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COMSAT TECHNICAL REVIEW
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INTELSAT VI: From Spacecraft to Satellite Operation

Non-INTELSAT VI Papers

Foreword: Making reality out of a vision

PIERRE J. MADON

The design, manufacture, and test of the INTELSAT VI satellite presented a real challenge, for several reasons. INTELSAT VI is the heaviest commercial telecommunications satellite placed in geostationary orbit to date, with a mass in excess of 4,000 kg. It is also physically quite large, particularly when deployed—some 11.6 m in height and 3.6 m in diameter. In addition, INTELSAT VI pushes the limit of technology for spin-stabilized satellites, including deployment of a solar generator drum to achieve the required power, and use of "superspin" to ensure dynamic stability throughout the transition from transfer orbit to geostationary orbit. The satellite also carries the most complex payload to date, with 48 transponders, sixfold frequency reuse at C-band through a combination of polarization and coverage pattern isolation, and on-board dynamic switching of digital traffic between antenna beams (satellite-switched time-division multiple access [SS-TDMA]).

The launch of the INTELSAT VI series encountered several setbacks that had to be overcome. The initial plan called for three of the five satellites to be launched using NASA's Space Transportation System (the Shuttle), and two using the Ariane 4 launch vehicle. However, the Shuttle *Challenger* disaster in January 1986, followed by failure of an Ariane vehicle in May of the same year, resulted in substantial delay of the INTELSAT VI program. The subsequent plan entailed launching three satellites with Ariane 4 and two with Titan III vehicles. Although one Titan launch left INTELSAT 603 stranded in low earth orbit, and currently the subject of a reboost mission, the other four satellites were successfully placed in geostationary orbit, beginning with the first launch on October 27, 1989.

Despite these many challenges, all five INTELSAT VI satellites are functioning so well that it could be considered miraculous! In reality, their success is the result of a perfect job done primarily by the satellite manufacturer, Hughes Aircraft Company, with significant assistance from both COMSAT and INTELSAT. This and the previous two issues of *COMSAT Technical Review* document that achievement.

Pierre J. Madon received the Diploma of Engineer from the Ecole Polytechnique, Paris, in 1955; the Auditor ENSAE from the Engineering School of Aeronautics and Astronautics, Paris, in 1957; and an M.S. in electrical engineering form Harvard University in 1958. From 1957 to 1986, he was with Nord Aviation (later Aerospatiale) as Program Manager for the launch vehicle DIAMANT; Head of the Departments of Analog Computers, Digital Computers, and Electronic Equipment Designers; and Program Manager for the SYMPHONIE telecommunications satellite and the Ariane launch vehicle. He subsequently served as Director of the Aerospatiale plant in Les Mureaux, France, and as General Manager of EUROSATELLITE. From 1983 to 1986, he was Space Programs Director for Aerospatiale.

Mr. Madon joined INTELSAT in 1986 as Senior Director of the Engineering Division. He was promoted to Vice President, INTELSAT Engineering and Research, in 1992. His tenure at INTELSAT has encompassed the launch of the INTELSAT VI series of satellites and the deployment and initiation of the INTELSAT VI system, operation, and services. The INTELSAT VII and INTELSAT K programs were also initiated, and their procurement is well under way. In addition, the FOS procurement program has been initiated. Mr. Madon is a member of the AIAA.

Editorial Note

S. B. BENNETT, Guest Editor, INTELSAT
G. HYDE, Associate Guest Editor, COMSAT

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

The first issue in the CTR INTELSAT VI series* described the overall development process, as well as system planning, specification of the spacecraft bus and communications payload, and the design for SS-TDMA and frequency-division multiple access (FDMA) services. The second issue focused on the design of the INTELSAT VI spacecraft and its communications payload, dealing with 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 on-board SS-TDMA package.

