOCTF implementation makes use of two special cases of multicast: unicast (one-to-one communications) and broadcast (one-to-all communications). Figure 17 shows a model of the TDMA data communications network addressing scheme.

Although the functions of ICP and IDP are different, these processors use the same data from the TRMS sites, NRDE sites, and the ISCC to perform their functions. Thus, they can be treated as members of a heterogeneous group that share message reception as a common characteristic. The PSF provides a convenient vehicle for implementing group communications for such an application. In general, as messages are received from the TRMS sites and ISCC by the PSF (via the HDLC/DS-1000 links), the PSF performs the message translation (from DS-1000 packet to Ethernet packet) and attaches the multicast address for the ICP/IDP group to the messages as they are placed on the Ethernet. This allows each message transmitted to the IOCTF to be placed on the Ethernet bus so that the on-line ICP and IDP can both process the message for their particular functions, thus reducing link traffic.

During the design phase, the group communications concept was extended to groups that change dynamically according to processor state. Defining "on-line" and "test" as two separate Ethernet subnetworks permits on-line operation and testing (both new application and troubleshooting) using the same Ethernet, without the need to physically reconfigure the redundant ICP and PSF processors.

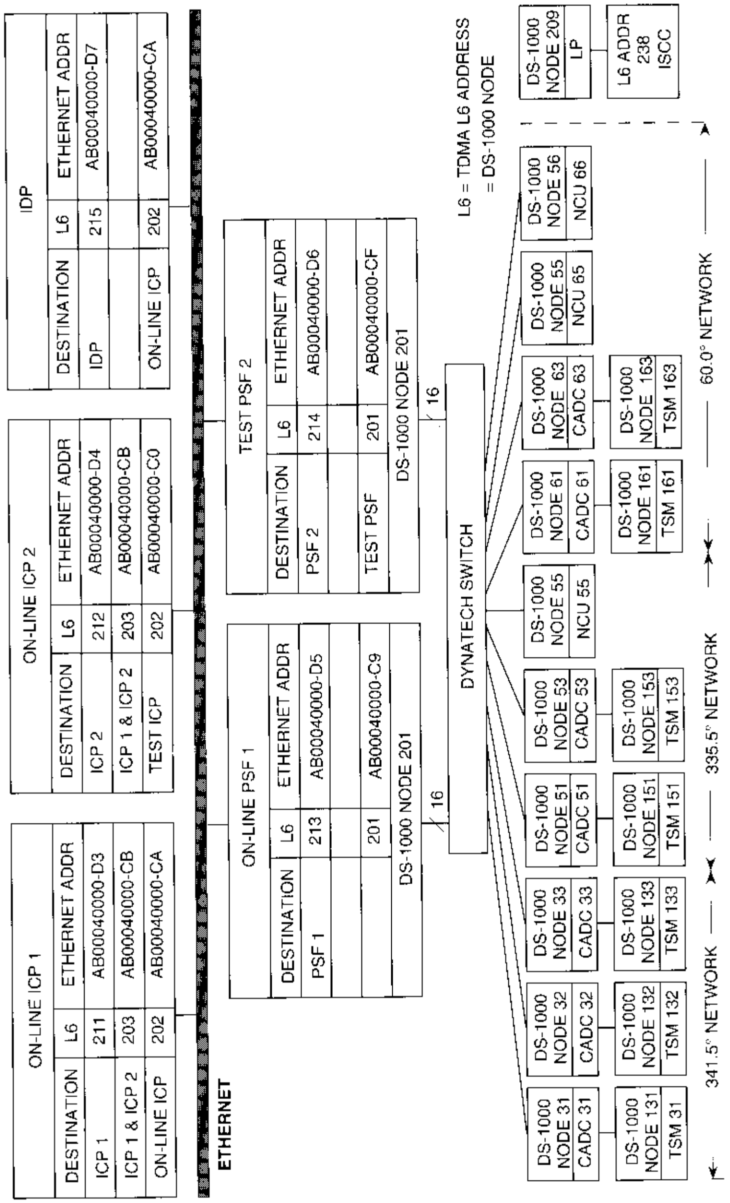


Figure 17. *TDMA Network Addressing Model*

The Ethernet communications nodes are sensitive to their operational mode and change the multicast addressing of their Ethernet interface card whenever the mode changes. Therefore, no interaction takes place between processors that are in different states. For example, PSF1 AND ICP2 can be in the online state carrying out normal operational TDMA functions, while PSF2 and ICP1 are configured for the test state, performing test and checkout functions. These groups are bound by their processor states, and the Ethernet communications software treats each group separately.

Since the remote DS-1000 nodes (CADC, TSM, link control, and NCU) have no knowledge of the group communications scheme implemented within the IOCTF Ethernet LAN, they normally send their messages to a generic IOCTF address (ICP or PSF), and the PSF determines the appropriate group destination for the message. This means that the remote processors do not have direct control over sending messages to a particular IOCTF processor. The PSF to which a remote processor is connected will route any received message to its final destination based on the processor's own state (on-line or test); however, individual IOCTF Ethernet node addressing is possible for test purposes.

Conclusions

The inclusion of the SSTDMA subsystem on board the INTELSAT VI spacecraft as an active element in the overall SSTDMA system made it necessary to integrate the IOCTF and ISCC systems into the SSTDMA HQS responsible for monitoring and controlling the SSTDMA networks. The role of the IOCTF was elevated to that of an active, on-line element which, together with the ISCC, performs critical SSTDMA network control functions such as coordinated SSBTP changes and TSO frequency corrections. This necessitated significant changes to the IOCTF system architecture to improve reliability. A complete overhaul of the data communications system was undertaken to provide reliable computer-to-computer communications between the IOCTF and the TDMA control and monitoring elements located in various parts of the world.

The modified IOCTF is the operational focal point for both fixed TDMA and SSTDMA operation. In this capacity, it supports central network control, monitoring, and diagnostic functions and provides the central hub for TDMA data communications. The IOCTF also maintains a central database of operational parameters, including BTP data, satellite position parameters, and reference terminal operational parameters. The flow of status, monitoring, and event history data from the tdma controlling and monitoring elements is centrally managed by the IOCTF. These data are stored in an historical database and can be retrieved for troubleshooting purposes.

Acknowledgments

The design, implementation, and test of the SSTDMA Headquarters Subsystem was a team accomplishment that required a significant effort by many people. The authors would like to thank C. Kullman and R. Parthasarathy who, as SSTDMA program managers, coordinated the development effort. They also wish to acknowledge the contributions, suggestions, and support of J. Lunsford, S. Tamboli, R. Bedford, C. Maranon, N. Ide, L. Peters, R. Kaiser, L. Gerber, D. Vukmer, D. Song, B. Pettersson, X. Zhu, K. Wilkens, and many others during design, implementation, and test of the HQS.

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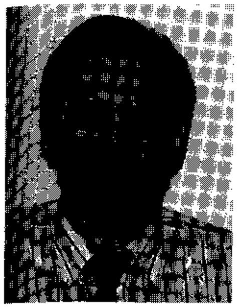

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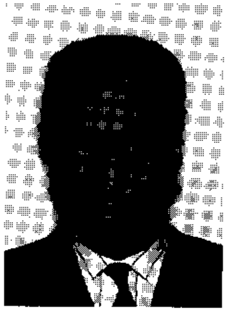

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Index: communication satellites, time division multiple access,
INTELSAT, oscillators, synchronization

INTELSAT VI SSTDMA subsystem timing source oscillator control

C. L. MARANON, J. A. LUNSFORD, T. INUKAI, AND F. H. LUZ

(Manuscript received February 25, 1991)

Abstract

The time-division multiple access (TDMA) terminals in the INTELSAT satellite-switched TDMA (SSTDMA) system derive their timing from reference bursts transmitted by a pair of reference terminals. The reference terminals synchronize their timing to the metric switch state generated in the microwave switch matrix on board the INTELSAT VI satellite, which in turn is synchronized to an onboard oscillator. To maintain plesiochronous capability within the system, the onboard timing source oscillator (TSO) must be controlled relative to a high-stability oscillator located at a reference terminal. This paper describes the theoretical background and physical implementation of the onboard TSO control approach for the INTELSAT VI SSTDMA system. Implementation of the TSO control algorithm involves various elements of the SSTDMA system, including the SSTDMA reference terminal equipment, the INTELSAT Operations Center TDMA Facility, and the INTELSAT Satellite Control Center. An overview of the TSO control system is provided, followed by a discussion of the theoretical basis for the TSO control system, a description of the functions and procedures performed in each element of the system, and a comparison of simulation and operational performance data.

Introduction

The timing required to generate the switch frame and switch masterframe intervals in the satellite-switched time-division multiple access (SSTDMA) subsystem on the INTELSAT VI satellite is provided by an onboard oscillator. The SSTDMA reference terminals synchronize the TDMA frame and superframes to the switch frame and switch masterframe intervals via a metric burst transmitted by the reference stations [1],[2]. Consequently, the timing accuracy and stability of the SSTDMA system depend on the accuracy and stability of the onboard oscillator. A highly stable oscillator with an accuracy of better than 1 part in 10^{11} is necessary to provide network timing that conforms to International Telephone and Telegraph Consultative Committee (CCITT) Recommendation G.811 [3] on international digital link interconnection. Since timing sources currently capable of providing the long-term stability required for plesiochronous operation in TDMA systems are unsuitable for satellite applications, it is necessary to control the onboard timing source oscillator (TSO) relative to a highly stable terrestrial timing source.

The INTELSAT VI satellite includes a high-stability, voltage-controlled crystal oscillator (VCXO) in its SSTDMA switching payload. This oscillator has a worst-case drift of 5 parts in 10^{11} per day. The INTELSAT SSTDMA system, which employs a high-accuracy oscillator at the reference stations, measures onboard clock drift against the reference and sends oscillator frequency correction messages to the satellite to adjust the frequency of the onboard oscillator. With this technique, the long-term timing accuracy of the SSTDMA network is controlled to within 1 part in 10^{11}, and any inaccuracy resulting from short-term drift and clock correction errors is absorbed by the terrestrial interface buffers at the traffic stations. The TDMA traffic terminals are allocated 500 µs of buffer for this purpose.

The SSTDMA reference terminal equipment (SSRTE) contains acquisition and synchronization units (ASUs) that establish and maintain synchronization between the reference station and the onboard switch state timing [1],[2], [4]–[6]. Figure 1 illustrates the onboard oscillator correction process employing the ASU for phase error measurement. The ASU transmits a metering burst once every TDMA frame, using timing derived from its reference clock. The metering segment of the burst is truncated by the trailing edge of the synchronization window on the satellite and detected by the phase error measuring circuit in the ASU on the ground. The ASU compares the received metering segment with the transmitted segment to determine the displacement between the metering burst center and the window edge. In practice, multiple measurements over 32 to 64 consecutive frames are necessary to yield high measurement accuracy.

The measured value, Δx, is accumulated over T_0 seconds to generate a long-term incremental phase error, s_i, where T_0 is preselected for a given correction procedure (typically a few hours to 1 day). The phase error measurement is repeated n times over a clock correction interval, $T = nT_0$, and a cumulative correction value is calculated and sent to the satellite to compensate for future clock drift.

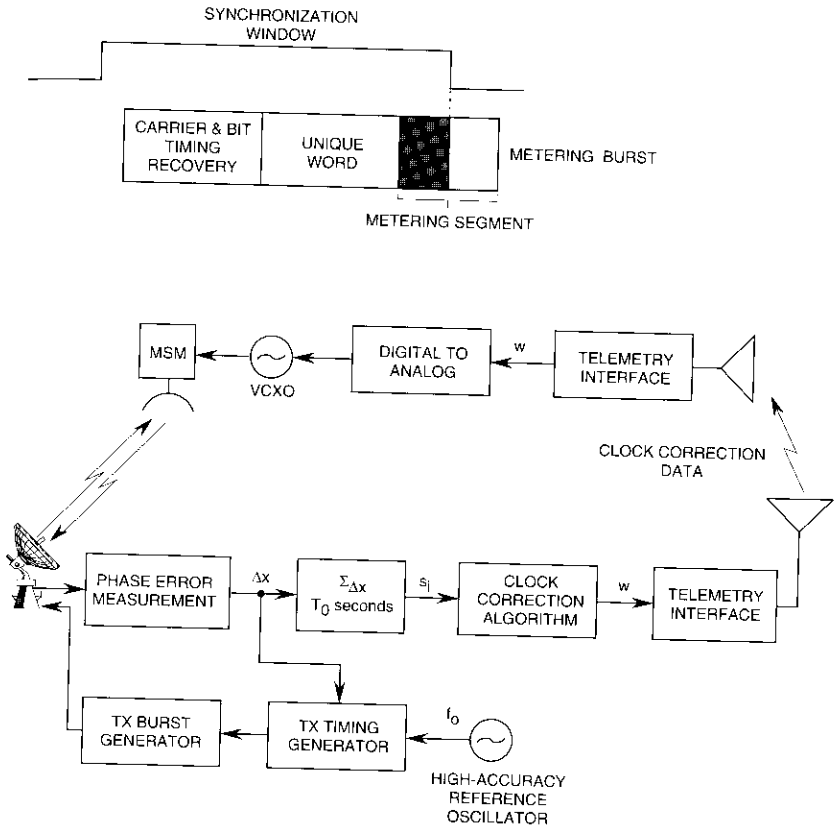


Figure 1. *Onboard Clock Correction Diagram*

This paper discusses in detail the theoretical basis for the TSO control system, and describes the functions and procedures performed in each element of the system. The software implementation of the TSO control functions in the INTELSAT Operations Center TDMA Facility (IOCTF) and the INTELSAT Satellite Control Center (ISCC) is then described, and simulation and operational performance data are compared.

Basic theory of TSO control

From the alternative onboard clock control schemes previously investigated [7]–[9], a scheme based on linear drift prediction was selected for the INTELSAT system, since the VCXOs on board INTELSAT VI are highly stable, with very predictable drift characteristics. This technique has been successfully demonstrated through extensive computer simulations and actual field operation, and has been shown to provide satisfactory performance for the INTELSAT SSTDMA system. This section discusses the clock drift measurement technique, illustrates the computation of a clock correction value, and presents the results of an error analysis. Estimation of a typical clock correction period is also addressed.

Clock drift measurement

The incremental phase error, s_i, shown in Figure 1 is the integral of the clock correction error and Doppler shift over T_0 seconds, and is given by

$$\begin{aligned} s_i &= \int_{t_{i-1}}^{t_i} \left\{ [1 + r(t)](1 - w) - [1 - r_d(t)] \right\} \mathrm{d}t \\ &\approx \int_{t_{i-1}}^{t_i} \left[r(t) - w + r_d(t) \right] \mathrm{d}t \\ &= \int_{t_{i-1}}^{t_i} \left[r(t) - w \right] \mathrm{d}t + \frac{1}{c} \bullet \left[r(t_i) - r(t_{i-1}) \right] \end{aligned} \tag{1}$$

where

t_i = $t_{i-1} + T_0$

$r(t)$ = free-running onboard oscillator drift, $\Delta f/f_0$

$r_d(t)$ = $\frac{1}{c} \bullet \frac{\mathrm{d}r(t)}{\mathrm{d}t}$ = Doppler shift at time t

w = cumulative correction for the current interval

$r(t)$ = satellite range from the reference station at time t

c = speed of light.

In equation (1), the effect of Doppler shift on the phase error measurement appears as a change in the signal propagation time, due to satellite motion. This indicates that the Doppler term can be easily computed from the range measurement at times $t_i - 1$ and t_i, and subtracted from s_i. With the Doppler component removed from the phase error measurement, equation (1) can be simplified as follows:

$$s_i = \int_{t_{i-1}}^{t_i} \left[r(t) - w \right] \mathrm{d}t \tag{2}$$

The phase error, s_i, is the sum of short-term transmit (or receive) timing corrections, Δx, over T_0 seconds. In normal operation, the phase error measurement will not be affected by the false detection and misdetection of a unique word, since short-term correction automatically compensates for previous miss estimation, if any. In case of a temporary system outage and subsequent reacquisition, the phase error, Δx, can be linearly interpolated during the outage period, provided that the outage is relatively short. Alternatively, a backup ASU at a different earth station can be used to measure onboard clock drift.

Clock correction based on first-order drift prediction

The concept of clock correction is illustrated in Figures 2 and 3. Based on the clock drift measurement over time interval T (= nT_0), the cumulative correction is determined by minimizing the estimated cumulative phase error at the end of the next correction interval, $T' = mT_0$. Successive correction intervals are not necessarily equal, and any integer multiple of T_0 can be chosen for each interval. This allows the clock correction procedure to accommodate unexpected (or unpredictable) clock drifts by dynamically adjusting the measurement period.

To derive an expression for a clock correction value, assume that the current correction interval begins at time t_0 and lasts for $T = nT_0$ seconds. The cumulative phase error, $y(t)$, is expressed by

$$y(t) = y_0 + \int_{t_0}^{t} \left[r(t) - w \right] \mathrm{d}t \quad , \quad t_0 < t \le t_0 + T \tag{3}$$

where y_0 is the initial phase error at $t = t_0$. The phase error is periodically sampled at time $t_i = t_{i-1} + T_0$, $1 \le i \le n$, and its sampled values are given by

$$y_i = y(t_i) = y_{i-1} + s_i \quad , \quad 1 \le i \le n \tag{4}$$

The measured phase errors are fitted to a curve, using a polynomial to predict future clock drift. Empirical results based on computer simulation and actual measurements, as shown later, indicate that a second-order polynomial yields a good approximation for the phase error. Since clock drift is a derivative of a phase error function, this is equivalent to a first-order polynomial approximation of the clock drift. Although a higher-order polynomial provides a better approximation to the measured data, it does not necessarily yield a better prediction because of high sensitivity to measurement errors. The polynomial approximation of the measured cumulative phase errors, $y_a(t)$, and the corresponding clock drift, $r_a(t)$, are given by

$$y_a(t) = a_0 + a_1 \left(\frac{t - t_0}{T_o} \right) + a_2 \left(\frac{t - t_0}{T_o} \right)^2 \quad , \quad t_0 < t \le t_n \tag{5}$$

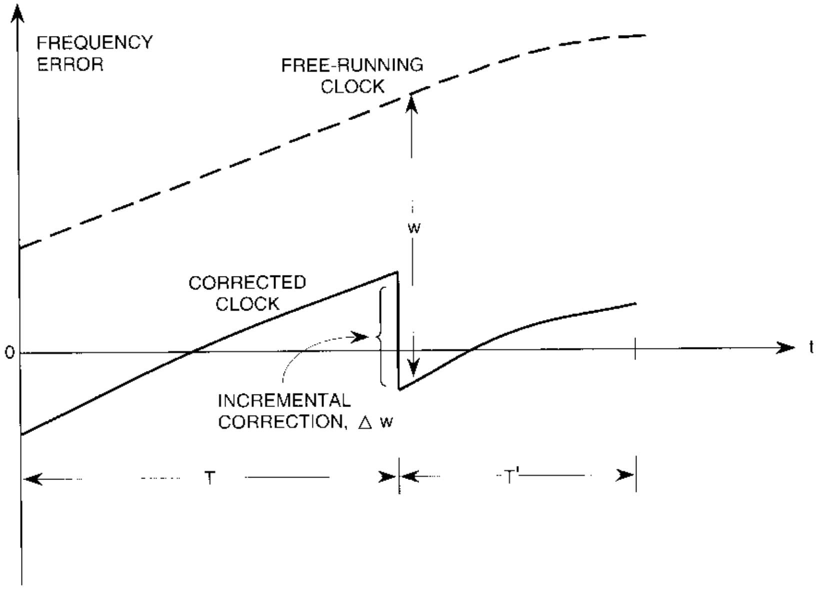


Figure 2. *Clock Drift With and Without Correction*

$$r_a(t) = r(t) - w = \frac{a_1}{T_o} + \frac{2a_2}{T_o} \bullet \left(\frac{t - t_0}{T_o} \right) \ , \quad t_0 < t \le t_n \tag{6}$$

In equations (5) and (6), the coefficients a_i, $0 \le i \le 2$, are obtained by minimizing the mean-square error

$$e = \sum_{i=0}^{n} \left[y_a(t_i) - y_i \right]^2 \tag{7}$$

The least mean-square error solution is given by the following matrix expression:

$$A = K^{-1} H Y \tag{8}$$

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} A & B & C \\ B & D & E \\ C & E & F \end{bmatrix} \bullet \begin{bmatrix} z_0 \\ z_1 \\ z_2 \end{bmatrix}$$

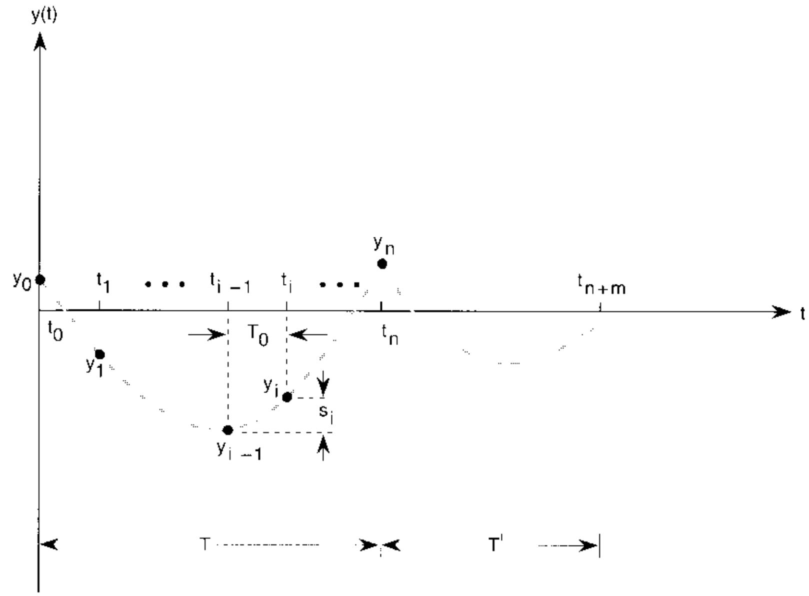


Figure 3. *Cumulative Phase Error of the Corrected Clock*

where

$$\begin{aligned}
A &= (b_2 b_4 - b_3 b_3) & B &= (b_2 b_3 - b_1 b_4) \\
C &= (b_1 b_3 - b_2 b_2) & D &= (b_0 b_4 - b_2 b_2) \\
E &= (b_2 b_1 - b_0 b_3) & F &= (b_2 b_0 - b_1 b_1) \\
b_0 &= n + 1 & b_1 &= b_0 n/2 \\
b_2 &= b_1(2n + 1)/3 & b_3 &= b_1^2 \\
b_4 &= b_2(3nb_0 - 1)/5 & &
\end{aligned}$$

$$z_0 = \frac{1}{d} \sum_{i=0}^{n} y_i \qquad z_1 = \frac{1}{d} \sum_{i=0}^{n} i y_i \qquad z_2 = \frac{1}{d} \sum_{i=0}^{n} i^2 y_i$$

$$d = b_0 A + b_1 B + b_2 C$$

The function $y_a(t)$ approximates the cumulative phase error $y(t)$ in the interval (t_0, t_n). If the long-term drift does not change abruptly, $y_a(t)$ can be used to extrapolate $y(t)$ in the next correction interval (t_n, t_{n+m}), where $t_{n+m} = t_n + T' = t_n + mT_0$. The incremental frequency correction, Δw, is then chosen such that the estimated cumulative phase error becomes zero at the end of the next correction interval. Thus, Δw must satisfy

$$y(t_n)+\int_{t_n}^{t_{n+m}}\left[r_a(t)-\Delta w\right]\mathrm{d}t=0 \qquad (9)$$

From equation (6), the incremental correction value is obtained as follows:

$$\Delta w=\frac{1}{mT_o}\left[y(t_n)+ma_1+m(m+2n)a_2\right] \qquad (10)$$

The new cumulative correction, w', is the sum of the previous correction, w, and the incremental correction, Δw, as

$$w'=w+\Delta w \qquad (11)$$

In Figure 4, the above clock correction technique is demonstrated for a linear drift. The drift to be compensated is

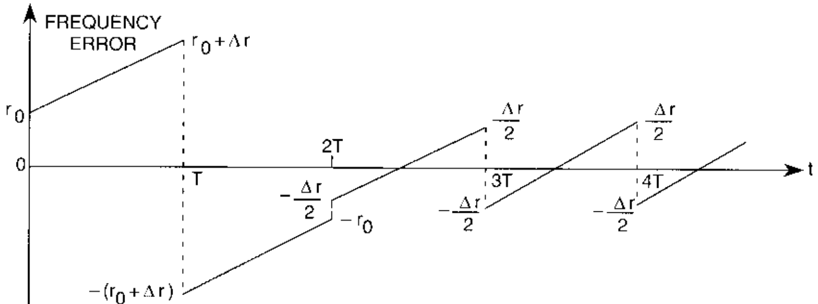
$$r(t)=r_o+\Delta r\left(\frac{t}{T}\right) \quad , \quad t\geq 0 \qquad (12)$$

where all the initial parameters are set to zero. A fixed interval is chosen for each correction step [*i.e.*, $m = n$ in equation (10)]. After two transient intervals, the onboard clock accuracy is controlled to within $\pm\Delta r$. In the steady state, the cumulative phase error at the ASU varies between 0 and $-\Delta rT/8$, and the traffic station must absorb this phase error in a buffer. Since the phase error measurement data will not be available to the traffic station for buffer pointer alignment, the traffic station must provide a buffer that is twice the worst-case phase error, that is

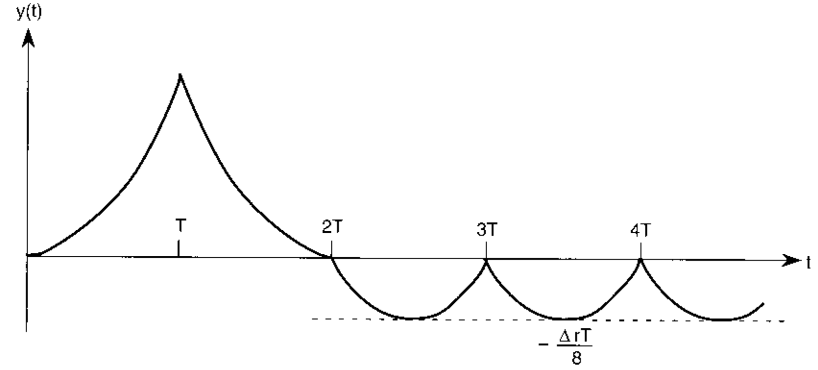
$$B_c=\Delta rT/4 \qquad (13)$$

Effects of quantization, prediction error, and other error components

In practice, the accuracy of clock correction is degraded by quantization error, prediction error, range measurement error, synchronization error, and other error terms. The impact of these errors on clock correction accuracy and traffic station buffer size is analyzed below. A numerical example, which takes these error terms into account, is given for typical clock correction parameters.



(a) Clock Drift

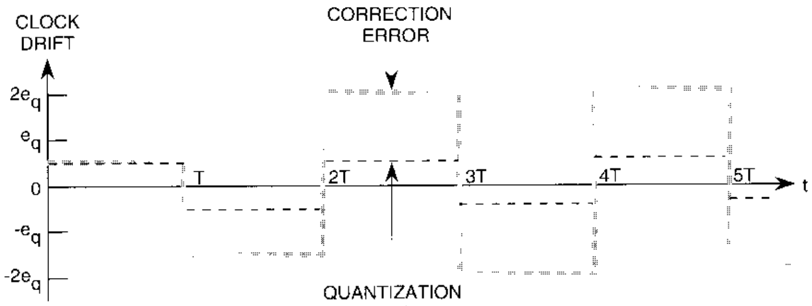


(b) Cumulative Phase Error

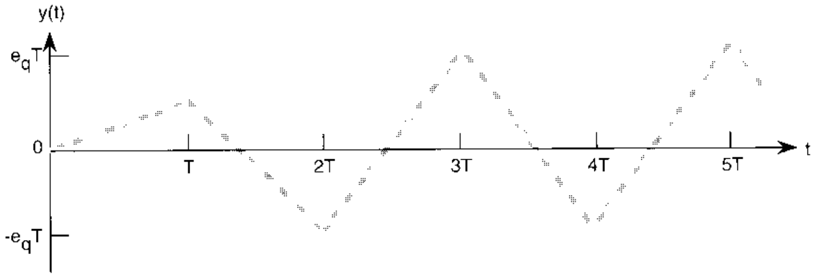
Figure 4. *First-Order Correction of Linear Drift*

QUANTIZATION

The frequency of the master oscillator in the INTELSAT VI satellite is adjusted by controlling the VCXO voltage using a 12-bit control message. Thus, a new frequency setting is rounded to the nearest value among 4,096 possible quantization levels. This quantization affects the accuracy of subsequent phase error measurements. Let e_q be the worst-case quantization step size. (Note that quantization step size varies depending on the frequency setting, since oscillator transfer characteristics are not linear.) The fact that the quantization error is random from one interval to another may adversely affect successive clock corrections. It can easily be shown [7] that a quantization error of $\pm e_q/2$ results in a clock correction error of $\pm 2e_q$ and a cumulative phase error of $\pm e_qT$ in the worst case. Figure 5 illustrates the effect of quantization on clock accuracy



(a) Clock Correction Error



(b) Cumulative Phase Error

Figure 5. *Effect of Quantization*

and phase error. The traffic station buffer size needed to absorb this quantization error, B_q, is then given by

$$B_q = 4e_qT \tag{14}$$

The effect of quantization can be minimized by employing the following technique. Since the quantization error is known to the ASU, its effect on phase error measurements can be calculated precisely. During each phase error measurement, e_qT_0 can be subtracted from s_i in equation (2) to yield a new s_i, as is done for satellite motion. This procedure reduces the required traffic station buffer size to $B_q = 2e_qT$.

PREDICTION ERROR

Clock drift is generally not perfectly linear with time, and will result in prediction error when extrapolated into the next correction period. Consider the following linear clock drift function with a small change, e_p, in the drift rate:

$$r(t) = (1 \pm e_p)\Delta r\left(\frac{t}{T}\right) - \frac{\Delta r}{2} \quad , \quad 0 \le t \le T \tag{15}$$

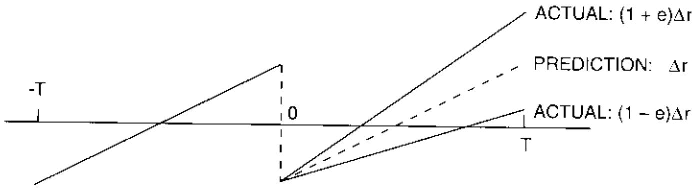
Figure 6 shows the effects of slope prediction error on clock drift and cumulative phase error. The phase error increases in either a positive or negative direction, depending on the sign of the error term. The additional traffic station buffer size required is twice the increase in $y(t)$ and is given by

$$B_p = \left(4e_p + \frac{e_p}{1 - e_p}\right) B_c \tag{16}$$

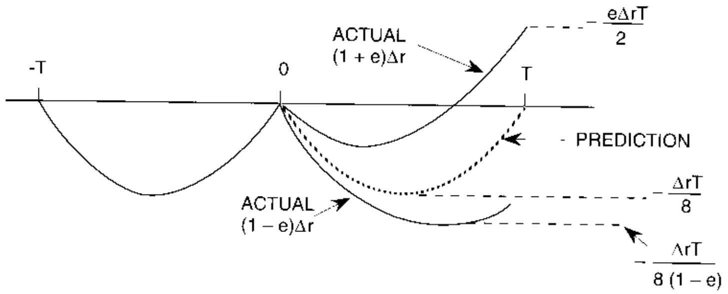
where $0 \le e_p \le 0.5$, and B_c is given by equation (13). According to this equation, drift prediction errors of 0.01, 0.05, and 0.1 will result in increases in buffer size of 5, 25, and 51 percent, respectively.

RANGE MEASUREMENT ERROR

Measurement error is introduced when the satellite motion component is subtracted from a short-term phase error, s_i. In the normal mode of operation,



(a) Clock Drift



(b) Cumulative Phase Error

Figure 6. *Effect of Prediction Error*

the satellite range from the ASU location can be measured quite accurately, for example, within ±10 TDMA symbol periods (±166 ns). Let $\Delta r(t)$ be the range measurement error at time t. The contribution of this error term to the cumulative phase error is derived from equations (1) and (4) as follows:

$$\Delta y_i = \sum_{j=1}^{i} \Delta s_j = \frac{1}{c}[\Delta r(t_i) - \Delta r(t_0)] \tag{17}$$

which is bounded by ±20 symbols (±332 ns) in the worst case. Since curve-fitting smooths random measurement errors, the actual contribution to overall performance is insignificant [*e.g.*, no more than $\pm 5.5 \times 10^{-13}$ in clock inaccuracy and 2.7 µs in earth station buffer size for a clock correction period of 1 week ($T = 7$ days)].

The effect of satellite motion can also be removed using a Doppler cancellation method. Satellite motion yields TDMA frame timing offsets in both the transmit and receive directions at the ASU. These offsets have the same magnitude, but opposite polarities. Thus, the addition of transmit and receive timing offsets removes the effect of Doppler shift. Because this technique is self-contained and does not require range measurements, it was adopted for the current implementation. A more detailed discussion is provided later.

ASU SYNCHRONIZATION ERROR

ASU TDMA synchronization error has a similar, but less significant, impact on clock correction performance than range measurement error. In steady-state synchronization, the timing error can be controlled to within a few TDMA symbols. For example, a synchronization error of ±2 symbols will result in an additional earth station buffer size of 0.27 µs for $T = 7$ days.

OTHER ERROR TERMS

Other error sources which degrade clock correction performance include errors caused by the time lag between the computation of a clock correction value and its implementation at the satellite, arithmetic precision for computation, and an interpolation error during a short system outage. These error terms are generally insignificant compared to those for clock drift and quantization.

Traffic station buffer requirement

A reliable clock correction procedure is implemented by establishing upper and lower thresholds, Y_{max} and Y_{min}, on the measured phase error, $y(t_i)$. The phase error should not exceed these extremes in normal operation. However, if it does exceed a preset threshold at some measurement epoch (due to a change in drift rate), the current correction interval must be terminated, and a clock correction message sent to the satellite. As shown in Figure 7, an over-threshold phenomenon is most likely to occur in the middle or at the end of the correction interval. The impact of this overshoot will be an increase in $y(t)$ by $r_m T_0$, and in the traffic station buffer size by

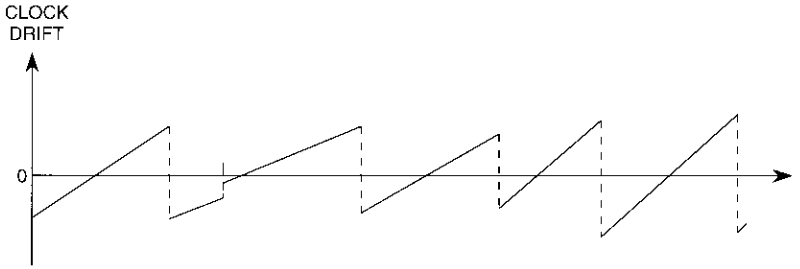
$$B_m = 2 r_m T_o \tag{18}$$

where r_m is the worst-case inaccuracy of an onboard clock.

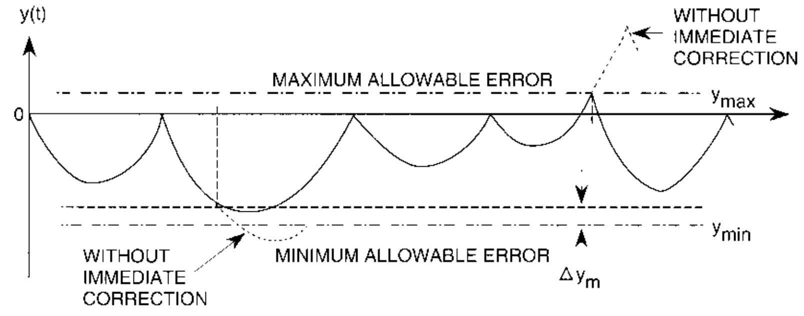
From equations (13), (14), (16), and (18), the total traffic station buffer size required for clock correction is given by

$$B = B_c + B_q + B_p + B_m + B_o \tag{19}$$

where B_o is the sum of all other error terms. A proper clock correction period should be selected such that the total buffer requirement for correction is not more than the 500 µs allocated in the INTELSAT VI TDMA terminal.



(a) Clock Drift



(b) Cumulative Phase Error

Figure 7. *Effect of Lower and Upper Thresholds*

Numerical example

The clock correction procedure described above is illustrated below for the typical design parameters given in Table 1. As quantization step size gradually changes from 2×10^{-11} to 8×10^{-11} during satellite life for a positive-drift oscillator, the clock correction period, T, must be selected such that the traffic station buffer size, B, as given in equation (19), does not exceed 500 µs. The clock drift, Δr, in equation (12) is obtained from the daily drift rate, Δr_s, shown in Table 1 by $\Delta r = \Delta r_s T$, where T is expressed in days (*e.g.*, $\Delta r = 5 \times 10^{-11} \times 10 = 5 \times 10^{-10}$ for $T = 10$ days).

TABLE 1. EXAMPLE OF CLOCK CORRECTION PARAMETER VALUES

PARAMETER	VALUE
Onboard Clock Drift, Δr_s	5×10^{-11} per day
Worst-Case Inaccuracy, r_m	1×10^{-9}
Quantization Step Size, e_q	2×10^{-11} ~ 8×10^{-11}
Prediction Error, e_p	0.1 (10%)
Phase Measurement Period, T_o	6 and 24 hr

Table 2 summarizes the contributions of various error terms to the total buffer size. A typical clock correction period varies from 10 to 14 days, depending on the parameter values selected. In practice, an actual period may be shorter or longer due to uncertainty regarding the amount of clock drift and predictability.

Expressions for the phase thresholds are obtained from the various error terms discussed previously, as follows:

$$Y_{\max} = e_q T + \frac{e_p \Delta r T}{2} + r_m T_o + \frac{B_o}{4} \tag{20a}$$

$$Y_{\min} = -\left(\frac{\Delta r T}{8} + e_q T + \frac{e_p \Delta r T}{8(1-e_p)} + r_m T_o + \frac{B_o}{4} \right) \tag{20b}$$

For the first example in Table 2 ($T_0 = 6$ hr, $e_q = 4 \times 10^{-11}$, and $T = 12$ days), these values are $Y_{\max} = 75.1$ µs and $Y_{\min} = -152.0$ µs. Since a clock correction value, Δw, in equation (10), does not depend on the coefficient, a_0, of a polynomial curve fit, more practical phase error thresholds such as $Y_{\max} = -Y_{\min} \approx 114$ µs can be used to provide the same performance.

TABLE 2. CONTRIBUTIONS OF VARIOUS ERROR TERMS TO BUFFER SIZE

BUFFER COMPONENT	BUFFER SIZE (µs)			
	$T_0 = 6$ hr $e_q = 4 \times 10^{-11}$ $T = 12$ days	$T_0 = 24$ hr $e_q = 4 \times 10^{-11}$ $T = 10$ days	$T_0 = 6$ hr $e_q = 8 \times 10^{-11}$ $T = 10$ days	$T_0 = 6$ hr $e_q = 2 \times 10^{-11}$ $T = 14$ days
Drift, B_c	155.5	108.0	108.0	211.7
Quantization, B_q	165.9	138.2	276.5	96.8
Prediction, B_p	79.5	55.2	55.2	108.2
Margin, B_m	43.2	172.8	43.2	43.2
Other Error Terms, B_o	10.0	10.0	10.0	10.0
Total	454.1	484.2	492.9	469.9

The above discussion has assumed positive-drift oscillators, which were selected for INTELSAT VI spacecraft. An oscillator may exhibit a positive-negative drift characteristic in which the direction of oscillator drift changes from positive to negative during its life. In this case, the same clock correction procedure described above can be used, but may result in a slightly shorter correction period (*e.g.*, 9 days *vs* 10 days) [4].

Physical implementation

TSO correction involves three functions which are performed in various elements of the network:

- *Phase Error Measurement and Reporting.* The phase error of the onboard oscillator is measured periodically at the ASU in each reference terminal. The error measurements are accumulated by the control and display console (CADC) in the SSRTE [2] over a period called the clock phase reporting interval (CPRI). The CADC transmits the cumulative phase to the IOCTF at the end of each CPRI. The reporting interval corresponds to T_0 in Figure 3, while the reported phase corresponds to y_i.
- *Clock Correction Prediction.* The prediction algorithm, executed in the IOCTF control processor [10], stores the values of reported phase over a relatively long interval called the TSO correction interval (TCI). The TCI is typically 15 to 30 days and corresponds to T in Figures 3 and 4. The prediction algorithm solves equation (10) by using the stored values of reported phase to determine the incremental frequency correction, Δw, which will cause the phase error to return to

near zero over the next correction interval. At the end of each TCI, the IOCTF control processor (ICP) provides the value of Δw to the ISCC for further processing.

- *Oscillator Correction.* The ISCC receives the values of Δw from the IOCTF and computes the oscillator control integer (OCI) based on the cumulative value of frequency corrections and the characteristic curve for the on-line oscillator. Once computed, the OCI is transmitted via telemetry to the spacecraft.

Figure 8 illustrates the overall TSO correction system and the processing that is performed in each system element.

A PC-based monitor and control unit (MCU) has been developed for testing and maintenance of the ASU, and is not intended for use during normal operation. The MCU allows the operator to monitor ASU performance and modify certain ASU parameters.