This third issue in the INTELSAT VI series covers 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. The first paper deals with the execution of an extended in-house monitoring program, from unit-level design and analysis through development and all phases of the extensive and complex test plan. The second paper details the planning and implementation of an INTELSAT VI launch, as well as post-launch operations such as deployment, attitude, and in-orbit bus tests. In-orbit RF testing of the payload from a telemetry, tracking, command, and monitoring (TTC&M) earth station, including measurements of antenna patterns, transponder performance, and telemetry, command, and ranging subsystem performance are discussed in the third paper. The design, implementation, and operation of an INTELSAT post-1989 TTC&M earth station, and the associated special-purpose complex, are the subject of paper four. Paper five covers

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*Refer to pages 503 through 507 of this issue for a listing of the papers scheduled for publication in this series. Papers on other topics may also be included.

the management and operation of the communications payloads on-station, including interfacing with the INTELSAT VI networks and bringing new services, carriers, and earth stations on line. The last paper in this issue deals with the upgrading and use of the spacecraft operations resources required for the INTELSAT VI fleet, especially increasing the level of automation and data processing capabilities and making the transition to a centralized telecommanding mode.

Presented in a related fourth issue on the INTELSAT system and applications will be papers on earth station considerations, as well as on digital, video, and other modulation coding techniques used in the INTELSAT VI era. Also covered will be the successful reboost of INTELSAT 603 from low earth orbit to geosynchronous orbit. The fifth issue will be devoted to describing all aspects of the SS-TDMA system, which was first used for commercial purposes on INTELSAT VI.

The editors trust that this comprehensive treatment of the INTELSAT VI system will prove useful to future system planners. The papers in the CTR INTELSAT VI series are the result of a major effort by a large group of authors from COMSAT, INTELSAT, and Hughes Aircraft Corporation, and we congratulate them on their substantial achievement.

Simon B. Bennett received a B.E.E. from City College of New York in 1959 and an M.E.E. 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. Since 1974 he has been at INTELSAT, where he has been manager of spacecraft programs, directed systems planning studies, and managed the operation of INTELSAT's 15-satellite fleet (including the INTELSAT VI series). He is currently Assistant to the Senior Director of Engineering.*

Geoffrey Hyde received a B.A.Sc. in engineering physics and an M.A.Sc. in electrical engineering from the University of Toronto in 1953 and 1959, respectively, and a Ph.D. 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).

Index: communication satellites, INTELSAT, reliability, testing

Ensuring a reliable satellite

C. E. JOHNSON, R. R. PERSINGER, J. J. LEMON, AND K. J. VOLKERT

(Manuscript received August 14, 1991)

Abstract

The uniquely successful and thorough monitoring approach used for all INTELSAT spacecraft since INTELSAT IV is presented. Because INTELSAT VI is the largest commercial communications satellite placed in service to date, it presented many new and complex problems to the contractor. Very comprehensive test plans, tests, and monitoring approaches were developed and executed. The major features of this monitoring program are discussed herein. The ground test program is sketched, from unit level through launch site, and the test data handling system and its use are presented. Testing unique to the INTELSAT VI program is also reviewed. This includes near-field anechoic chamber antenna measurements methodology, facilitation, and antenna testing; off-load 1-g deployment of solar arrays and reflector antennas; and electrostatic discharge testing. Finally, some of the problems (and their solutions) arising from the sheer size of the spacecraft and the change in launch vehicles are discussed.

Introduction

INTELSAT programs are unique in the commercial aerospace industry in terms of the large application of resources to in-residence monitoring of spacecraft design, fabrication, integration, and test. This practice was initiated by COMSAT during the INTELSAT IV program and has been continued by COMSAT, and then INTELSAT, during the INTELSAT IV-A, V, and VI programs. In-residence support levels peaked at 88 man-years during the second year of the INTELSAT VI program. In this program, INTELSAT staff concentrated on program management, system engineering, and product assurance, while

COMSAT and other technical assistance contractors provided participatory monitoring of design and test activities.

The INTELSAT VI spacecraft is the largest commercial communications satellite placed in service to date. The communications capacity provided by this spacecraft series is vital for continuation and expansion of the INTELSAT network. At the outset of the INTELSAT VI program, INTELSAT management decided to continue the in-residence monitoring concept which had proven so successful on previous spacecraft programs, and further, to expand the scope of this monitoring in the early stages of unit design and analysis. In previous programs, the monitoring effort was concentrated at the spacecraft system-level test phase; however, it was recognized that problems with unit design and fabrication defects detected during system-level testing were leading to costly program delays. Consequently, for INTELSAT VI greater effort was focused on unit design, manufacturing processes, and testing, and worst-case circuit and thermal analyses were performed on all units. As a result, the failure rate of units during spacecraft-level ambient and environmental testing was very low. During launch-site testing of five spacecraft, there were only three unit failures. The in-orbit unit failure rate has also been low for the four spacecraft at synchronous altitude.