Like the CADC, the MCU can receive all phase error measurements from the ASU and perform all the processing implemented in the CADC, IOCTF, and ISCC. Thus, the MCU provides an emergency means of computing the OCI in the event of complete failure of the data links or system elements. However, unlike the ISCC, there is no electronic link from the MCU to the satellite command generation system [11] for coding and transmitting the OCI to the satellite. In the unlikely event that the MCU must be used to compute the OCI, the value would be communicated verbally to the ISCC or to telemetry, tracking, command, and monitoring (TTC&M) sites for command generation and transmission. Use of the MCU in this contingency mode would require either that the digital data links between IOCTF and both reference terminals are not operational, or that the IOCTF or ISCC cannot perform its TSO frequency correction functions for a long period of time.

The MCU is also programmed to perform a detailed simulation of the TSO correction system. In this simulation, the onboard oscillator can be programmed to emulate the characteristics of any oscillator on any satellite, using the actual characteristic curve data for the selected oscillator. A number of anomalous system events, such as ASU switchover and failure of an SSRTE, can also be programmed. The simulation performs all the processing of every element in the system, including the ASU, CADC, IOCTF, and ISCC. Any parameter that can be set in the system can also be set in the simulation. This tool was invaluable in verifying the performance of the system during its implementation.

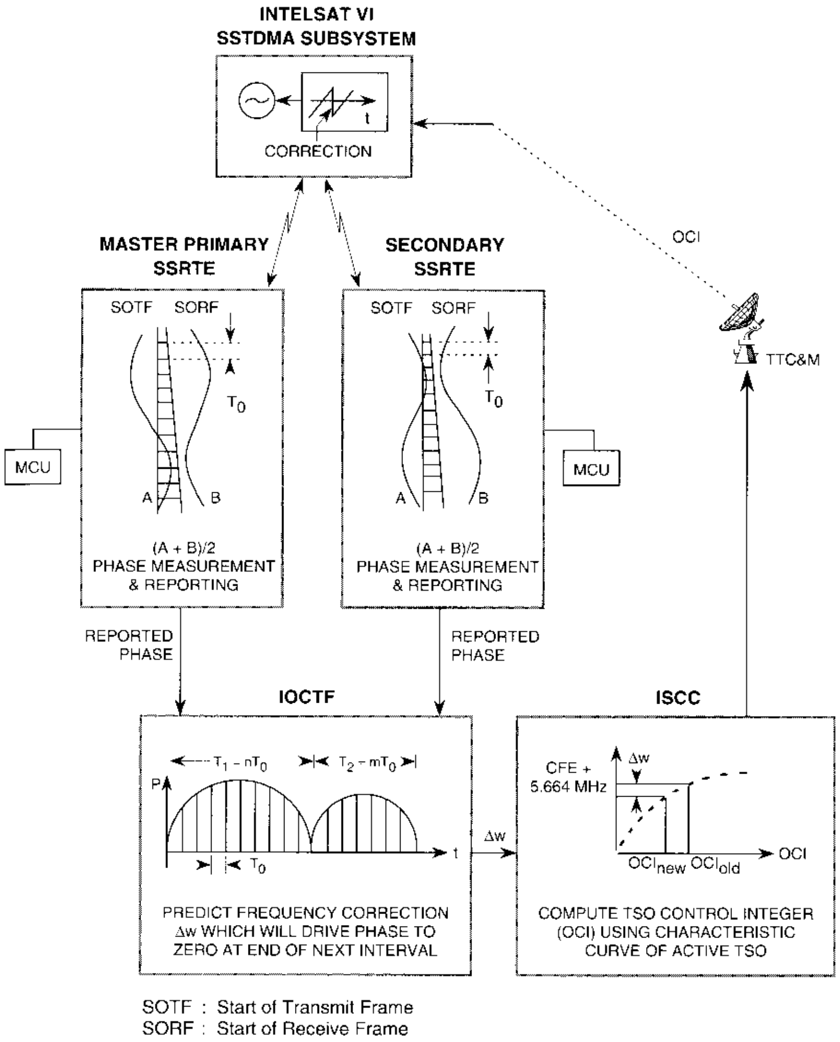


Figure 8. *TSO Correction System*

Phase error measurement and reporting

The phase error measurement and reporting procedures consist of the clock phase measurement (CPM) procedure implemented in the ASU, and the clock phase reporting (CPR) procedure implemented in the CADC. The CPM procedure is responsible for measuring raw TSO phase, once per control frame, and reporting this information to the CADC once per superframe. The CPR procedure accumulates raw phase information from the redundant ASUs in the SSRTE and reports the cumulative phase data to the IOCTF once each CPRI.

CLOCK PHASE MEASUREMENT PROCEDURE

The ASUs at the master primary reference terminal (MPRT) and the secondary reference terminal (SRT) periodically and independently measure the phase of the switch frame relative to a high-stability local timing source (LTS) in their respective SSRTEs, using an innovative technique developed by NTT [12] which automatically eliminates Doppler from the measurement. The LTS is a cesium oscillator with a long-term stability of better than 1 part in 10^{11}. Figure 9 illustrates the NTT phase measurement approach.

The 60.416-MHz symbol clock derived from the LTS oscillator is provided to a reference pulse generator in the phase measurement circuitry. The counter in this generator is set to zero at ASU initialization. The counter increments each clock pulse to a count of 30,932,992 (the number of symbols in a control frame). At the maximum count, the generator resets the counter and generates a reference pulse. The reference pulse thus has a periodicity of one control frame (1.024 s) with the stability of the LTS.

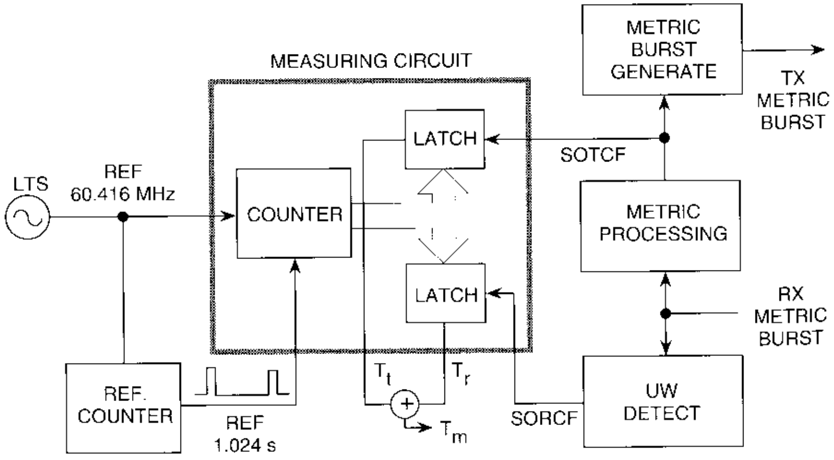


Figure 9. *NTT Phase Measurement Approach*

The reference pulse is provided to a phase measurement counter and is used to reset the count to zero. Because the counter is clocked once each symbol interval by the local symbol clock, the output of the phase measurement counter represents the number of symbols since the reference pulse. The start of transmit control frame (SOTCF) generated by the metric processing circuitry in the ASU, and the start of receive control frame (SORCF) detected in the ASU at each superframe boundary, latch the reference counter output at these two instants. The sum of these two numbers, divided by 2, represents the midpoint between the SOTCF and SORCF relative to the reference pulse. This is illustrated in Figure 10 for two points in time.

The movement of the SOTCF due to path length variation will be equal to—but in the opposite direction from—that of the SORCF. Thus, the midpoint will

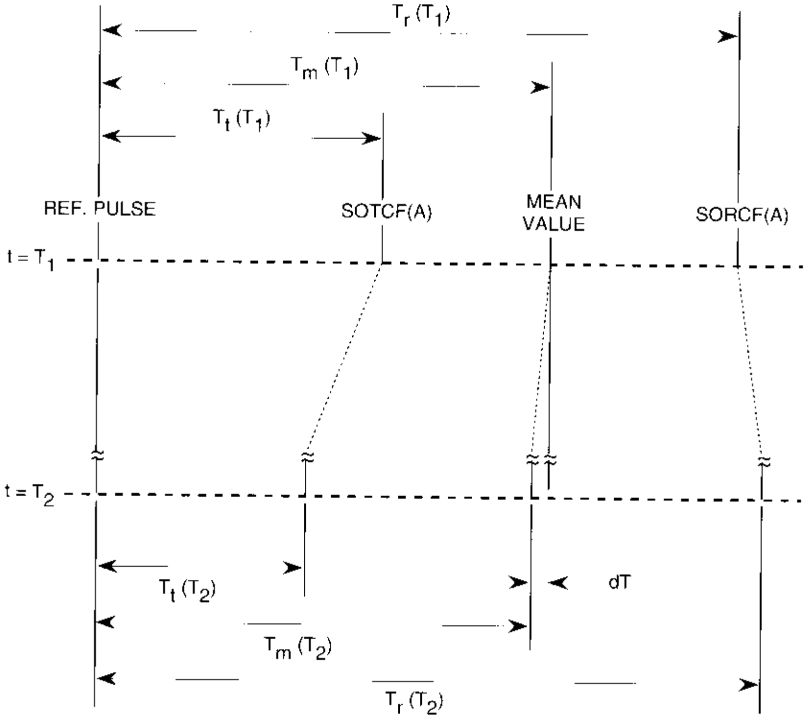


Figure 10. *ASU Phase Measurement Circuit*

be unaffected by satellite movement. However, movement of the SOTCF and SORCF relative to the reference pulse (due to a frequency difference between the onboard TSO and the LTS) will be equal and in the same direction. Consequently, the midpoint will move relative to the reference pulse in proportion to the TSO frequency inaccuracy. A more detailed discussion is provided in Bedford *et al.* [2].

Once during each control frame, both the on-line and standby ASUs in each SSRTE measure the TSO phase. The measured phase value at control frame i is given by

$$T(i) = t(T) + t(R) \tag{21}$$

where $t(T)$ is the distance (in symbols) between the SOTCF and the reference pulse, and $t(R)$ is the distance (in symbols) between the SORCF and the reference pulse.

Although each ASU performs the phase measurement in each control frame, they only report the measured phase to the CADC once a superframe. In addition, the division by 2 is not performed in the ASU, but is performed later in the IOCTF prior to execution of the prediction algorithm.

CLOCK PHASE REPORTING PROCEDURE

The CPR procedure continuously executes on the on-line CADC. The procedure receives and stores the CPRI from the IOCTF via the IOCTF data link. The CPRI is specified as a binary number in units of superframe intervals, and can have a value from 0 to 65,535 (0 s to 298.26 hr). When a CPRI is received from the IOCTF, the CADC begins counting superframe intervals. It accumulates the phase data reported by the on-line ASU and reports the cumulative phase when the superframe count reaches the CPRI value.

As mentioned above, each ASU reports a raw phase measurement, $T(i)$, once a superframe to the CADC. However, because of the way the ASU initializes the reference generator counter, the reported values of $T(i)$ from the on-line and standby ASUs will have a constant skew between them. To prevent this skew from corrupting the cumulative phase measurement in the event of an ASU redundancy switchover, the CPR procedure performs the phase accumulation differently depending on whether a redundancy switch has occurred in the current CPRI.

At the kth reporting instant, the CPR procedure calculates the cumulative phase, $S(k)$, as follows. If there was no ASU redundancy switchover in the last reporting interval, then

$$S(k) = S(k-1) + [T(k) - T(k-1)] \tag{22}$$

where

$S(k-1)$ = cumulative phase reported in the last reporting interval
$T(k)$ = $T(i)$ from the on-line ASU at the current reporting instant
$T(k-1)$ = $T(i)$ from the on-line ASU at the last reporting instant.

[The values of $T(i)$ are corrected for counter overflow.]

In the event of an ASU redundancy switchover, the CPR procedure bases the cumulative phase calculation on the phase change between successive superframes reported by the on-line ASU. The phase change between superframes is given by

$$\mathrm{d}T(i) = T(i) - T(i-1) \tag{23}$$

where $T(i)$ is the value reported to the CADC in the current superframe, and $T(i-1)$ is the value reported in the previous superframe. The CPR procedure computes the reported value of $S(k)$ as follows:

$$S(k) = S(k-1) + \sum_{i=1}^{N} \mathrm{d}T_1(i) + \sum_{j=N+2}^{\mathrm{CPRI}} \mathrm{d}T_2(j) \tag{24}$$

where $\mathrm{d}T_1(i)$ is derived from the values of $T(i)$ reported by the on-line ASU prior to the switchover, and $\mathrm{d}T_2(j)$ is derived from the values of $T(i)$ reported by the on-line ASU (previously standby) after the switchover. [The first value of $\mathrm{d}T(i)$ after the switchover is invalid.]

For monitoring purposes, the CADC calculates a running average of the cumulative phase over a period of eight consecutive superframes. This is equivalent to measuring the short-term frequency offset between the LTS and the TSO on board the spacecraft. If the value of average phase exceeds a threshold value, $P_{\max}$, received as a parameter from the IOCTF, a local alarm is generated.

Clock correction prediction

The IOCTF ICP receives cumulative phase reports each CPRI from the MPRT and SRT. It processes these reports to determine the incremental frequency correction, Δw, which will cause the phase error to return to near zero over the next correction interval. A number of operational considerations are taken into account in designing the algorithms implemented in the ICP.

OPERATIONAL CONSIDERATIONS

Three modes of operation have been designed into the TSO control software in the IOCTF: cold start, warm start, and normal operation. The major differences between these modes are the duration of the CPRI and TCI, and the number of correction cycles (expressed in TCIs) performed in each mode. Figure 11 illustrates the transitions between modes. Following completion of the specified number of TCI cycles in cold-start mode, the system automatically transitions to either warm-start or normal mode, depending on the number of TCI cycles specified for warm start. At the completion of the number of cycles specified for warm start, the system automatically transitions to normal mode. Transitions from normal mode to either cold or warm start require operator intervention.

Figure 12 shows the operator screen for entering the necessary parameters for each mode of operation. In addition to the CPRI and TCI for the various modes, as well as the number of TCI cycles for cold and warm start, this display permits the operator to specify a number of other parameters, including the on-line oscillator identification number and the desired time of day for executing corrections.

The purpose of the cold-start mode is to prevent plesiochronous slips during the initial periods when the TSO is likely to have a large frequency error. This may be the case after initial SSTDMA network startup and after a TSO redundancy switchover. During cold start, the IOCTF will perform several TSO corrections within a short period of time to adjust the TSO frequency as quickly as possible. Typical values are 10 minutes for the CPRI, and from 1 to 4 hours for the TCI.

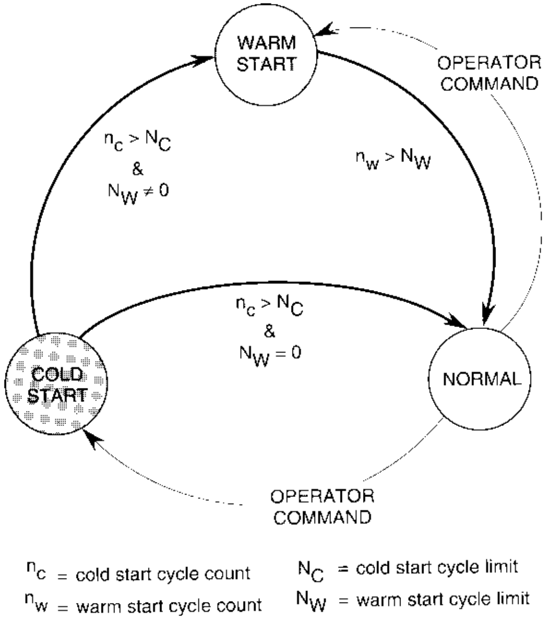
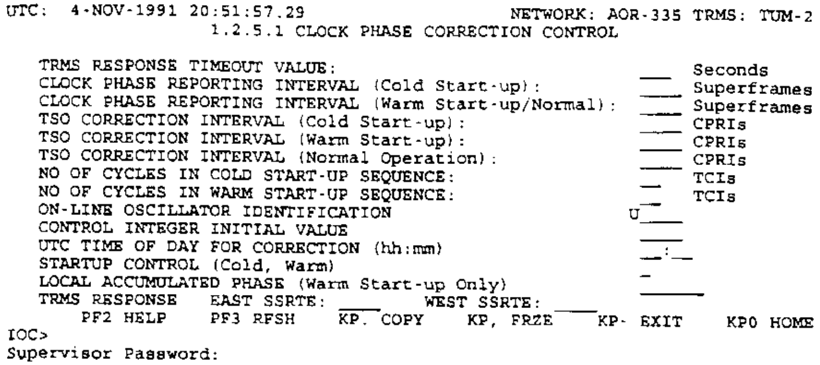


Figure 11. *TSO Correction Mode State Transition Diagram*



```
UTC:  4-NOV-1991 20:51:57.29                      NETWORK: AOR-335 TRMS: TUM-2
                    1.2.5.1 CLOCK PHASE CORRECTION CONTROL

   TRMS RESPONSE TIMEOUT VALUE:                                    ___  Seconds
   CLOCK PHASE REPORTING INTERVAL (Cold Start-up):                 ____ Superframes
   CLOCK PHASE REPORTING INTERVAL (Warm Start-up/Normal):          ____ Superframes
   TSO CORRECTION INTERVAL (Cold Start-up):                        ____ CPRIs
   TSO CORRECTION INTERVAL (Warm Start-up):                        ____ CPRIs
   TSO CORRECTION INTERVAL (Normal Operation):                     ____ CPRIs
   NO OF CYCLES IN COLD START-UP SEQUENCE:                         __   TCIs
   NO OF CYCLES IN WARM START-UP SEQUENCE:                         __   TCIs
   ON-LINE OSCILLATOR IDENTIFICATION                              U____
   CONTROL INTEGER INITIAL VALUE                                   ____
   UTC TIME OF DAY FOR CORRECTION (hh:mm)                          __:__
   STARTUP CONTROL (Cold, Warm)                                    _
   LOCAL ACCUMULATED PHASE (Warm Start-up Only)                    _____
   TRMS RESPONSE   EAST SSRTE: ____       WEST SSRTE: ____
       PF2 HELP    PF3 RFSH    KP. COPY    KP, FRZE    KP- EXIT    KP0 HOME
IOC>
Supervisor Password:
```

Figure 12. *Clock Phase Correction Control Screen*

A warm start is performed to limit the amount of phase accumulation at times when the TSO is likely to have a small (possibly unknown) frequency error. This may occur after a network failure that resulted in loss of phase data. The CPRIs used for warm start and normal operation are the same; the difference is the length of the TCI. In this mode, the CPRI has a typical duration of 4 to 6 hr, and the TCI is 2 to 4 days. This permits the correction instant to be scheduled at a convenient time, while preventing the crossing of a phase error threshold.

During normal operation, the IOCTF periodically executes the correction algorithm using the normal CPRI and TCI. The normal values are initially based on measurements conducted on each of the onboard oscillators during network tests, prior to commencement of SSTDMA operation. These values are subsequently updated based on operational experience. In the Atlantic Ocean Region (AOR, 335°E) and Indian Ocean Region (IOR, 60°E) SSTDMA networks, the parameters are set so that a TSO frequency correction occurs once every 2 or 3 weeks and the SSRTEs send phase data reports every 4 hours.

SOFTWARE DESCRIPTION

Figure 13 illustrates the software processes and data flows for the IOCTF TSO frequency correction process. The message transmitter and message receiver processes are responsible for sending/receiving data to/from the TDMA reference and monitoring station (TRMS) sites and the ISCC. The logic for

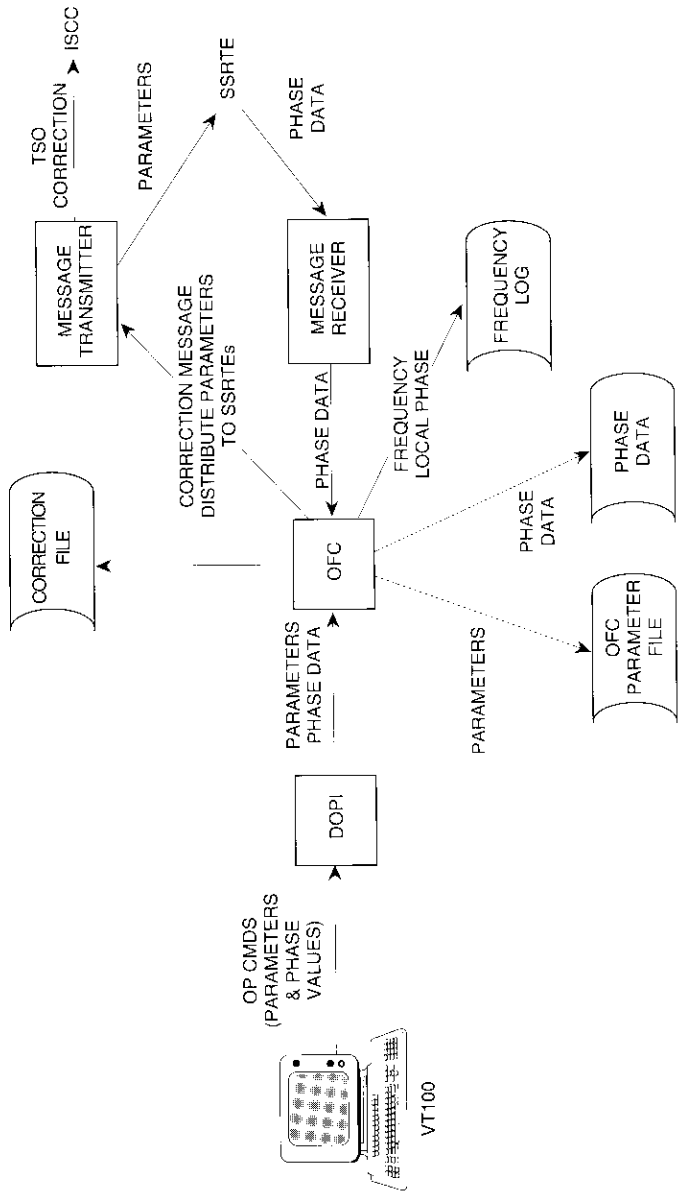


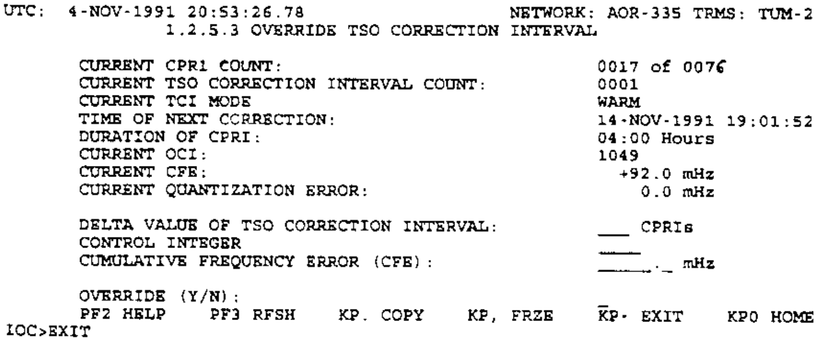
Figure 13. *Process Architecture OFC Scenario*

performing TSO frequency corrections is partitioned between the display processor operator interface (DOPI) process and the oscillator frequency correction (OFC) process.

The DOPI process permits the operator to control the performance of the TSO frequency correction algorithm by initiating cold- and warm-start processing, and to optionally modify certain parameters such as a phase threshold, which, if exceeded, triggers an unscheduled TSO frequency correction. Another DOPI function is to enable the operator to enter missing clock phase data for any CPRI within the current correction interval. This provides a manual backup in case data have not been received due to data link or TRMS equipment problems. Reported cumulative phase data may be obtained from the SSRTE operator display and relayed verbally to the IOCTF operator for manual entry any time prior to the scheduled correction time.

To account for loss of operational TSO parameters such as OCI and cumulative frequency error (CFE), DOPI permits these parameters to be overridden during operation. DOPI also allows the operator to advance or back off the next scheduled correction within a preset range. Figure 14 shows the operator screen for performing the above override functions for operational TSO parameters.

The OFC process maintains local CPRI and correction cycle timing, processes the Clock Phase Measurement Data messages from both reference terminals, and performs all computations associated with a TSO frequency correction. To protect against data loss due to equipment failure, all phase data and current frequency correction parameters are stored in backup files. To facilitate long-term performance monitoring, the OFC process maintains a time-stamped TSO frequency log file which is used for frequency and phase plots and is accessible to the ISCC.



```
UTC:  4-NOV-1991 20:53:26.78                    NETWORK: AOR-335 TRMS: TUM-2
                1.2.5.3 OVERRIDE TSO CORRECTION INTERVAL

      CURRENT CPR1 COUNT:                           0017 of 0076
      CURRENT TSO CORRECTION INTERVAL COUNT:        0001
      CURRENT TCI MODE                              WARM
      TIME OF NEXT CCRRECTION:                      14-NOV-1991 19:01:52
      DURATION OF CPRI:                             04:00 Hours
      CURRENT OCI:                                  1049
      CURRENT CFE:                                    +92.0 mHz
      CURRENT QUANTIZATION ERROR:                       0.0 mHz

      DELTA VALUE OF TSO CORRECTION INTERVAL:       ___ CPRIs
      CONTROL INTEGER                               ___
      CUMULATIVE FREQUENCY ERROR (CFE):             ____._ mHz

      OVERRIDE (Y/N):
      PF2 HELP    PF3 RFSH    KP. COPY    KP, FRZE    KP- EXIT    KP0 HOME
IOC>EXIT
```

Figure 14. *Override TSO Correction Interval Screen*

The overall timing of TSO frequency processing is depicted in Figure 15, which illustrates the key messages passed between the various system elements participating in the TSO correction process. The messages are identified as follows:

M214 Clock Phase Reporting Parameters (CPRI, P_{max}) from the IOCTF to the MPRT and SRT CADCs
M057 Cumulative Phase Report from the MPRT and SRT CADCs to the IOCTF
M209 TSO Correction Notification Alarm from the IOCTF to the MPRT and SRT CADCs
M252 TSO Correction Warning from the IOCTF to the ISCC
M253 TSO Correction Alarm from the IOCTF to the ISCC
M074 TSO Correction Confirmation from the ISCC to the IOCTF

Upon operator-initiated cold- or warm-start operation, the DOPI process forwards all operator-supplied parameters to the OFC process, which in turn sends the clock phase reporting parameters (CPRI, P_{max}) to both reference terminals via the message transmitter process. OFC processing is performed based on a local CPRI timer. At the end of each local CPRI, the OFC process determines the availability of a valid phase report from either the MPRT or SRT, and derives a cumulative local phase term, $y(k)$, as follows:

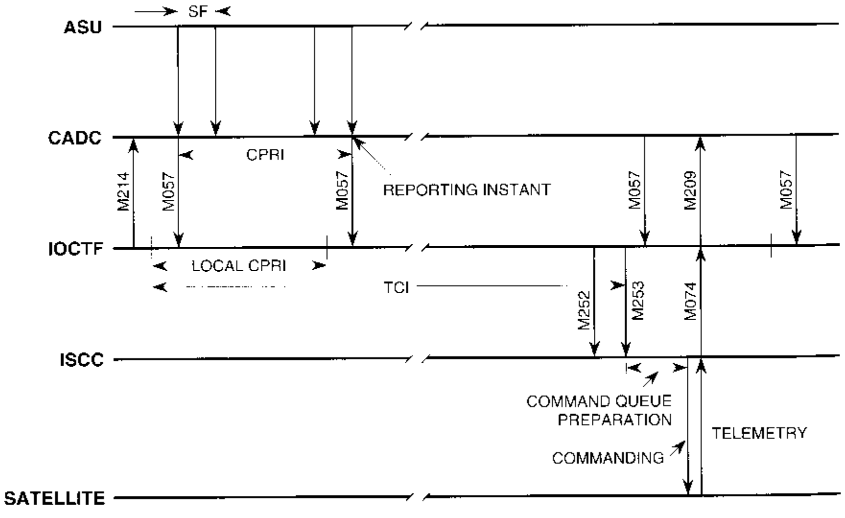


Figure 15. *Overall TSO Phase Reporting*

$$y(k) = y(k-1) + \left[P_i(k) - P_i(k-1)\right] \tag{25}$$

where

P_i = SSRTE phase data report
i = 1 or 2, depending on which SSRTE is selected (MPRT is preferred)
k = index of the current CPRI within the correction interval
$k - 1$ = index of the previous CPRI within the correction interval.

The OFC process raises a Missing Phase Data Alarm if the local phase term could not be calculated due to lack of valid phase reports (*i.e.*, no phase data were received from the same SSRTE during the current and previous local CPRIs).

At some time (an operator-supplied parameter) before the end of the current TCI, the OFC process will send a TSO Correction Warning message to the ISCC indicating that a scheduled TSO frequency correction is forthcoming. At the end of the current TCI, the OFC process calls the TSO correction algorithm to calculate the required frequency correction, Δw, and send a TSO Correction Alarm to the ISCC. The alarm message contains satellite identity, TSO identity, CFE, tentative time of next TSO frequency correction, and a checksum. The ISCC must acknowledge reception and checksum verification of this message within 60 seconds. Otherwise, the OFC process will generate a warning through the IOCTF alarm system. If an acknowledgment is received, but the returned TSO identity does not match the forwarded TSO identity, a warning message is generated. Also, if the OFC process does not receive a TSO Correction Confirmation message from the ISCC within half a CPRI after sending the TSO Correction Alarm, an alarm will be raised.

If any values of local phase are missing at the end of the current TCI, an alarm message is raised and processing is halted until the operator manually enters the missing phase values or initiates a cold or warm startup. To calculate the amount of frequency correction to be applied, the OFC process determines the duration of the next TCI. During cold and warm start, the durations of all CPRIs and TCIs are determined based on the values specified by the operator via the Clock Phase Correction Control screen (Figure 12).

During the normal mode of operation, the OFC process schedules the date and time of the next TSO frequency correction to occur at times that do not conflict with satellite commanding activities, and during normal working hours to ensure adequate operational support. Accordingly, the OFC process advances or retards the time of the next scheduled TSO frequency correction by lengthening or shortening the TCI in multiples of the CPRI, so that the next TSO frequency correction occurs Monday through Friday around a predefined nominal time of day.

Figure 16 illustrates the principle of the advance/backoff algorithm. At the time of the current correction, the algorithm computes the time for the next correction. This value is adjusted so that it occurs at a predetermined time of day, T_c, using parameters specified by the operator via the Clock Phase Correction Control screen. If the computation results in the next correction occurring on a Saturday or Sunday, then the correction time is retarded or advanced so that it occurs at T_c on either a Friday or a Monday. Operator-selected upper and lower margin limits constrain the allowable range for TSO frequency correction advance or backoff. Normally, these limits will be such that backoff/advance is within 20 percent of the nominal length of the TCI. If the overall adjustment is outside these limits, then no adjustment is made.

The procedure for computing the frequency correction is based on a least squares polynomial fit of the cumulative local phase data, as described previously. A second-order polynomial is fitted to n observations of $y_a(t)$, $t = 1, 2, 3, \ldots, n$. The values of $y_a(t)$ are the values of the local phase computed from the reported phase each CPRI, divided by 2. The phase $y_a(m)$ is extrapolated to the end of the adjusted next TCI $(t_n + mT_0)$, where m is the number of CPRIs in the next TCI, and T_0 is the length of a CPRI. The values of the coefficients a_0, a_1, and a_2 of the quadratic polynomial are obtained by solving equation (8) using the n local phase samples. Based on these values, the frequency correction, Δw, is computed from equation (10).

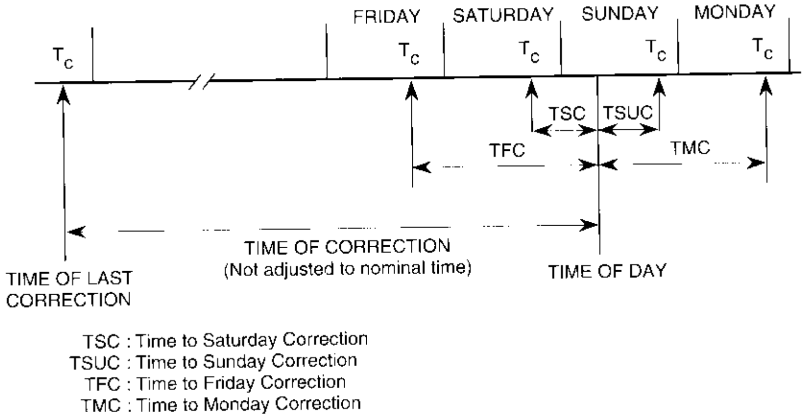


Figure 16. *Advance/Backoff Time Diagram*

A CFE is generated from the computed values of Δw as follows:

$$\mathrm{CFE}(i) = \mathrm{CFE}(i-1) + \Delta w \tag{26}$$

where

$\mathrm{CFE}(i-1)$ = CFE at the end of the previous TCI (0 at startup)

$\mathrm{CFE}(i)$ = CFE at the end of the current TCI. (Reset to zero if a special startup flag is set in the TSO Correction Alarm message)

i = index, which is incremented each time a TSO frequency correction is calculated

Δw = incremental frequency correction reported by the IOCTF in the TSO Correction Alarm message.

The value of CFE(i) is transmitted to the ISCC via the TSO Correction Alarm message (M253). The ISCC uses this value to compute the new value of OCI for transmission to the spacecraft via telemetry.

Operational experience has shown that computing the CFE in the above way results in a tendency to overcorrect or undercorrect the oscillator, due to the effects of quantization error. More satisfactory performance is obtained by basing CFE(i) on a predetermined value of OCI. The IOCTF first determines the new value of OCI by searching the characteristic curve data for the element that yields the minimum error relative to the CFE, as follows:

$$\min\left[5.664 \times 10^6 + \mathrm{CFE}(i) - F(N)\right] \tag{27}$$

where $F(N)$ is the frequency on the characteristic curve corresponding to an OCI of N. The value of N yielding the minimum error is called $\mathrm{OCI}_{\mathrm{new}}$.

This concept is illustrated in Figure 17. In this example, the previous value of OCI is $N - 1$, and the oscillator exhibits a positive drift of Δw hertz. The value of OCI which generates the minimum quantization error relative to 5.664 MHz + CFE(i) is $N + 1$. Thus, $N + 1$ is selected as the new value of OCI ($\mathrm{OCI}_{\mathrm{new}}$).

The cumulative effects of quantization error can be removed by adjusting the CFE as follows:

$$\mathrm{CFE}(i) = F(\mathrm{OCI}_{\mathrm{new}}) - 5.664 \times 10^6 \quad \mathrm{Hz} \tag{28}$$

At startup, CFE(I) is set to zero. Thus, the first computed value of CFE(i) is based on CFE(i − 1) = 0.

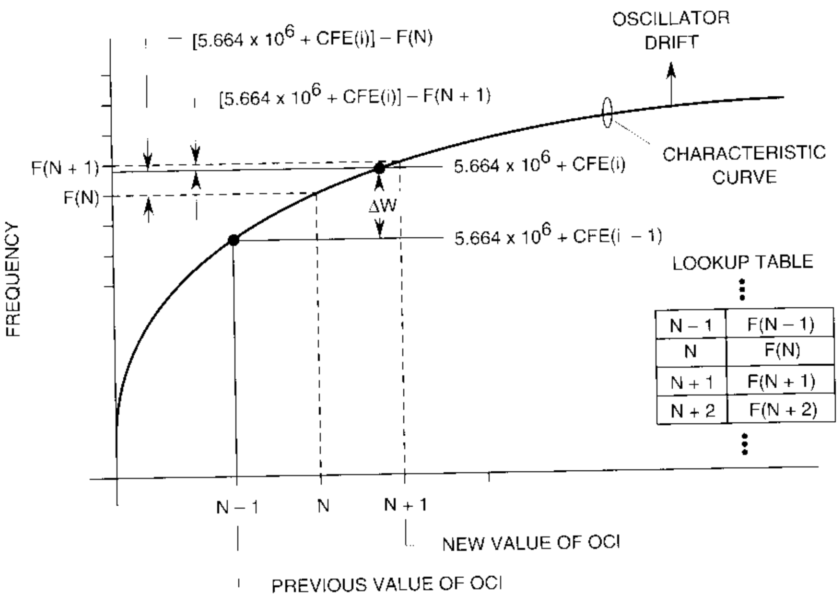


Figure 17. *Computation of CFE*

TSO frequency adjustment

The ISCC computes a 12-bit binary number called the OCI, which is transmitted to the spacecraft via telemetry in order to control the frequency of the on-line oscillator. Figure 18 shows the ISCC processors involved in TSO frequency correction. (Pettersson *et al.* [11] provides a detailed description of the ISCC.) Determination of the new OCI and generation of the command sequence are performed under operator control using the PC-based INTELSAT VI Repeater Command Assistance Program (RCAP).

When the command coordination system (CCS) processor receives the TSO Correction Alarm message (M253) containing the new value of CFE(i), an operator activates RCAP, which retrieves the characteristic curve of the active (on-line) TSO. This curve is stored as a lookup table of 12-bit numbers *vs* frequency. RCAP obtains from the table the new value of OCI *(N)* which matches 5.664 MHz + CFE(i).

After RCAP has generated the command sequence for the obtained OCI, the CCS operator initiates commanding of the TSO. The communications and control processor (CCP) detects the completion of TSO commanding from telemetry and returns to the IOCTF a TSO Correction Confirmation message containing the OCI just implemented.

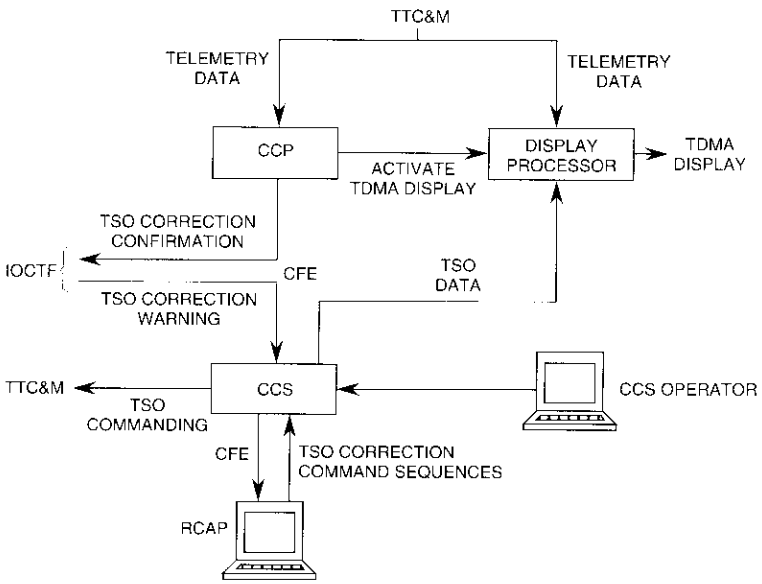


Figure 18. *ISCC TSO Correction Scenario*

Selection of operational parameters

This section discusses the selection criteria for the TCI which are used for normal operation, as well as the threshold value, P_{thres}, for the accumulated phase. Crossing this threshold will cause an unscheduled TSO frequency correction.

The requirement that the TSO correction interval be chosen such that the total buffer size for traffic terminals is less than 500 µs provides an upper limit for the length of the TCI. On the other hand, to achieve good performance of the TSO correction algorithm, the TCI must be long enough to ensure that, for a given TSO frequency drift, quantization effects do not dominate. To satisfy both potentially conflicting requirements, the influence of TCI length on the performance of the TSO correction algorithm was evaluated.

The TSO correction algorithm does not exhibit an oscillatory response if, during each TCI, the accumulated phase goes through an extreme (maximum of the positive drift oscillator). Simulations have shown that the ratio between the maximum amount of phase accumulated in any TCI over a period of years and the amount of phase that would have accumulated if there were no quantization can aid in assessing the impact of quantization effects on TSO correction performance. This ratio, illustrated in Figure 19, drops dramatically

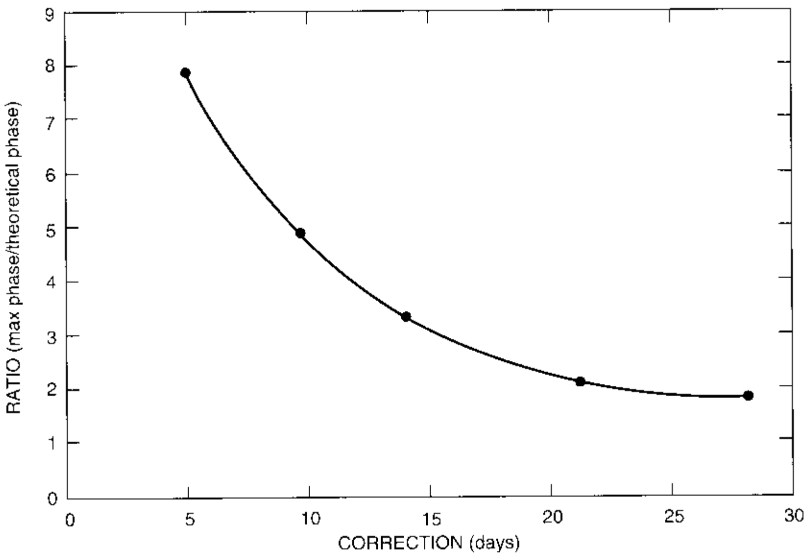


Figure 19. *Ratio of Maximum Phase/Theoretical Phase vs Correction Time*

with longer TCIs before asymptotically approaching a limit of about 2 for smaller values.

The suggested minimum length of TCI, $t_{\min}$, to be selected for operations is given by

$$T_{\min} = \frac{4|\Delta a_0|}{|a_1|} \tag{29}$$

where Δa_0 is the quantization error, in hertz, which yields the same phase error as the combined error terms discussed previously; and a_1 is the TSO frequency drift in hertz per second (Hz/s).

In deriving this equation, steady-state operation of the frequency correction algorithm is assumed. In this case, the relative TSO frequency offset changes as follows over a TCI:

$$f_0(0 \le t \le T) = -\frac{a_1}{2} \bullet T + a_1 \bullet t \tag{30}$$

where a_1 is the TSO frequency drift in Hz/s, and T is the length of TCI in seconds.

Since the accumulated phase peaks a $t = T/2$, the maximum value of accumulated phase, $\mathrm{AP}_{\max}$, can be calculated as

$$\mathrm{AP}_{\max}\left(\frac{T}{2}\right) = c \bullet \int_0^{\frac{T}{2}} \left(-\frac{a_1}{2} \bullet T + a_1 t\right) \mathrm{d}t = -c a_1 \frac{T^2}{8} \tag{31}$$

where c is a scaling constant (-2 × 60.412 × 10^6 / 5.664 × 10^6 symbols), which reflects the phase measurement method employed by the ASU (opposite sign, no division by 2).

Since the worst-case contribution of all error terms can also be expressed as quantization effect, and based on the requirement that the relation between observed and theoretical maximum phase must be less than x, T must satisfy

$$c\,|\,a_1|\frac{T^2}{8} + |\,c \Delta a_0 T\,| < xc\,|\,a_1\,|\,\frac{T^2}{8} \tag{32}$$

From above equation, the minimum T can be determined as

$$T_{\min} > \frac{8|\Delta a_0|}{(x-1)|a_1|} \tag{33}$$

Based on the observation that no oscillatory responses occur as long as the ratio, r, is below 3, and that the worst-case impact of all error terms can be expressed as quantization effects, equation (29) is obtained. In addition, based on the maximum buffer size of 500 µs, the accumulated phase must be constrained to a range of ±15,000 symbols (P_{thres}), and the suggested upper limit for TCI length becomes

$$T < \sqrt{\frac{4B_s}{3c\,|\,a_1|}} \tag{34}$$

where

B_s = buffer size in symbols
c = scaling constant (-20.33 symbols)
a_1 = TSO frequency drift in Hz/s.

Using equations (29) and (34), it is possible to size the operational TCI so that it satisfies the stability requirement and constrains the maximum accumulated phase to agree with plesiochronous operation.

System performance

Figure 20 presents TSO frequency and phase error data as a function of CPRIs obtained from both the operational system and a simulation of the system as implemented in the MCU. The oscillator measured is the U5580 oscillator on the INTELSAT 602 spacecraft from May 29, 1990, through August 5, 1990. In both instances, the CPRI is set to 660 superframes (3 hr) and the TCI to 10 days.

The data begin with a manual correction to the oscillator on May 29. The initial value of OCI was significantly in error, resulting in a starting frequency error of approximately -1.35 mHz. On June 5, a warm start was executed. Due to the initially large frequency error, the system required several cycles to settle to a frequency error oscillation with approximately zero mean. The variation between the simulated results and the actual data is attributed to the chaotic nature of the actual oscillator instantaneous phase, as opposed to the well-behaved phase of the simulated oscillator.

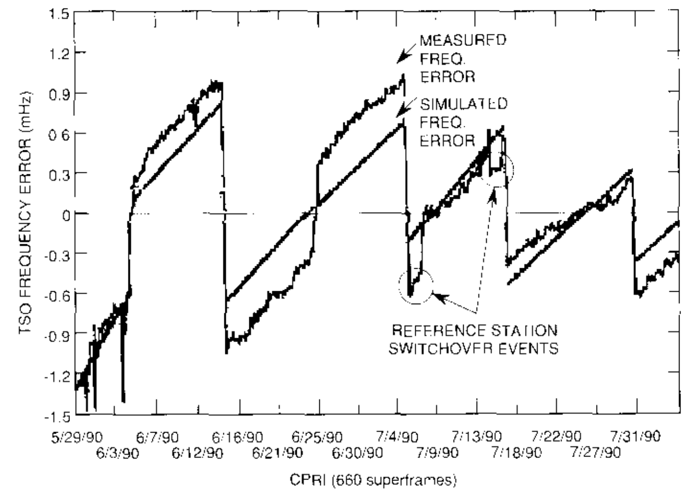
The figure shows two reference station switchover events that occurred on July 5 and July 15. The frequency shifts are due to the frequency difference between the cesium oscillators at each reference station. As expected, these events had no effect on the subsequent scheduled correction.

Summary and conclusions

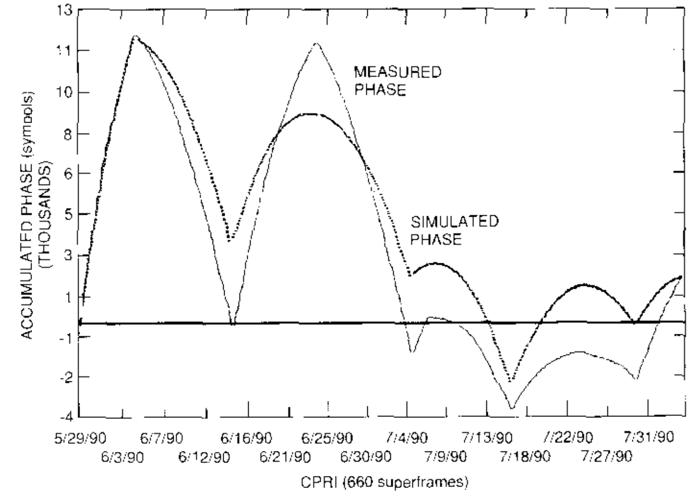
The TSO on board the INTELSAT VI spacecraft plays an important role in the operation of the SSTDMA system. Its significance derives from its stability and the way in which its operation affects the overall network. An extensive study of TSO performance, combined with the development of a thorough software simulation of the subsystems involved in the process, underlay the development of a mathematical algorithm for correction and control of the TSO. Methods for conducting measurements were also developed and implemented in the network.

Acknowledgments

The authors wish to express their appreciation to all those involved in the development, implementation, and realization of the TSO design. Special thanks are due to C. Kullman and R. Parthasarathy of INTELSAT, who managed and coordinated the development effort. The authors would also like to acknowledge J. Dicks and R. Scott of INTELSAT for their constant assistance throughout the program, and S. J. Campanella of COMSAT Laboratories for developing the concept of clock control using metering bursts.



(a) Frequency Error



(b) Accumulated Phase

Figure 20. *Measured/Simulated TSO Frequency and Phase Error (5/29/90 – 8/5/90)*

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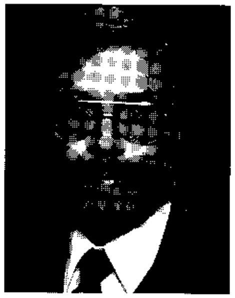
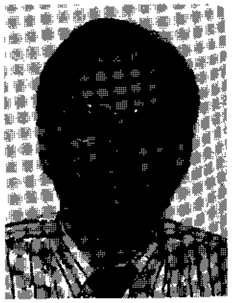


John A. Lunsford received a BSEE from the University of Maryland in 1973 and an MSEE from the University of Pennsylvania in 1980. From 1973 to 1980, he worked on advanced radar signal processing equipment development projects for the RCA Missile and Surface Radar Division (MSRD), including the AEGIS Advanced Radar Signal Processor for the U.S. Navy's AEGIS shipboard radar system. He joined COMSAT Laboratories in 1980, where he participated in a number of TDMA system specification and equipment development efforts, including the system specifications for the INTELSAT TDMA/DSI system. From 1985 to 1989, Mr. Lunsford worked as an independent contractor for INTELSAT, where he made major contributions to the SSTDMA system design and specification, as well as the specifications for the INTELSAT Operation Center TDMA Facility, Satellite Control Center, and SSTDMA burst time plan generation software system. In addition, he had a principal role in the implementation, installation, testing, and documentation of all elements of the SSTDMA system.

Mr. Lunsford rejoined COMSAT Laboratories in 1990 as manager of the Network Systems department in the Network Technology Division, where he led an engineering team performing research and development in the areas of onboard processing, ISDN, TDMA, network control, and system architectures for advanced satellite communications systems. He is currently manager of the Network Engineering department, where he is responsible for hardware development for various satellite communications projects.

Thomas Inukai received BS and MS degrees in communications engineering from the Tokyo Electrical Engineering College, Tokyo, Japan, and a PhD in electrical engineering from the City University of New York. He is currently Principal Scientist in the Network Technology Division at COMSAT Laboratories, where he directs research and development activities in the areas of advanced satellite communications systems, network architectures, onboard baseband processing, and VSAT networks. His recent contributions include satellite network architecture development for BISDN with onboard fast-packet switching, systems studies for the NASA Information Switching Processor, systems engineering to develop fixed satellite service network architecture in the Commercial Satellite Communications Initiatives (CSCI) program, a network architecture study for the Canadian Advanced Satcom system, and satellite network architecture designs for the Advanced Communications Technology Satellite (ACTS) system and the ITALSAT system.

Prior to joining COMSAT, Dr. Inukai was with Western Union Telegraph Company and with North Electric Company, Delaware, Ohio. He is a member of IEEE, AIAA, and Sigma Xi, and has authored numerous papers on onboard baseband processing, SSTDMA systems, digital signal processing, and graph theory.



Friedrich Luz received a Diploma in physics from the Eberhard-Karl-University, Tuebingen, Germany, in 1978. From 1979 to 1982 he was with CGR Koch & Sterzel in Essen, Germany, where he was responsible for the software design of an ultrasonic scanner as part of a government-funded research project. From 1982 until 1986 he was with Kraftwerksschule E.V. in Essen, where he participated as a project engineer in the development of a nuclear power plant simulator. After joining INTELSAT in 1986, Mr. Luz has throughout the SSTDMA project had the primary responsibility for software design and verification testing of the SSTDMA Headquarters Subsystem, SSTDMA reference terminals, and nonreference diagnostic equipment. He is currently a supervisor in the Network Operations and Development Department. Mr. Luz is a member of the IEEE Computer Society.

Index: INTELSAT, satellite networks, time division multiple access, diagnosis, expert systems

The INTELSAT VI SSTDMA network diagnostic system

S. P. TAMBOLI, X. ZHU, K. N. WILKINS, AND R. K. GUPTA

(Manuscript received January 9, 1991)

Abstract

The system-level design of an expert-system-based, near-real-time diagnostic system for INTELSAT VI satellite-switched time-division multiple access (SSTDMA) networks is described. The challenges of INTELSAT VI diagnostics are discussed, along with alternative approaches for network diagnostics and the rationale for choosing a method based on burst unique-word detection. The focal point of the diagnostic system is the diagnostic processor, which resides in the central control and monitoring facility known as the INTELSAT Operations Center TDMA Facility (IOCTF). As real-time information such as burst unique-word detection data, reference terminal status data, and satellite telemetry alarm data are received at the IOCTF, the diagnostic processor continuously monitors the data streams. When a burst status change is detected, a "snapshot" of the real-time data is forwarded to the expert system. Receipt of the change causes a set of rules to be invoked which associate the traffic pattern with a set of probable causes. A user-friendly interface allows a graphical view of the burst time plan and provides the ability to browse through the knowledge bases.

Introduction

With the launch of the first INTELSAT VI satellite, a significant new mode of operation involving onboard dynamic beam switching for satellite-switched time-division multiple access (SSTDMA) was introduced. The transition from fixed-beam TDMA to SSTDMA was transparent to traffic terminals, provided that the major components of the onboard SSTDMA communications subsystem perform their switching and control functions properly. To detect and isolate faults in the onboard SSTDMA subsystem, a diagnostic capability is essential. A number of onboard and ground-based diagnostics alternatives were evaluated, and a system was designed which derives diagnostic information from burst detections performed in the reference terminal equipment (RTE).

The INTELSAT VI SSTDMA diagnostic system, which is responsible for near-real-time network fault detection and isolation, went into operation in January 1990, concurrent with the first SSTDMA network. Diagnostic monitoring is conducted in the INTELSAT Operations Center TDMA Facility (IOCTF), a central control and monitoring facility located at INTELSAT Headquarters in Washington, D.C. This paper discusses the nature of the INTELSAT VI SSTDMA diagnostics problem, alternative approaches to its resolution, the rationale and design of the approach finally implemented, and the initial operational experience.

The INTELSAT VI SSTDMA diagnostics problem

The INTELSAT VI repeater configuration (Figure 1) consists of five sections: receive antennas and receivers; input multiplexers; interconnection static switch matrices and the SSTDMA communications subsystem; traveling wave tube amplifiers (TWTAs)/solid-state power amplifiers (SSPAs); and output multiplexers and transmit antennas. The section unique to INTELSAT VI is the SSTDMA communications subsystem (Figure 2), which performs dynamic beam switching.

A failure in the repeater can have an effect ranging from loss of traffic in single or multiple beams, to a total network outage. Broadly, failures can be classified as either permanent hardware failures or soft failures. Permanent hardware failures include the failure of active or passive components (*e.g.*, devices, solder/epoxy joints, or connections). Such failures can be corrected by switching to a redundant component, if available. The SSTDMA hardware failure modes and their estimated failure probabilities are listed in (Table 1). The highest probabilities of hard failure are associated with TWTAs and receivers, which are common hardware for INTELSAT VI static and SSTDMA operation. For critical components of the repeater, sufficient redundancy is implemented (Table 2) to enhance the operational reliability of the INTELSAT VI satellites [1]. If any one element fails, a redundant element can be substituted by ground command. The balance of this paper focuses on soft failures and their implications for diagnostics.

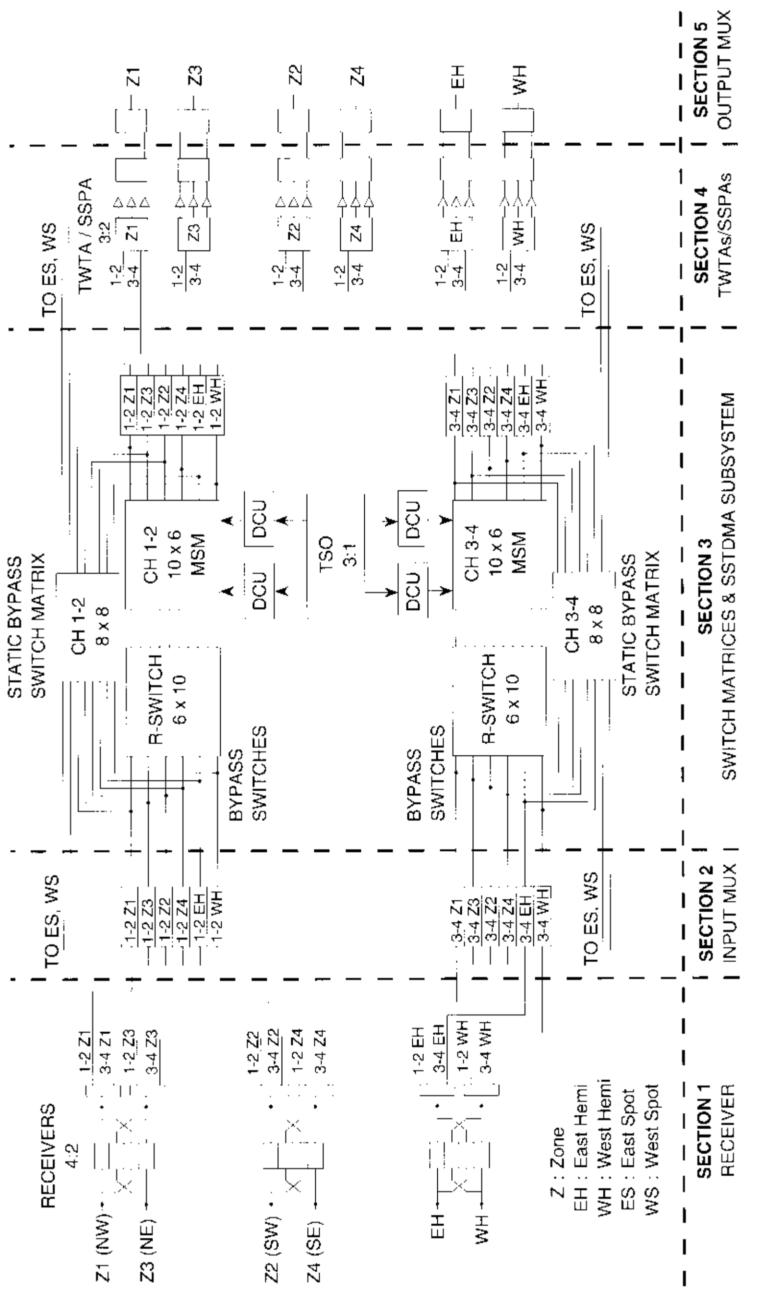


Figure 1. *INTELSAT VI Repeater Configuration*

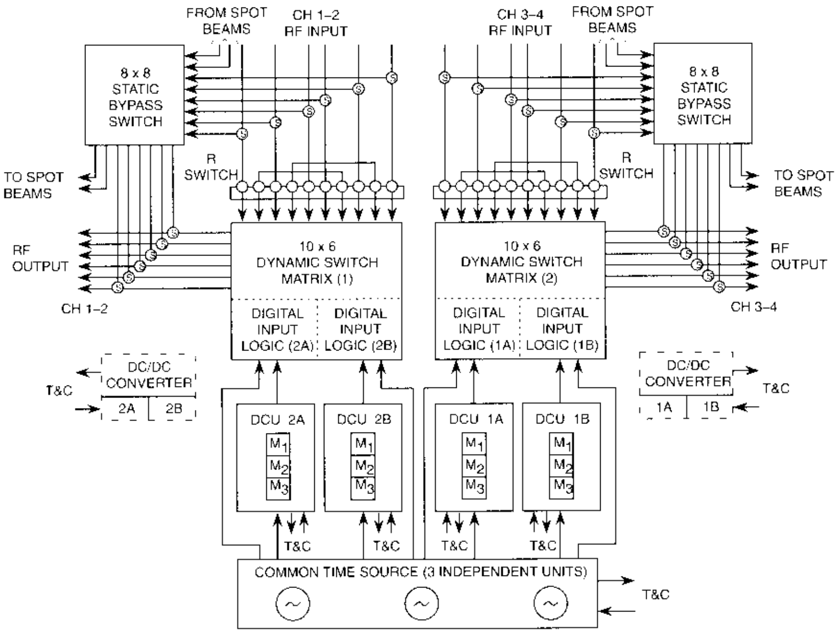


Figure 2. *Onboard SSTDMA Subsystem*

TABLE 1. FAILURE MODES AND ESTIMATED FAILURE PROBABILITIES FOR SSTDMA SUBSYSTEM

(Overall reliability for 10 years, including redundancy = 0.99)

ONBOARD HARDWARE FAILURES	FAILURE MODE	PROBABILITY OF ONE OCCURRENCE PER MISSION (10 YEARS)
TWTAs, Including Driver Amplifiers	Hardware failure, including excessive gain change	0.81
Receivers	Hardware failure	0.51
MSM	MSM row failure, including preamplifier	0.30
	MSM power supply/input logic	0.07
DCU	Hardware failure	0.14
Timing Source (TS)	Hardware failure	0.08

TABLE 2. REDUNDANCY OF CRITICAL COMPONENTS

COMPONENT	REDUNDANCY	COMMENTS
TWTA/SSPA	3-for-2	–
Receiver	4-for-2	12 receivers arranged in three groups.
MSM	10-for-6	Permits four cross-point failures in six input ports.
DCU	2-for-1	In each channel bank. Each DCU contains three memories (on-line, off-line, and standby) for storing a maximum of 64 switch states per 2-ms TDMA frame.
TSO	3-for-1	With one TSO kept as a hot standby.

Soft failures, also known as single/multiple-event upsets or bit-flips, occur when direct hits by high-energy cosmic radiation [2] cause flip-flops to change the states of registers or memories. Such failures are recoverable by refreshing the flip-flops or by switching to a redundant memory/logic unit.

As indicated in Figure 2, the onboard SSTDMA subsystem dynamically switches as many as six uplink beams to six downlink beams within a 2-ms frame. This switching is available on transmission channel 1-2 (uplink center frequency 5,970 MHz) and transmission channel 3-4 (uplink center frequency 6,050 MHz). There is one microwave switch matrix (MSM) for each transmission channel. Each channel also contains two hemispheric beams and four zone-beam transponders. The MSM connectivity is switched in accordance with a sequence programmed in the on-line memory of the active distribution control unit (DCU). There are two DCUs per channel, for redundancy, and each DCU has three identical memories. Each memory stores a complete switch state time plan (SSTP) and can assume the operational role of on-line, off-line, or standby memory [3],[4].

For the on-line memory controlling the switching sequence, onboard logic applies forward error correction (FEC) to the switch data to detect SEUs. Data corrupted by SEUs are corrected before being clocked to the MSM. The corrected data are also written back to the appropriate on-line memory location. SEU detection and correction are indicated by a telemetry flag. Data destined for other functions, such as last state address (LSA) and telemetry readout, are also susceptible to SEUs.

Most MEUs are detected and the correction attempt is indicated in telemetry. However, since a small number of MEUs may not be detectable, telemetry data alone are not sufficient to detect all memory errors.

No active error detection and correction is applied to the off-line and standby memories. To prevent a buildup of errors, the off-line memory is read and compared to a master memory image on the ground at every telemetry masterframe (13.8 s). If an error is detected, the memory is reprogrammed by ground command. In this way, the integrity of the off-line memory is maintained should it become necessary to switch to this memory due to suspected corruption of data in the on-line memory.

Given the nature of hard and soft failures, onboard isolation of SSTDMA-related faults would be extremely difficult and time-consuming without the aid of a diagnostic tool. The primary motivation for developing the diagnostic system was to minimize network downtime by rapidly isolating faults in the portion of the payload pertaining to SSTDMA in general, and to the onboard SSTDMA subsystem in particular. However, since traffic downtime is likely to be dominated by earth segment factors such as traffic terminal availability and spurious RF interference, the diagnostic system should also be capable of monitoring and diagnosing faults related to the earth segment. Accordingly, the problem addressed by the INTELSAT VI SSTDMA diagnostic system was to isolate a network fault to the level of resolution shown in Figure 3, in near-real time.

Alternative approaches to INTELSAT VI SSTDMA diagnostics

A broad classification of the various alternative approaches to SSTDMA diagnostics is shown in Figure 4. Both onboard and ground-based approaches were considered [5]. Studies demonstrated that an onboard approach would require significant modification of the existing repeater design, with resulting mass and power penalties. The added cost and schedule risks were also evaluated, and it was decided that a ground-based approach would be more suitable.

The ground-based continuous-wave (CW) carrier monitoring method [6] requires transmission of six in-band carriers (at frequencies $f_1, f_2, \ldots, f_6$), one from each beam, as depicted in Figure 5. The monitoring stations in the downbeams receive, detect, and monitor the CW carriers. Onboard failures are identified by detecting the presence or absence of CW carriers during different switch states. The CW monitoring approach offers the operational advantages of refined diagnostic results with minimal failure mode ambiguity. This technique also provides the capability to perform in-orbit and functional tests on the INTELSAT VI satellites in the absence of traffic. In the INTELSAT VI network, the TDMA reference and monitoring stations (TRMS) could transmit and detect pilot signals in the hemispheric and northern zone beams. However, in the southeast and southwest zone beams, additional equipment would be needed to enable one of the traffic terminal host stations to transmit and detect

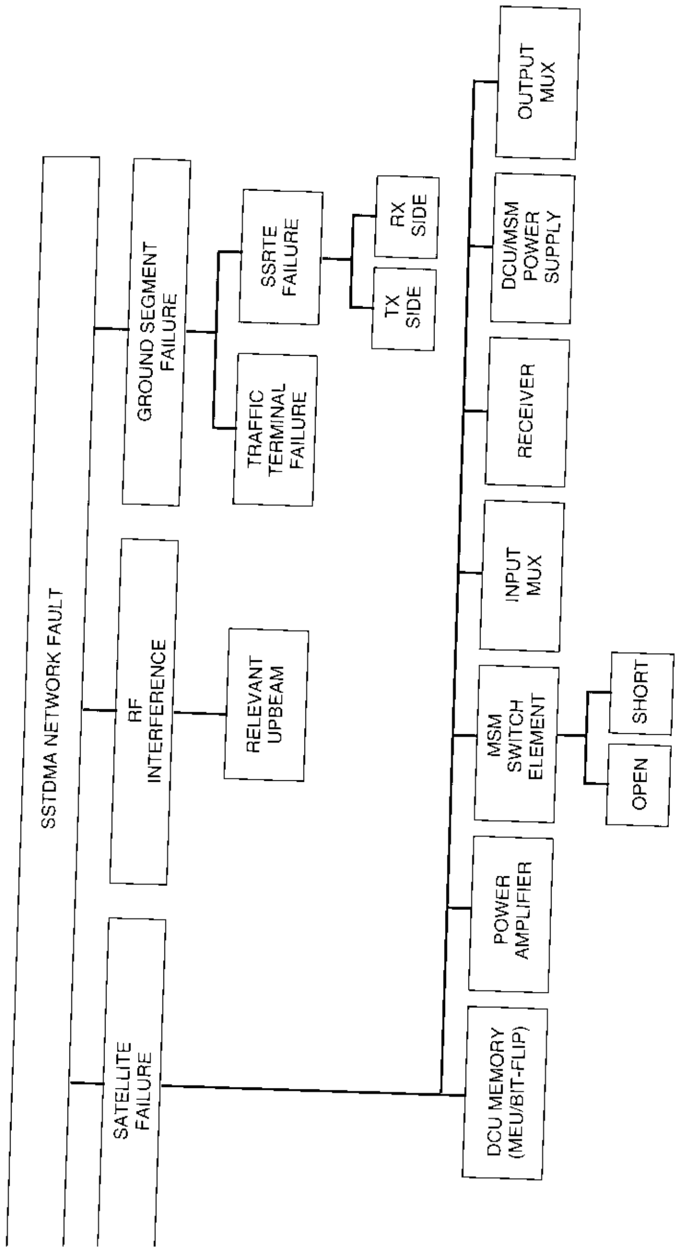


Figure 3. *SSTDMA Network Failure Modes*

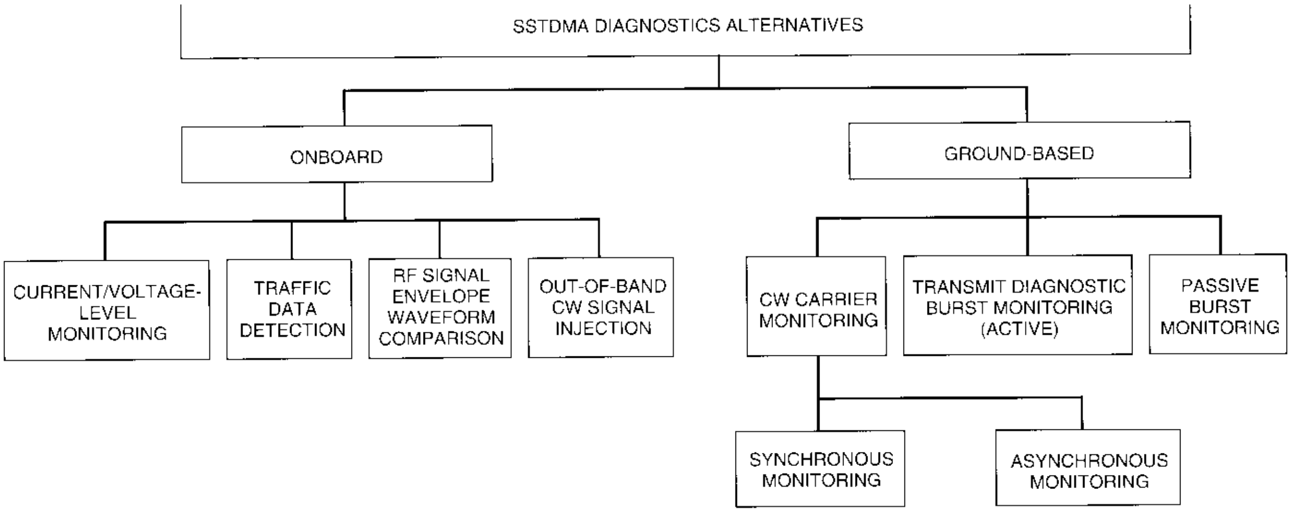


Figure 4. *Alternative Approaches to SSTDMA Diagnostics*

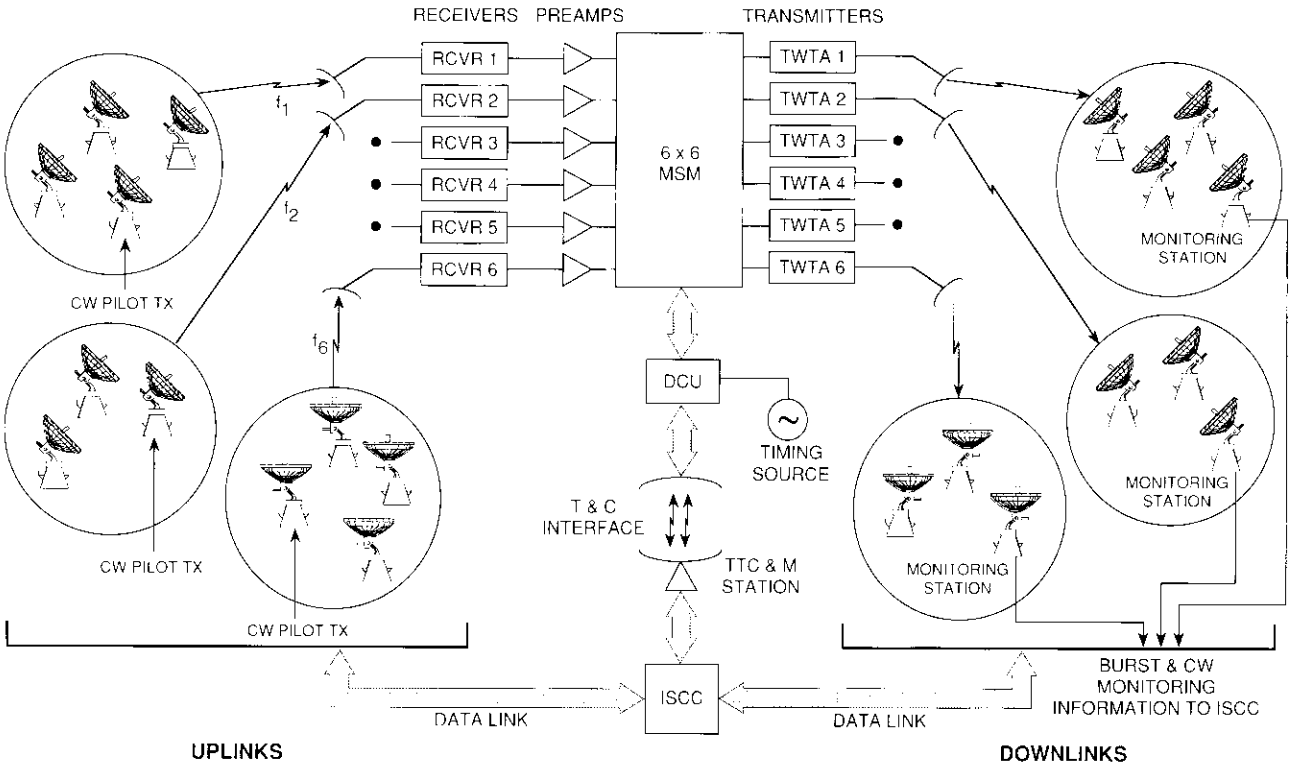


Figure 5. *Ground-Based CW Carrier Monitoring System Block Diagram*

CW carriers. Ultimately, the advantages of the CW monitoring approach were outweighed by other factors, such as the additional cost/complexity of synchronous or asynchronous CW monitoring equipment, the interfering impact of the CW carriers on TDMA/quadrature phase shift keying (QPSK) signal performance, and the relative simplicity of the alternative burst monitoring approach [6].

The burst monitoring approach can be implemented in either active or passive mode. Both techniques rely on diagnostic equipment installed in the two sets of SSTDMA reference terminal equipment (SSRTEs), as well as at two designated stations located in the nonreference beams (referred to as nonreference diagnostic equipment [NRDE]). Figure 6 shows the location of SSRTEs and NRDEs in the INTELSAT VI beams.

In the active approach, a region of the SSTDMA frame is reserved for diagnostic bursts. Each SSRTE and NRDE transmits a diagnostic burst in every uplink beam used for SSTDMA service. The SSTP is structured so that bursts received at the satellite in the diagnostic burst region are broadcast to all downlink beams used for SSTDMA service. The SSRTEs and NRDEs receive all diagnostic bursts and check connectivity based on the presence or absence of a diagnostic burst. The SSRTEs and NRDEs also collect burst detection data and forward them to a central monitoring facility, such as the IOCTF, for fault isolation and diagnosis.

In the passive approach, the SSRTEs and NRDEs do not transmit a diagnostic burst. Instead, reference and traffic bursts are monitored by the SSRTEs and NRDEs to detect a unique word (UW). The received pattern of UWs is compared with that expected by the burst time plan, and the comparison data are forwarded to the IOCTF for further analysis. At the IOCTF, these comparison data are analyzed on the basis that each failure mode will generate its own distinct pattern of UW loss. The analysis can be further corroborated by telemetry data.

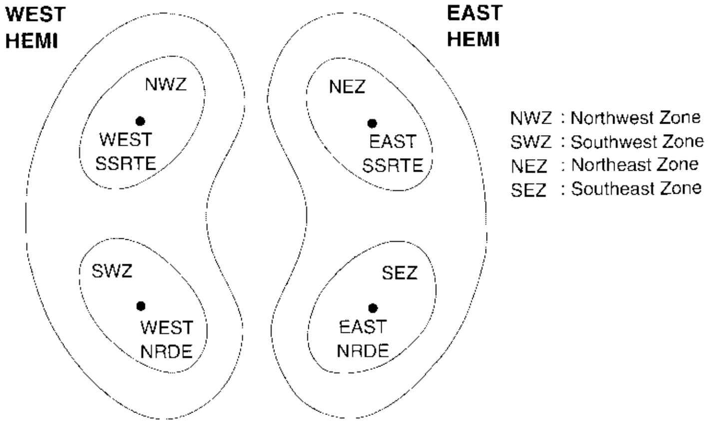


Figure 6. *Location of SSRTEs and NRDEs in the Beams*

Both the active and passive approaches were analyzed and, after careful consideration, the passive approach was selected. The passive approach significantly reduces the complexity of the SSRTE design, and when augmented with telemetry data is comparable in its ability to identify failure modes. Furthermore, its reduced complexity results in lower system cost. The active approach requires additional space in each frame, thus decreasing frame utilization efficiency. It also requires that broadcast switch states be provided as a permanent feature of frame architecture. This would increase the network's susceptibility to spurious RF interference, which is sometimes inadvertently present in an operational environment. Experience has shown that spurious RF interference is the leading cause of traffic downtime in TDMA networks.

After selection of the passive burst monitoring approach augmented with telemetry data, both conventional analysis methods and those based on artificial intelligence were considered for final implementation. An artificial intelligence approach utilizing expert systems was chosen, for reasons discussed later.

Objective and assumption

The overall objective of the SSTDMA network diagnostic system is to generate a report isolating a network fault, in accordance with the "fault tree" drawn in Figure 3, within 3 minutes of detecting a change in the status of any burst. The diagnostic report should provide the operations staff with a detailed explanation of the suspected fault. In designing this system, it was assumed that the probability of a simultaneous failure of multiple components is negligible. Thus, at any given time, a diagnosis generated by the system assumes the failure of a single component or unit.

System overview

An overview of the diagnostic system is provided in Figure 7. The INTELSAT VI repeater and the onboard SSTDMA subsystem have already been discussed. The overall system has four additional key elements:

- *SSTDMA Reference Terminal Equipment.* Each SSRTE is equipped with two diagnostic receivers designed for burst UW detection [4]. The detection data and other SSRTE status data are periodically forwarded to the IOCTF.

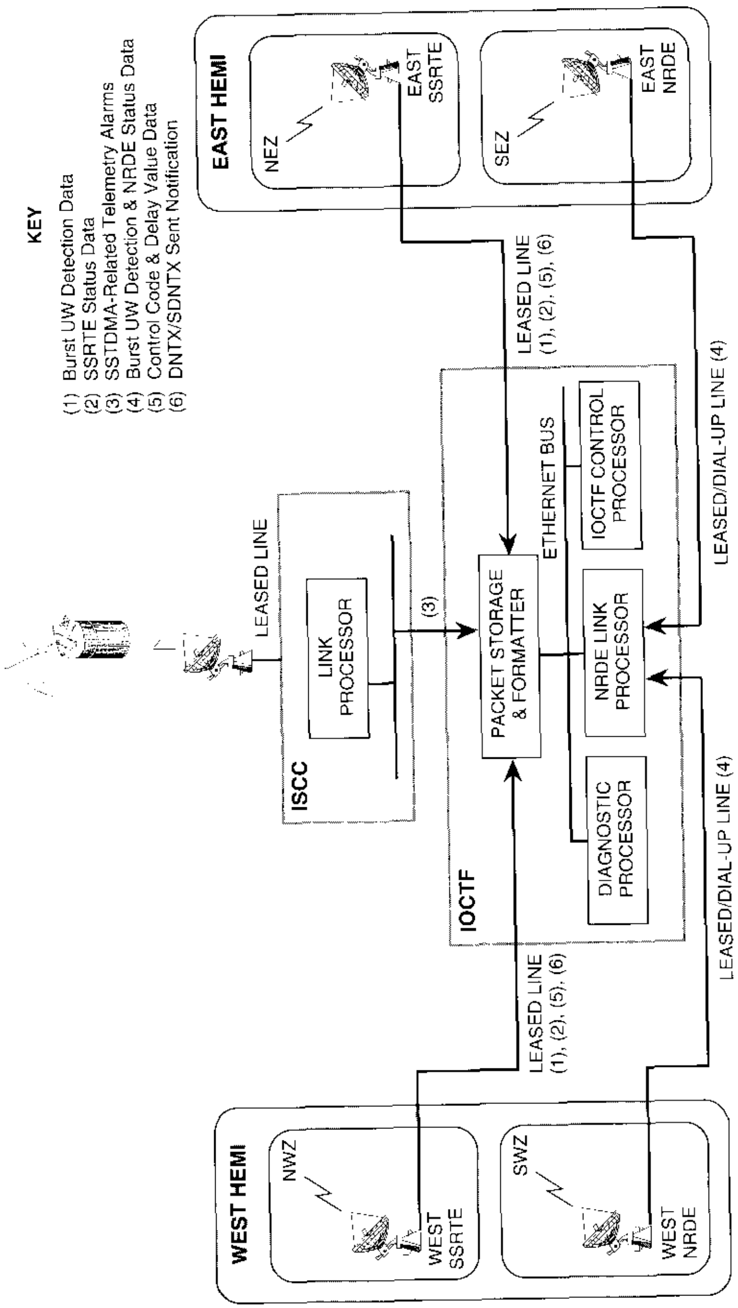


Figure 7. *Overview of SSTDMA Diagnostic System (Single SSTDMA Network)*

- *Nonreference Diagnostic Equipment.* The NRDEs are located at designated stations in the nonreference beams. Each NRDE is equipped with one diagnostic receiver. The NRDEs also forward UW detection data to the IOCTF.
- *INTELSAT Satellite Control Center.* The ISCC monitors spacecraft telemetry and forwards relevant alarms to the IOCTF.
- *Diagnostic Processor.* Located in the IOCTF, the diagnostic processor receives near-real-time data inputs from the SSRTEs, NRDEs, and the ISCC, and analyzes them to generate a diagnostic report [7].

SSTDMA reference terminal equipment

The SSRTE components relevant to diagnostics are shown in Figure 8. Each SSRTE is capable of receiving up to four IF downchains. The SSRTE has two demodulator units, each with two switches for independently selecting any one of the four downchains. Each unit also contains two demodulators and an associated diagnostic receiver [4]. The diagnostic receiver stores a time plan to establish the position of bursts in the TDMA frame. The receiver then implements a receive burst monitoring (RBM) procedure to determine the presence or absence of burst UWs, in accordance with the time plan. The logic followed by the RBM procedure is explained below.

At initialization, all bursts are declared "burst not received" (BNR). If the correct UW pattern for the received burst is detected in 24 consecutive frames, then the status of the burst is changed to "burst received" (BR). The status can change from BR to BNR in the following way. If the correct UW pattern is not detected in four consecutive frames, a frame count is started and incremented every frame. If the correct UW pattern is detected in four consecutive frames, the count is stopped and reset to zero. If the frame count reaches 512, the burst is declared BNR. Figure 9 illustrates the stages in the processing of RBM data, as well as other relevant diagnostics data, which lead to generation of a final diagnosis.

Each diagnostic receiver maintains an RBM data table for two downbeam transponders. Both receivers report their RBM tables to the on-line control and display console (CADC) of the SSRTE, normally every 16 s. In the event of a burst status change, tables are reported at 1-s intervals. The CADC combines and aggregates tables from both diagnostic receivers, and for each receiver-demodulator combination appends a change of status indicator (CSI), an effective time, and a validity flag. These data, known as the UW detection message, are then sent to the diagnostic preprocessor in the IOCTF at 16 s intervals. A dedicated leased line is used for computer communication between the SSRTE and the IOCTF.