The INTELSAT 603 spacecraft, stranded in low earth orbit (at the time of this writing) due to a launch vehicle failure, is operating normally in transfer orbit configuration. The only anomaly observed is an increase in propellant tank pressures, apparently caused by a small pressurant leak past a pressure regulator. INTELSAT has contracted with NASA and Hughes Aircraft Company (HAC) to support an INTELSAT 603 reboost rescue mission, currently scheduled for May 1992.

Because the INTELSAT VI spacecraft was a new design, extensive developmental and qualification testing was performed. A nonflight prototype spacecraft was constructed, and unique electrostatic discharge (ESD) testing was conducted on the prototype and one flight spacecraft. The physical size of INTELSAT VI created new challenges for ground handling, transportation, and test support equipment design. To achieve mass and launch size efficiency, all modern communications satellites incorporate deployable antennas, solar panels, and other appendages designed to function in the zero-g space environment, but which need to be supported for deployment and operation in the 1-g test environment. Testing of the large C- and Ku-band antenna systems in the HAC near-field antenna test range is discussed. Unique off-loading implementations for antenna and solar panel deployments are described, as is off-loading of the despun shelf during thermal vacuum testing.

The INTELSAT approach to program monitoring

The important elements which make up the COMSAT/INTELSAT approach to program monitoring include the negotiated test plan, unrestricted access to work in progress and to data, the right of approval of rework and failure dispositions, and substantial in-residence monitoring at the prime contractor and major subcontractor facilities, supported by computing capability and augmented with headquarters engineering support and laboratory assistance.

This approach was implemented at the beginning of the INTELSAT IV spacecraft series, and the resulting reliability in orbit has been outstanding. Since then, no spacecraft that achieved synchronous orbit has been lost from service prior to propellant depletion, and all INTELSAT IV spacecraft exceeded their orbital design life. Reliability in orbit, based on the availability of transponders, has far exceeded contract requirements. In contrast, other spacecraft series produced by the same contractors, and using much hardware with an INTELSAT program heritage, have experienced major problems in orbit, resulting in some cases in the loss of one or more spacecraft. Table 1 presents statistics on the INTELSAT V spacecraft series and on the initial reliability of the INTELSAT VI series.

The INTELSAT VI negotiated test plan became part of the contract with HAC. The plan defined the scope of testing (in the unit, subsystem, and system test programs) necessary to show compliance with all performance specifications. It detailed the testing to be performed on engineering models, prototype, protoflight, and flight hardware, and also defined the environmental conditions to which hardware would be exposed, which encompassed worst-case predicted in-orbit conditions with specified margins.

The INTELSAT VI contract provided for essentially unrestricted access to work in progress, data, and documentation related to the effort of the contractor and subcontractors. HAC and its subcontractors were very cooperative in providing this access, which is essential to effective monitoring.

Overview of the satellite ground test program

The INTELSAT VI program included thorough qualification and acceptance testing at the unit, subsystem, and system levels. Roughly 40 percent of the program cost was attributable to testing. The objective of the qualification test program was to demonstrate that the design was adequate for the expected operating environment, with appropriate margins. The goal of the acceptance test program was to verify workmanship and confirm that performance complied with all specifications. Spacecraft specification development has been discussed

TABLE 1. STATISTICAL DATA FOR INTELSAT V AND VI SERIES SPACECRAFT

CHARACTERISTICS	INTELSAT V	INTELSAT VI
Spacecraft in Series	15	5
Spacecraft in Synchronous Orbit	13[a]	4[b]
Spacecraft in Communications Service	13	3[c]
Years in Orbit per Spacecraft	3.0–11.2	0.25–2.25
Accumulated Years in Orbit	105	4.6
Transponders per Spacecraft	27–32	48
Total Transponders in Orbit	384	192
Accumulated Transponder-Years	3,049	221
Communications Unit Failures	29	5
Transponders Lost[d]	3	0

[a] Two INTELSAT V launch failures.
[b] One launch failure left INTELSAT 603 in low earth orbit. May be recovered if reboost mission is successful.
[c] INTELSAT 601 has completed in-orbit test, but has not yet been placed in communications service.
[d] The ability to prevent transponder loss in the presence of unit failures is attributable to the redundancy scheme design.

in companion papers by Pontano *et al.* [1] and Cantarella and Porcelli [2]. Specification compliance was demonstrated during system-level testing where possible, although unit-level test results had to be used in some cases. Verification through analysis was used only when verification through testing was not possible.

Qualification

The INTELSAT VI qualification test program included a developmental vehicle (DV), a structural thermal model spacecraft (STM), and a prototype spacecraft (Y1). Table 2 contains the structural environmental test matrix for the program. The primary spacecraft structure was designed to 1.5 times the quasistatic launch vehicle loads. The specifications required the spacecraft to "elastically" withstand loads equivalent to 1.5 times predicted flight levels with a 10-percent margin of safety (*i.e.*, 1.65 times flight levels). HAC statically tested the DV to 1.65 times the quasistatic loads.

TABLE 2. STRUCTURAL ENVIRONMENTAL TESTING

TEST	STATIC	ACOUSTIC[a]	RANDOM[a]	SINE[b]	SHOCK
Developmental	1.65 × flight[c]	Qual[d]	Qual[d]	Qual[d]	Flight + 6 dB (3 events)
Life	Flight[e]	Flight (60 s)	Flight (60 s/axis)	Flight (4 oct/min)	Flight (1 event)
Qualification	1.5 × flight[c]	Flight + 3 dB (2 min)	Flight + 3 dB (2 min/axis)	1.5 × flight (2 oct/min)	Flight + 6 dB (3 events)
Protoflight	1.2 × flight[e]	Flight + 2 dB (90 s)	Flight + 2 dB (90 s/axis)	1/2 × flight (3 oct/min)	Flight + 3 dB (1 event)
Acceptance	Flight[e]	Flight (60 s)	Flight (60 s/axis)	Flight (4 oct/min)	Flight (1 event)

[a] Test durations stated are minimum values. Protoflight and qualification test durations were always 1.5 and 2.0 times flight, respectively.
[b] Sweep rates used (octaves/minute) are given in parentheses.
[c] Except for composite and low-ductility structures, which were tested to 1.65 times flight.
[d] Not required at system level.
[e] All composite and low-ductility structures were acceptance proof-tested to 1.5 times flight.

The STM, which consisted of the DV with a simulated payload and complete antenna farm, was vibrated sinusoidally to 1.5 times preliminary loads acceptance cycle (PLAC) values supplied by the launch vehicle agencies. A solar thermal vacuum test was performed on the STM at the Jet Propulsion Laboratory (JPL) facility, simulating transfer orbit and synchronous orbit thermal conditions.

The Y1 spacecraft was exposed to a complete qualification program, which included acoustical vibration to predicted flight levels +4 dB, three-axis sine vibration to 1.5 times flight, infrared thermal vacuum (IRTV) to flight +10°C, ESD at 10 mJ, pyroshock, and deployments. Table 3 lists the Y1 IRTV thermal conditions.

Protoflight and flight

The essential elements of the system-level program were the pre-environmental reference performance measurements (integrated system test, IST-1), environmental exposure (acoustic, random, and sine vibration, pyroshock, and IRTV), and a post-environmental performance verification (IST-2). Repeater performance was measured over the expected operating

TABLE 3. Y1 IRTV TEST CONDITIONS

TEST PHASE	ORBITAL CONDITION	ECLIPSE	HEAT LOAD	TEMPERATURE MARGIN (°C)
1	Transfer orbit cold	No	Low	-10°
2	Transfer orbit hot	No	Nominal	+10°
3	Summer EOL	No	High	+10°
4	Equinox EOL	No	High	Nominal
5	Equinox BOL	Yes	Low	Nominal
6	Winter BOL	No	Low	-10°
7	Ambient	–	–	–

range (with margin) in the non-spinning despun compartment thermal vacuum test prior to antenna installation. Further test data on preflight and in-flight repeater performance are given in a companion paper by Rosell *et al.* [3]. Details of antenna system design, implementation, and prelaunch testing are given by Persinger *et al.* [4].

Table 4 presents the protoflight and flight IRTV conditions. Protoflight testing included ESD exposure to 3 mJ, in addition to the complete acceptance test program. The duration of the system test program for the last two spacecraft was 9 months. Earlier spacecraft required substantially longer.