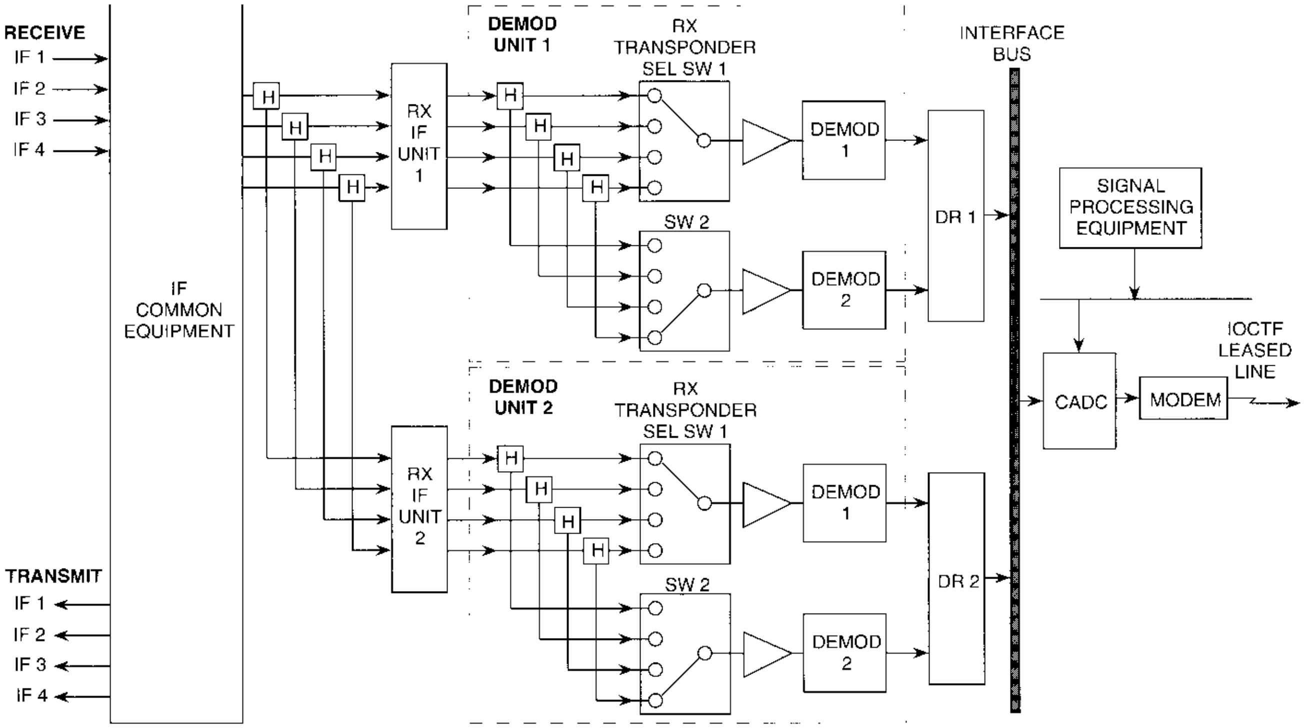


Figure 8. *SSRTE Components Relevant to Diagnostics*

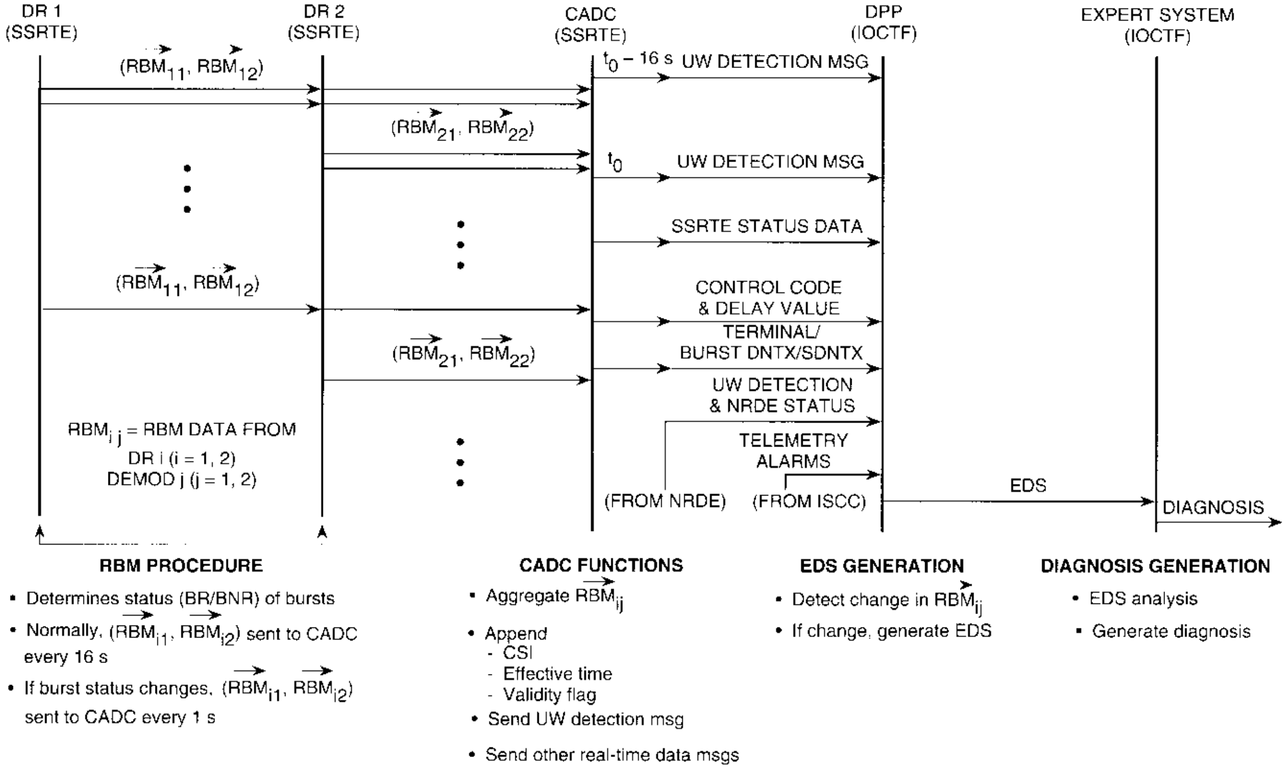


Figure 9. *Stages of Diagnostic Data Processing*

In addition to the UW detection message, the SSRTE sends three other types of critical data to the diagnostic preprocessor:

- *SSRTE Status Data.* These data contain detailed information about the status of protocols implemented by the SSRTE, as well as the status of the major equipment/subsystems of the SSRTE. These data are sent continuously at 16-s intervals.
- *Control Code and Delay Value Data.* These data contain the control code (DNTX, IAP1, IAP2, SYNC) sent by the SSRTE to each terminal, and the associated value of delay. These data are sent continuously at 10-s intervals.
- *Notification of Traffic Terminal/Burst DNTX.* Each time the "do not transmit/selective do not transmit" (DNTX/SDNTX) control code is sent to a traffic terminal or burst, an immediate notification is also sent.

If the preprocessor detects a change in the status of a burst, it generates an event data set (EDS) file, which represents a snapshot of the network. The file contains the relevant portions of all real-time data received by the diagnostic processor within a predetermined time window. The EDS file is sent to the expert system, which then generates a diagnosis.

Nonreference diagnostic equipment

The NRDEs are installed at stations located in the nonreference beams, which are typically the southern zone beams of the INTELSAT VI satellite. Each NRDE is equipped with one diagnostic receiver identical in function to that of the SSRTE. Hence, each NRDE is capable of monitoring up to two downbeam transponders. UW detection and NRDE status data are forwarded to the diagnostic processor in the IOCTF via a leased line or dial-up interface.

INTELSAT Satellite Control Center

The ISCC monitors the real-time telemetry data received from the satellite by dedicated telemetry, tracking, command, and monitoring (TTC&M) stations. The control center screens the data and sends to the diagnostic preprocessor only those alarm indications relevant to the onboard SSTDMA subsystem, as well as other alarms related to the C-band repeaters in transmission channels 1-2 and 3-4. Two types of alarm indications are sent by the ISCC, and are used to corroborate the fault diagnosis.

Out-of-Limit Alarms are generated when the load current monitor for the following critical components of the repeaters falls outside nominal range:

- Hemispheric and zone beam receivers
- TWTAs and SSPAs (channels 1-2 and 3-4)
- MSM power supply
- Timing source oscillator (TSO).

An alarm is also generated when the voltage for the MSM power supply falls outside the nominal range.

An *Uncommanded Status Change Alarm* is generated whenever there is an uncommanded change in status of any of the following:

- Memory role control (on-line/off-line/standby)
- TSO control (1/2/3)
- Substitution switch control (active/inactive)
- LSA (decimal value)
- Memory error (bit-flip) indication (normal/error).

Diagnostic processor

The diagnostic processor is the focal point of diagnostic activity in the network because it receives and processes all real-time data flows from the SSRTEs, NRDEs, and the ISCC. Expert-system-based analysis is also conducted at the diagnostic processor [7].

Figure 10 is a conceptual overview of the diagnostic processor. This processor communicates with other processors in the IOCTF over a 10-Mbit/s Ethernet, and can support up to four SSTDMA networks simultaneously. The two major subsystems of the diagnostic processor are the diagnostic preprocessor and the diagnostic expert system (DES). Each subsystem has its own user interface, and the functions of the two subsystems are decoupled from each other. The only communication between the two subsystems is through the EDS and the diagnostic processor time plan (DPTP) files, which are sent from the preprocessor to the DES.

The diagnostic preprocessor is a front-end processor that performs data monitoring, event detection, and data reduction, while the DES embodies the intelligent decision-making capability of the system. The DES could have been implemented using conventional software development methods; however, an approach based on an expert system shell was chosen because the powerful features built into the shell (such as an inference engine, object-oriented programming environment, graphics editing, and windowing) allow rapid prototyping by a small development team. Also, it was possible to involve the users early in the development process. In addition, the shell's capability for

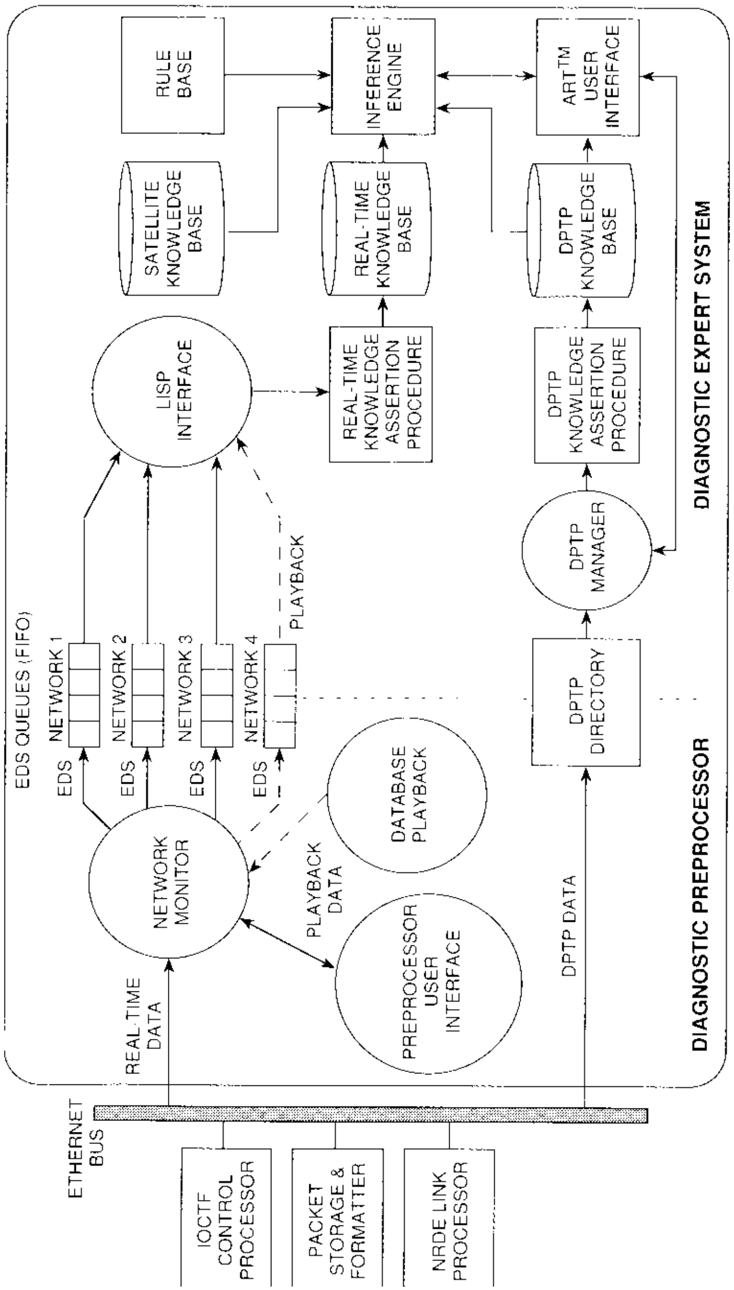


Figure 10. *Diagnostic Processor Conceptual Overview*

incremental system refinement allows interactive expansion and easy incorporation of heuristic knowledge. All of these factors yield short-term cost benefits in software development and long-term cost benefits in software maintenance.

The expert system shell selected for DES implementation was the commercially available LISP-based package known as ART™ (Automated Reasoning Tool). The system-level design and implementation of the diagnostic processor are described in detail below.

DIAGNOSTIC PREPROCESSOR

The diagnostic preprocessor performs two primary functions and a supplementary function. The primary functions are event detection and EDS generation, which are handled by the network monitoring process. The preprocessor continuously monitors the incoming stream of UW detection messages from the SSRTEs and NRDEs to detect a burst status change event. Such an event occurs when all of the following conditions are met:

- The CSI for any one of the diagnostic receiver-demodulator combinations is set.
- The data validity flag indicates that data from the demodulator are valid.
- The effective time of burst status change is valid.

Event detection establishes the effective time of burst status change, which in turn initiates EDS generation. Figure 11 gives an overview of the EDS generation procedure.

The effective time, ET, provides a reference for the opening of a time window. The window aperture extends from ET – ($M \times 16.3$ s) to ET + ($N \times 16.3$ s), where M and N are integer values programmable by the operator. Real-time data that fall within this window are screened, and the contents critical to diagnostics are extracted for inclusion in the EDS. In effect, the EDS represents a snapshot of the network taken at time ET.

The supplementary function of the preprocessor is to provide a database playback capability. This feature allows prerecorded real-time data to be played back through the network monitor for fine-tuning of the EDS generation procedure and diagnostic rules.

DIAGNOSTIC EXPERT SYSTEM

The DES is triggered by reception of an EDS from the preprocessor. The DES analyzes the relationship of the incoming real-time data with respect to the

DATA SOURCE	DATA TYPE	MESSAGE PERIODICITY	RELEVANT TIME STAMP	CRITICAL CONTENT OF DATA IN EDS	NO. OF DATA MESSAGES PER EDS
SSRTE	UW Detection	1/16 s	Effective Time of Burst Status Change	Change Status Indicators Data Validity Flags. Transponder ID Rx Burst Monitoring Data	1
	SSRTE Status	1/16 s	Time Stamp of Communications Process Header	Status of Rx & Tx Protocols Satus of Equipment: Subsystems SPE & ASU Status	2
	Control Code & Delay Value	1/10 s	Time of Extraction	Authorization Status of Terminal SSRTE Role Control Code & Delay Sent to Each Terminal	2
	Terminal/Burst DNTX/SDNTX	Random (Event-Driven)	Time of DNTX Generation	Type of Code. SSRTE Role Tx Terminal Number Rx Burst/Terminal Number	All Within Window
NRDE	UW Detection and Status	1/16 s	Effective Time of Burst Status Change	Change Status Indicators Data Validity Flags. Transponder ID Rx Burst Monitoring Data NRDE Status Data	1
ISCC	Out-of-Limit Alarm	Random (Event-Driven)	Time of Alarm Generation	Out-of-Limit Type Current Value Nominal High & Low Values	All Within Window
	Uncommanded Status Change Alarm	Random (Event-Driven)	Time of Alarm Generation	Component ID Old & New Status	All Within Window

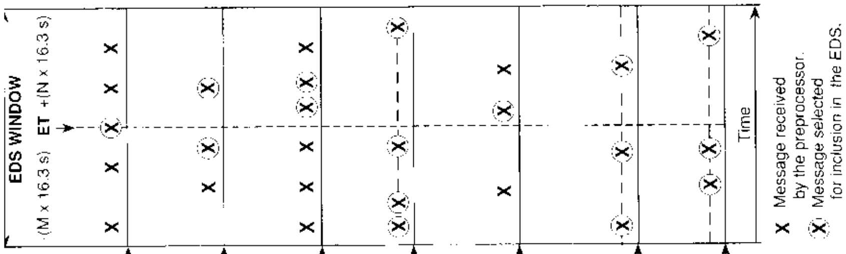


Figure 11. *EDS Generation by the Preprocessor*

resident knowledge bases and draws conclusions regarding possible network anomalies. Interactive inputs from the operator are not necessary in order to reach a conclusion. The reasoning process of the DES proceeds from a set of input conditions to a set of conclusions, using forward-chaining logic. During the process, several intermediary conclusions are obtained.

The DES comprises four knowledge bases, a rule base, and a user interface, as described below.

Knowledge Bases

The DES knowledge bases are partitioned based on the type of data and the degree to which the data are subject to change. These four knowledge bases are broadly classified as static, semi-static, and dynamic, as follows:

• Satellite Knowledge Base	Static
• DPTP Knowledge Base	Semi-Static
• Real-Time Data Knowledge Base	Dynamic
• User Interface Data Knowledge Base	Static

The components of each knowledge base are shown in Figure 12.

Partitioning allows the static and semi-static knowledge bases to be loaded in the working memory during system initialization, significantly reducing the on-line processing time needed to generate a diagnosis. The system is designed so that each knowledge base can be loaded independently. Once loaded in working memory, the objects of the knowledge bases are equally accessible to the rules.

The components of the satellite knowledge base correspond to the various elements in the INTELSAT VI repeater. Telemetry alarm IDs are included as a slot in the satellite knowledge base schema to provide a lookup mechanism for correlating telemetry alarms with repeater elements. Figure 13 is an example of a satellite knowledge base for the TWTA element.

The DPTP knowledge base contains information about the SSTDMA network configuration, terminal assignments, beam assignments, SSTP, and burst time plan (BTP). This knowledge base is time-plan-dependent and is updated with every time plan change. A DPTP Manager process handles the translation of a DPTP into an ART™-compatible format, and also asserts the data into the DPTP knowledge base. Figure 14 is an example of a burst schema in the DPTP knowledge base.

The real-time knowledge base contains critical information about the real-time data and is updated by generation of the EDS. A LISP interface program stores the state of the last EDS and compares it with the current EDS; changes

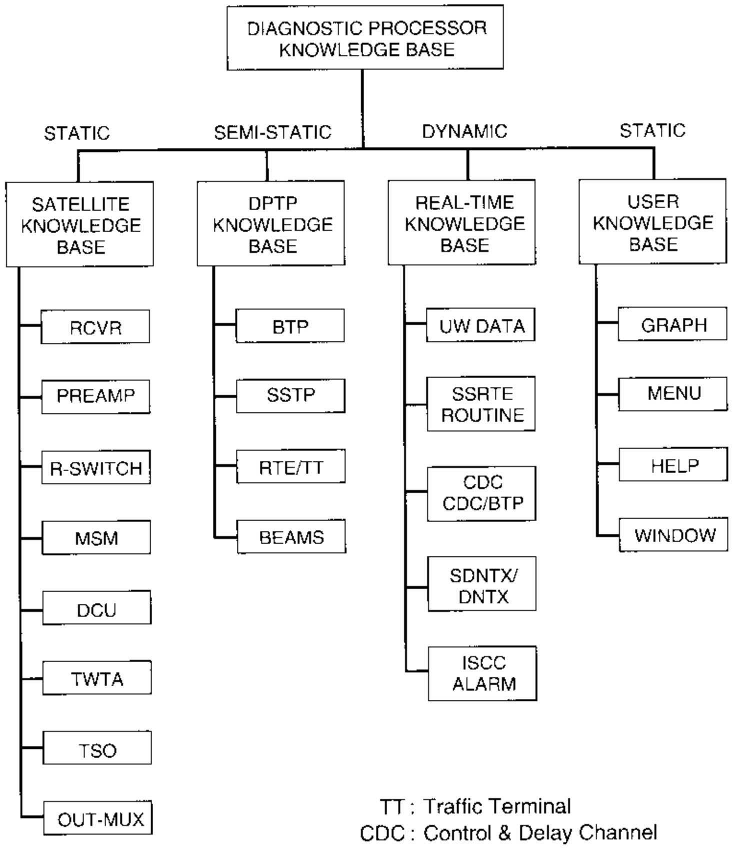


Figure 12. *DES Knowledge Base Structure*

```
(DEFSCHEMA TWTA-NW-1
    (INSTANCE-OF HP-AMPLIFIERS)
    (HP-AMPLIFIER-OF SATELLITE)
    (CHANNEL 1)
    (BEAM-ID  41)
    (BEAM-NAME NW)
    (SCC-PIN-ID     PW12416
                    PW12628) )
```

Figure 13. *Schema Block in Satellite Knowledge Base (Example)*

```
(DEFSCHEMA B_19_XP-41_3102
    (INSTANCE-OF      BURST)
    (BURST-OF         3102)
    (DOWNBEAM-ID      41)
    (BURST-NO         19)
    (BURST-TYPE       T)
    (UPBEAM-ID        51)
    (TRANSMIT-STATION BYO-1A)
    (TRANSMIT-TERMINAL-ID 68)
    (BURST-POSITION   86496)
    (BURST-LENGTH     9496)
    (STATUS NV) )
```

Figure 14. *Burst Schema in DPTP Knowledge Base (Example)*

are then identified and asserted into the real-time knowledge base. Figure 15 is an example of the schema for UW detection data. The slot corresponding to burst status is initially set to Not Valid (NV), and its value is updated by the UW data contained in the EDS. Figure 16 is the state transition diagram for the burst status.

Diagnostic Rules

The diagnostic procedure is implemented in five phases, so that the rules can be executed ("fired") in an orderly fashion. The five phases, and the key functions of each phase, are charted in Figure 17.

In the Wait phase, the system is awaiting the arrival of an EDS from the preprocessor. All the knowledge base elements except those of the EDS are in working memory. The rules are in their initial status, and each necessary instantiation status which references existing knowledge base elements is already established. This state ensures that the diagnostic process requires the least possible time once an event is detected.

When an EDS is received, the Read phase begins by reading the EDS and updating real-time knowledge base elements. If a burst loss condition is detected, the Rule Execution phase begins, in which the diagnostic rules are fired in accordance with the conditions they satisfy. One or more causes of network failure are identified in this phase.

The Synthesis and Diagnosis phase develops the various diagnoses, coordinates actions between them, and finalizes them. The finalized diagnosis schema, including probable causes and supporting evidence, is then released to the user interface for display.

```
(DEFSCHEMA UW-DETECTION
        (SPACECRAFT-ID)
        (SOURCE-ID)
        (FLOW-STATUS)
        (WITH-IN-WINDOW)
        (TIME-OF-TRANSMISSION)
        (DR)
        (NRDE)
        (DEMOD)
        (EFFECTIVE-TIME)
        (CHANGE-STATUS-INDICATOR)
        (DATA-VALIDITY)
        (TRANSPONDER-ID)
        (PORT-ID)
        (RB1-STATUS)
        (RB2-STATUS)
        (BURST-STATUS)
        (BTP-NUMBER)
        (DIAG-RCVR-STATUS)
        (DR-FAULT-STATUS)
        (POWER-SUPPLY-FAILURE)
        (DEM-UNIT-TOTAL-FAULT)
        (MODULE-FAULT)
        (LCL-CLK-GEN-MODULE-FAULT)
        (DEMOD-#1-UW-DET-MODULE-FAULT)
        (DEMOD-#2-UW-DET-MODULE-FAULT)
        (RFAS-PROC-MODULE-FAULT)
        (INTFC-PROC-MODULE-FAULT) )
```

Figure 15. *Schema Block for UW Detection Data (Example)*

The Cleanup phase ends the diagnosis cycle by retracting EDS elements and intermediary facts from working memory. The diagnosis rules are reinitialized, and the system is returned to the Wait phase.

The time between the occurrence of an event and the generation of a diagnostic report is the aggregate of data collection and preprocess time, real-time knowledge base update time, and diagnosis rule execution time. On average, data collection and preprocessing take about 30 to 40 s, due to message processing delay in the network nodes. Updating the real-time (EDS) knowledge base takes approximately 30 s, depending on the number of elements with changed status. This time is necessary to establish pattern matches and a pattern net for diagnosis rules. The time required for rule execution varies with the complexity of the rule. The total time required by the overall process is normally less than 2 minutes, which is well within the initial 3-minute performance objective set by the users.

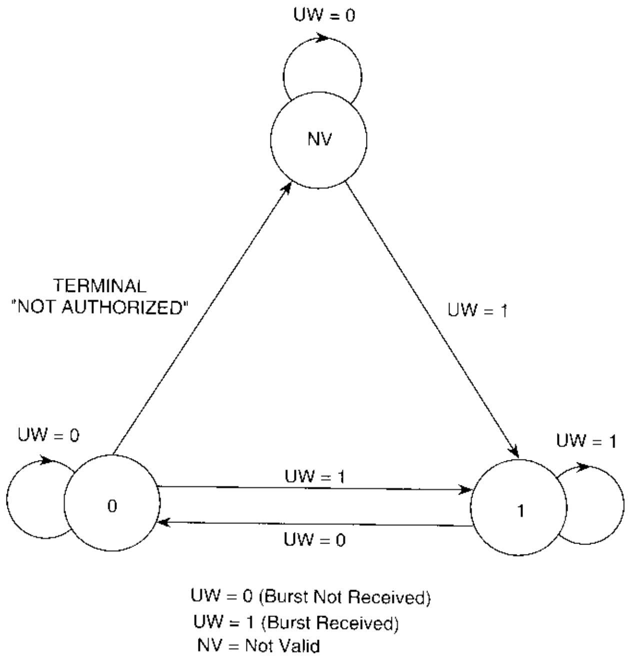


Figure 16. *UW Status Transition Diagram*

The system has been implemented with a total of 40 diagnostic rules, which are partitioned into different categories, depending on the type of network anomaly identified. The general syntax of a rule is as follows:

Rule Name:
  Phase Control Pattern
  Priority Control Pattern
  Status and Configuration Conditions
  => Action

The phase control pattern allows partitioning of rules by function, and controls the manner in which the rules are fired by constraining them to procedural behavior rather than opportunistic behavior. The priority control pattern allows rules to be interdependent by exhausting one rule completely

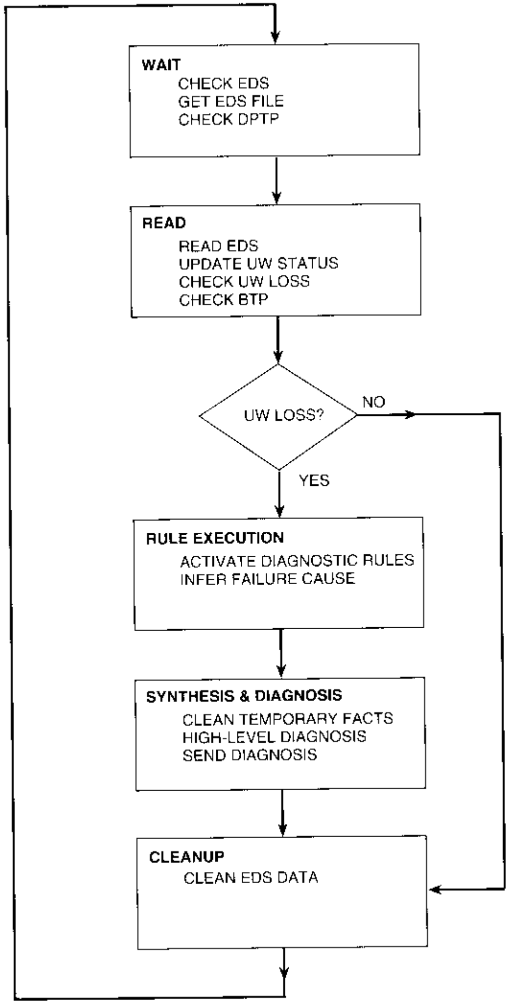


Figure 17. *Diagnostic Phase Control Flowchart*

before another is fired. The status and configuration conditions form the core of the rule that accesses the knowledge bases. Figure 18 lists examples of some conditions associated with typical network anomalies. The conditions of the rules are expressed verbally, instead of in ART™ format, to enhance understandability.

Network Anomaly: Satellite Receiver Failure

- All bursts in the affected upbeam are declared BNR.
- In case of dual channel bank operation, bursts in the upbeams of both channel banks are declared BNR.
- Terminals controlled in the affected upbeam fail.
- Out-of-limit telemetry alarm may be received.

Network Anomaly: DCU Memory Error Type 3 (bit-flip) Switchover Time is Corrupted, Thereby Affecting Two Adjacent Switch States

- All bursts scheduled in a particular portion of the frame covering one switch state are declared BNR.
- If the DCU memory error affects the
  - TAS region, traffic terminals may be shut down by the SSRTE due to loss of synchronization on the principal burst.
  - RBD region, each SSRTE shuts down the other SSRTE.
  - Metric region, the ASU loses synchronization.
- Uncommanded Status Change alarm is most likely received.

Network Anomaly: MSM Diode Failure (permanent open)

- All bursts in a particular upbeam-to-downbeam path are declared BNR.
- Terminals transmitting their principal burst in the affected upbeam are shut down.

Figure 18. *Diagnostic Rules for Typical Network Anomalies*

It is sometimes possible to observe conditions that match more than one network anomaly. In this case, multiple diagnoses are generated. With further operational experience, it is intended to associate probabilities with each of the multiple diagnoses.

It is also possible that none of the sets of the observed conditions will match a network anomaly. In this case, the cause of failure is declared "unknown" and the following critical information is displayed:

- Identities of bursts (terminals) declared BNR
- SDNTX/DNTX alarms sent to terminals
- Status of metric burst at each SSRTE
- Telemetry alarms (if any).

The unknown diagnosis can be analyzed further using the playback facility.

User Interface

During design of the expert system, special consideration was given to the requirement for a user-friendly interface. The user community was actively involved throughout the development cycle. Of the 250 rules used to build the system, almost half relate to the user interface.

The interface is object-oriented, employing menus and icons, and allowing all operations to be performed by either the mouse or the keyboard. The menu hierarchy is illustrated in Figure 19. Among the many functions supported by the menus, three are particularly noteworthy. The first function is the ability to browse through knowledge bases related to the satellite, earth station, and burst time plan. A graphical view of the SSBTP can be obtained to facilitate understanding of network configuration and control. A second function allows manual switching of background and foreground time plans (DPTPs), with provision for automatic switchover as a future enhancement. Finally, diagnosis archives are automatically maintained for retrieval and analysis of historical data. Figure 20 is an example of the screen display when a satellite failure is diagnosed, and Figure 21 shows a screen display when RF interference is diagnosed.

Verification and validation

The diagnostic processor was verified and validated in two steps. First, the flow of real-time data was simulated to verify the logic of the network monitoring process that generates the EDS. The simulated EDS was then used to verify the logic of the diagnostic rules and the diagnosis generation procedure. The rules were verified under a wide range of network configurations.

In the second step, the diagnostic processor was further validated by testing in an actual SSTDMA network environment. Spacecraft anomalies were simulated by implementing special SSTPs that caused abnormal connectivity in the onboard MSM [8].

In one example of system verification and validation tests, an MEU in the on-line memory of the active DCU was simulated. The MEU occurred in the switch control word, adversely altering the connectivity in a given switch state. In this test, the network was configured with 12 transponders and 22 traffic terminals. A special SSTP was used in which a particular switch state (No. 13) was modified to simulate the MEU.

When the DCU memory containing the special switch state was brought on line, a burst status change condition was triggered. The status of the UW detection table from the west SSRTE indicated that two traffic bursts were not received. By comparing this with the DPTP information in the knowledge base,

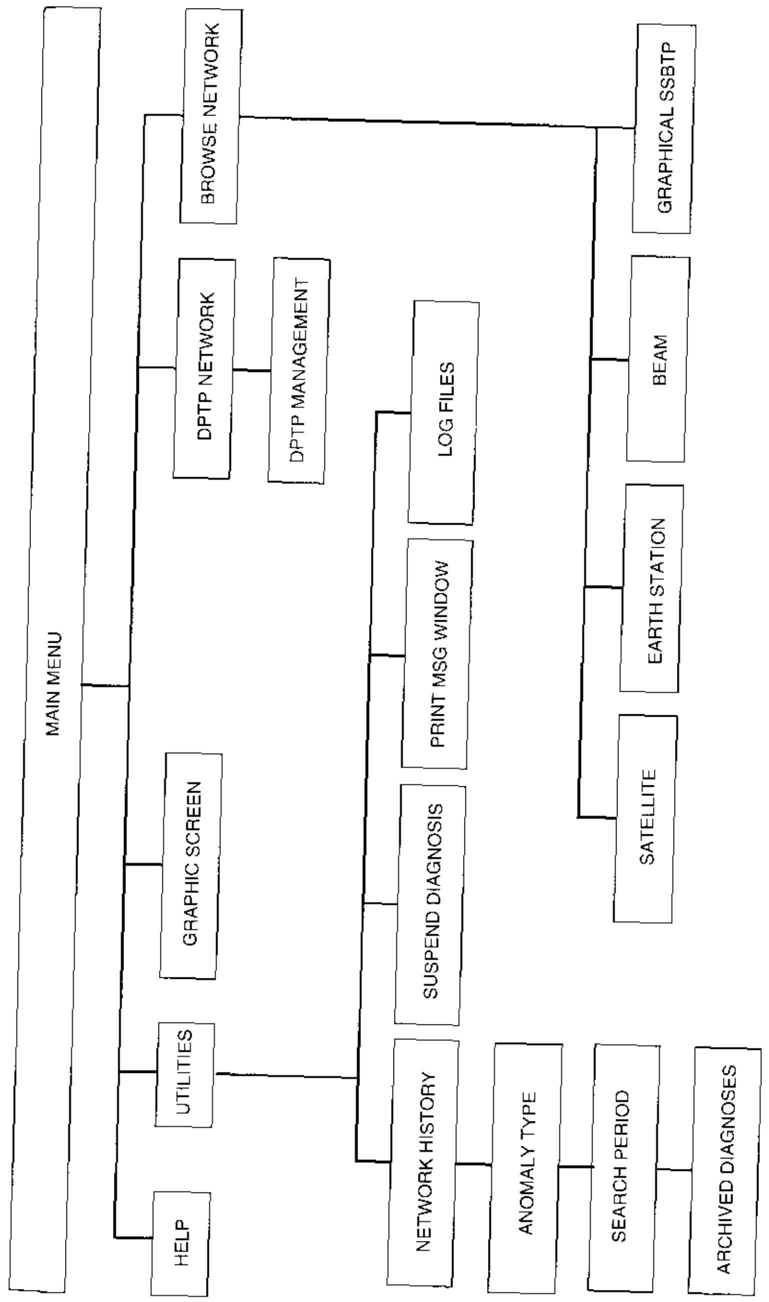
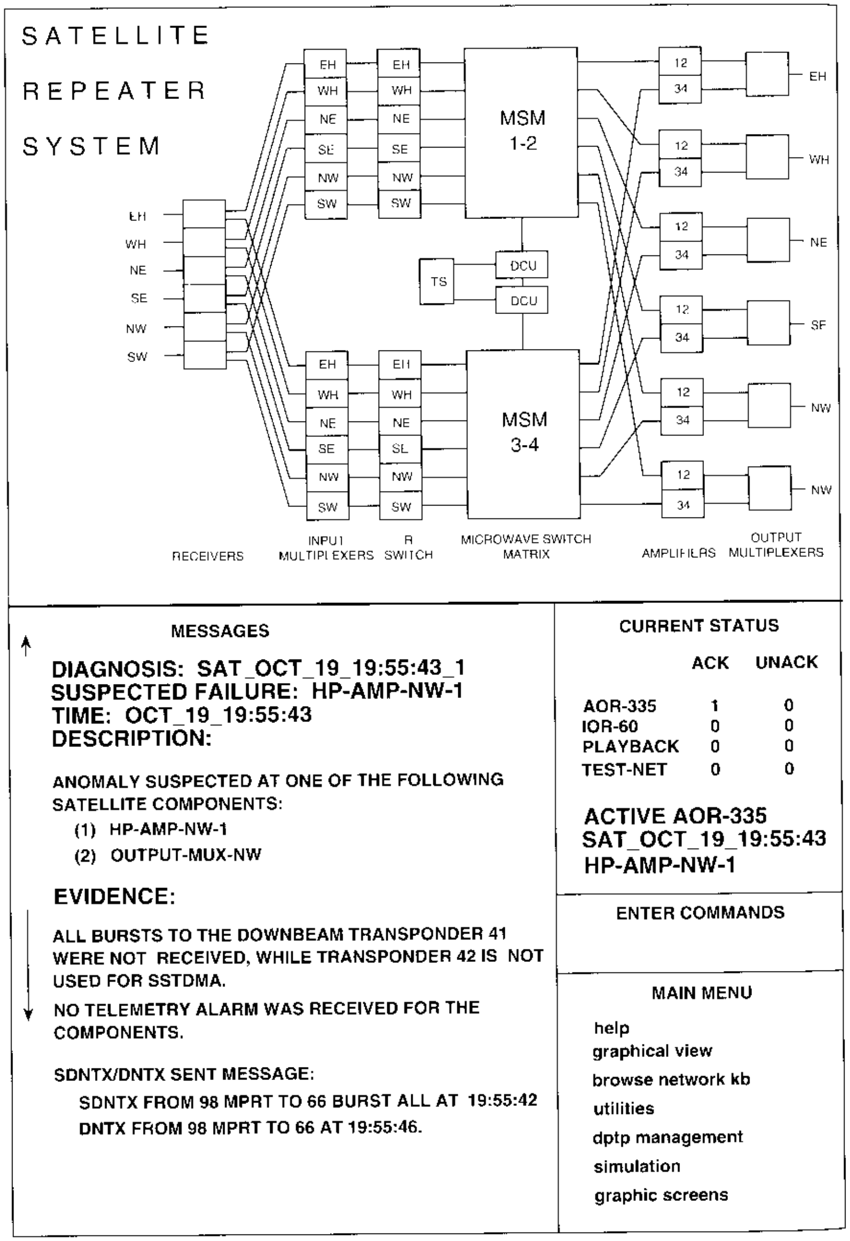


Figure 19. *User Interface Menu Hierarchy*



DIAGNOSIS: SAT_OCT_19_19:55:43_1
SUSPECTED FAILURE: HP-AMP-NW-1
TIME: OCT_19_19:55:43
DESCRIPTION:

ANOMALY SUSPECTED AT ONE OF THE FOLLOWING SATELLITE COMPONENTS:
(1) HP-AMP-NW-1
(2) OUTPUT-MUX-NW

EVIDENCE:

ALL BURSTS TO THE DOWNBEAM TRANSPONDER 41 WERE NOT RECEIVED, WHILE TRANSPONDER 42 IS NOT USED FOR SSTDMA.

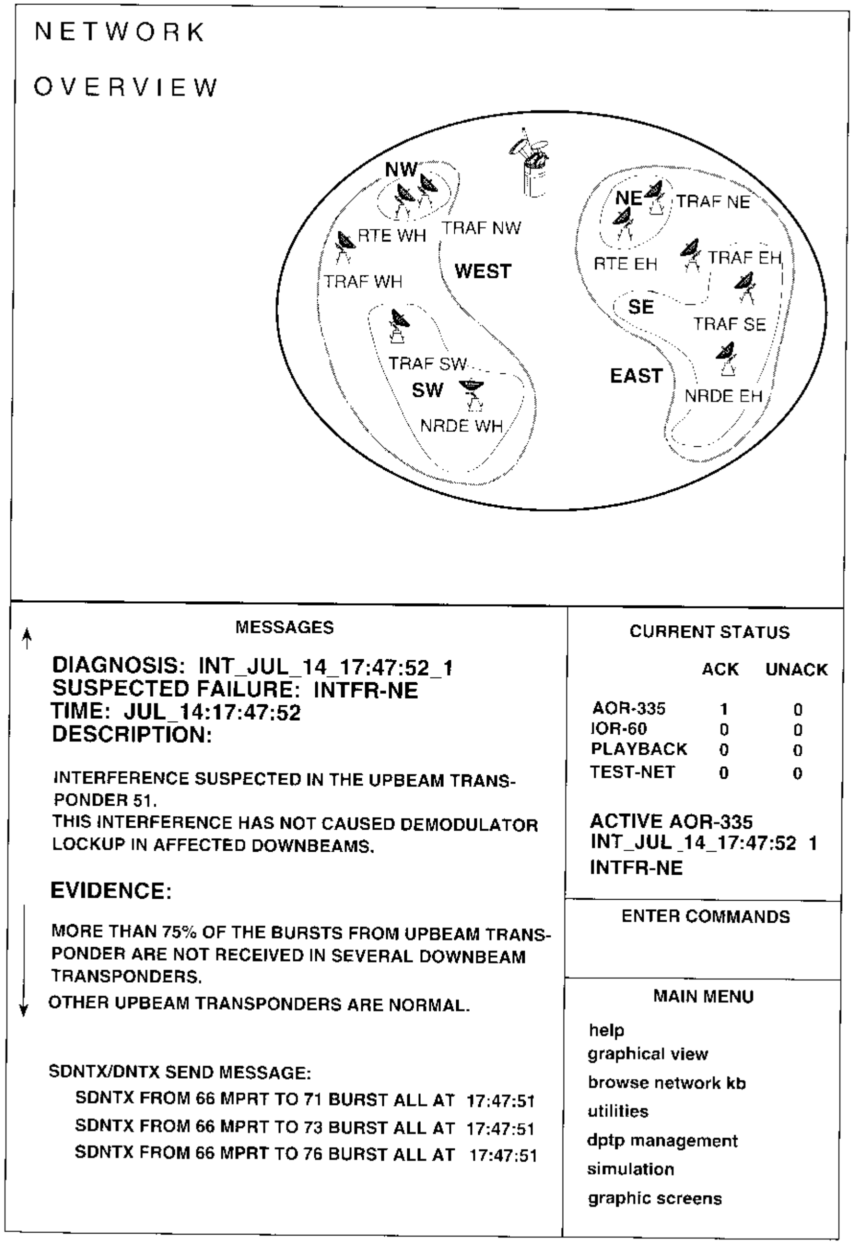
NO TELEMETRY ALARM WAS RECEIVED FOR THE COMPONENTS.