Launch site testing

The INTELSAT VI program includes thorough performance verification testing at the launch site. The spacecraft is shipped to the launch site in separate containers housing the spun section, despun section, solar panels, batteries, and launch vehicle adapter. The launch site test program verifies that all sections have survived transportation stress and that the rebuild of the various elements is accomplished correctly. Because of the complexity of the antenna test range required, antenna pattern measurements are not performed at the launch site. The launch campaign duration was 3 months for an Ariane launch and 4 months for a Titan launch.

Test data handling system

The need for an automated test data storage and review capability at the contractor's facility was recognized during the INTELSAT V program. The engineering staff experienced difficulty in conducting timely review and trend

TABLE 4. FLIGHT SPACECRAFT IRTV TESTING

TEST PHASE	ORBITAL CONDITION	ECLIPSE	HEAT LOAD	TEMPERATURE MARGIN (°C)
1	Transfer orbit	No	Nominal	+5° *
2	Summer EOL	No	High	+5°
3	Equinox EOL	Yes	High	Nominal
4	Equinox EOL	Yes	Low	-5° *
5	Winter BOL	No	Low	-5° *
6**	Summer BOL	No	High	Nominal
7**	Equinox EOL	No	High	+5°
8**	Equinox BOL	No	Low	Nominal

* ±10°C for INTELSAT 602 protoflight.
** INTELSAT 602 protoflight only. No performance testing, monitor only.

detection for the large quantity of data generated during the spacecraft test program, particularly for the repeater and antenna subsystems. The test data handling system (TDHS) implemented for INTELSAT V provided automation of data review and analysis, but was limited by the need for initial manual entry of data from the engineers' notebooks.

The INTELSAT VI contract required that the contractor transfer test data to INTELSAT in near-real time, in machine-readable format, and from a central location. All test procedures specified requirements for the types of data to be transmitted and the format of the data records. HAC implemented a TDHS facility called "TDHS Central," where data from unit, subsystem, system, and launch site testing were collected, stored, and then transferred to the INTELSAT TDHS computer facility at the program office in El Segundo, California.

The major problem encountered was the need to ensure the timeliness and accuracy of unit data received from the many international and domestic subcontractors and from the HAC unit areas. Since HAC did not require delivery of data in machine-readable format from the subcontractors, a large manual data entry effort was required. Fortunately, data from repeater and antenna subsystem testing were collected and stored in machine-readable format, so that a timely transfer of error-free data was possible.

The INTELSAT TDHS hardware facility includes a central computer room with Hewlett-Packard (HP) A900 series computers and more than 3 Gbyte of disk storage. There is also a central terminal room, with additional terminals located in engineers' offices and at each system test location within HAC.

Subsequently, some application programs were implemented on personal computers (PCs), and the capability to down-load data to these computers was developed. Hardware costs for the program were approximately $700,000. In addition, maintenance and support costs are approximately $87,000 per year. The TDHS staff level of effort (in man-years per year) was 6 in 1984 and 1985, 5 in 1986 and 1987, decreasing to 3 at the end of the program.

The TDHS provides the capabilities of archival, retrieval, and extensive analysis of spacecraft telemetry data. During system-level testing, telemetry data were transmitted to INTELSAT TDHS in real time from each HAC system test equipment location, using INTELSAT-provided modems and leased telephone circuits. The spacecraft in-flight configuration provides one normal and one dwell telemetry stream at 4,800 bit/s each. Each stream requires 55 Mbyte of disk storage per day. During much of the test program, HAC performed parallel testing of the spun and despun sections, with each generating two telemetry streams requiring 220 Mbyte of storage per day. The TDHS objective was to provide at least 5 days of storage per spacecraft under test, in order to allow INTELSAT engineers time to perform delayed in-depth analysis of real-time data, thereby eliminating the requirement for around-the-clock test monitoring. During thermal vacuum testing, HAC also transmitted temperature sensor and thermocouple scan data to the TDHS for storage.

Although disk space for storing real-time data was necessarily limited, a capability for archival storage of data for selected periods was provided to allow further analysis and comparison of data from different test phases, as well as from different spacecraft. Archival records were also provided to the INTELSAT telemetry, tracking, command, and monitoring (TTC&M) department for use in software development and mission training.

Analysis software provided displays of real-time or historical data on terminals (and on PCs running terminal emulation programs), similar to the displays provided at the INTELSAT Launch Control Center. Single and multiple plots of telemetry channels could be generated, and the ability to scan telemetry data for selected events was provided. During ESD testing and acoustic and sine dynamic exposure, every telemetry channel could be screened for changes in telemetered status, and the telemetered content of on-board registers and memory could be reviewed. The results of ESD testing are discussed later in this paper.

In addition to telemetry processing software, an extensive capability for analyzing and detecting changes in repeater performance and antenna pattern data was provided. Repeater performance data were acquired during the despun thermal-vacuum test phase and during the IST-1 and IST-2 pre- and post-environmental ambient test phases. The ability to compare measured performance with specifications, or with any previous test phase, was provided. Selected performance data were transferred to a PC, where a reference performance database was generated for each spacecraft. This database has been used by satellite operations departments for comparisons with in-orbit test data and for in-orbit operations predictions.

For the antenna subsystem [4], an extensive capability for receiving, processing, plotting, and analyzing pattern measurement data from the HAC far-field and near-field antenna ranges was implemented [5]. An automated pattern comparison capability was developed to screen differences between thousands of far-field patterns and pre- and post-environmental near-field patterns, and flag those differences which require engineering evaluation. During INTELSAT 605 post-environmental near-field testing, the computer flagged a discrepancy that was traced to a loose antenna feed element. Without automated processing, this discrepancy would not have been discovered, and the spacecraft would have been launched with the malfunction.

Program-unique testing

Three unique approaches developed to permit proper testing of the exceptionally large and complex INTELSAT VI spacecraft are described in this section.

Near-field anechoic chamber measurements

The INTELSAT VI system-level measurement plan required that antenna pattern measurements be made for the complete antenna farm before and after spacecraft environmental exposure. Originally it was thought that these measurements would be performed using a relatively short slant range which existed at the beginning of the INTELSAT VI contract in April 1982. Because of the large size of the antenna farm and despun compartment, it was quickly recognized that the slant range would require significant zero-g off-loading, which would present difficulties when trying to measure antenna patterns over a 20° square measurement window. HAC's solution to this problem was to implement a planar near-field anechoic chamber, which provides absolute co-polarized and cross-polarized far-field measurements without the need to move the spacecraft under test. Compact and spherical near-field ranges were considered, but rejected because movement of the antenna farm was still required.

Over the course of the INTELSAT VI program, the HAC near-field facility has yielded programmatic advantages and proven to be cost effective. The absolute measurements provided by the near-field range eliminated the need for far-field range testing at HAC of the Selenia-supplied spot and global antennas. Also, it was possible to implement antenna design changes after the hemi/zone antennas had left the far-field range and been mounted on the spacecraft. In fact, just prior to completion of INTELSAT 602, the receive beacon tracking system (BTS) antenna array was replaced and recalibrated using near-field techniques. It would not have been economically feasible to return the antenna farm to the far-field range.

The HAC near-field anechoic chamber is located adjacent to the spacecraft assembly area and allows easy access for spacecraft integration and test. The planar scanner is 6.5 × 6.5 m and can probe the near-field radiation of an antenna under test from 4 to 14 GHz, using a variety of linearly and circularity polarized probe horns. The near-field-to-far-field transformation software and associated data processing can be run in the near-field chamber, or off-line to allow the near-field computer to continue with measurements.

The heart of the near-field measurement system is an HP8410 network analyzer, which was chosen over a receiver because of its ability to make high-speed measurements. Typically, in the course of one near-field planar scan, six beams are measured for two polarizations at six frequencies. The near-field measurement computer moves the probe with the aid of a laser system and coordinates the required multiplexing of the beams, polarization, and frequencies. Attenuation control is also required during the different polarization states to ensure proper dynamic range. The near-field RF equipment can be configured to test the transmit antennas in the transmit mode and the receive antennas in the receive mode. Phase drift has been shown to be less than 3° over a 10-hour scan. The duration of a scan depends on the frequency (or frequencies) and size of the antenna under test.