SDNTX/DNTX SENT MESSAGE:
SDNTX FROM 98 MPRT TO 66 BURST ALL AT 19:55:42
DNTX FROM 98 MPRT TO 66 AT 19:55:46.

	ACK	UNACK
AOR-335	1	0
IOR-60	0	0
PLAYBACK	0	0
TEST-NET	0	0

ACTIVE AOR-335
SAT_OCT_19_19:55:43
HP-AMP-NW-1

Figure 20. *Screen Display for Satellite Failure Diagnosis*



DIAGNOSIS: INT_JUL_14_17:47:52_1
SUSPECTED FAILURE: INTFR-NE
TIME: JUL_14:17:47:52
DESCRIPTION:

INTERFERENCE SUSPECTED IN THE UPBEAM TRANSPONDER 51.
THIS INTERFERENCE HAS NOT CAUSED DEMODULATOR LOCKUP IN AFFECTED DOWNBEAMS.

EVIDENCE:

MORE THAN 75% OF THE BURSTS FROM UPBEAM TRANSPONDER ARE NOT RECEIVED IN SEVERAL DOWNBEAM TRANSPONDERS.
OTHER UPBEAM TRANSPONDERS ARE NORMAL.

SDNTX/DNTX SEND MESSAGE:
SDNTX FROM 66 MPRT TO 71 BURST ALL AT 17:47:51
SDNTX FROM 66 MPRT TO 73 BURST ALL AT 17:47:51
SDNTX FROM 66 MPRT TO 76 BURST ALL AT 17:47:51

	ACK	UNACK
AOR-335	1	0
IOR-60	0	0
PLAYBACK	0	0
TEST-NET	0	0

ACTIVE AOR-335
INT_JUL_14_17:47:52 1
INTFR-NE

Figure 21. *Screen Display for RF Interference Diagnosis*

the diagnostic processor immediately identified the missing traffic bursts and displayed the following messages:

```
TB 22 BYO-2A 68 XPNDR 51/11 LOST
TB 23 LEK-2A 72 XPNDR 51/11 LOST
```

By utilizing the EDS and DPTP information, the diagnostic rules identified the BNR status bursts and displayed their positions in the frame, along with the affected switch state, transmit terminals, transmit beam, and receive beam. It was found that all bursts (two traffic bursts in this example) located at switch state 13 in the northeast-zone-to-east-hemisphere connectivity (XPNDR 51) were detected as BNR.

The expert system's inference procedure delivered the following conclusive diagnosis:

```
DIAGNOSIS:        SAT_MAR_20_18:17:22
SUSPECTED FAILURE: DCU BANK 1-2 BIT-FLIP (MEU).
TIME:          MAR_20_18:17:22

DESCRIPTION:
TYPE 1 DCU MEMORY ERROR SUSPECTED IN TRANSMISSION CHANNEL 1

EVIDENCE:
ALL BURSTS ASSIGNED IN SWITCH STATE 13 ARE DETECTED BNR
IN DOWNBEAM TRANSPONDER 51. CONNECTIVITY IN SWITCH STATE 13
MAY BE ALTERED.

SDNTX/DNTX SENT MESSAGE: NONE
METRIC BURST STATUS:
     IN XPNDR 51 MB SYNC, SMF SYNC.
     IN XPNDR 51 MB SYNC, SMF SYNC.
     IN XPNDR 41 MB SYNC, SMF SYNC.
     IN XPNDR 41 MB SYNC, SMF SYNC.
TELEMETRY ALARM: NONE
```

Initial operational experience

The diagnostic system was brought into operation with commencement of SSTDMA network service. The SSTDMA Atlantic Ocean Region (AOR) network currently operates in a three-transponder, seven-earth-station configuration. All network anomalies that have occurred thus far have been diagnosed correctly. Most have been related to traffic terminal failures, with one anomaly being related to spurious RF interference.

For each network anomaly, the diagnostic system generated a report within an average of 2 minutes of event occurrence. This allowed the operator to immediately begin a well-directed investigation of the event, without spending time on information gathering and synthesis. Without the diagnostic system, identifying the source of RF interference would have taken considerably longer because the operator would have had to contact every traffic terminal in the network. With the aid of the diagnostic system, the originating upbeam was identified immediately, significantly reducing the number of traffic terminals to be contacted and minimizing network downtime.

As an example, during the interference event, the diagnostic processor generated the following display (PB = principal burst, TB = traffic burst):

```
PB 6 TUM-2A 71 XPNDR 51/51 LOST
PB 7 LEK-2A 72 XPNDR 51/51 LOST
PB 8 GHY-6A 73 XPNDR 51/51 LOST
PB 6 TUM-2A 71 XPNDR 51/41 LOST
PB 7 LEK-2A 72 XPNDR 51/41 LOST
PB 8 GHY-6A 73 XPNDR 51/41 LOST
PB 12 GHY-6A 73 XPNDR 51/41 LOST
TB 14 TUM-2A 71 XPNDR 51/41 LOST
TB 15 TUM-2A 71 XPNDR 51/41 LOST
TB 16 LEK-2A 72 XPNDR 51/41 LOST
TB 17 LEK-2A 72 XPNDR 51/41 LOST
TB 18 GHY-6A 73 XPNDR 51/41 LOST

*** FAULT DIAGNOSIS FOR NETWORK AT 335.00 DEGREES EAST***
DIAGNOSIS:        INT_JUL_14_18:07:50 1
SUSPECTED FAILURE: INTERFERENCE-NORTH EAST ZONE
TIME:          JUL_14_18:07:50

DESCRIPTION: INTERFERENCE FROM UPBEAM XPNDR 51 SUSPECTED.
NO DEMODULATOR LOCK-UP IN AFFECTED DOWNBEAMS.
EVIDENCE:
MORE THAN 75% OF BURSTS FROM UPBEAM XPNDR NOT RECEIVED IN
SEVERAL DOWNBEAM XPNDRS. BURSTS FROM OTHER UPBEAMS NORMAL
SDNTX/DNTX SENT MESSAGE:
```

```
SDNTX FROM 66 MPRT TO 72 BURST ALL AT 18:07:49
SDNTX FROM 66 MPRT TO 73 BURST ALL AT 18:07:50

MB STATUS :
      XPNDR 51 MB SYNC LOSS, SMF SYNC LOSS
      XPNDR 41 MB SYNC, SMF SYNC

TELEMETRY ALARM : NONE
```

Conclusions

A near-real-time diagnostic system for INTELSAT VI SSTDMA networks has been successfully designed and implemented. Expert system technology was used to develop an automated network diagnostic capability, which was successfully demonstrated. Initial operational experience has proven the usefulness of the system in helping the operational staff to efficiently analyze network anomalies. The supporting evidence furnished with each diagnosis serves to enhance the operator's confidence in the system.

Significant technical and cost advantages were obtained by choosing a passive burst monitoring approach. Use of an expert system shell for implementing the diagnostic procedure allowed a small team to complete the entire project within 1 year, and within the prescribed cost limits. Designing the rules independently allowed one group of rules to be refined without affecting the other rules. As INTELSAT gains experience with SSTDMA operation, the rules will be further refined by adding heuristic knowledge to improve the accuracy of the diagnosis.

Acknowledgments

The authors would like to thank F. Assal, R. Bedford, J. Campanella, G. Forcina, A. Grossblatt, R. Kaiser, J. Lunsford, F. Luz, R. Parthasarathy, R. Peters, and B. Pontano for their many valuable suggestions and technical inputs at various phases of the diagnostic system design.

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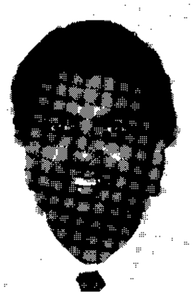
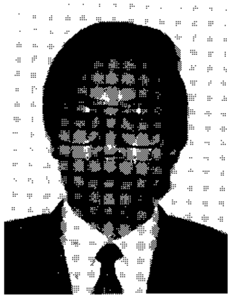
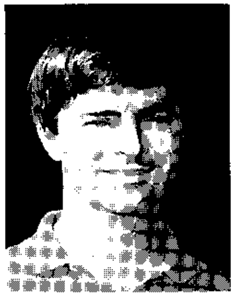


Satish P. Tamboli received a BSc in electrical engineering and computer science from George Washington University in 1977, and an MSc in operations research from Stanford University in 1979. He is currently a Senior Engineer in the Communications Engineering Department at INTELSAT, where his principal interests are INTELSAT network evolution and integration in the global ISDN/BISDN. He is also leading the effort to develop SDH transport capability within the INTELSAT system. In addition at INTELSAT, he has been involved in testing the fixed TDMA system, and in design and development of the SSTDMA system. Prior to joining INTELSAT, Mr. Tamboli was with Texas Instruments, where he was responsible for fabricating 4K and 16K static RAM integrated circuits.

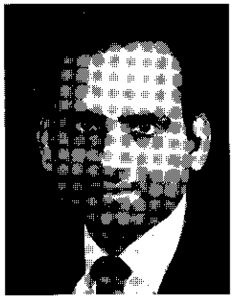


Xiaobo Zhu received a BSEE from the National University of Defense Technology, Changsha, China, in 1982; an MS in astronautics engineering from the Chinese Academy of Space Technology, Beijing, China, in 1985; and an MSEE in communications engineering from the George Washington University in 1991. From 1985 to 1987, he worked at the Chinese Academy of Space and Technology in Beijing.

Since joining INTELSAT in 1987, Mr. Zhu has been involved in the design and implementation of the INTELSAT SSTDMA network, especially the SSTDMA diagnostic subsystem. He was honored with the INTELSAT Exceptional Award of 1990 for his contributions to the SSTDMA project. He is currently a System Engineer at INTELSAT, working on the analysis and design of digital satellite networks.



Kim N. Wilkins received a BMath in 1977 and MMath in 1978 from the University of Waterloo, Canada, in computer science and artificial intelligence. From 1978 to 1979, he worked for Advanced Computer Techniques, and subsequently for COMSAT General. In 1981, he joined INTELSAT's MIS staff, where he played a major role in building the network of computers and distributed processing at the ISCC and TTC&M sites. He served as project manager for implementation of the EEGO System, an INTELSAT-wide system for procurement, general ledger, budgeting, and inventory control. He also had a key role in building the first expert system at INTELSAT for SSTDMA diagnostics, and currently supports the development of expert systems throughout INTELSAT.



Ramesh K. Gupta received a BSc (honors) in electronics and communications engineering from Punjab University, Chandigarh, India, in 1974, and an MSc and PhD in electrical engineering from the University of Alberta, Edmonton, Canada, in 1976 and 1980, respectively. He also received an MBA from the Wharton School of Business, University of Pennsylvania, in 1989. He was Punjab University Merit Scholar (1970–74) and was awarded the Alberta Government Telephones Centennial Fellowship (1976 79) for graduate research in telecommunications.

In 1980, he joined COMSAT Laboratories, where he is a Department Manager in the Satellite and Systems Technology Division. He has contributed to the application of hybrid MIC and GaAs MMIC technology in advanced satellite subsystems, and has been responsible for development of wideband microwave switch matrix (MSM) arrays, components for a 120-Mbit/s CQPSK on-board modem, and active beam-forming networks for single- and multibeam Ku-band phased-array antennas using MIC and MMIC technologies. He has also contributed to the spacecraft and ground network study and support effort for the INTELSAT VI satellite program.

Dr. Gupta has served as Vice-Chairman (1987–88) and Chairman (1988–89) of the Washington, DC/Northern Virginia Chapter of the IEEE Microwave Theory and Techniques (MTT) Society. He has authored/coauthored more than 45 papers on solid-state devices and circuits, GaAs MMICs, advanced microwave subsystems, and satellite systems. He holds two patents and was a co-recipient of the ICDSC-8 Best Paper Award for his contributions to a paper documenting the development and testing of the SSTDMA subsystem for INTELSAT VI. He is a Senior Member of IEEE.

Index: communication satellites, time division multiple access, command & control, INTELSAT

The Satellite Control Center and its role in testing and operation of the INTELSAT VI SSTDMA system

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AND T. J. DUFFY

(Manuscript received February 6, 1991)

Abstract

The satellite-switched time-division multiple access (SSTDMA) subsystem on board the INTELSAT VI satellite is an active element of the SSTDMA system. Its role requires the participation of the INTELSAT Satellite Control Center (ISCC) to generate, coordinate, and transmit command sequences to the satellite in support of burst time plan changes and onboard timing source oscillator control. To provide this capability, the ISCC is included as part of the INTELSAT Headquarters Subsystem and interfaces with the INTELSAT Operations Center TDMA Facility (IOCTF). This paper provides a general description of the ISCC, including the ISCC elements that support SSTDMA and the ISCC interface with the IOCTF. The discussion focuses on the functions and procedures used in the ISCC to generate command sequences for implementing various types of burst time plan changes, and to control the onboard oscillator to which SSTDMA system timing is synchronized.

Introduction

Prior to the era of satellite-switched time-division multiple access (SSTDMA), the interface between the INTELSAT Satellite Control Center (ISCC) and the INTELSAT Operations Center (IOC) was largely by verbal contact between their respective controllers; there was no electronic interconnection between the two facilities. Exchanges between them consisted mostly of requests for non-time-critical changes in transponder connectivities.

SSTDMA operations require synchronized, accurate control of resources, both on the ground and on board the INTELSAT VI satellite [1],[2]. With the advent of SSTDMA, a number of new procedures and tools had to be developed and implemented in the ISCC to support in-orbit testing (IOT) and day-to-day operation of the complex onboard SSTDMA subsystem. Due to the time-critical nature and relative complexity of SSTDMA operations, direct interfacing also had to be provided between certain processing systems in the two control centers.

The INTELSAT Operations Center TDMA Facility (IOCTF) is the hub of the SSTDMA control and monitoring network [1],[3]. It coordinates with the various network elements, including the SSTDMA reference terminal equipment (SSRTE), to perform network control functions such as startup, transmission and implementation of new SSTDMA burst time plans (SSBTPs), and control of satellite timing source oscillator (TSO) frequency drift [1],[3]–[5]. In addition, the IOCTF collects large amounts of data from the SSRTEs, the ISCC, and nonreference diagnostic equipment (NRDE) to support monitoring and diagnostics capability [3],[6]. SSTDMA network alarms and messages from these sources are provided to a diagnostic system within the IOCTF.

The ISCC (Figure 1) serves as the hub of the Integrated Satellite Control System (ISCS), a worldwide star network of telemetry, tracking, command, and monitoring (TTC&M) stations [7] used by INTELSAT for the tracking, telemetry processing, commanding, monitoring, and ranging of all INTELSAT satellites. The ISCC is implemented as a distributed processing system with an Ethernet backbone. Functions are distributed over various Hewlett-Packard (HP) A900 processors and fall into two groups: common support functions and spacecraft-specific functions.

Common support functions include support for data storage and retrieval, interfaces to external elements, satellite command generation, alarm processing, and network management. These functions are performed by the following processors (depicted above the Ethernet bus in Figure 1):

- *Historical Retrieval Processor.* The HRP stores data and provides satellite engineers with tools for inspecting and analyzing past and current spacecraft activities.

- *Network Concentrators and Link Processors.* The NCs and LPs perform application-level and link-level processing to provide communications between the ISCC and external facilities such as the TTC&M sites and the IOCTF.

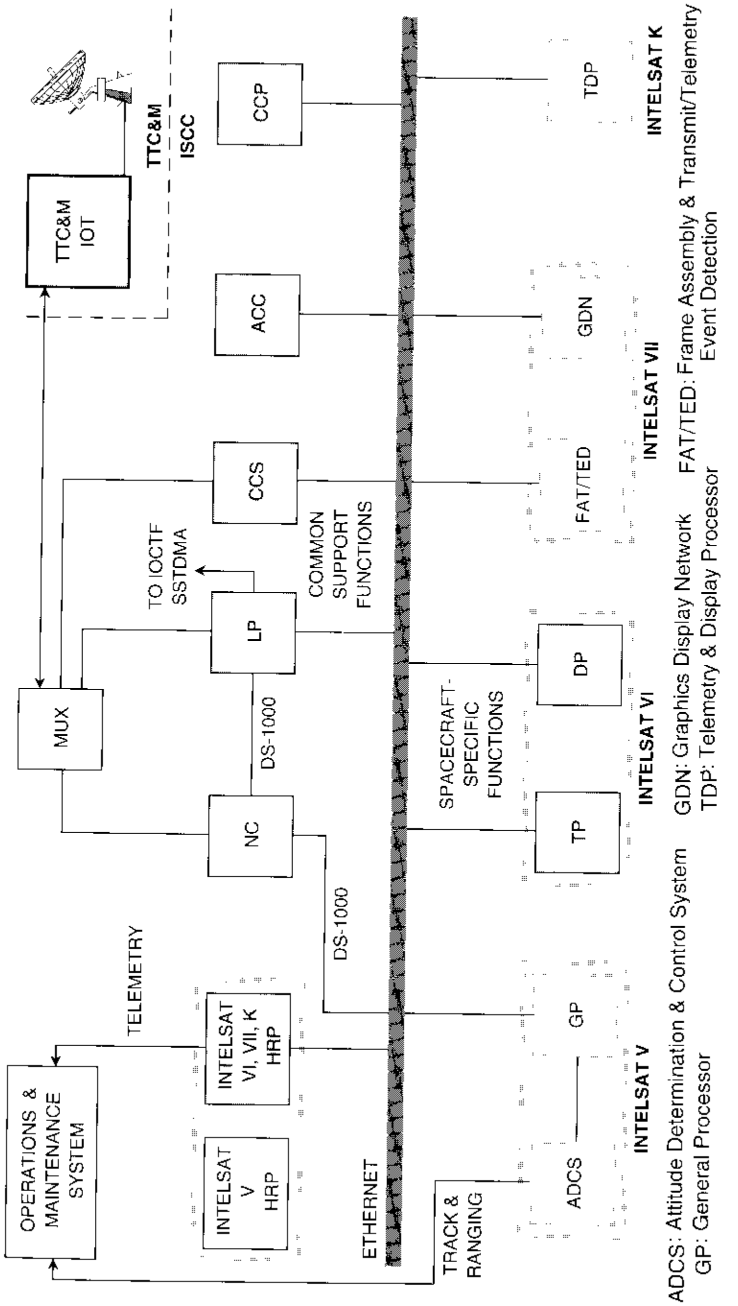


Figure 1. *ISCC Functional Block Diagram*

- *Command Coordination System.* The CCS serves as the focal point for spacecraft commanding activities for all satellites. The CCS integrates the control for all spacecraft, utilizing common commanding mechanisms and resources.
- *Alarm and Control Consolidation System*: The ACC system provides a centralized operator interface to the other ISCC processors. Events and alarms pertaining to the health of the spacecraft and the processing network are received and managed in a central database.
- *Communications and Control Processor.* The CCP provides ISCS control and management functions. In addition to maintaining the operational status of the Ethernet, the CCP performs a wide variety of functions, including network initialization, processor time synchronization, global file management, network configuration control, event and alarm processing, telemetry line management, activity scheduling, and display configuration.

Spacecraft-specific functions are organized according to the particular requirements of each spacecraft series. These functions primarily address telemetry processing and display processing. The following processors are specific to INTELSAT VI:

- *Telemetry Processor.* The TP performs telemetry capture and validation, telemetry line monitoring, multicasting of validated telemetry frames onto the ISCC local area network (LAN), transmission to the HRP of telemetry frames having bad checksums, limit and status checking, command detection and verification, spacecraft ID and mode stuffing, bit stuffing, and overriding of telemetry validation errors.
- *Display Processor.* The DP provides real-time telemetry displays and strip chart output for operational monitoring. It also generates displays and hard copy of both normal and dwell telemetry, and strip chart output for normal telemetry.

The major satellite control function performed at the ISCC is the generation of commands to configure or maneuver the spacecraft. A number of PC-based command assistance programs (CAPs) provide a means for spacecraft engineers to examine current spacecraft subsystem configurations and safely generate commands that will change the subsystem to a desired configuration. The desired configuration is specified both graphically and in text, using a menu-driven interface, or from systematically prepared maneuver or configuration files. The spacecraft commands generated by the CAPS are written to files called command queues and made available to the CCS. Figure 2 provides an overview of the processors involved in a CAP system.

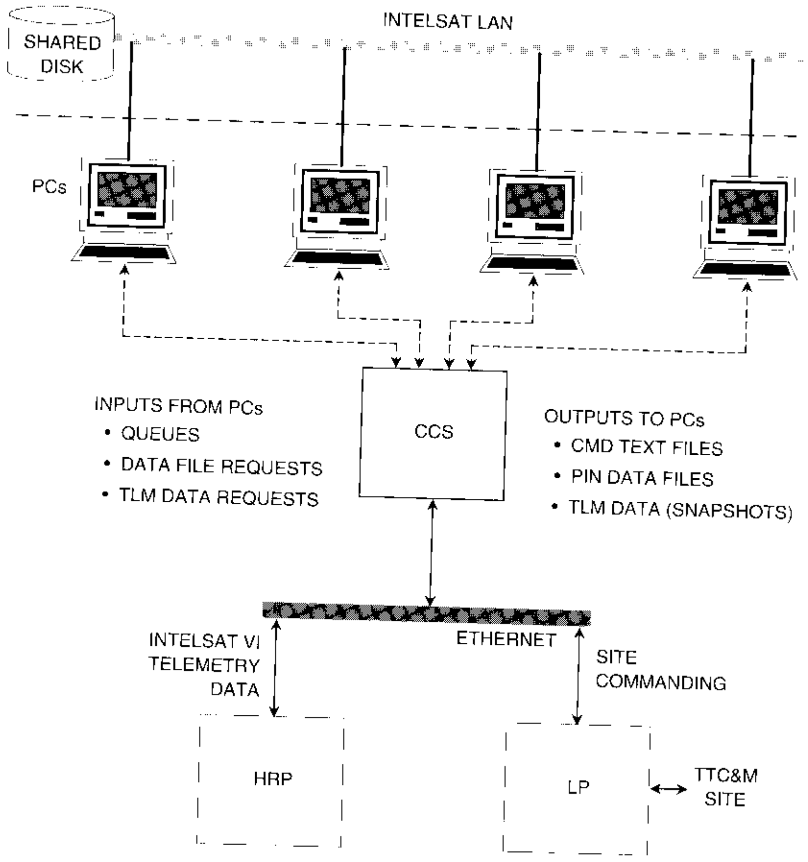


Figure 2. *Command Assistance Program Overview*

CAPs are executed as an option under the CCS shell. Other shell options provide a means for engineers to electronically approve and transfer a command queue to the real-time CCS system, which controls the execution of command queues and sends commands to the designated spacecraft. There are currently five major CAP categories:

- *Power.* This CAP generates command sequences for battery/power system maintenance.
- *Repeater.* The repeater CAP (RCAP) is used for general communications system configuration. As will be described later, the RCAP for INTELSAT VI is called RCAP6 and is used extensively for generating command sequences to configure the SSTDMA subsystem.

- *Dwell.* This CAP is used to set up dwell memory locations.
- *ADCS.* The attitude determination and control system (ADCS) CAP generates command sequences to determine and control spacecraft attitude.
- *Antenna.* The antenna CAP (ANTCAP) supports antenna positioning.

Each CAP is specific to a particular series of satellites. The CAP functions require command text files, parameter identification number (PIN) data, and telemetry snapshots to derive the necessary command sequences. The CCS maintains the current versions of the command text and PIN database files, and forwards requests for telemetry data to the appropriate processor. The CAP PCs are linked to the CCS via RS-232 asynchronous links and can operate in two modes: individual and LAN. When a PC is operating in the individual mode, data files are acquired and stored on the requesting PC's disk. When a PC is operating in LAN mode on the INTELSAT PC LAN, data are stored on a common drive to allow other CAP PCs access to the information.

The ISCC interfaces with the IOCTF through an HP DS-1000 link between the ISCC's redundant link processor and the IOCTF's packet store and formatter (PSF) computers. Figure 3 is a functional representation of the interconnection between the two facilities. Switches are provided on either end of the interfacility link for security reasons.

A detailed message protocol has been developed to interface the two control centers. Four main message types are transferred over the link:

- Switch state time plan (SSTP) data
- Synchronized SSBTP change coordination messages
- TSO correction data
- Satellite limits/status alarm data.

These message types are summarized here and described in greater detail later in this paper.

SSTP data are generated as part of the SSBTP, to modify or replace the current SSBTP [5]. The data are loaded from magnetic tape into the IOCTF control processor (ICP), which distributes them to traffic terminals and TDMA reference and monitoring station (TRMS) sites [3]. The SSTP portion of the SSBTP is downloaded by means of file transfer to the CCS in the ISCC, and subsequently to the RCAP6 PC, where it is used to generate memory load commands.

Synchronized SSBTP change coordination messages are passed between the ICP (in the IOCTF) and the CCS during BTP changes to synchronize satellite and ground station activities. From the ICP, the messages are passed to the TRMS sites via the PSF.

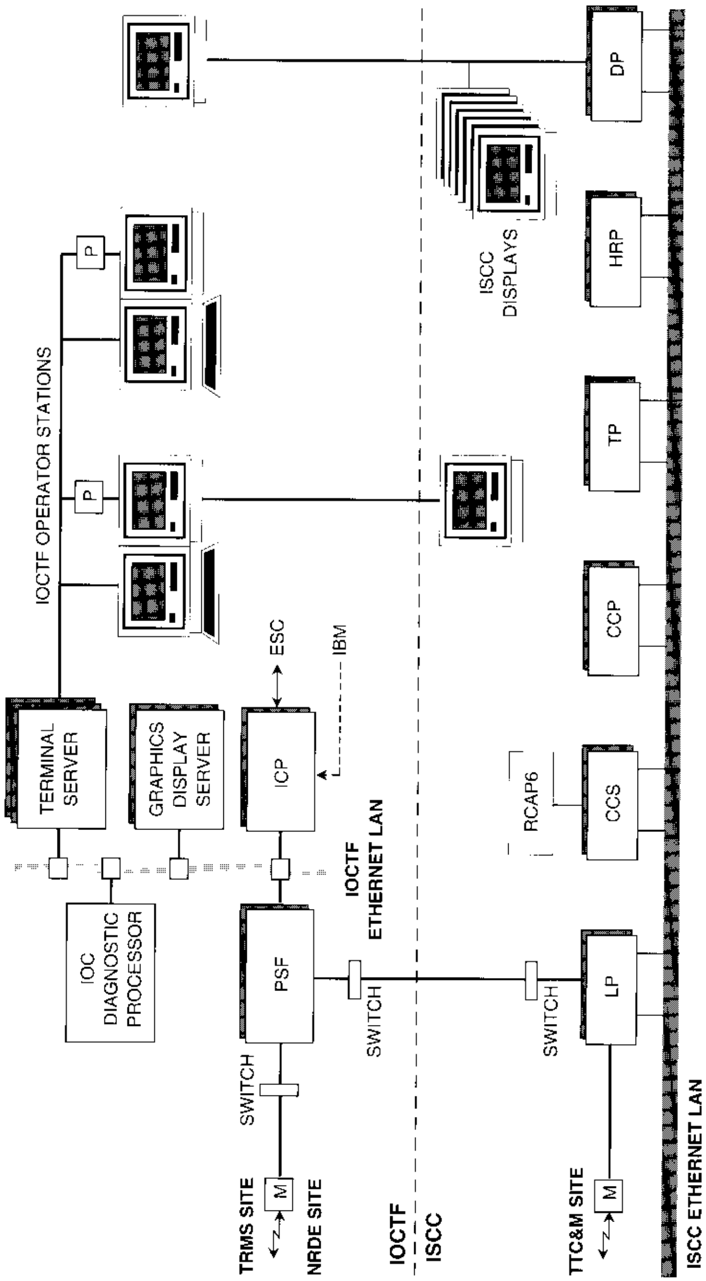


Figure 3. *IOCTF/ISCC Interface*

TSO frequency drift measurement data from the TRMS sites are passed through the PSF to the ICP, where they are used to determine when the TSO frequency should be corrected by ground command. The ICP sends the appropriate messages and data to the CCS when a correction is required.

A subset of the ISCC's satellite limits/status and alarm data is sent over the link to the diagnostic processor in the IOCTF for use in determining probable causes of SSTDMA network problems. One major area of concern is the resolution of multiple-event upsets in the SSTDMA subsystem on board the INTELSAT VI spacecraft.

Telemetry and command control of the INTELSAT VI SSTDMA payload

Because of the SSTDMA subsystem, the INTELSAT VI payload is significantly more complex than those of INTELSAT's earlier satellites. In exchange, the subsystem provides significant flexibility in both operation and redundancy. The functionality of the SSTDMA subsystem has been extensively described in References 1, 2, and 8. This section briefly describes the SSTDMA subsystem elements, their configuration control via telecommand from the ground, and their capability to be monitored via telemetry.

The INTELSAT VI SSTDMA subsystem consists of three major units and two sets of redundancy switches. The major units are the timing source, the distribution control unit (DCU), and the microwave switch matrix (MSM). The two sets of redundancy switches are the MSM bypass S-switches and the MSM row redundancy R-switches. Figure 4 is a functional block diagram of these units.

Timing source

The timing source provides timing for the SSTDMA subsystem. Each of the three redundant timing sources comprises two units: a TSO and the timing source digital electronics (TSDE).

The TSO is an oven-stabilized, voltage-controlled crystal oscillator (VCXO). Twelve commandable relays allow the oscillator frequency to be controlled to a resolution in the order of 0.1 mHz over a 2.2-Hz total control range. The 12 bits of relay control data (the TSO control integer) sent by ground command are digital-to-analog (D/A) converted to provide an analog control signal to the VCXO [1],[4].

The TSDE divides the TSO's 5.664-MHz output signal down to the three basic units of time used throughout the SSTDMA subsystem: the frame, switch frame, and switch masterframe [1]. The TSDE also provides the telemetry and storage for the 12-bit TSO control integer.

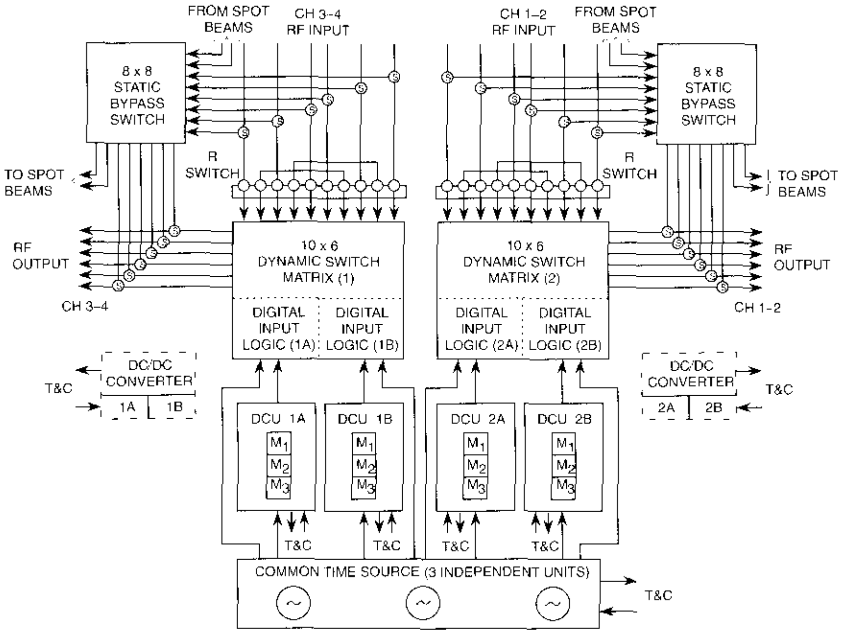


Figure 4. *INTELSAT VI SSTDMA Subsystem*

The three command-selectable modes of operation associated with the timing source are *off*, *standby*, and *active*. In the active mode, both the TSO and the TSDE are powered, and timing synchronization information is provided. In the standby mode, only the oscillator and its oven are powered.

When it is initially powered on, a TSO requires about 30 days of warm-up to stabilize sufficiently in frequency. The normal operational configuration is to command one of the three units to the active mode, while another is in standby mode and the third TSO is off. The state of each timing source is determined by the contents of the oscillator control word, which is set by ground command. The load current monitor (LCM) provides current consumption telemetry for each timing source.

Distribution control unit

The DCU controls the dynamic beam switching of the MSM in the SSTDMA subsystem. The MSM in each transmission channel is controlled from a separate DCU. For redundancy, two DCUs are provided in each transmission channel in a 2-for-1 configuration; one DCU is powered on, the other off.

Switching patterns for controlling the msm are stored in the DCU memories by ground command. There are three separate memories in each DCU, and each memory can store the interconnection and timing information for 64 switch states. Each of the three memories is configured by the memory control word (MCW) to be in a separate state. There are three possible states. The on-line state controls SSTDMA switching; the off-line state indicates that the memory is ready to load by ground command; and the standby state is a redundant spare. Only the off-line memory can be loaded by telemetry command. A full memory loading command sequence includes 192 commands requiring some 40 minutes of continuous commanding.

The telemetry control word (TCW) configures the DCU telemetry buffer to read one of the three DCU memories. The memory selected is independent of the MCW. Thus, any of the memories may be read out in telemetry, regardless of its state (on-line, off-line, or standby).

The substitution state control (SSC) and the last state address (LSA) control are also programmable for the active memory in the MCW.

All commands are verifiable in telemetry. In addition, a single-bit telemetry indication of the detection of corrupted on-line memory data is provided. This indication remains in a 1 state until the on-line memory forward error correction (FEC) syndrome is zero. The FEC is capable of detecting multiple bit errors and correcting single bit errors.

Microwave switch matrix

The MSM is capable of rapid RF interconnect switching under the control of the DCU. The MSM can be subdivided into RF, digital, and power functions. The RF portion of the MSM comprises preamplifiers and dynamic switch matrices. Each preamplifier is associated with a row in a dynamic switch matrix.

The digital portion of the MSM consists of the interface logic, which performs serial-to-parallel decoding of the switch data from the DCU and then applies a voltage bias to the appropriate PIN diode switch driver in the MSM. For redundancy, there are two interface logic units for each transmission channel. Either unit can be selected as the on-line unit by ground command.

The power portion of the MSM contains power supplies and power switching units. The MSM power supplies receive on/off commands and provide telemetry of power supply output voltage. Dedicated LCMs telemeter the current consumption of each MSM power supply.

One of two redundant MSM power supplies provides power to the MSM in each transmission channel. The power switching units provide a commandable cross-strap redundancy path for the power supply voltage to the DCU and MSM. They also provide a commandable redundant power path for the two interface logic units associated with each channel.

Redundancy switches

Switches are provided which route RF signals through either the static switch matrix (to bypass the SSTDMA subsystem), or the MSM. Each transmission channel has 12 bypass S-switches—six for the uplink and six for the downlink. The uplink and downlink switches are ganged and correspond to the six SSTDMA beams. The S-switch configuration is commandable, and the switch positions are verifiable via telemetry.

The MSM row redundancy (R-switch) network is arranged in a ring and provides the capability to switch each of the six uplink RF paths into the appropriate rows of the 10 × 6 MSM. The various positions of the R-switches are commandable simultaneously and verifiable via telemetry.

In the event of a failure in an active row of the MSM, the uplink accessing the failed row can be switched to another row. This requires a combination of R-switch rotation and reprogramming of the DCU memory to switch to the alternate row. The commanding capability, which facilitates the selection of an alternate DCU to control an MSM, provides the ability to perform row redundancy changes with only minor impact on traffic.

Telemetry processing and displays

The INTELSAT VI telemetry subsystem [9],[10] supports the transmission of raw telemetry data from the satellite to TTC&M stations and the ISCC. The telemetry data stream is bit- and frame-synchronized and is placed on the Ethernet, where various processors in the ISCC can access the data.

After relevant segments of data are extracted from the raw data stream, the data are checked against PIN databases within each processor. Each subsystem has an associated group of PINs that are used to check limits, generate alarms, and update displays.

Certain displays required for SSTDMA system operation use non-telemetered data, the value/status of which can be determined from extrinsic software functions on the ground or from commands. The extrinsic functions use telemetered data as an input.

PIN database

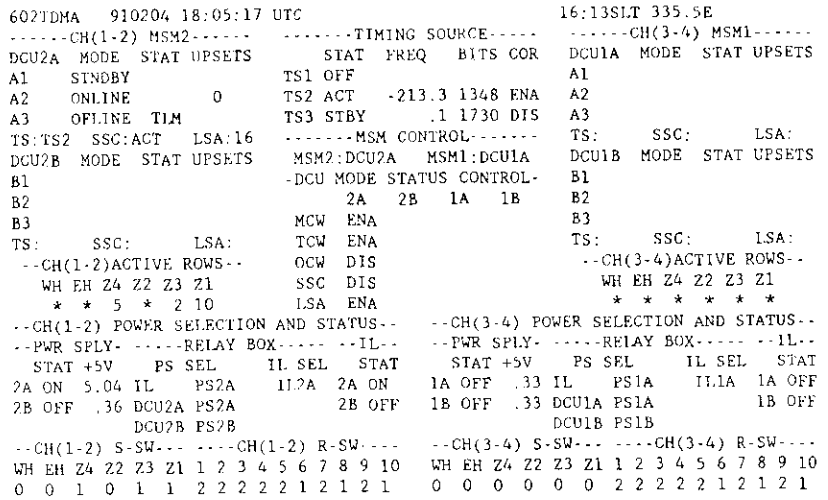
A PIN is a group of data bits which represents a specific function or value of one of the satellite's various subsystems or ground support system data. PINs are not all the same length; their length is defined by the parameter they represent. The data in each PIN are updated either directly or indirectly (derived) from telemetry. Along with the data representing functions and values, the PINs contain identification numbers that allow them to be easily identified with their associated subsystem. Both short and long text forms can be provided for further information. The PIN also allows for quick cross-referencing to the more traditional telemetry word and frame numbers, since the PIN name includes a concatenation of those numbers.

The PINs are used by a number of different processors in the ground support network. For example, the telemetry processor uses PINs to perform limit-checking and status verification, and raises alarms accordingly. Depending on the information specified in the PIN table, the display processor extracts appropriate telemetry information and categorizes the data under different subsystems so that displays for various subsystems can be updated. In addition, the PIN databases are used throughout the network, as well as by CAPs, for telemetered status derivation, pulse and serial command verification, and text generation. Two groups of PINs are related to the SSTDMA subsystem: the DCU memory subsystem telemetry data and the repeater subsystem telemetry data.

Displays

Each engineering subsystem, including SSTDMA, requires telemetry displays tailored for its particular needs. The displays used for INTELSAT VI are monochrome visual display units (VDUs) containing up to 80 × 32 alphanumeric characters. To reduce the number of VDUs required at any one time, satellite-loaded command text is present in all displays, in addition to the more specific subsystem telemetry. Telemetry displays are used for visual, functional verification of a command execution. Although the command database for INTELSAT VI operations contains telemetry verification information for each command, to enable automatic verification (*e.g.*, a switch state changes from 0 to 1) there is often more than one verification available, and the use of displays allow the engineers to quickly ascertain the overall status of a subsystem. The telemetry display is updated continually, as long as the ISCC is receiving the satellite transmission.

Operation of the SSTDMA system is supported by a number of displays that provide assistance for different types of command operations. Inevitably, some overlap of information is necessary to minimize the number of displays required for any one operation. Overall subsystem status is provided by the TDMA display. The on/off status of units is shown, as are redundancy configurations, switch configurations, on-line/off-line units and memories, DCU status, and commanded TSO frequency offset. Figure 5 shows a sample TDMA display.



```
602TDMA   910204 18:05:17 UTC                            16:13SLT 335.5E
------CH(1-2) MSM2------  -------TIMING SOURCE-----   ------CH(3-4) MSM1------
DCU2A  MODE  STAT UPSETS     STAT  FREQ   BITS COR   DCU1A  MODE  STAT UPSETS
A1     STNDBY             TS1 OFF                    A1
A2     ONLINE         0   TS2 ACT  -213.3 1348 ENA   A2
A3     OFLINE  TLM        TS3 STBY     .1 1730 DIS   A3
TS:TS2  SSC:ACT   LSA:16  -------MSM CONTROL-------  TS:     SSC:      LSA:
DCU2B  MODE  STAT UPSETS   MSM2:DCU2A   MSM1:DCU1A   DCU1B  MODE  STAT UPSETS
B1                        -DCU MODE STATUS CONTROL-  B1
B2                               2A   2B   1A   1B   B2
B3                         MCW  ENA                  B3
TS:      SSC:      LSA:    TCW  ENA                  TS:     SSC:      LSA:
 --CH(1-2)ACTIVE ROWS--    OCW  DIS                   --CH(3-4)ACTIVE ROWS--
   WH EH Z4 Z2 Z3 Z1       SSC  DIS                     WH EH Z4 Z2 Z3 Z1
    *  *  5  *  2 10       LSA  ENA                      *  *  *  *  *  *
--CH(1-2) POWER SELECTION AND STATUS--   --CH(3-4) POWER SELECTION AND STATUS--
--PWR SPLY- -----RELAY BOX----- --IL--   --PWR SPLY- -----RELAY BOX----- --IL--
  STAT +5V    PS SEL     IL SEL   STAT     STAT +5V    PS SEL     IL SEL   STAT
2A ON  5.04 IL     PS2A    IL2A  2A ON   1A OFF  .33 IL     PS1A    IL1A  1A OFF
2B OFF  .36 DCU2A PS2A           2B OFF  1B OFF  .33 DCU1A PS1A           1B OFF
            DCU2B PS2B                               DCU1B PS1B
--CH(1-2) S-SW--- ----CH(1-2) R-SW----   --CH(3-4) S-SW--- ----CH(3-4) R-SW----
WH EH Z4 Z2 Z3 Z1 1 2 3 4 5 6 7 8 9 10   WH EH Z4 Z2 Z3 Z1 1 2 3 4 5 6 7 8 9 10
0  0  1  0  1  1  2 2 2 2 2 1 2 1 2 1    0  0  0  0  0  0  2 2 2 2 2 1 2 1 2 1
```

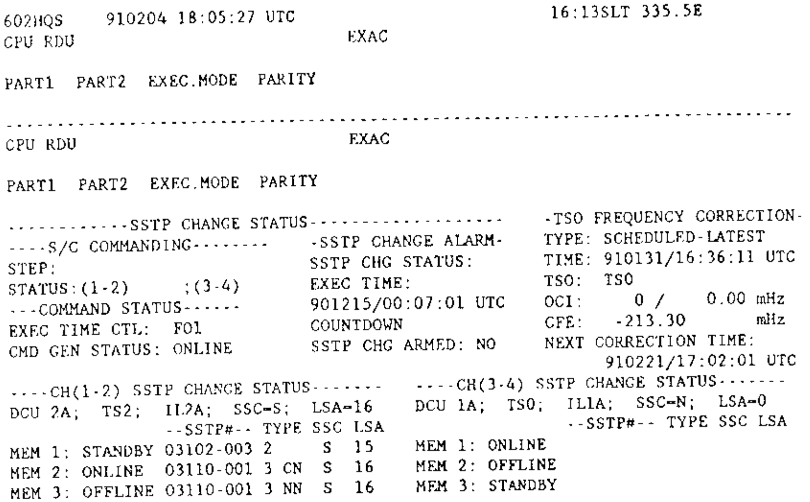
Figure 5. SSTDMA Subsystem Status Display

Information similar to that available in the IOCTF can be observed for activities which require the support of both the ISCC and IOCTF, such as countdown and status messages for coordinated memory rotations, and frequency offset and update times for TSO corrections. Figure 6 provides a sample of such a display. Via TCW selection, one memory of each DCU can be monitored in telemetry. To support this capability, a number of DCU displays are provided which show the contents of each of the 64 switch states of a memory, 16 per display. The contents of each memory are thus available for verification of memory loads or identification of memory corruption. One of these displays is shown in Figure 7.

Command coordination and generation

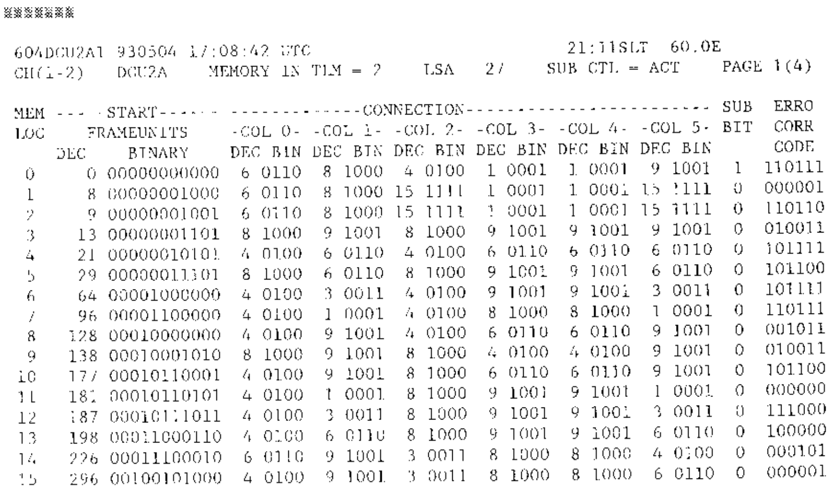
INTELSAT's Satellite Engineering Section (SES) is responsible for command generation and execution, while the ISCC controls the infrastructure used within the TTC&M network for command coordination (scheduling, processing, and transmission).

Prior to the INTELSAT VI era, all commanding was performed "manually." That is, commands were passed verbally to an operator at one of INTELSAT's TTC&M stations, who then entered them manually into the command generator for transmission to the spacecraft. As with all commanding, this process was supervised by an engineer in the ISCC, Washington D.C., who observed the commanding on a telemetry display. This approach is time-consuming,



```
602HQS     910204 18:05:27 UTC                                16:13SLT 335.5E
CPU RDU                                  EXAC

PART1  PART2  EXEC.MODE  PARITY

------------------------------------------------------------------------------
CPU RDU                                  EXAC

PART1  PART2  EXEC.MODE  PARITY

-----------SSTP CHANGE STATUS------------------    -TSO FREQUENCY CORRECTION-
----S/C COMMANDING--------     -SSTP CHANGE ALARM-    TYPE: SCHEDULED-LATEST
STEP:                          SSTP CHG STATUS:       TIME: 910131/16:36:11 UTC
STATUS:(1-2)      ;(3-4)       EXEC TIME:             TSO:  TSO
---COMMAND STATUS------        901215/00:07:01 UTC    OCI:     0 /   0.00 mHz
EXEC TIME CTL:  F01            COUNTDOWN              CFE:   -213.30      mHz
CMD GEN STATUS: ONLINE         SSTP CHG ARMED: NO     NEXT CORRECTION TIME:
                                                            910221/17:02:01 UTC

----CH(1-2) SSTP CHANGE STATUS-------      ----CH(3-4) SSTP CHANGE STATUS-------
DCU 2A;  TS2;  IL2A;  SSC=S;  LSA=16       DCU 1A;  TS0;  IL1A;  SSC=N;  LSA=0
                --SSTP#-- TYPE SSC LSA                   --SSTP#-- TYPE SSC LSA
MEM 1: STANDBY 03102-003 2     S  15       MEM 1: ONLINE
MEM 2: ONLINE  03110-001 3 CN  S  16       MEM 2: OFFLINE
MEM 3: OFFLINE 03110-001 3 NN  S  16       MEM 3: STANDBY
```

Figure 6. *SSTP/TSO Control Display*



```
▒▒▒▒▒▒▒

604DCU2A1 930504 17:08:42 UTC                            21:11SLT  60.0E
CH(1-2)   DCU2A    MEMORY IN TLM = 2    LSA   27    SUB CTL = ACT    PAGE 1(4)

MEM --- -START----- --------------CONNECTION------------------------ SUB  ERRO
LOC    FRAMEUNITS    -COL 0- -COL 1- -COL 2- -COL 3- -COL 4- -COL 5- BIT  CORR
   DEC     BINARY    DEC BIN DEC BIN DEC BIN DEC BIN DEC BIN DEC BIN      CODE
 0     0 00000000000  6 0110  8 1000  4 0100  1 0001  1 0001  9 1001  1  110111
 1     8 00000001000  6 0110  8 1000 15 1111  1 0001  1 0001 15 1111  0  000001
 2     9 00000001001  6 0110  8 1000 15 1111  1 0001  1 0001 15 1111  0  110110
 3    13 00000001101  8 1000  9 1001  8 1000  9 1001  9 1001  9 1001  0  010011
 4    21 00000010101  4 0100  6 0110  4 0100  6 0110  6 0110  6 0110  0  101111
 5    29 00000011101  8 1000  6 0110  8 1000  9 1001  9 1001  6 0110  0  101100
 6    64 00001000000  4 0100  3 0011  4 0100  9 1001  9 1001  3 0011  0  101111
 7    96 00001100000  4 0100  1 0001  4 0100  8 1000  8 1000  1 0001  0  110111
 8   128 00010000000  4 0100  9 1001  4 0100  6 0110  6 0110  9 1001  0  001011
 9   138 00010001010  8 1000  9 1001  8 1000  4 0100  4 0100  9 1001  0  010011
10   177 00010110001  4 0100  9 1001  8 1000  6 0110  6 0110  9 1001  0  101100
11   181 00010110101  4 0100  1 0001  8 1000  9 1001  9 1001  1 0001  0  000000
12   187 00010111011  4 0100  3 0011  8 1000  9 1001  9 1001  3 0011  0  111000
13   198 00011000110  4 0100  6 0110  8 1000  9 1001  9 1001  6 0110  0  100000
14   226 00011100010  6 0110  9 1001  3 0011  8 1000  8 1000  4 0100  0  000101
15   296 00100101000  4 0100  9 1001  3 0011  8 1000  8 1000  6 0110  0  000001
```

Figure 7. *DCU Display*

labor-intensive, and vulnerable to mistakes. In the INTELSAT VI era, the problems associated with manual commanding have been exacerbated by the lengthy serial commands necessary for INTELSAT VI. Although always available as an option in case of automated system failure, manual commanding is now rarely used.

With the introduction of the INTELSAT VI spacecraft, the philosophy of commanding was reviewed and modified. The primary change was the development and implementation of the HP A900-based processing system, known as the Command Coordination System (CCS), to centralize and automate commanding. The CCS provides the mechanism for executing commands generated by the SES. It also provides the link between the ISCC's real-time system and the PC-based CAPs. RCAP6 aids in generating commands for the SSTDMA subsystem on board INTELSAT VI. It communicates with the CCS processor via messages over an asynchronous data link. Figure 8 illustrates the basic interconnections of the systems involved in commanding the SSTDMA subsystem. For further details, refer to companion papers by Smith [10] and Wheeler [11].

Command coordination

The CCS provides flexibility which greatly improves the speed and ease of commanding. Commands can be sent individually by keyboard entry in the ISCC, or by running predefined files (queues) containing a list of commands. The keyboard entry method, referred to as individual interactive commanding (IIC), provides flexibility since the order of command does not have to be predefined. Queue commanding, while relatively inflexible since the command order is predefined, permits very fast commanding (*e.g.*, in changing from one spacecraft configuration to another), which is ideal for IOT. The system can also provide automation in the form of "timed queues" which, once in the system, will automatically execute at a predetermined time.

Through the use of control flags, each command in a queue can be processed differently, and prompts to the operator can be set or not set as required. For instance, after one command has been processed, the next may be automatically transmitted to the spacecraft, or the operator can be asked for "permission to transmit." Thus, control flags can be used to break the queue down into blocks. By allowing for prompts, the operator is given the ability to delay or skip individual commands. In a testing environment, each block can be used to set up a certain required test configuration on the spacecraft. Since each transmitted command is verified by the software prior to execution to ensure against corruption, security is not impaired to achieve faster commanding.

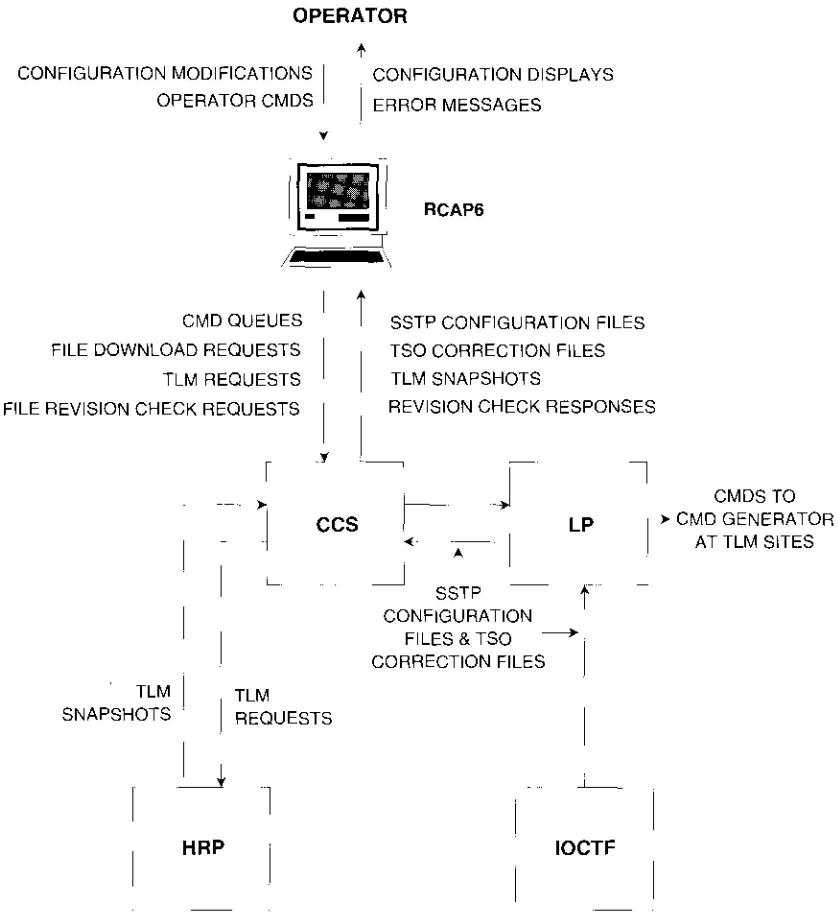


Figure 8. *SSTDMA Subsystem Command Generation System*

The use of queues has been invaluable in testing the INTELSAT VI SSTDMA subsystem, where a single memory load of 64 locations (192 commands for one channel) requires about 45 minutes of commanding with a fully automatic (*i.e.*, no operator prompt flags set) CCS queue. Considering that hundreds of memory loads are sent to the spacecraft during testing, manual commanding would mean a significant increase in test duration.

Command queue execution is a multistep process. The initial process for command generation on an RCAP PC is described below. Once a queue has been created, it must go through several stages of human approval to avoid errors. Queues can be approved to a certain level on the RCAP PC and then electronically transferred to the CCS system, where final approval is performed. Since this process is controlled by personal passwords, there is a high level of security against incorrect or unapproved commands being sent to the satellites.

Once in the CCS system and approved, the queue is placed in a library of call-up queues that can be executed immediately, or at some time in the future. Depending on the parameters contained, the queues may be used only once or an unlimited number of times. When the operator wishes to execute a queue, it is placed in the CCS "timeline"—a sequence of events that the CCS is to perform. Queues can be entered in the CCS timeline for immediate or future execution. Provisions exist for both operator-assisted and unassisted queues.

The CCS will acquire the necessary resources (*e.g.*, antenna and earth stations) at the time of command queue execution. In case of resource conflicts, each event in the CCS timeline has a priority level based on its importance to satellite safety. Once resources are available, commands are sent to the spacecraft at the times specified in the queue (or as soon as possible) until a command is reached that requires operator assistance. At that point, the queue is halted until the necessary operator input is received.

INTELSAT VI repeater command assistance program (RCAP6)

Each of INTELSAT's satellite series has a finite set of commands and associated telemetry, and each successive series has presented greater complexity in command functionality. With increasing complexity in the repeater, it has become more and more difficult for satellite engineers to manually generate the increasing volume of commands correctly and still ensure adherence to all operational constraints. For example, the numerous INTELSAT VI SSTDMA memory load commands require the use of complex Hamming code algorithms that are impractical to produce manually. Beginning with INTELSAT VI, a CAP (RCAP6) was created for the repeater subsystem. For the same reasons, RCAP5 was subsequently developed for INTELSAT V satellites.

SATELLITE DISPLAY AND MODIFICATION

In order to produce commands, RCAP6 effectively models the telemetry and command capabilities of the repeater through both graphical and tabular representation of the repeater configuration. Engineers can modify the RCAP6 representation of INTELSAT VI, which then produces the appropriate commands to make the same changes on the actual satellite. Operational constraints and signatures are built into the program and can be presented graphically or as messages. Since it closely models the real satellite, RCAP6 does not require that experienced engineers learn a different system. It also serves as an accurate software tool for new engineers to learn from and rely on.

The RCAP6 model of the spacecraft was created by analyzing the repeater and breaking its operation down into basic functions, which were then treated as logical switches for the purpose of programming. Many of the repeater's basic functions are similar, even though they are unconnected. For example, since many of the receiver redundancy switches are of the same make and are functionally the same, they can be represented by the same type of logical switch. Logical switch types vary in complexity from a simple on/off switch to the MSM found in the SSTDMA subsystem.

Each satellite function has at least one telemetry parameter associated with it and, for the purposes of ground processing, each of these telemetry parameters has a PIN associated with it. Consequently, the PIN is used to associate the telemetry parameters with individual logical switches. The PINs are stored in RCAP6 in a configuration file which associates them with their appropriate logical switches, an RCAP6 identifying tag, and information on how RCAP6 should display the logical switch.

RCAP6 routines allow the program to capture the current status of each logical switch from telemetry, via the HRP (see Figure 8), and store that status in a configuration file. Other routines graphically display the status of each logical switch and provide the operator with an interface whereby the RCAP6 status of each switch can be modified to produce the appropriate command to effect the same change on the real satellite.

RCAP6 provides engineers with two modes for representing the satellite: graphic displays and real-time display emulation. RCAP6 Graphic displays are broken down into subsets of the repeater and allow the operator to select displays of individual switches or units for modification. Graphic displays provide a best representation of the real repeater. Figure 9 shows one such display.

Traditionally, engineers have used 24 × 80-character alphanumeric displays to display telemetry. Because engineers may be more familiar with this format, RCAP6 also displays data in this format. As with the graphic display, the SSTDMA subsystem configuration can be modified from alphanumeric displays. The RCAP6 alphanumeric displays typically emulate the real-time displays provided by the display processors. An example of an alphanumeric display is shown in Figure 10.

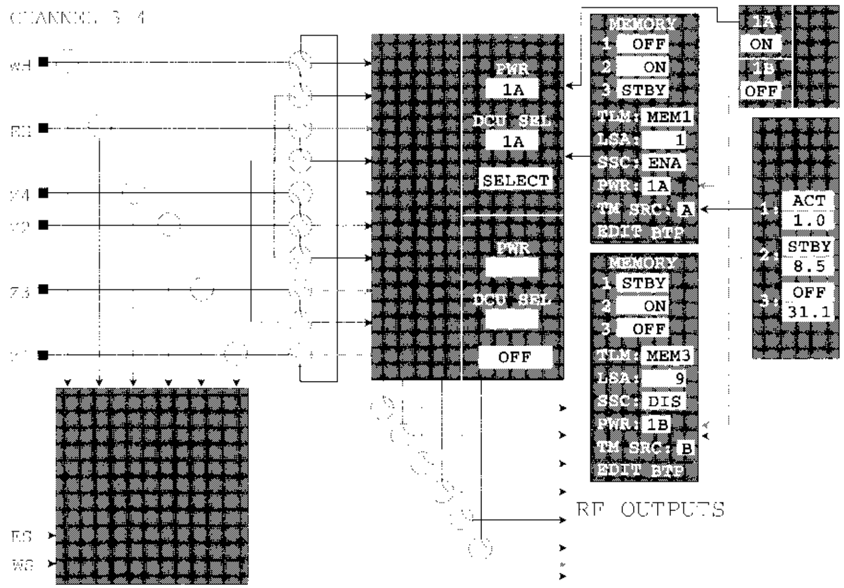
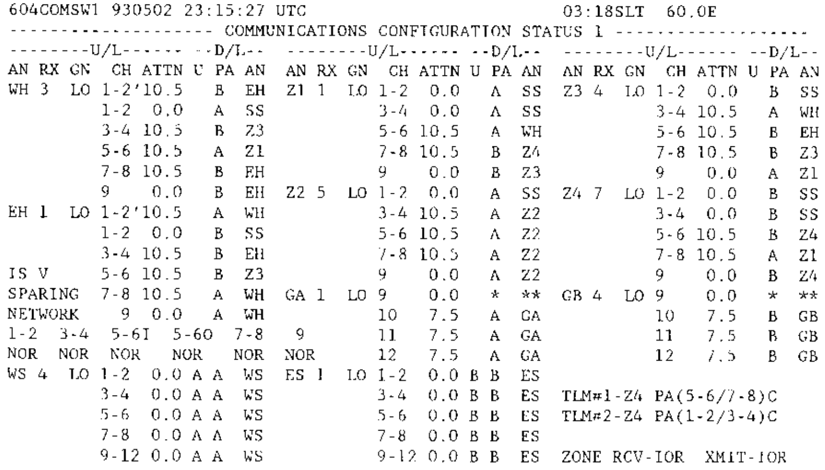


Figure 9. *RCAP6 SSTDMA Subsystem Graphic Display*



```
604COMSW1 930502 23:15:27 UTC                                  03:18SLT  60.0E
-------------------- COMMUNICATIONS CONFIGURATION STATUS 1 -------------------
--------U/L------ --D/L--  --------U/L------ --D/L--  --------U/L------ --D/L--
AN RX GN  CH ATTN U PA AN  AN RX GN  CH ATTN U PA AN  AN RX GN  CH ATTN U PA AN
WH 3  LO 1-2'10.5   B  EH  Z1 1  LO 1-2  0.0   A  SS  Z3 4  LO 1-2  0.0   B  SS
         1-2  0.0   A  SS           3-4  0.0   A  SS           3-4 10.5   A  WH
         3-4 10.5   B  Z3           5-6 10.5   A  WH           5-6 10.5   B  EH
         5-6 10.5   A  Z1           7-8 10.5   B  Z4           7-8 10.5   B  Z3
         7-8 10.5   B  EH           9    0.0   B  Z3           9    0.0   A  Z1
         9    0.0   B  EH  Z2 5  LO 1-2  0.0   A  SS  Z4 7  LO 1-2  0.0   B  SS
EH 1  LO 1-2'10.5   A  WH           3-4 10.5   A  Z2           3-4  0.0   B  SS
         1-2  0.0   B  SS           5-6 10.5   A  Z2           5-6 10.5   B  Z4
         3-4 10.5   B  EH           7-8 10.5   A  Z2           7-8 10.5   A  Z1
IS V     5-6 10.5   B  Z3           9    0.0   A  Z2           9    0.0   B  Z4
SPARING  7-8 10.5   A  WH  GA 1  LO 9    0.0   *  **  GB 4  LO 9    0.0   *  **
NETWORK    9  0.0   A  WH           10   7.5   A  GA           10   7.5   B  GB
1-2  3-4  5-6I  5-6O  7-8   9       11   7.5   A  GA           11   7.5   B  GB
NOR  NOR  NOR   NOR   NOR  NOR      12   7.5   A  GA           12   7.5   B  GB
WS 4  LO 1-2  0.0 A A  WS  ES 1  LO 1-2  0.0 B B  ES
         3-4  0.0 A A  WS           3-4  0.0 B B  ES  TLM#1-Z4 PA(5-6/7-8)C
         5-6  0.0 A A  WS           5-6  0.0 B B  ES  TLM#2-Z4 PA(1-2/3-4)C
         7-8  0.0 A A  WS           7-8  0.0 B B  ES
         9-12 0.0 A A  WS           9-12 0.0 B B  ES  ZONE RCV-IOR  XMIT-IOR
```

Figure 10. *RCAP6 Repeater Subsystem Alphanumeric Display*

COMMAND GENERATION

Once the operator has modified the RCAP6 display of the satellite to obtain the desired configuration, the RCAP6 program compares those changes to the original configuration and produces the appropriate commands, in the sequence in which modifications were made. One change by an operator may require more than one command in order to reproduce the same change on the satellite. Where necessary, command routines are associated with particular logical switches.

The command database input files for command generation are the same dBase III+ files used to generate real-time system files. Command text is also generated for each command. There are two types of commands: serial and pulse. Serial command text is dependent on the command bit structure, since each serial command will typically perform more than one function. Pulse commands perform discrete functions and their text is generally fixed, although identical pulse command data may affect totally different functions, depending on which other commands precede the pulse command.

Once RCAP6 has generated the commands, the operator will use an RCAP6 interface to produce the commands in a file or command queue, in a format compatible with the real-time CCS. The operator has the option to set defaults for the CCS flags at this point. Individual commands, and their flags, can be modified using a PC-based command queue editor. Once the command queue has been generated, it can be printed, approved, and transferred to the CCS.

EXPERT SEQUENCES

Some satellite configuration functions may require many commands to produce a desired modification. In order to simplify these processes as much as possible for the operators, "expert sequences" have been produced within RCAP6. An expert sequence is an interface which requests specific information from the operator and then "cans" an involved series of processes into one operation. In this way, a large number of complicated commands can be produced with a minimum of effort. For instance, the laborious process of producing 192 commands, one by one, from an SSTP (as described later) can be reduced to a few operator keystrokes.

INTERFACES WITH CCS

RCAP6 can be run as a stand-alone program or from within the CCS PC operator interface shell. The shell provides a file transfer mechanism for sending the command queues to the real-time CCS. It also provides RCAP6 with access to the real-time system to perform a number of other functions, including transfer to RCAP6 of the SSTP data file from which memory loads are generated, access to the TSO correction messages transferred from the IOC over the IOCTF, program file revision checks, and telemetry snapshots. Through the CCS, RCAP6 accesses the latest telemetry data for a particular satellite from the current PIN database in the HRP. It then reads all relevant PIN status information to a file which represents the current satellite repeater configuration and is used as the basis for displaying that configuration.

Operating the INTELSAT VI payload as part of the SSTDMA system

Operation of INTELSAT VI SSTDMA subsystem requires close and accurate coordination between the SES/ISCC and the IOCTF. As detailed previously, processors in the two systems are linked in order to automate operation as much as possible. This section describes the functional role of the ISCC in the operation of the SSTDMA subsystem.

SSTP changes

Changing the satellite's onboard SSTP requires an involved series of operations. New SSTP data stored in the IOCTF must be made available to the ISCC system by transfer over the IOCTF link. The ISCC inputs these data to RCAP6 in order to generate commands required to upload the SSTP to the satellite. Commands are then sent to the satellite to exchange the old SSTP for the new one. Depending on the type of change, this action may also need to be coordinated with the SSTDMA network stations.

TYPES OF SSTP CHANGES

When it is necessary to change the programmed sequence of connectivities in the satellite, a new SSTP must be implemented on board. Basically, there are two categories of SSTP changes: coordinated and uncoordinated. Uncoordinated changes comprise three types:

- *Type 1.* Even though the MSM is designed to perform dynamic beam switching, it can also carry static traffic by making the same beam-to-beam connection in every switch state. This can occur simultaneously with SSTDMA. Changes to these static connections which do not affect SSTDMA Dynamic switching are referred to as type 1 changes.
- *Type 2.* An area of the SSTDMA frame is allocated for burst mode link analyzer (BMLA) testing between the network stations. Changes to these test slots are referred to as type 2 changes. They do not affect SSTDMA traffic.

- *Type 4*. Prior to a coordinated (type 3) change, it is necessary to load a "blind-slot" SSTP, which provides blanking of the switch state verification (SSV) slot. This is referred to as a type 4 change. Reappearance of the SSV after the type 3 change verifies that the satellite's SSTP has been changed correctly.

A *Type 3* SSTP change is coordinated across all SSTDMA network elements, including the reference terminals, traffic stations, and the satellite. (The reference terminals play a broad role in the operation of TDMA and SSTDMA networks, as described in Bedford *et al*. [12].) This coordinated change procedure is collectively known as an SSBTP change.

Two sets of SSTPs—new-normal SSTPs and blind-slot SSTPs—are used during a coordinated SSTP change. In a blind-slot SSTP, the SSV loopback switch state in both the east and west coverage areas is removed (*i.e.*, no connection is made). The blind-slot SSTP is loaded into the DCU memory ahead of time and rotated on line. Following execution of the uncoordinated blind-slot SSTP change, the new-normal SSTP is loaded into the off-line DCU memory in preparation for the coordinated change to the new BTP. After the change, the return of the loopback connectivities in the SSV switch state confirms that the memories have rotated. A special INTELSAT Headquarters Subsystem (HQS) display has been designed to contain the information associated with an SSTP change (see Figure 6).

COMMAND QUEUE PREPARATION FOR SSTP CHANGES

The distribution of an SSTP to the ISCC is initiated by IOCTF personnel. An electronic data link through the IOCTF, employing a file transfer protocol, is used to transfer the file. The SSTP file received at the ISCC is verified using a set of messages exchanged through the IOCTF. These file transfer and verification results are reported at the ISCC through the CCS resident event and alarm notification mechanism, identifying the data file received and its verification status.

As a backup in case of failure of the electronic data link, the SSTP file (with a checksum) can be retrieved by RCAP6 through use of a floppy disk. If the computed checksum does not match the checksum contained in the SSTP file, RCAP6 will disallow further processing.

Once the SSTP has been received successfully at the ISCC, the PC-based RCAP6 is used to retrieve the SSTP file from the HP A900-based CCS, generate the DCU memory load commands with appropriate error correction bits, and format the command queue into CCS format. In addition, RCAP6 is also used to generate the DCU mode commands to rotate memory, change the LSA, set the telemetry pointer to a specific memory (TLM), and set/not-set the SSC bit, as applicable.

CCS PROCESSING FOR SSTP CHANGES

The DCU memory load commands are generated as a call-up queue in RCAP6. This queue is first verified by SES engineers (as are all commands, to prevent errors in commanding), and then electronically transferred to the CCS. ISCC controllers are required to authorize the call-up queue from the database for transmission to the TTC&M site. Once the queue is scheduled, commands are automatically transmitted to the satellite, executed, and verified by the ground network.

COMMAND QUEUE EXECUTION FOR SSTP CHANGES

For uncoordinated SSTP changes, RCAP6 retrieves the SSTP from the IOCTF and converts the SSTP data into a call-up command queue for DCU memory loads. After proper verification and authorization, the off-line DCU memory is loaded with the new SSTP, and RCAP6 generates the DCU mode command to rotate the off-line memory to on-line, with the appropriate LSA, TLM, and SSC. In an uncoordinated SSTP change, execution of the command to rotate a memory from off-line to on-line does not need to be synchronized with the SSTDMA network.

For coordinated SSTP changes, the IOCTF transmits two SSTPs to the ISCC: a new-normal SSTP and a blind-slot SSTP. RCAP6 then retrieves both SSTPs and converts them into DCU memory load command queues. The blind-slot SSTP is loaded into the off-line DCU memory and rotated on-line. At this point, the reference terminal will declare the blind slot active since the loopback SSV switch state will be lost. The new-normal SSTP is then loaded into the off-line memory in preparation for the change to the new SSBTP. A key element in the SSBTP change procedure is the synchronization of transmission of the memory rotation Execute tone to the satellite, and to the activities of the reference terminals.

An RCAP6-generated command sequence used for memory rotation contains a special CCS instruction known as a decide-in-real-time (DIRT) command. DIRT commanding allows automatic or manual insertion of the execute time computed by the reference terminal into the DCU mode command queue residing in the computer at the TTC&M site. The DIRT command queue may contain either one or two memory rotation commands, depending on the number of transmission channels involved in the change. If both channels are being rotated, dual command processing unit (CPU) commanding is used to rotate both channel memories simultaneously.

The DIRT command(s) are transmitted to the satellite, and the CCS then accepts input of an execute time calculated by the SSTDMA reference stations. The execute time is specified in the equivalent Universal Time Coordinated (UTC) of the masterframe synchronization (MFS) chosen for the SSBTP change, minus approximately 14 s. Taking into account uncertainties, 14 s is the maximum time prior to the desired MFS that the Execute pulse can be sent without causing the rotation to occur on the previous MFS [1]. Once this UTC time is reached, the Execute pulse is automatically sent by the CCS, arming the memory rotation function on board the satellite. The memories then rotate at the next MFS.

Up to approximately 6 s before the designated UTC time, automatic or manual cancellation of the command can be introduced into the CCS, preventing transmission of the Execute pulse to the spacecraft. Beyond the 6-s mark, processing delays prevent cancellation. Automatic cancellation can be sent over the IOCTF from the SSTDMA network's TRMS sites.

Upon verification of the Execute bit to arm the DCU memory rotation, an SSTP Change Armed message is transmitted over the IOCTF to the TRMS sites, indicating that the satellite has executed the SSTP change. This message in turn triggers the final network countdown, resulting in a coordinated network SSBTP switchover synchronized with the start of the MFS on board the satellite.

Timing source frequency update

To maintain the average frequency of the TSO within the tolerance required by the network, the frequency of the active onboard TSO must be changed at regular intervals. The phase drift of the timing source on board the satellite is measured by the TRMS and used by the IOCTF to generate the necessary frequency correction data. A detailed description of the complex TSO correction system is given in a companion paper by Maranon *et al.* [4].

TSO corrections can be either scheduled or unscheduled. Scheduled corrections are prepared well in advance, and the approximate time of their occurrence is predicted at the last scheduled correction. A few hours before TSO frequency correction is to take place, a warning message generated by the SSTDMA ground system in the IOC is sent via the IOCTF to the ISCC. When the time arrives for frequency correction, an alarm message is sent containing the information needed to generate the frequency correction command.

For unscheduled corrections (most likely due to larger-than-predicted drifting of the TSO), only the alarm message is sent to the ISCC, indicating an abnormal drift requiring urgent correction.

CCS PROCESSING FOR TSO CORRECTION

The warning message sent to the ISCC contains information on the scheduled time of the pending TSO frequency correction. This information is extracted to update the HQS display. At the time of the frequency correction, the alarm message transmitted contains the value of the cumulative frequency error (CFE) and the estimated time of the next frequency correction. This message requires approval in the CCS by ISCC personnel. With the data provided in the alarm message, CCS generates a data file that is made accessible to the RCAP6 program.

COMMAND QUEUE PREPARATION FOR TSO CORRECTION

After the alarm message has been received, RCAP6 can be used to generate the command queue using expert sequences incorporated specifically for this function. RCAP6 has in memory TSO characteristic curve arrays for each oscillator on board the satellite. The array element closest to CFE in the TSO correction data file is used to generate an oscillator correction integer (OCI), which will form a TSO-specific serial command that is executed after the usual approval process.

COMMAND EXECUTION FOR TSO CORRECTION

Upon execution of the TSO frequency update command, the frequency change (in millihertz) and the four-digit decimal value of the OCI are updated in the TDMA display. The same information, along with the current CFE value, is shown on the HQS display. The TSDE relay positions representing the OCI are also provided via telemetry from the satellite.

DCU memory bit-flips and anomalies

The memory devices in the DCUs of the SSTDMA subsystem are susceptible to single- and multiple-event upsets (memory bit-flips) due to the impact of high-energy particles. These phenomena are described by Gupta *et al.* [8].

Single-event upsets (SEUs) can be corrected by the FEC circuitry in the DCU. The occurrence of a nonzero syndrome results in telemetry noting the event. Multiple event upsets (MEUs) are more troublesome because the FEC circuitry cannot correct multiple bit-flips in the same word read from memory. To complicate the problem, it is possible that the FEC circuit will attempt a correction that will cause the error syndrome to return to zero, but leave the memory in error. In this case, a MEU is masked to appear as an SEU, but may result in severe disruption of the normal operation of the MSM. Depending on the location of these upsets in the MSM control word, SSTDMA traffic may be impaired or totally interrupted. This section discusses the measures taken in the ground system to monitor SEUs and MEUs and to correct MEUs.

Errors encountered in the on-line memory will cause a telemetry flag to be set for one major telemetry frame, triggering an alarm in the ISCC to alert the operators. This alarm is also transmitted to the diagnostics processor in the IOC [6]. The status of the flag over time can be retrieved from the HRP to provide statistical data on upsets.

Although only the on-line memory has onboard error correction, any of the three memories can be selected for monitoring by telemetry. Under normal operating conditions, this will be the off-line memory. Because the on-line memory may experience MEUs and be unable to correct them, a copy of the on-line memory content is stored in the off-line memory.

Depending on which portions of the memory are affected, MEUs may have no effect on traffic, a partial effect on traffic, or may cause the network to fail. For example, an upset affecting only the SSTDMA test slots will not cause traffic loss; however, an upset elsewhere in the memory may cause the loss of some traffic bursts or even the loss of reference bursts, resulting in network failure. If an MEU has a major negative impact on the network, the on-line and off-line memories will be interchanged by ground command.

Even SEUs can corrupt the off-line memory; however, monitoring with telemetry can help to detect onboard upsets on the ground, for correction by ground command. In addition, historical data on off-line memory upsets are retrieved for statistical analysis.

Although other functions in the SSTDMA subsystem are vulnerable to upsets, only the on-line DCU memory is provided with onboard FEC. While the degree of vulnerability depends on the design of the unit, upsets in these other functions could also cause network problems, including failure. Again, ground monitoring procedures enable swift restoration of the correct status via ground command.

If MEUs occur that affect the SSTDMA network, it may be very difficult for spacecraft engineers to determine which functions of the SSTDMA subsystem are affected, and therefore what corrective action should be taken. In certain cases, MEUs in the DCU memories may not result in the error flag being set in telemetry, since the onboard correction will find a solution in which the memory content matches the associated error correction code, even though the resulting data written to memory are not the same as originally sent by command. In these cases, it is necessary to rely on ground analysis of the problem.

Outages of considerable duration could be experienced if it were necessary to obtain a verbal description of difficulties at each station, before evaluating the problem. To make this process more efficient, a diagnostic processor is included in the IOCTF [6]. This processor obtains data from diagnostic equipment at the TRMS, and from certain traffic stations equipped with NRDE. The diagnostic processor also receives a subset of the ISCC's telemetry status and alarm data. Careful consideration has been given to how particular problems on the spacecraft will affect the network, including equipment failure and upsets. These problems can be recognized by their symptoms, and a limited number of diagnoses can be presented to the engineers to direct their investigation and minimize outage periods.

In-orbit testing of the SSTDMA payload

The IOT of the INTELSAT VI satellites was a complex operation which required many years of careful planning and the development of new test methodologies. A companion paper by Rosell *et al.* [9] describes much of this process. Details of the IOT specific to the SSTDMA system are given below. Subjects covered include TSO testing, MSM, and related transponder performance checkout and verification, as well as redundancy handover and reconfiguration checkout [13].

Telemetry and command functional checkout

The telemetry and command functional checkout of the SSTDMA subsystem was a first-level check which verified that the command and telemetry capabilities were fully functional after launch. These tests did not involve any form of RF measurement, but did use continuous-wave (CW) signals to verify connectivity.

For each TSO, the turn-on, initial, and steady-state power consumption for the different units were recorded to verify proper operation. Further, the frequency update capability was verified by commanding TSO relays to the extreme low (all-0) and high (all-1) frequencies. In addition, TSO relays were commanded to the 010101010101 and 101010101010 configurations while frequency data were recorded. This method of detecting cross-coupling between telemetry and command bits resulted in discovery of an apparent short in the relay circuitry of one of the three TSOs on one particular satellite.

TSO checkout was followed by power-up of the primary and redundant units, in both straight and cross-strapped modes of operation. Initial and steady-state power consumption values were recorded, followed by functional verification of DCU mode commands, including TSO selection and memory rotation.

The commanding capability to simultaneously perform dual channel bank switching was also verified using the two CPUs on board the satellite. Further, to check proper loading of all 64 memory locations in the 12 DCU memories, a 10101010... command sequence, followed by a 01010101 . . . sequence, was loaded to each memory. This tedious task required some 18 hours of commanding to upload the more than 4,600 commands associated with this test.

The error detection and correction capability of each DCU was verified by deliberately loading a memory location with corrupted data. A DCU mode control command was then executed to rotate the memory on-line, thus starting active memory correction processing. Correct functioning of this feature was verified by observing the telemetered memory data being corrected. Also, the presence of a telemetered error flag was verified. Errors were introduced in switch data and error correction bits, with nominal performance. Although onboard error correction is capable of reliably correcting only one error per memory location at one time, its performance when presented with multiple errors in one location has also been observed in orbit. As predicted, the performance was found to be "uncertain."

Digital checkout

As part of the IOT of the SSTDMA payload, performance of the MSM and associated digital elements was verified. Testing also verified the MSM's ability to perform the dynamic switching required for SSTDMA operation.

Ideally, testing is performed with the support of four test stations, one in each zone beam (and thus also in a hemi beam), to verify that all interfaces between units within the satellite switching system are working properly. The presence of all four test stations also minimizes the command reconfigurations required to test the entire SSTDMA subsystem. The two test stations in the northern zone beams were used as both transmit and receive stations, while the two test stations in the southern zone beams acted as receive stations only. By using different configurations of the zone combination network known as the INTELSAT V/V-A compatibility switches, one zone uplink signal could appear at two of the zone inputs to the MSM at the same time. Thus, all points of the MSM could be tested without the need for the southern stations to transmit.

Several test configurations based on specific R-switch settings were used to check out all rows of the MSM, given different DCU, interface logic, memory, power supply, and TSO combinations. One example of an R-switch setting used in the test is shown in Figure 11. For each test configuration, the DCU memory was loaded with an SSTP; Figure 12 depicts the contents of this memory.