The first phase of the INTELSAT VI antenna farm near-field measurement sequence involves alignment of the despun compartment and hemi/zone reflector antennas to each other and to the scan plane. The hemi/zone alignment techniques are based on the use of tooling balls and a dual theodolite system. Alignment support software indicates the current translation and rotation of the various hardware in a common coordinate system, and provides information on how to achieve the alignment goal. There are four separate alignment configurations:

- Transmit hemi/zone position
- Receive hemi/zone position
- Global position
- Ku-band spot beam antenna position.

Each of the four positions of the despun compartment optimized the required scan area for the antennas being measured. The despun compartment is first aligned to the scan plane to within ±0.1° in azimuth and elevation. For the hemi/zone positions, the appropriate reflector is detached from the despun compartment and aligned to the feed array. The reflector-to-feed-array geometry, as defined by far-field alignment measurements, is repeated to within ±0.01° RF. Typically this requires three to four iterations and is implemented by translation and rotation of the reflector on its own alignment tower or support structure. The reflector is supported by a ring with a three-point attachment to eliminate reflector distortion. Once the reflector is aligned to its feed array, the reflector and scan plane are surveyed to determine the scan plane orientation in the antenna coordinate system. This azimuth and elevation angle are then recorded for future analysis.

Optical-to-RF near-field alignment repeatability between IST-1 and IST-2 measurements is on the order of 0.025°. The global and Ku-band antennas use optical cubes to reference the antenna angular position to the scan plane. Figure 1 shows the INTELSAT 602 spacecraft in the HAC near-field chamber.

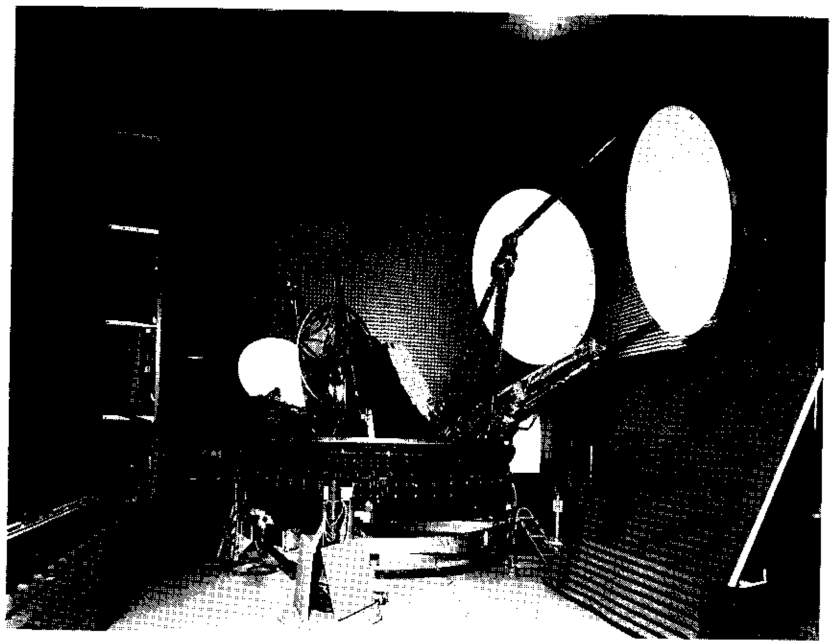


Figure 1. *INTELSAT VI Satellite on Planar Near-Field Range Showing RF and Antenna System*

Prior to the near-field measurement of a given antenna subsystem, the near-field hardware is properly configured and an initial RF checkout is performed to ensure proper dynamic range, linearity, and the absence of RF leakage. This is very important in near-field testing, as it eliminates problems prior to commencement of the 10-hr scan. The desired pattern data are then measured through 23-dB test couplers. For the INTELSAT VI hemi/zone antenna subsystem, each antenna is measured in the three ocean region switch positions. Figures 2 and 3 illustrate the excellent agreement of the near-field-to-far-field data obtained for the INTELSAT 604 spacecraft, Atlantic Ocean Region, zone 3 and zone 4 receive beams, respectively. Both co-polarized and cross-polarized antenna performance are shown.