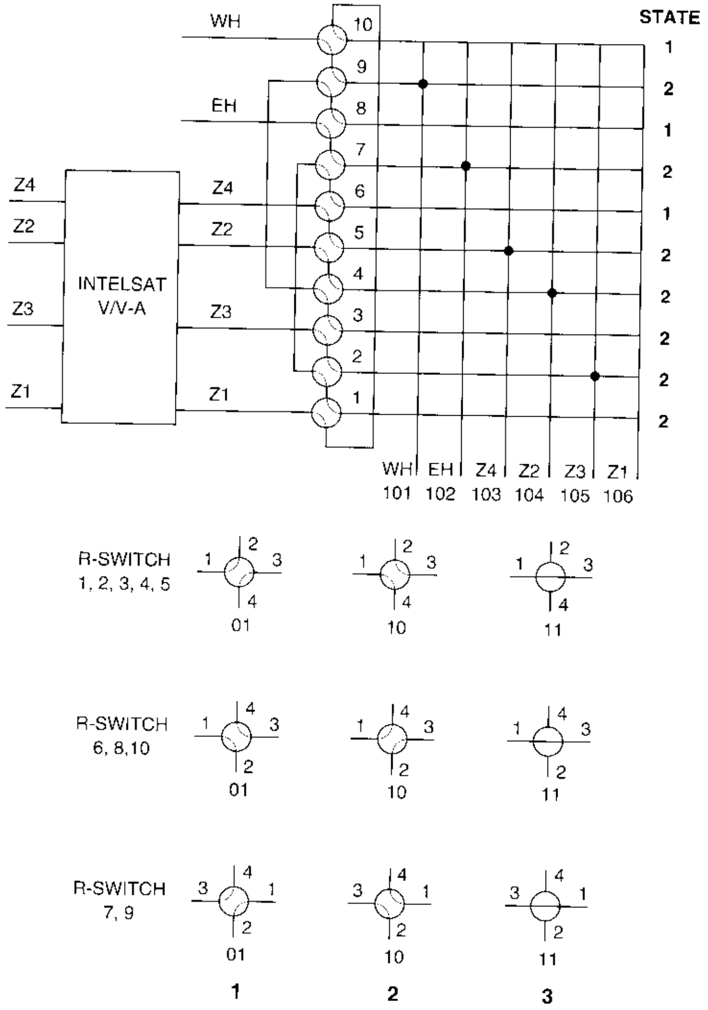


Figure 11. *Example R-Switch Setting*

The SSTP used for testing was designed so that, within a 2-ms time period, each row of the MSM is successively connected to all six downbeams at the same time. Thus, a single CW signal at one input row will appear simultaneously on all six downbeams once during the 2-ms cycle. The position of the CW signal in time during the 2-ms cycle will depend on the input row to which the signal is applied. By using the R-switches and the INTELSAT V/V-A sparing network, the signal can be routed to each of the 10 rows.

DCU LOAD R-SWITCH CONFIG: 2222212121

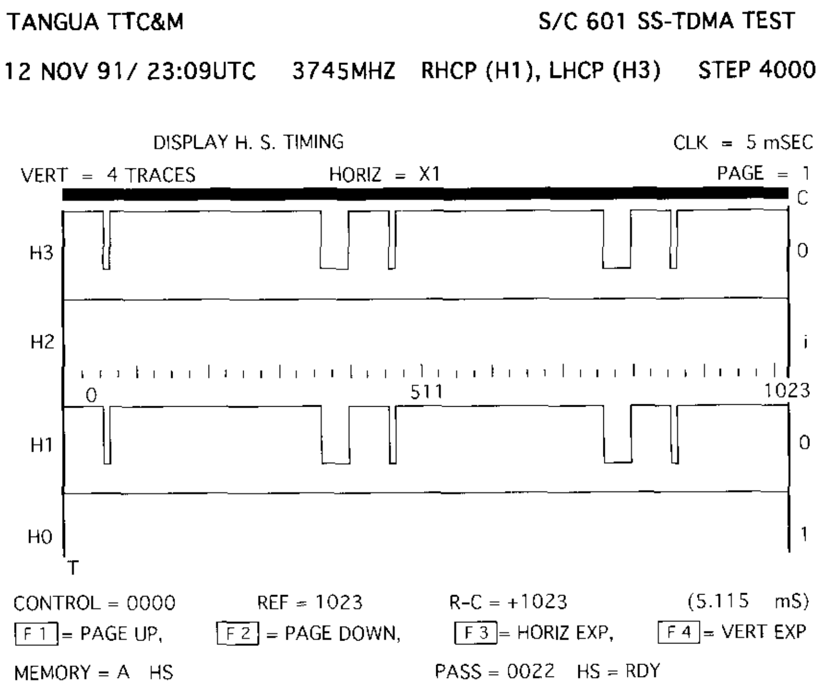
MEM AD1	SWITCH DATA (HEX)	SW-OVER TIME (FRAME UNITS)	SUBST STATE (BIN)	ERROR CORR (BIN)	MEM ADD	SWITCH DATA (HEX)	SW-OVER TIME (FRAME UNITS)	SUBST STATE (BIN)	ERROR CORR (BIN)
0	FFFFFF	0	0		32	444444	968	0	
1	000000	21	0		33	444444	996	0	
2	777777	42	0		34	555555	1028	0	
3	333333	63	0		35	555555	1056	0	
4	666666	84	0		36	555555	1084	0	
5	888888	105	0		37	555555	1112	0	
6	999999	126	0		38	555555	1140	0	
7	FFFFFF	147	0		39	555555	1168	0	
8	000000	168	0		40	666666	1200	0	
9	000000	201	0		41	666666	1228	0	
10	000000	234	0		42	666666	1256	0	
11	000000	267	0		43	666666	1284	0	
12	000000	300	0		44	666666	1312	0	
13	111111	340	0		45	666666	1340	0	
14	111111	373	0		46	777777	1372	0	
15	111111	406	0		47	777777	1400	0	
16	111111	439	0		48	777777	1428	0	
17	111111	472	0		49	777777	1456	0	
18	222222	512	0		50	777777	1484	0	
19	222222	545	0		51	777777	1512	0	
20	222222	578	0		52	888888	1544	0	
21	222222	611	0		53	888888	1572	0	
22	222222	644	0		54	888888	1600	0	
23	333333	684	0		55	888888	1628	0	
24	333333	717	0		56	888888	1656	0	
25	333333	750	0		57	888888	1684	0	
26	333333	783	0		58	999999	1716	0	
27	333333	816	0		59	999999	1744	0	
28	444444	856	0		60	999999	1772	0	
29	444444	884	0		61	999999	1800	0	
30	444444	912	0		62	999999	1828	0	
31	444444	940	0		63	999999	1856	0	

Figure 12. *Test SSTP Loaded in DCU Memory*

The test stations located in the two hemispheric and four zone beams were requested to photograph the test patterns observed for each test configuration, using a logic analyzer or a digital oscilloscope. A sample of a measured test pattern is provided in Figure 13. These data were returned by facsimile to INTELSAT Headquarters where the correct response, and thus the correct operation of the satellite's SSTDMA subsystem, was verified in real time during the test.

RF performance testing of the SSTDMA subsystem

In addition to the use of RF signals to verify the digital performance of the SSTDMA subsystem, RF testing was also employed to verify RF performance of the transponders used for SSTDMA service [9]. Even though the MSM provides very rapid beam-connectivity switching, it was important that the quality of the RF link not be sacrificed. The SSTDMA RF checkout was performed as part of the payload IOT. Units such as the receivers, TWTAs, and SSPAs had been tested for RF performance through the non-SSTDMA static switch matrix (SSM) at an earlier stage of the payload IOT. Similar tests were conducted for the SSTDMA subsystem, but with the MSM instead of the SSM in-line.



TANGUA TTC&M S/C 601 SS-TDMA TEST

12 NOV 91/ 23:09UTC 3745MHZ RHCP (H1), LHCP (H3) STEP 4000

DISPLAY H. S. TIMING CLK = 5 mSEC

VERT = 4 TRACES HORIZ = X1 PAGE = 1

CONTROL = 0000 REF = 1023 R-C = +1023 (5.115 mS)

F 1 = PAGE UP, F 2 = PAGE DOWN, F 3 = HORIZ EXP, F 4 = VERT EXP

MEMORY = A HS PASS = 0022 HS = RDY

Figure 13. *Sample of Measured Test Pattern*

Although the MSM is designed for rapid, repetitive beam connectivity switching, the RF measurements for the MSM were made in static mode, since the IOT equipment was not designed to measure a time-bursted signal. This in no way differed from the MSM's RF performance when operated in a non-static mode, since the beam connections were static for the periods in which the bursted signals were passed through those connections. In order to provide these static connections, only memory location 0 was used. This was accomplished by making the LSA equal to zero. Thus, only beam connectivity defined in the first memory location (0) was processed by the DCU, resulting in a continuous connection.

The MSM can simultaneously connect one uplink beam to as many as six downlink beams. While this is desired during SSTDMA operation, it should be avoided for the RF tests on the downlink, since, along with the desired measurement signal, any unwanted cross-polarization signal will also be seen by the sensitive IOT equipment, producing inaccurate measurements. Therefore, only single-point connections were made through the MSM; that is, one uplink beam to one downlink beam.

The SSTDMA RF tests were specifically aimed at evaluating those units not tested in the other payload RF IOTs, such as the MSM input R-switches and the MSM itself. The MSM contains input amplifiers, solid-state modularized switching ports, and output trim pads. The input amplifiers and trim pads equalize insertion loss between the various possible connections. This equalization was one of the primary functions to be checked during the RF tests.

The measurement techniques were the same as those used during the non-SSTDMA payload RF testing, and the parameters measured were saturation flux density, equivalent isotropically radiated power (EIRP), in-band frequency response, gain-to-noise temperature ratio (*G/T*), and group delay response.

Since 60 different single-point connections are possible through each of the two MSMs [channels (1-2) and (3-4)], and each connection requires a unique memory load, the spacecraft configuration commands required for the tests were considerable. Further, the input R-switches had to be reconfigured a number of times to ensure that each switch port was tested, and to provide access to each of the 10 MSM input rows. However, the time required for the commanding was greatly reduced by using predefined command queues sent via the CCS system.

Redundancy handover checkout

As with the other units on board the spacecraft, the SSTDMA system is provided with redundant equipment and considerable flexibility to avoid permanent loss of service-carrying capability due to single-point failures [8]. If a unit fails completely, loss of service is likely to occur until a replacement unit can be put on line. However, if a unit is exhibiting degraded service or only partial failure and some traffic is still being carried, it is important to replace the degraded units without bringing down the remaining traffic. Reconfigurations may also be necessary for thermal- or power-balancing of the payload. To ensure that traffic is maintained, a "hot switch" can be performed to place a redundant unit (in powered standby mode) on line. Hot-switching outages for TWTAs and other components are usually on the order of 1 ms, which may be tolerable to some services. SSTDMA may see some unique-word (UW) losses during a hot switch, but a break in timing of approximately 1 s must occur before bursts are disabled, and 2 s before the network will fail. However, while switching a TWTA on line is comparatively simple, certain types of SSTDMA redundancy handovers are considerably more complicated, perhaps requiring the simultaneous execution of more than one command.

The redundancy handover tests were performed while a simulated SSTDMA network was being operated over the spacecraft, to ensure that the expected handover outages were not exceeded. The types of handover tests are described below.

INTERFACE LOGIC HANDOVER

The interface logic is the means by which the DCU controls beam connectivity within the MSM. This logic can be swapped with less than 25-ms RF loss and requires only one command to be sent to the spacecraft. Each interface logic unit has a buffer between it and the DCU, which allows switching with minimal impact on the network as long as power is maintained to the buffer during switching.

DCU HANDOVER

The DCU handover process requires that both DCUs for the affected channel be powered at the same time. The time that both units are on must be minimized, since extended power-on of both DCUs is likely to violate spacecraft thermal constraints. This requirement is complicated by the need to configure the redundant DCU in the same manner as the on-line DCU, prior to its being put on line. Many commands must be sent to the spacecraft in order to load the DCU memory and set the LSA, SSC, and so forth. Once this is completed, the actual DCU handover requires only one command to effect the synchronized handover of the DCUs, with no impact on the network. However, since the interface logic is now operating from the same power supply as the now off-line DCU, the on-line power supply for the interface logic must be selected before the off-line DCU can be powered down.

INTERFACE LOGIC POWER HANDOVER

This procedure is performed following the DCU handover. As previously stated, the buffer between the DCU and the interface logic allows for hot switching of the logic, as long as power is maintained to the buffers. However, when switching power to an interface logic unit, the power cycling to the buffers causes the new logic unit to be in a "random" state which prevents proper operation of the MSM. This state can be cleared only by sending a command to select the on-line DCU for the interface logic. A considerable service outage could occur until the second command is sent to the spacecraft; however, a solution was identified by SES staff. Both the Power Switch and

DCU Select commands can be loaded to the spacecraft at the same time, one in each of the two command CPUs. By sending two consecutive command execute tone pulses to the spacecraft, spaced 50 ms apart, the relative speed of execution of the two CPUs can be eliminated, since one DCU select command will always occur after the Power Switch command. In this way, service can be maintained throughout the power handover. After the procedure is complete, the now off-line power supply and DCU are turned off.

ROW REDUNDANCY HANDOVER

Although a 6 × 6 MSM is sufficient for SSTDMA operation, a 10 × 6 MSM was provided for redundancy. If an input row fails, the R-switch network can be reconfigured so that rows other than the failed row can be accessed. With this reconfiguration, beams in other than the failed row may be redirected to alternative rows. Since the loaded SSTP mapping reflects a particular R-switch configuration, the currently loaded SSTP mapping will not be valid for any other R-switch configuration. Therefore a new SSTP map must be generated based on the new R-switch configuration.

To avoid considerable loss of service, the SSTP memory loads must be swapped simultaneously with the R-switch reconfiguration. Since the memory rotation and R-switch commands are not synchronized, the redundant DCU must be used to perform row redundancy handovers. Because the DCU for the MSM is selected by the same command that reconfigures the R-switches, these events are synchronized and traffic outage is avoided. The redundant DCU is powered and loaded with a memory load reflecting the required R-switch configuration. A command is then sent to the spacecraft to place this DCU on line, simultaneously reconfiguring the R-switches. These two events are synchronized such that a break of approximately 25 ms is experienced, which has very little impact on the network. To prevent the need for a complete power supply handover, the originally on-line, now off-line, DCU is loaded with the new connectivity plan and then reselected on line. The other DCU can then be powered off.

TIMING SOURCE OSCILLATOR

Because the SSTDMA stations cannot tolerate the relatively large changes in phase and frequency offsets between one onboard oscillator and another, hot-switching of the TSOs is not admissible and therefore this function was not tested.

Summary and conclusions

The SSTDMA subsystems of five INTELSAT VI satellites were tested using the approach described herein. Comparison of the test data with prelaunch data has verified that, apart from some minor discrepancies, the on board SSTDMA subsystems are functioning as expected. The spacecraft operational experience has been very encouraging. The first overall system test took place on December 14, 1990, when the first coordinated SSBTP change was successfully performed involving the entire SSTDMA Atlantic Ocean Region traffic-carrying network. Traffic was successfully maintained throughout the switch.

Acknowledgments

Preparation for the operational phase and IOT of a spacecraft is a team effort. The authors would like to express their gratitude to their many colleagues at INTELSAT and Hughes, particularly to E. Magnusson for support and helpful discussions, and to J. Chen and his staff for their dedicated efforts in providing the software required to facilitate the testing and operation of the INTELSAT VI SSTDMA system. They also wish to thank the SES and ISCC staff for their test support.

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[13] C. L. Kullman *et al.*, "Deployment, Test, and Transition to Operation of the INTELSAT SSTDMA System" *COMSAT Technical Review*, Vol. 22, No. 2, Fall 1992, pp. 523–548 (this issue).

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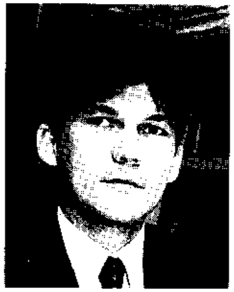
Aloysius K. Kwan received a BSEE and MSEE from the University of Michigan in 1971 and 1976, respectively. Before joining INTELSAT, he was with COMSAT Telesystems, where he was involved with the design and development of TDMA ground stations and IF burst modems. After joining INTELSAT in 1983, he was involved with the development of DCME and DSI specifications. Mr. Kwan is currently a Senior Engineer with the RF System Group in the Satellite Engineering Section, where he is responsible for the daily operation of the INTELSAT space segment, as well as defining and overseeing operational issues for future satellites and the associated ground systems.

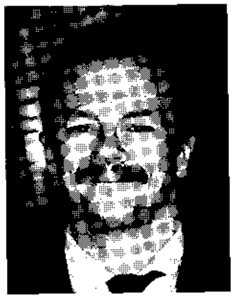


Stewart B. Sanders joined British Telecom International in 1981 and worked at BTI's earth station at Madley, England. He attended Worcester Technical College and received an HNC in electronics in 1986, also attending a number of courses at BTI's engineering colleges. During his time at Madley, he worked on a number of different earth station systems, although primarily on the activation and support of the first fixed TDMA service.

Mr. Sanders joined INTELSAT in 1987 and worked at the Yamaguchi TTC&M/IOT facility as a Technical Representative, and was responsible for the IOT facility from 1988 to 1989. At Yamaguchi, he supported a number of INTELSAT and non-INTELSAT launches and provided IOT measurement support at Fucino for INTELSAT 513. He also worked on installation of the INTELSAT VI ground network system at the site. In 1989, he moved to Washington, D.C., to join INTELSAT's Satellite Engineering Section as an RF Systems Engineer, where he provides day-to-day and on-call support for the INTELSAT satellite network. He has helped to define and test software for INTELSAT VI and planned satellite operations, and has been a team member for all of the INTELSAT VI launches, bus IOTs, payload IOTs, and SSTDMA testing. His role during the payload IOTs includes responsibility for satellite safety and the provision of command support.

F. Lin Khoo received a BSEE in 1983 and an MSEE in 1987, both from George Washington University. She is currently a Spacecraft Payload Engineer in INTELSAT's Spacecraft Communications and Payload Engineering Department, where her responsibilities include spacecraft payload performance specification and evaluation, as well as monitoring of the spacecraft payload during integration and test. In addition, she supports spacecraft launches, payload testing, monitoring, operation, and anomaly investigations of all INTELSAT in-orbit satellites. She has also participated in INTELSAT R&D activities involving emerging spacecraft payload technologies.

Prior to joining INTELSAT in 1986, Ms. Khoo was employed by Satellite Business Systems, where she was involved with the testing and evaluation of digital applications equipment for satellite communications. From 1983 to 1985, she was an engineer in COMSAT World Systems Division, where she was involved with the design, implementation, and testing of the COMSAT TDMA/DSI system. She is a member of Tau Beta Pi and Eta Kappa Nu.



Thomas J. Duffy received a BA in mathematics from the University of Maryland in 1980. He was a systems and scientific software engineer at Martin Marietta Environmental Systems prior to joining the INTELSAT VI team in 1985. Working for Contel as a contractor on the INTELSAT VI Ground Network project, he designed and developed systems for the communications and control processor. In addition, he was selected to design, implement, and coordinate the production of the pioneering Repeater Command Assistance Program (RCAP6), which enables engineers to quickly reconfigure the INTELSAT VI communications subsystem through a graphical interface that automatically generates the correct spacecraft commands to accomplish the requested reconfigurations. Subsequent to RCAP6, he was been active in the design and development of ground network software for the INTELSAT K and INTELSAT VII, and is now an INTELSAT staff member.

Index: communication satellites, INTELSAT, time division multiple access, in-orbit tests, operations

Deployment, test, and transition to operation of the INTELSAT SSTDMA system

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Abstract

Satellite-switched time-division multiple access (SSTDMA) operates in conjunction with an onboard satellite switch that allows a traffic terminal to reach many downbeam coverage areas through only one upbeam. This flexibility reduces the requirement for earth station equipment and allows more efficient use of the space segment. The implementation plan for SSTDMA included extensive testing of the system and careful planning for transition to service. Testing was performed at the SSTDMA reference terminal equipment (SSRTE) contractor's facility and at SSRTE-equipped earth stations. The earth station tests involved the first-launched INTELSAT VI satellite, the SSRTE with all supporting equipment, traffic terminal simulators, and three fully functional traffic terminals at INTELSAT Signatory earth stations. Success was achieved at each stage of testing, and the first SSTDMA network was placed into service in May 1990, as planned.

Introduction

The INTELSAT VI satellites contain onboard switches in two transponder banks (banks 1-2 and 3-4), each with six transponders: east and west hemispheric; and northeast, southeast, northwest, and southwest zones. Each switch can dynamically connect any of six upbeams with any of six downbeams in each bank. Compared with fixed time-division multiple access (TDMA) used over INTELSAT V/V-A, where each upbeam has a fixed connection to only one downbeam, the INTELSAT satellite-switched TDMA (SSTDMA) system on INTELSAT VI allows an earth station to communicate through one upbeam to many downbeams. This increases system flexibility and can reduce earth station costs. Details regarding these onboard switches—their system impact, specification, design, implementation, and testing—are given in References 1 through 5.

It would have been prohibitively costly to design and manufacture completely new reference terminals for SSTDMA. Therefore, from late 1987 to late 1988, two spare sets of fixed TDMA reference terminal equipment (RTEs) from the initial TDMA implementation were modified in-plant by the manufacturer into SSTDMA RTEs (SSRTEs). These first two SSRTEs were tested extensively in-plant for about 8 months at the module, system, and (simulated) SSTDMA network levels. In mid-1989, when confidence in equipment performance was attained, the first two SSRTEs were shipped and installed at the Tanum, Sweden, and Etam, West Virginia, earth stations. Further discussion of the reference terminals may be found in Bedford *et al.* [6].

During the same time period, the INTELSAT Operations Center TDMA Facility (IOCTF) and the INTELSAT Satellite Control Center (ISCC) underwent major modifications to accommodate SSTDMA operation, as discussed in Luz *et al.* [7]. The new IOCTF for SSTDMA included a diagnostics subsystem, described by Tamboli *et al.* [8], to assist operators in identifying and correcting network problems. The burst time plan (BTP) generation software was completely redesigned for SSTDMA operation, as discussed by Mizuike *et al.* [9]. This new software was available for test at the same time as the SSRTEs and the new IOCTF.

Thorough testing is an important element in the successful introduction of a complex system. The number and variety of problems uncovered during SSTDMA testing proved this concept. The approach taken for SSTDMA involved the following:

- Testing of individual subsystems, followed by complete system tests.
- Testing of the system with nearly all conceivable network configurations.
- Participation of two different manufacturer types of traffic terminals.
- Simulation of a range of network loads.
- Adherence to testing in an operational environment to the maximum extent possible, using operational systems, databases, and procedures.
- Access to all necessary expertise and contractors during the test effort in order to correct problems.
- Availability of adequate time to fully accomplish the test plan.

Since the testing would be conducted using the first-launched INTELSAT VI satellite (INTELSAT 602), which was temporarily located in an in-orbit test (IOT) slot at 322°E, it was not possible to utilize the normal communications antennas at any of the participating earth stations. Consequently, temporary antennas and associated ground communications equipment (GCE) had to be arranged at the Etam and Tanum earth stations prior to the first tests.

The initiation of SSTDMA operation on the Atlantic Ocean Region (AOR) 335.5°E satellite was carefully planned to limit traffic interruption during the transition from fixed TDMA to SSTDMA to less than 30 minutes. The transition was a two-stage process. First, the fixed TDMA service from the AOR INTELSAT V satellite was transferred to INTELSAT 602. Then, a few weeks later, fixed TDMA was converted to SSTDMA. This approach simplified system transfer and minimized risks because it reduced the complexity of the initial traffic transfer between satellites and gave each earth station time to adjust RF performance for the new satellite. During the initial period of SSTDMA operation, contingency arrangements were identified to ensure continued service in the event of SSTDMA system or satellite problems.

Test program

The SSTDMA test program was conducted in two separate phases: witnessed in-plant tests and INTELSAT field tests. Figure 1 is a simplified flow diagram of the overall test program.

During each test phase, each subsystem (SSRTE, satellite payload, INTELSAT Headquarters Subsystem [HQS], TDMA system monitor [TSM], and SSTDMA BTP [SSBTP] generation software) was tested first as an individual element, using simulators where necessary to verify the interfaces with other elements of the SSTDMA system. This was done to limit the scope and complexity of testing needed to confirm that each subsystem operated according to specification.

Witnessed in-plant tests

Throughout all phases of in-plant testing, INTELSAT stationed one system engineer at the manufacturer's facility to witness formal and informal tests, and to provide immediate response to any design- or test-related questions. Figure 2 shows the equipment configuration for in-plant tests. All tests were performed with an engineering model of the INTELSAT VI microwave switch matrix (MSM), two SSRTEs, and two TDMA traffic simulators (TTSs). This allowed simulation of a complete network, including the satellite payload.

The major new component in the SSRTE (compared with the RTE in fixed TDMA) is the acquisition and synchronization unit (ASU), which synchronizes

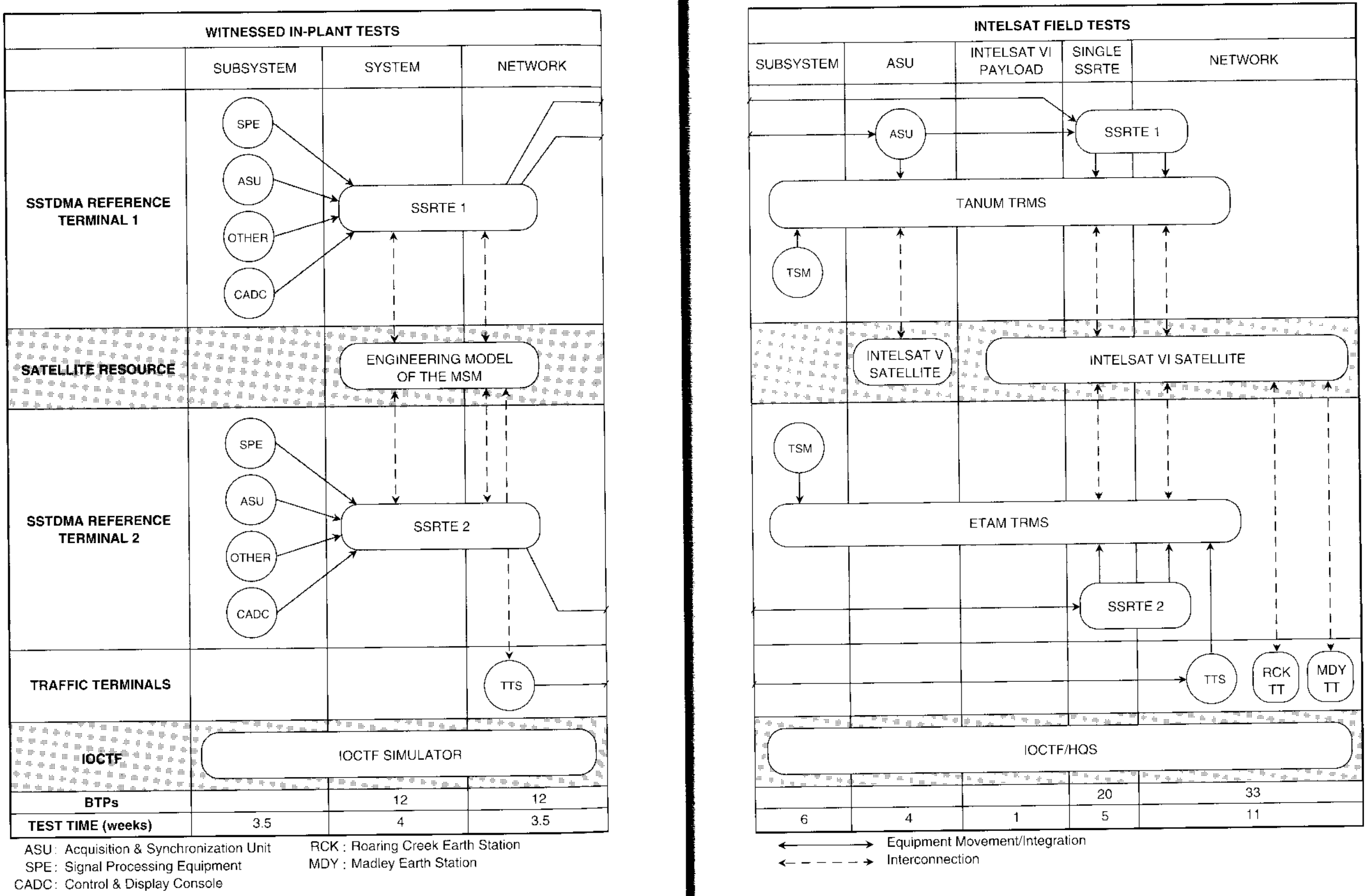


Figure 1. SSTDMA Test Program Flow Diagram

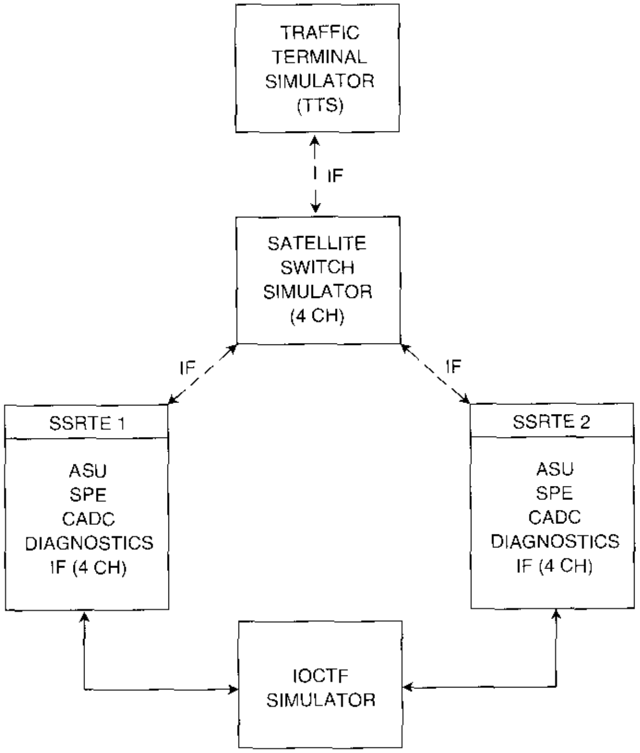


Figure 2. In-Plant (Network) Test Configuration

SSTDMA network timing with that of the satellite switch. Initial tests focused on the performance of this unit, together with its associated monitor and control unit (MCU). After confirming ASU performance, the SSRTE was tested as a complete subsystem, using a simulator for the IOCTF functions. The final series of tests involved two SSRTEs in a simulated network, using special test time plans to verify operation under a range of network configurations and loading.

INTELSAT field tests

Following successful completion of in-plant tests, the SSRTE terminals were moved to TDMA reference and monitoring stations (TRMSs) for testing over satellite links. Contracts to provide TRMS service on the AOR 335.5°E SSTDMA network had previously been placed with the Etam, West Virginia, and Tanum, Sweden, earth stations using temporary antennas and GCE at each site, as discussed above.

Figure 3 shows the various elements participating in the network test phase. INTELSAT operators (AT&T and BTI, respectively) offered the use of spare TDMA traffic terminals and antennas at Roaring Creek, Pennsylvania, and Madley, U.K., thus making possible a realistic test of traffic terminal performance. In addition to these real traffic terminals, a traffic terminal simulator located at Etam could generate traffic bursts, but without any baseband functions.

After successful testing of the individual subsystems, they were integrated and tested as an entire system. The four major objectives of these on-site tests were as follows:

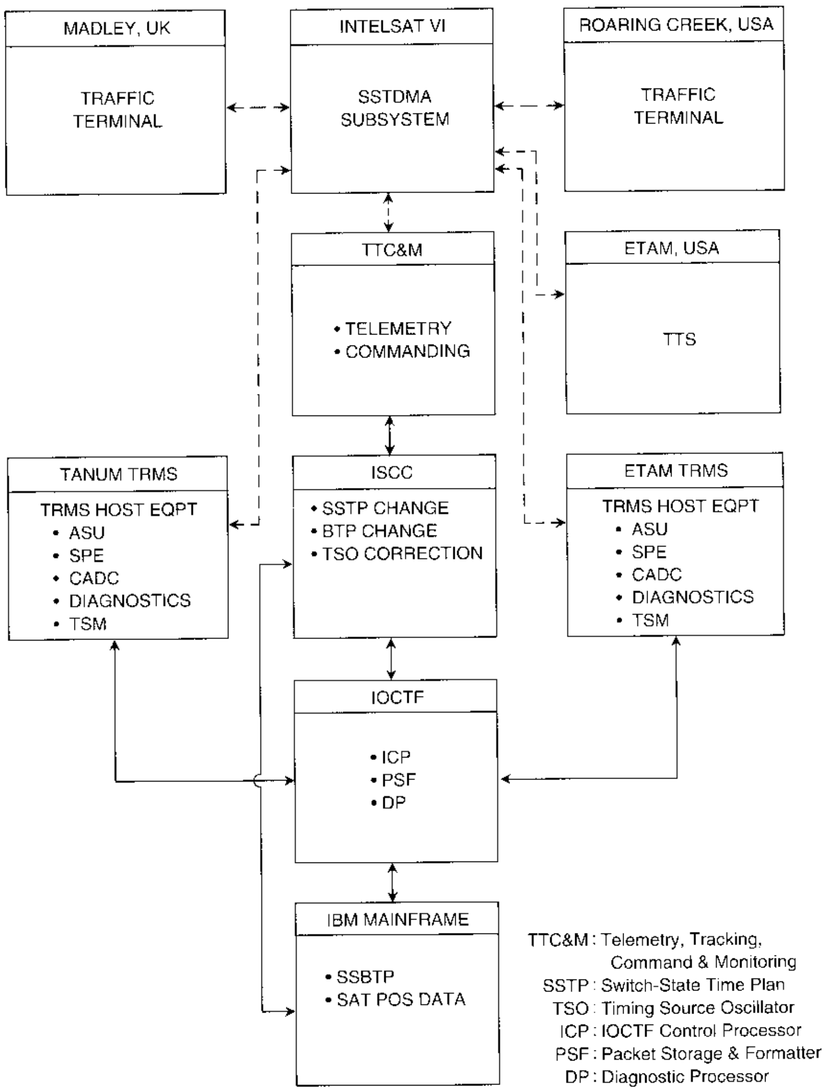
- To optimize the operational parameters of the ASU and verify the clock (timing source oscillator [TSO]) correction algorithm.
- To verify compatibility among the elements of the system.
- To verify performance of the entire system, according to specification, in a real (rather than simulated) network environment.
- To confirm the operational readiness of the system using real operational databases, real traffic terminals, and real operational procedures.

These subsystem, ASU, payload, and system/network tests are discussed in greater detail below.

SUBSYSTEM TESTS

The introduction of SSTDMA required extensive modifications to the TSM software. Stand-alone tests were conducted for time-plan processing, measurements and measurement display processing, operator interface, database editor, data link interface, and operating system software.

The HQS [9] consists of those components of the IOCTF and ISCC that support SSTDMA operations. The IOCTF coordinates such critical functions as SSBTP change, database management and distribution, and TSO frequency correction [10]. These functions were tested intensively under strict configuration control at both the IOCTF and ISCC [11] to avoid affecting operational systems already existing in these areas. As the central coordinator of SSTDMA network operations, the HQS depends on reliable and efficient data transfer between all elements of the system. Hence, a large portion of the testing was focused on data flow management functions.



TTC&M : Telemetry, Tracking, Command & Monitoring
SSTP : Switch-State Time Plan
TSO : Timing Source Oscillator
ICP : IOCTF Control Processor
PSF : Packet Storage & Formatter
DP : Diagnostic Processor

Figure 3. On-Site Network Test Configuration

ASU OPTIMIZATION

Before INTELSAT 602 became available, fixed-connectivity transponders on an INTELSAT V satellite, together with the engineering model of the MSM located at Tanum earth station, were used for ASU acquisition and synchronization tests. The optimum operational parameters for the ASU were determined, and the algorithm for TSO correction [10] was verified.

INTELSAT VI SSTDMA PAYLOAD TESTS

Following the launch of INTELSAT 602, basic verification of the SSTDMA payload was performed during the satellite IOT [11],[12]. In these tests, continuous-wave (CW) signals were transmitted and received in all the coverage areas of the INTELSAT VI SSTDMA payload. A specific switch state time plan (SSTP) was loaded into the distribution and control unit (DCU) memory on board the satellite [4], and each receiving earth station compared its received burst CW pattern with the expected pattern. The IOT also included tests of the telecommanding and telemetry functions of the SSTDMA payload.

SYSTEM AND NETWORK TESTS

To simplify the initial test plan and avoid delays in the schedule after INTELSAT 602 became available, the test teams at Etam and Tanum independently performed compatibility tests between the SSRTE and the satellite payload. The satellite was configured by the ISCC with a simple satellite SSTP containing only those switch states necessary for metric burst and reference burst acquisition and synchronization. The basic SSRTE timing functions were then verified.

Following these separate SSRTE tests, the SSTP was modified to allow both SSRTEs to operate in the normal master primary reference terminal (MPRT) and secondary reference terminal (SRT) relationship. The system was exercised with the benchmark time plans and configurations used during in-plant SSRTE testing, to check network functions such as startup, acquisition and synchronization, SSRTE role change, SSBTP change, and other control protocols. As tests progressed and confidence in compatibility between the SSRTE and the satellite increased, a TTS at Etam was introduced to assume the role of the traffic terminals in each time plan. During this phase, the new data communications system linking the HQS and the SSRTEs was integrated and verified. Testing concentrated on basic functions such as passing application-level messages between the SSRTE and the HQS.

At this point, the Madley and Roaring Creek traffic terminals joined the network, and tests were conducted using time plans produced by the SSBTP generation software. The following standard set of network functions was tested for each time plan:

- Network startup, both remotely from the IOCTF and locally at the SSRTES
- Coordinated SSBTP changes
- Uncoordinated SSTP changes (for non-time-critical reconfiguration of the SSTDMA payload)
- TSO frequency corrections
- Terminal acquisition and synchronization
- HQS data transfer and monitoring
- Effects of swept and CW interference
- TSM functions
- Distribution of time plans from HQS
- Diagnostic processor functions.

Other specific tests performed included the effects of redundancy handover in the SSTDMA payload of the satellite [11], minimum guard times between bursts, extremes of clock/Doppler drift, and traffic terminal equipment switchover. In all configurations, traffic was exchanged between the two traffic terminals, and bit error rate (BER) measurements were taken to assess baseband performance.

The AOR 335.5°E startup and follow-on operational time plans were tested at length, with full participation of the traffic terminals. The testing also included a stability test lasting 3 to 4 days at the end of the test period. The Madley and Roaring Creek traffic terminals, and the TTS at Etam, assumed the roles of all terminals defined in the east and west hemi and the northeast and northwest zone beams. For each terminal, acquisition and synchronization protocols were exercised, SSRTE promotion procedures were verified, and SSBTP changes between startup and follow-on time plans were performed. A preliminary version of the Indian Ocean Region (IOR) 60°E startup time plan was tested in a similar manner. However, because the IOR east reference beam is in the southeast zone instead of the northeast zone, this time plan could be tested with only one SSRTE in the west.

Test results

The subsystems making up the SSTDMA system were tested first as stand-alone elements under simulated conditions to prove the basic operation of each subsystem. Subsequent on-site tests over a period of almost 5 months allowed integration and testing of the complete operational SSTDMA system. Approximately 30 time plans were generated by the SSBTP software and used to progressively stress-test the system by varying the network parameters, as follows:

- From 1 to 54 defined traffic terminals
- From 2 to 12 transponders per network
- Between 1 and 4 connectivities in each terminal acquisition and synchronization (TAS) group
- Up to 4 TAS groups
- From 1 to 4 acquisition tables
- Between 1 and 27 defined terminals per acquisition table
- Single and dual control and delay channel (CDC) operation
- Immune and nonimmune network configurations
- Dual channel bank operation
- Metric bursts in 1 or 2 banks.

During the course of testing, numerous problems were identified and resolved in the various subsystems. In the SSRTE, 51 action items were identified for the ASU, signal processing equipment (SPE), and MCU subsystems; 44 for the control and display console (CADC) subsystem in the SSRTE; and 32 for the TSM. Successful regression and stability testing concluded the on-site test period, and preparations for transition to an operational network began with a very high degree of confidence.

Traffic terminal experience gained from testing

Apart from the specific comments presented below, from a traffic terminal operator's viewpoint the fixed TDMA and SSTDMA terminals perform identically.

BER tests between Roaring Creek and Madley showed good results, with BERs of 8.8 × 10^{-10} received at Madley and zero errors at Roaring Creek (averaged over approximately 2 weeks). During SSBTP changes, no degradation in BER was observed across the change. BER tests on the traffic portion of principal bursts from Madley (received at Madley) also showed excellent results.

The staff at Roaring Creek encountered some difficulty in configuring the traffic terminal related to principal burst mapping. Unlike fixed TDMA, in SSTDMA the principal burst has one subburst with only one traffic channel assigned to it. This principal burst is used by the reference terminals for traffic terminal acquisition and synchronization support. Since the single traffic channel is not intended for use, it should not be mapped to a physical terrestrial interface module (TIM). The Roaring Creek terminal would not accept a condensed time plan/master time plan (CTP/MTP) without a receive destination for the principal burst. In addition, the terminal would not accept a new SSBTP with fewer maps than the current SSBTP. Both of these problems were corrected easily: the first by manually assigning a dummy destination to the principal burst, and the second by creating additional dummy maps. Both problems are unique to one traffic terminal type, and these simple workaround procedures were documented and made available to other traffic terminal users.

Two uses of the principal burst for in-service performance monitoring have been suggested. First, by linking a TIM or a 120-Mbit/s BER tester to the traffic portion of the principal burst and comparing it to the looped-back return burst, individual terminal performance can be locally assessed. Second, if all traffic terminals were required to transmit an identical pseudorandom bit sequence, and the TSM were equipped to decode such a sequence, rapid fault isolation would be possible. Both suggestions are worthy of further consideration. Since the principal burst is broadcast to both SSRTEs, a traffic terminal may see a loopback of its own principal burst if the terminal is located in and can access the reference beams. Traffic terminals in nonreference beams will not have this capability. During the SSTDMA tests, Madley was located in the reference beams and used this feature successfully as a guide to traffic terminal performance. Other traffic terminal operators situated in reference beams may also wish to use this feature.

In SSTDMA, all terminals are acquired by "sequential acquisition," whereas in fixed TDMA parallel acquisition is also used. As a result, SSTDMA takes longer to acquire all of the traffic terminals than would fixed TDMA. This depends on the number of terminals in the network and the number of terminals sharing a particular common acquisition window (CAW). As an example, in the AOR SSTDMA network where eight terminals share one CAW, a terminal may be acquired in a minimum of 3 s or a maximum of 107 s.

During fail-safe SSBTP change tests, the Madley operators reported a previously unseen problem which appears to be specific to one type of terminal. A fail-safe SSBTP change is a contingency procedure invoked by the MPRT when it detects a change in satellite connectivity after issuing an SSBTP Change Cancel command. In this case, the MPRT forces an SSBTP change in the ground terminals. The time between the instant of connectivity change in the satellite and the instant of successful fail-safe SSBTP change is approximately 2 s. During this interval, a traffic terminal may detect some receive bursts as missing due to the connectivity change in the satellite. Madley noted that a TIM associated with a missing burst and configured for digital noninterpolated (DNI) operation reacts to loss of the unique word by declaring an Alarm Indication signal (AIS) for the DNI channels. When the SSBTP change occurs and the burst number associated with the TIM changes, the AIS takes about 11 minutes to clear under control of a background software task in the traffic terminal. The condition is operator-correctable if it is recognized.

SSBTP generation observations

One question investigated during testing of the operational SSBTP for the IOR 60°E network was whether traffic terminals required reference bursts in all receive transponders, or could operate correctly with reference bursts in the control (timing and reference) transponder only. Operation in such a configuration had never been tested. The results indicated that the traffic terminals require reference bursts only in the control transponder. This feature has been used to improve the space segment efficiency of the IOR SSTDMA network.

Generating the various test and operational SSBTPs significantly increased knowledge of the capabilities and limitations of the highly complex SSBTP generation software. It was concluded that, rather than producing an SSBTP for maximum frame efficiency (which was the original design goal), a tradeoff was necessary to minimize the number of TIMs required at the traffic terminals, since this is a significant cost item for users. Further modifications are being made to the SSBTP software to provide additional flexibility and efficiency in this area.

In several of the time plans, the acquisition window was reduced from the nominal duration of 2,048 to 1,024 symbols, to test the feasibility of reducing acquisition window size in progressing from one time plan to the next. By using smaller acquisition windows, frame overhead can be reduced. No problems were noted in acquisition for either the ranging or prediction methods of determining satellite position.

Overall system performance

Tests with interfering carriers proved that SSTDMA has greater network resilience than fixed TDMA. In interference-immune configurations, only bursts in the interfering upbeam and in the downbeams into which the interfering carrier was switched sustained outages. As expected, the network remained operational. In interference-nonimmune configurations, the network went into survival mode, restarting automatically without operator intervention at the SSRTEs upon removal of the interfering carrier.

During testing with traffic terminals, it was noted that the selective do not transmit (SDNTX) control function of SSTDMA differs from that for fixed TDMA in that it is invoked only when the principal burst is declared lost by the reference station, and is not invoked by the loss of other nonprincipal traffic bursts. Thus it was not possible to inhibit the transmission of specific nonprincipal bursts by using SDNTX messages. In response to a suggestion from the Madley traffic terminal staff, the SSRTEs and HQS were modified to allow manual transmission of SDNTX as desired. This feature was successfully tested.

One major upgrade introduced as part of the SSTDMA program was revised computer communications protocols between the HQS and the SSRTEs. Data links were changed to use a standard link protocol, and were successfully tested. As a result, the reliability of data transmission has improved significantly.

Tests of the diagnostic subsystem under simulated or real network anomalies resulted in correct diagnoses by the expert system diagnostic processor [8] in the IOCTF.

Although not directly related to initial in-plant or on-site SSTDMA testing, an interesting result of later SSTDMA testing from the Clarksburg earth station concerned the performance of SSTDMA using inclined-orbit satellites. The tests utilized the ability to offset the onboard TSO frequency of the INTELSAT 604 satellite to simulate a range change, as would be experienced under inclined-orbit conditions. After minor SSRTE modifications by the manufacturer, correct operation of SSTDMA was verified over range and range rate changes equivalent to a frame movement of more than 8 symbol/s. This is equivalent to a satellite inclination of more than 2°.

Operational configurations

The two fixed TDMA networks, operating over satellites at orbital locations AOR 335.5°E and IOR 60°E, had similar operational configurations. Traffic over both networks was predominately thick-route east-west/west-east. Following the transition of these networks to SSTDMA operation, the configurations have become quite different. The AOR network still carries mainly thick-route traffic between North America and Europe, but now also incorporates traffic between these regions and Africa. The IOR network, on the other hand, has evolved into a thin-route, high-connectivity network serving a large number of traffic terminals, which takes advantage of the features of the SSTDMA system. There are currently no plans to convert the remaining fixed TDMA network on the Atlantic Ocean Region 342°E satellite to SSTDMA.

Atlantic Ocean Region

In the AOR, fixed TDMA operation was introduced in 1986 in a two-zone transponder configuration on an INTELSAT V-A satellite at 335.5°E. The west zone transponder provided coverage for traffic terminals in the U.S. and Canada, while the east zone transponder provided coverage for five traffic terminals in Europe (*i.e.*, in France, Germany, Sweden, Switzerland, and the United Kingdom). All traffic connections were from east to west, or vice versa, with no loopback traffic within the same zone beam transponder.

The zone beams of INTELSAT V-A do not cover countries in Africa. Including such users would have required allocating hemispheric beam transponders to the fixed TDMA network, which was not possible because of the very heavy demand on the hemispheric beam transponders to meet non-TDMA service requirements. Further, since potential users in Africa needed to communicate with both Europe and North America, three hemispheric transponders (two configured east/west and one configured east/east) would have been necessary to meet traffic requirements on the fixed TDMA network over an INTELSAT V-A satellite. The additional IF and RF equipment required for reference and traffic terminals would not have been justifiable for the resulting traffic levels and transponder fill factors.

Deployment of an INTELSAT VI satellite to 335.5°E, and introduction of SSTDMA on that satellite, resolved the dilemma. First, in addition to the northwest and northeast zone beams, the southeast zone beam on INTELSAT VI provides coverage of Africa [3],[14], thus enabling potential users such as Kenya, Nigeria, and South Africa to join the TDMA community. Second, no additional IF, RF, or transponder-hopping equipment is required by existing reference and traffic terminals, even though the number of zone transponders in the network increases from two to three. Finally, the dynamic switching capability of the SSTDMA system can accommodate traffic from Europe to Africa with the same IF and RF equipment as is used for carrying traffic to North America.

Figure 4 shows the configuration of the startup SSBTP for the AOR 335.5°E network. In addition to existing terminals in the fixed TDMA network, the Kenya traffic terminal which accesses the southeast zone transponder is also included. Other traffic terminals in Africa will join the SSTDMA network in the future. It should be noted that because of the limited number of transponders in this network, there is only one reference beam pair, and thus an interference-immune configuration is not possible.

Indian Ocean Region

Fixed TDMA operation in the IOR was introduced in 1985 on an INTELSAT V satellite in a two-hemispheric-beam transponder configuration. In 1988, the network was expanded to four transponders through inclusion of west and east zone transponders. In anticipation of network expansion, certain users

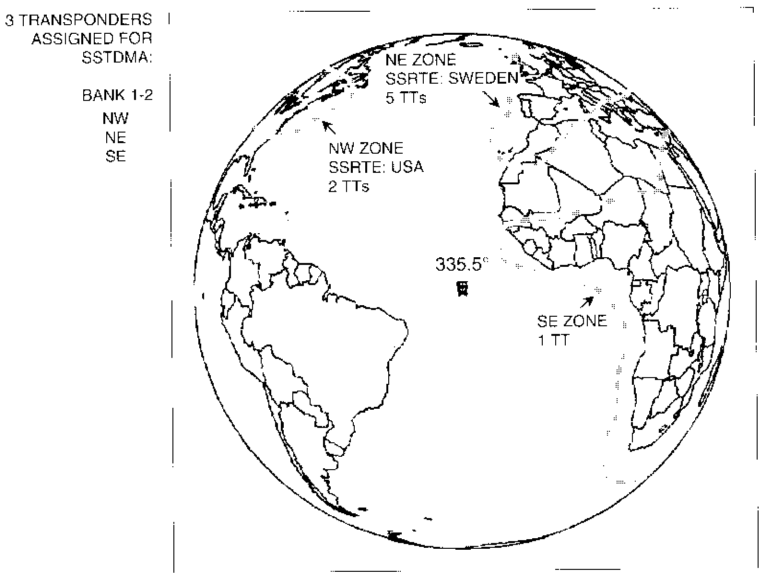


Figure 4. INTELSAT VI at 335.5°E (AOR)

procured additional IF, RF, and transponder-hopping equipment which enabled them to operate in both the hemispheric and zone transponders. However, other users, for economic reasons, decided not to equip themselves for operation in more than one transponder. Because of the resultant heavy loading in the hemispheric transponders and the inability of the fixed TDMA system to dynamically connect users in the hemispheric beams to those in the zone beams, not all users desiring TDMA links could be accommodated. Specifically, four traffic terminals in Asia equipped only for the east zone transponder could not communicate with two terminals in Europe equipped only for the west hemispheric transponder. As with the AOR fixed TDMA network, all the traffic in the IOR fixed TDMA network was east to west, or vice versa, with no loopback traffic.

Generating the startup IOR SSBTP was a challenging task that involved a number of iterations with the IOR TDMA users. The startup traffic initially forecast by users for year-end 1991 exceeded 9,000 bearer channels, which was considerably higher than anticipated. The relatively high level of loopback traffic to be introduced, together with increased east/west traffic, meant that additional transponders would be required, particularly to cover the east. The initial traffic forecast also included a relatively large number of small links, which correspondingly increased the number of subbursts and TIMS required. In addition, in order to cover traffic terminals in the Middle East, the INTELSAT VI northeast zone beam had to be included in the SSTDMA network. In the IOR configuration of the INTELSAT VI satellite, the northeast zone beam is almost entirely outside the coverage area of the east hemispheric beam [14]; therefore, inclusion of this beam in the network would affect development of the SSBTP in terms of both control and the overall number of subbursts.

To accommodate the initial forecast of 9,000 bearer channels, a preliminary SSBTP was developed based on a 10-transponder configuration that also included the bank 1'-2' hemispheric transponders of the INTELSAT VI satellite. Although these transponders do not have satellite-switched connectivity, they can be used in a fixed east/west connectivity as part of the overall SSBTP. It was necessary to include these transponders, since the two hemispheric transponders in bank 3-4 which have satellite-switched capability were unavailable due to non-TDMA service requirements. The preliminary SSBTP that was developed called for more IF, RF, and transponder-hopping equipment than users could procure in the time available before initiation of SSTDMA in the IOR. In addition, the number of TIMs required was considerably higher than users expected. Accordingly, users submitted revised (lower) TDMA traffic forecasts. In a parallel effort to reduce the number of TIMs, INTELSAT reviewed the subburst-forming algorithms of the SSBTP generation software and made some refinements which, together with greater familiarity with the use of the SSBTP software, resulted in generation of an SSBTP that was acceptable to the users.

To accommodate the revised startup traffic forecast, the IOR SSTDMA network had an eight-transponder configuration, with six transponders in bank 1-2 and two in bank 3-4. Figure 5 depicts the network configuration. Since there were three reference beam pairs, an interference-immune configuration was possible. To reduce overhead, all traffic terminals were controlled in bank 1-2 and there was no TAS region or reference bursts in bank 3-4. The additional frame space in bank 3-4 could then be used to accommodate more traffic. The startup SSBTP for the IOR included 25 traffic terminals and accommodated approximately 7,500 bearers which, with a digital circuit multiplication gain of 4, equates to more than 30,000 voice channels. The number of traffic subbursts (and thus TIMs) required in the network was approximately 115.

Introduction of SSTDMA in the IOR overcame the connectivity difficulties mentioned above since all terminals in the east, whether equipped for hemispheric or zone beam operation, can correspond with any terminal in the west. Loopback traffic can also be accommodated without additional IF or RF equipment, although additional TIMs are required. While a key feature of the SSTDMA system is its ability to accommodate traffic in any connectivity without

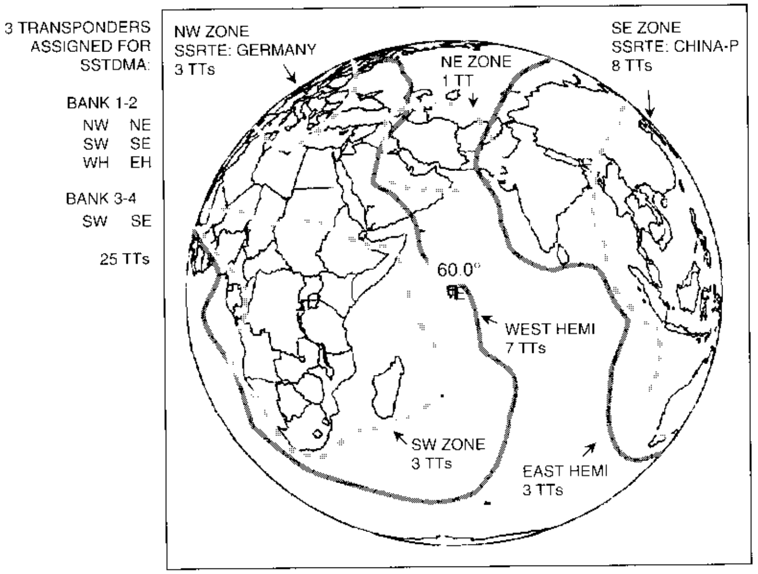


Figure 5. INTELSAT VI at 60°E (IOR)

additional IF and RF equipment, experience gained to date in developing SSBTPs for the IOR indicates that the cost of additional TIMs can only be justified when the amount of traffic added with each additional connectivity is large.

Transition to SSTDMA operation

The transition from fixed TDMA to SSTDMA operation on INTELSAT 602 at AOR 335.5°E was planned in great detail, and included the provision of contingency arrangements.

Contingency arrangements

Prior to cutover to SSTDMA on the AOR 335.5°E satellite, a contingency plan was developed to allow reversion to fixed TDMA operation in the unlikely event that serious problems were encountered with SSTDMA. This plan maintained all four fixed-TDMA RTE systems in "hot standby" for 5 months until a spare INTELSAT VI satellite was available in that region. Two of these backup RTEs were then dismantled, leaving one RTE in each beam to support fixed TDMA.

A fixed TDMA network with two RTEs has no RTE site redundancy, which could theoretically result in reduced traffic availability. However, it was believed that several months of experience with SSTDMA operations would make any return to fixed TDMA both highly unlikely and of relatively short duration, possibly during an emergency engineering upgrade to the SSRTEs. In addition, this contingency scheme released two RTE systems for upgrade and relocation as part of the overall transition plan to implement the second SSTDMA network in the IOR. This two-RTE-fixed TDMA backup was maintained until 1 year after cutover to SSTDMA operation.

For the IOR 60°E SSTDMA network, a full four-RTE fixed TDMA backup was maintained until the spare INTELSAT VI satellite became available in that region at 63°E in May 1992.

Fortunately, these contingency arrangements did not have to be employed. Further, from a practical aspect, the decision to revert to fixed TDMA would not necessarily have been easy, even with contingency plans in place. It would have been necessary to consider many factors, particularly the reduced capacity and connectivity between the SSTDMA and fixed TDMA backup configurations. This was especially true in the IOR network, but even in the simpler AOR case, where a fixed TDMA backup time plan had been generated with baseband assignments similar to those of the operational SSTDMA time plan, a reversion would have resulted in the loss of traffic terminals in the southeast zone beam (Africa), and their links with all correspondents. Thus, any decision to revert would have had to carefully weigh the certain traffic losses and considerable coordination required against whatever system problems were being experienced in SSTDMA.

Cutover to live traffic

As mentioned previously, the transition to SSTDMA on the AOR 335.5°E satellite was a two-phase process. The first phase—the transfer of existing fixed TDMA service from INTELSAT 510 to INTELSAT 602—was accomplished on April 28, 1990. This approach allowed IF/RF link optimization with the new satellite, which would otherwise have complicated the SSTDMA cutover. INTELSAT VI has different performance characteristics which required uplink and downlink gain changes at all reference and traffic terminals. In the fixed TDMA networks, traffic terminals had operated at a transponder input backoff of approximately 7 dB below the reference burst level. This provided protection to the reference bursts in case of traffic burst overlap, while still allowing good baseband performance. In SSTDMA, protection of the reference bursts is inherent in the system architecture, so traffic burst signal levels could be increased to operate at nominally the same level as the reference bursts.

Prior to the fixed TDMA transfer on April 28, all terminals adjusted uplink and downlink gains as determined by IOT data for INTELSAT VI. The satellite MSM and associated support systems were programmed for the fixed connectivity necessary for fixed TDMA. The service transfer was a relatively straightforward satellite transfer. The "pass in the night" (PIN) method was followed by link measurements and equalization adjustments using the burst mode link analyzer (BMLA) to restore correct performance at the reference stations.

Procedures for the transition to SSTDMA were initiated 2 weeks before cutover, with transmission of the SSTDMA time plan from the IOCTF to all traffic terminals, and transmission of the various operational databases to the SSRTEs at Tanum and Etam. A few hours prior to cutover, the ISCC loaded the operational SSTP into the off-line DCU memory on board INTELSAT 602 and prepared the necessary command queues for memory rotation. New satellite position data (necessary for terminal acquisition) were generated, loaded into the IOCTF, and transmitted to the SSRTEs.

One hour prior to cutover, the IOCTF began contacting all traffic terminals to ensure readiness for transition. Conference calls were established with the four reference stations, and the RTEs at Tanum and Etam were instructed to cease operation (the fixed TDMA network continuing with only the Berçenay and Mill Village RTEs). Tanum and Etam then began reconfiguring the reference stations for SSTDMA operation. This entailed the relocation of host station alarm interfaces, equalizer units, and IF cables from the RTE to the SSRTE system.

Since a synchronous BTP change was not possible between the fixed TDMA and SSTDMA time plans, it had originally been intended that all traffic terminals would manually load the new database upon deliberate failure of the fixed TDMA network, and then reacquire in the SSTDMA system. However, it was discovered that in one type of traffic terminal design this loading process could take a considerable amount of time. Because Etam used this type of terminal and was effectively carrying the majority of traffic on this network, it was decided to force an automatic traffic rearrangement at Etam, resulting in an immediate switch of foreground and background databases, and thus eliminating the delay which would otherwise have been incurred.

One minute prior to termination of the fixed TDMA network, after confirming readiness at the Etam traffic terminal (BTP change interlock disabled), the Berçenay reference station initiated a traffic rearrangement countdown sequence. Etam confirmed that the databases had switched and the terminal was ready for startup of SSTDMA.

At 0001 Universal Time Coordinated (UTC) on May 19, 1990, Berçenay reference station terminated the fixed TDMA network by ceasing transmission of the controlling reference burst. The ISCC was immediately instructed to rotate memories to place the SSTP on-line in the satellite; the Tanum and Etam SSRTEs connected receive and transmit chains; and, upon confirmation, SSTDMA network startup was initiated from the IOCTF. After startup of the Tanum and Etam SSRTEs was complete, terminal acquisition commenced and all terminals were acquired within 4 minutes, except for one station which came up at 0017 UTC (the delay being due to the time required for manual loading of the new database in that terminal).

While the IOCTF verified baseband operation with each traffic terminal, some basic SSRTE tests were performed, such as role changes and reacquisitions to confirm network operation under SSRTE failure conditions.

Within 2 hours after the startup of SSTDMA, correct operation of the TSM, IOCTF monitoring functions, diagnostic processor functions, and orderwire circuits had been confirmed. The satellite payload had also been configured for normal redundant operation, with a copy of the operational SSTP loaded in the off-line DCU memory. Apart from some minor baseband mapping discrepancies which were quickly resolved at the respective traffic terminals, only one major traffic problem was experienced. This was a loss of all baseband traffic at one station. On-site engineers from the traffic terminal manufacturer identified this as a local fault with new digital speech interpolation equipment and were able to restore service after approximately 14 hours.

Transition to SSTDMA in the IOR was initiated in late 1991 with the beginning of system tests using the Beijing, China, and Raisting, Germany, SSRTE facilities. Transition was completed and SSTDMA operation commenced on January 31, 1992.

SSTDMA operational experience

SSTDMA has been operating for approximately 30 months on the AOR 335.5°E satellite, and for about 10 months on the IOR 60°E satellite. Both networks have operated according to specification, without any system- or SSRTE-related problems. This success can be credited to the overall system design, together with the extensive preoperational testing and debugging.

Based on data collected since the beginning of fixed TDMA operation, the average traffic availability from 1985 to 1990 was 99.9 percent. With the additional interference immunity of the SSRTE and immune network configurations, it is expected that SSTDMA will achieve an even greater availability in the long term. Current experience indicates a similar availability for SSTDMA as for fixed TDMA.

Three coordinated SSBTP changes have been performed: in December 1990 and April 1992 on the AOR 335.5°E network; and in July 1992 on the IOR 60°E network. TSO corrections are performed, on average, once every 2 weeks.

The payload presents another potential failure point. One uncertainty is the occurrence of multiple bit-flips in the SSTDMA payload (specifically, in the DCU memory, which defines the switching sequence and connectivities), which could affect network operation. Payload monitoring on the operational INTELSAT VI satellites has shown an average of 10 single bit-flips per month for the on-line DCU memory (containing an operational SSTP with a last state address [LSA] of 16), and an average of 40 per month for all memory locations in the off-line DCU memory. Single bit-flips are automatically corrected and do not affect traffic. However, this frequency of occurrence is higher than was originally predicted for radiation effects at a geostationary orbit, possibly due to the current extremely high radiation levels and the inaccuracy inherent in estimates of the effect of radiation on semiconductor devices. In any event, only one multiple bit-flip has been detected. This occurred in October 1992, causing the temporary loss of three traffic terminals on the IOR 60°E network until a rotation of the DCU memories was commanded. A more detailed discussion of multiple bit-flips and the October 1992 event will be provided when current studies are completed.

Operational experience has highlighted the importance of network monitoring, particularly in the nonreference beams, to diagnose burst anomalies and provide some qualitative measurement of link performance. Nonreference diagnostic equipment [8] will help to fulfill this monitoring requirement when it is deployed at collocated traffic terminals in the nonreference beams of the AOR and IOR networks in 1993.

Operational procedures and network support will continue to be improved as knowledge is gained through events such as SSBTP changes, TSO corrections, and network anomalies. Potential enhancements have already been identified, particularly in the IOCTF, ISCC, and diagnostic subsystem areas, to improve day-to-day operation and monitoring. Examples of such enhancements include provision of additional telemetry alarms to the diagnostics processor to aid in payload fault diagnosis; display of intermediate accumulated phase values to aid in monitoring TSO correction functions; and modifications to the user interface on the diagnostics processor. This type of adaptive maintenance activity is expected to continue over the life of the system, as operational and user requirements evolve.

The fixed TDMA/SSTDMA simulation facility at INTELSAT Headquarters has been upgraded by the installation of a complete SSRTE. The fixed TDMA system relied heavily on network simulation for BTP verification, as well as for testing of system upgrades and RTE modifications. The upgraded facility will be used in a similar way to support SSTDMA. Experience has shown that pre-testing of all upgrades or configuration changes prior to network implementation saves the network from traffic outages and improves overall system availability. The simulation facility is also used for training INTELSAT and reference station staff.

Summary

The successful implementation of SSTDMA has been traced through the preparatory stages of planning, subsystem-level equipment testing, earth station facility integration, and system testing. This was followed by verification of SSTDMA network operation over INTELSAT 602, and finally by the transition to operation in the AOR on May 19, 1990, over the satellite at 335.5°E. Transition to SSTDMA over the 60°E INTELSAT VI satellite occurred shortly thereafter. Subsequent operation continues to be highly successful.

Acknowledgments

The authors wish to thank their many colleagues at NEC, COMSAT, BT, AT&T, Swedish Telecom, and INTELSAT. The NEC staff's commitment to the SSTDMA reference terminal implementation and deployment has been outstanding. The staffs of COMSAT, BT, and Swedish Telecom made essential contributions to the design and testing of the system, including the field tests with the INTELSAT 602 satellite. The authors gratefully acknowledge the contributions of all those who participated in defining and implementing the SSTDMA system. The SSTDMA networks were implemented under a very demanding schedule that required significant sacrifice from all involved.

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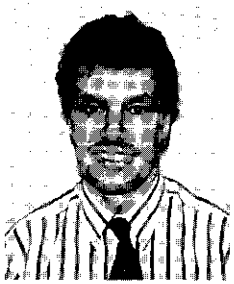

Steven J. Smith served a 4-year electronics apprenticeship with the Ministry of Defense in Great Britain, and received an HNC in electronic engineering from Worcester Technical College in 1978. He joined RCA as an Electronic Engineer in 1979, specializing in digital systems design, and worked on various contracts for the British Ministry of Defense and for the European Space Agency in Noordwick, the Netherlands. In 1985, he joined INTELSAT as a Technical Representative with responsibility for the TRMS/TDMA facility at Pleumeur Bodou Earth Station in France. In 1986 he moved to Washington, D.C., as Supervisor of TRMS network operations, and is currently responsible for the operation and technical support of the INTELSAT TTC&M and TRMS/TDMA networks.

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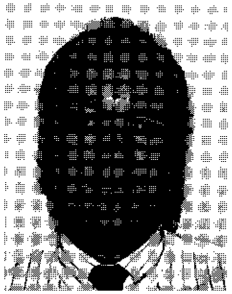
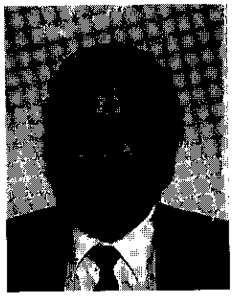


Roger Bedford received a BSc in electronic engineering from Bolton Institute of Technology, England, in 1974; and a MSc in telecommunications from Essex University, England, in 1975. From 1975 to 1977 he worked on satellite system analysis and earth station design for the Marconi Company. In 1977, he joined Bell-Northern Research Laboratories in Canada, where he was involved in the integration of Canadian domestic satellites into the trans-Canada telephone network. He subsequently joined Miller Communications Systems, where he was responsible for system and hardware design of a 3-Mbit/s TDMA system.

Mr. Bedford joined INTELSAT in 1981, and took major responsibility for the design evaluation, installation, and testing of the reference terminals for the INTELSAT 120-Mbit/s fixed TDMA system. In 1986, he became Principal Project Engineer for the design and development of the INTELSAT 120-Mbit/s SSTDMA system. Since 1990, he has been Project Manager for the INTELSAT SSTDMA implementation program.



Peter W. Roach graduated in telecommunications engineering from Porthcurno Engineering College, England, in 1963. Prior to joining INTELSAT in 1979, he was with the foreign service staff of Cable and Wireless Ltd., where he was involved in providing and operating a wide range of international terrestrial and satellite telecommunications services in the Caribbean, the Middle East, and West Africa. Since joining INTELSAT, he has been involved primarily in operational planning and implementation, and is currently Manager of Communications Operations in the INTELSAT Operations Plans Division.

Paul Nethersole joined the British Post Office in 1968 and was involved with the evolution of telegraph communications and message-switching systems via mainframe computers. In 1978 he moved to Madley Earth Station, performing contract supervision/performance verification duties for antenna, SHF, and GCE installations. He subsequently took responsibility at Madley for the introduction of TDMA, and was involved in the initial user's meetings in Washington, D.C., and Paris. This responsibility was expanded to operations and maintenance, as well as commissioning, when the first of the three terminals at Madley became live in 1985. Mr. Nethersole is currently Earth Station O&M Manager at Madley, with overall responsibility for satcoms at Madley Communications Centre.

George J. Burns has been with AT&T for the last 25 years. From 1968 to 1980, he was a communications technician at AT&T Cedarbrook, New Jersey, underground Autovon complex and was primarily responsible for maintaining AT&T's first electronic switch (the No. 1 ESS), as well as supporting Private Line services, LMX, L4 cable, TH1, and TD2 radio systems. He was subsequently promoted to management in AT&T's Midwestern Region in Kansas City, Missouri, and was a member of AT&T's Enhanced Services Division. This team engineered, installed, and maintained the first 900 services and the first 800 SPC network. In 1984, Mr. Burns transferred to AT&T's Domestic Satellite Center in Hawley, Pennsylvania, where he interfaced with AT&T Bell Laboratories to engineer, install, and maintain the TDMA system for the Defense Commercial Telecommunications Network project, consisting of 10 TDMA stations located at various military bases throughout the continental U.S. In 1987, he transferred to AT&T's International Satellite Center at Roaring Creek, Pennsylvania, where he is currently responsible for the engineering and technical support of TDMA for the Etam, West Virginia, and Roaring Creek earth stations.

Translations of Abstracts

La conception du système AMRT-CS d'INTELSAT

J. A. LUNSFORD, J. F. PHIEL, R. BEDFORD ET S. P. TAMBOLI

Sommaire

Le système INTELSAT d'accès multiple par répartition dans le temps avec commutation à bord du satellite (AMRT-CS), qui a vu le jour lors de la mise en service de la série de satellites INTELSAT VI, est le système de télécommunications commerciales le plus avancé au monde. Du fait qu'il permet une commutation dynamique entre faisceaux à bord du satellite, sa mise en oeuvre a nécessité d'importantes modifications dans le système de gestion de réseau utilisé pour l'AMRT fixe de la génération INTELSAT V, tout en minimisant l'impact sur les terminaux de traffic existants. Pour assurer le réglage du synchronisme entre le commutateur embarqué et le système AMRT, l'installation AMRT du Centre d'exploitation d'INTELSAT (IOCTF) et le Centre de contrôle des satellites INTELSAT (ISCC) sont devenus des éléments de gestion actifs du système AMRT-CS. Cet article donne une vue d'ensemble de ce dernier et décrit les principaux éléments du système de gestion, les modifications de la conception de l'architecture de la trame AMRT, la répartition des paquets dans la trame pour assurer la gestion du réseau, et, entre autres, les procédures de gestion du réseau utilisées pour la commande de l'oscillateur embarqué et le changement de plan de trame.

La station de référence et de surveillance AMRT-CS d'INTELSAT

R. BEDFORD, A. BERNTZEN, J. A. LUNSFORD, Y. ISHI,
H. NAKAMURA ET T. KIMURA

Sommaire

Cet article décrit l'équipement dans chaque station de référence et de surveillance du système INTELSAT d'accès multiple par répartition dans le temps avec commutation à bord du satellite (AMRT-CS) à 120 Mbit/s. Cet équipement se compose d'un organe d'acquisition et de synchronisation (ASU), qui est chargé d'acquérir et de maintenir la synchronisation avec la séquence de commutation à bord du satellite, d'un appareil de traitement en temps réel du signal numérique pour l'exécution des fonctions de gestion du réseau, d'un pupitre de commande et de visualisation chargé d'établir les interfaces avec l'opérateur et l'installation AMRT du Centre d'exploitation d'INTELSAT (IOCTF), et de l'organe de surveillance du système INTELSAT, qui est chargé des mesures en temps réel du signal analogique du paquet. Cet équipement est une version

y la interfaz del ISCC con la IOCTF. Se discuten las funciones y procedimientos empleados en el ISCC para generar secuencias de telemandos con que ejecutar los diversos cambios en el plan de asignación de ráfagas, y para controlar el oscilador de a bordo con el que está sincronizada la temporazación del sistema SSTDMA.

Emplazamiento, prueba y transición a la operación del sistema SSTDMA de INTELSAT

C. L. KULLMAN, S. J. SMITH, K. P. CHAUDHRY, R. BEDFORD,
P. W. ROACH, P. NETHERSOLE Y G. J. BURNS

Abstracto

El sistema de acceso múltiple por distribución en el tiempo con conmutación a bordo del satélite (SSTDMA) funciona en combinación con un conmutador a bordo del satélite que le permite a una terminal de tráfico alcanzar muchas zonas de cobertura de los haces descendentes por medio de un solo haz ascendente. Esta flexibilidad reduce el equipo de estación terrena necesario y facilita el uso más eficiente del segmento espacial. El plan de introducción para el SSTDMA incluyó pruebas extensas del sistema y una cuidadosa planificación para efectuar la transición al servicio. Las pruebas se hicieron en la planta del contratista del equipo de terminal de referencia SSTDMA (SSRTE) y en estaciones terrenas equipadas con SSRTE. Las pruebas en las estaciones terrenas se hicieron a través del primer satélite INTELSAT VI lanzado, el SSRTE con todo el equipo de apoyo, simuladores de terminales de tráfico y tres terminales de tráfico totalmente operativas en estaciones terrenas de Signatarios de INTELSAT. Todas las etapas de las pruebas concluyeron satisfactoriamente y la primera red SSTDMA entró en servicio en mayo de 1990, tal como estaba planeado.

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List of Acronyms

ACC	alarm and control consolidation (system)
ACI	acquisition cycle interval
ACTP	abridged condensed time plan
ADCS	attitude determination and control system
AIS	alarm indication signal
AOR	Atlantic Ocean Region
ART^{TM}	Automated Reasoning Tool (software)
ASCII	American National Standard Code for Information Interchange
ASU	acquisition and synchronization unit
AT	acquiring terminal
AT&T	American Telephone and Telegraph Company
BER	bit error rate
BMLA	burst mode link analyzer
BNR	burst not received
BR	burst received
BS	blind slot
BSS	burst service slot
BTI	British Telecom International
BTP	burst time plan
BTR	bit timing recovery
CADC	control and display console
CAP	command assistance program
CAW	common acquisition window
CBTR	carrier and bit timing recovery
CCITT	International Telephone and Telegraph Consultative Committee
CCS	command coordination system
CDC	control and delay channel
CFE	cumulative frequency error
CH	channel
CM	change manager
CN	current normal
C/N	carrier-to-noise ratio
CPM	clock phase measurement
CPR	clock phase reporting
CPRI	clock phase reporting interval
CPU	command processing unit
CR	carrier recovery

CSI	change of status indicator
CTCA	constrained terminal control assignment
CTP	condensed time plan
CTTE	common TDMA terminal equipment
CW	continuous-wave
D/A	digital-to-analog
DCME	digital circuit multiplication equipment
DCU	distribution and control unit
DDI	direct digital interface
DEC	Digital Equipment Corporation
DELNI	digital Ethernet LAN interconnect
DES	diagnostic expert system
DIRT	decide in real time
DMS	DCU memory status
DNI	digital noninterpolated
DNTX	do not transmit
DOPI	display processor operator interface
DP	display processor
DPP	diagnostic preprocessor
DPTP	diagnostic processor time plan
DR	diagnostic receiver
DRTP	diagnostic receiver time plan
DSI	digital speech interpolation
EBP	extended bin-packing
EDS	event data set
EH	east hemispheric (beam)
EIC	effective instant of change
EIRP	equivalent isotropically radiated power
ES	east spot (beam)
ESC	engineering service circuit
ET	effective time
FAT/TED	frame assembly and transmit/telemetry event detection
FDMA	frequency-division multiple access
FEC	forward error correction
FOS	Flight Operations Section [INTELSAT, obs., use Satellite Engineering Section (SES)]
GCE	ground communications equipment
GDN	graphics display network
GDS	graphic display server
GDU	graphic display unit
GMT	Greenwich mean time

GP	general processor
GPIB	general-purpose interface bus
GPS	Global Positioning System
G/T	gain-to-noise temperature ratio
GT	guard time
HDLC	high-level data link control
HP	Hewlett-Packard
HPA	high-power amplifier
HQS	Headquarters Subsystem (INTELSAT)
HRP	historical retrieval processor
IAP*n*	initial acquisition, phase *n*
ICP	IOCTF control processor
IDP	IOCTF diagnostic processor
IESS	*INTELSAT Earth Station Standard*
IIC	individual interactive commanding
IL	interface logic
INOP	Inoperative (status code)
IOC	INTELSAT Operations Center
IOCTF	INTELSAT Operations Center TDMA Facility
IOR	Indian Ocean Region
IOT	in-orbit test
IRT	inoperative reference terminal
ISCC	INTELSAT Satellite Control Center
ISCS	Integrated Satellite Control System
ITA	International Telegraph Alphabet
ITS	idletime slot
KDD	Kokusai Denshin Denwa Company, Ltd.
LAN	local area network
LAPB	link access protocol on B-channel
LAS	link available slot
LCM	load current monitor
LED	light-emitting diode
LHCP	left-hand circular polarization
LNA	low-noise amplifier
LP	link processor
LSA	last state address
LTS	local timing source
MB	metric burst
MCU	monitor and control unit
MCW	memory control word
MEU	multiple-event upset

MFS	masterframe synchronization
MPRT	master primary reference terminal
MSB	most significant bit
MSM	microwave switch matrix
MSRT	master secondary reference terminal
MTP	master time plan
NC	1) network concentrator 2) no connection
NCU	NRDE control unit
NEC	Nippon Electric Company
NEZ	northeast zone (beam)
NN	new normal
NPDGEN	network parameters data generation
NPRC	network packet recirculator and concentrator
NRDE	nonreference diagnostic equipment
NRTP	NRDE time plan
NV	not valid
NWZ	northwest zone (beam)
OCI	oscillator control integer
ODBM	operational database manager
OFC	oscillator frequency correction
O&M	operations and maintenance
PC	personal computer
PIN	parameter identification number
POR	Pacific Ocean Region
PROM	programmable read-only memory
PRT	primary reference terminal
PSF	packet store and formatter
PSTN	public switched telephone network
QPSK	quadrature phase shift keying
RB	reference burst
RBD	reference burst distribution
RBM	receive burst monitoring
RBP	reference beam pair
RCAP	Repeater Command Assistance Program
RCP	RTE control panel
RCTP	reference (terminal condensed) time plan
RFAS	receive frame acquisition and synchronization
RGB	red, green, and blue
RHCP	right-hand circular polarization
RIVT	reporting interval validity time

ROP	reference terminal operational parameters
RSO	redundancy switchover
RTE	reference terminal equipment
SAG	spectrum analyzer gate
SAW	subacquisition window
SC	service channel
SCPC	single channel per carrier
SDNTX	selective do not transmit
SES	Satellite Engineering Section (INTELSAT)
SEU	single-event upset
SEZ	southeast zone (beam)
SGT	SDNTX generation
SMF	switch masterframe
SMW	switch masterframe synchronization word
SOF	start of frame
SORCF	start of receive control frame
SORF	start of receive frame
SORMF	start of receive masterframe
SOTCF	start of transmit control frame
SOTF	start of transmit frame
SOTMF	start of transmit masterframe
SOTSF	start of each transmit superframe
SPC	satellite prediction coefficient
SPE	signal processing equipment
SRT	secondary reference terminal
SSBTP	SSTDMA burst time plan
SSC	substitution state control
SSCTP	SSTDMA condensed time plan
SSM	static switch matrix
SSMTP	SSTDMA master time plan
SSOG	*Satellite System Operating Guide* (INTELSAT)
SSPA	solid-state power amplifier
SSRTE	SSTDMA reference terminal equipment
SSTDMA	satellite-switched time-division multiple access
SSTP	switch state time plan
SSTSM	SSTDMA system monitor
SSV	switch state verification
SUA	startup acquisition
SWZ	southwest zone (beam)
SYNC	synchronization
TACTP	test abridged condensed time plan

TAS	terminal acquisition and synchronization
TASS	terminal acquisition and synchronization support
T&C	telemetry and command
TCG	time code generator
TCI	TSO correction interval
TCTP	TDMA system monitor condensed time plan
TCW	telemetry control word
TDMA	time-division multiple access
TDP	telemetry and display processor
TIM	terrestrial interface module
TLM	telemetry
TMARGL	timing margin, lower limit
TMARGU	timing margin, upper limit
TOC	time of change
TONC	time of next change
TP	telemetry processor
TRMS	TDMA reference and monitoring station
TS	1) terminal server 2) timing source
TSDE	timing source digital electronics
TSM	TDMA system monitor
TSO	timing source oscillator
TT	traffic terminal
TT&C	telemetry, tracking, and command
TTC&M	telemetry, tracking, command, and monitoring
TTC&R	tracking, telemetry, commanding, and ranging
TTS	TDMA traffic simulator
TTY	teletype
TWTA	traveling wave tube amplifier
UTC	Universal Time Coordinated
UTCA	unconstrained terminal control assignment
UW	unique word
VCXO	voltage-controlled crystal oscillator
VDU	visual display unit
VOW	voice orderwire
WAN	wide area network
WH	west hemispheric (beam)
WS	west spot (beam)