Absolute saturated effective isotropically radiated power (e.i.r.p.), flux density to saturate, and gain-to-noise temperature ratio (G/T) measurements are made in the near-field chamber for each antenna subsystem. These tests verify the combined performance of the antenna and transponder subsystems. It is interesting to note that measurement of e.i.r.p. does not require the combination of separate antenna gain and output power measurements, but is a single measurement at the peak of the near-field beam. The near-field power measurement is then transformed to a far-field peak e.i.r.p. by using the pattern data. Reference 5 provides more detail on this subject. Swept frequency measurements are also conducted to verify proper operation of the transponder/antenna interface.

The most ambitious use of the near-field chamber on the INTELSAT VI program has been the near-field calibration of the BTS—the system that provides closed-loop pointing performance for the hemi/zone antennas. Normally the BTS is calibrated on a far-field range, where a plane wave illuminates the reflector and the resulting modulation index contours are measured. The advantage of far-field calibration is that the BTS antenna ferrite modulator assembly and the beacon tracking receiver (BTR) can be calibrated as a unit. Near-field calibration of the BTS requires that accurate mathematical models of the modulator assembly and BTR be combined with the measured amplitude and phase antenna data to predict the modulation index response of the BTR. Amplitude and phase calibration between the sum and difference channels is required to be accurate to ±0.25 dB and ±3.0°, respectively. Figure 4 illustrates the agreement of near-field-to-far-field antenna patterns for the INTELSAT 604 transmit BTS azimuth channel (Figure 4a), as well as the in-orbit to near-field agreement of the INTELSAT 602 receive azimuth channel modulation index contours (Figure 4b). Currently, 5 out of 10 BTS calibrations have depended on near-field measurements.

The programmatic and technical advantages offered by the HAC near-field chamber have contributed to the successful operation of the INTELSAT VI

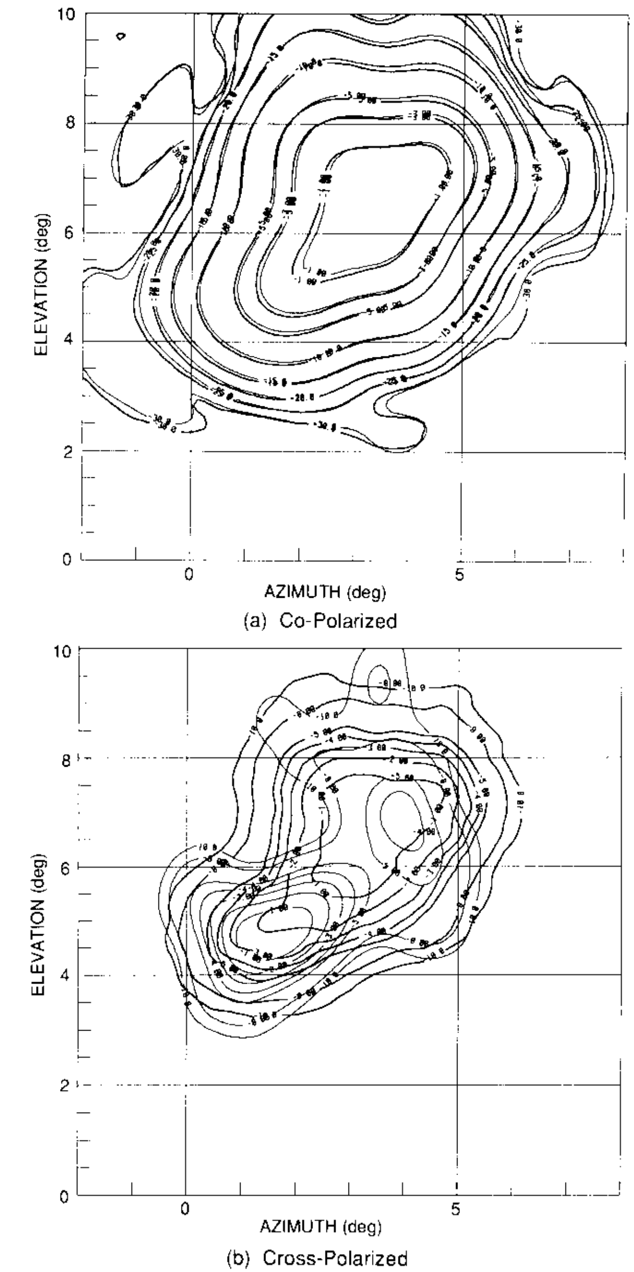
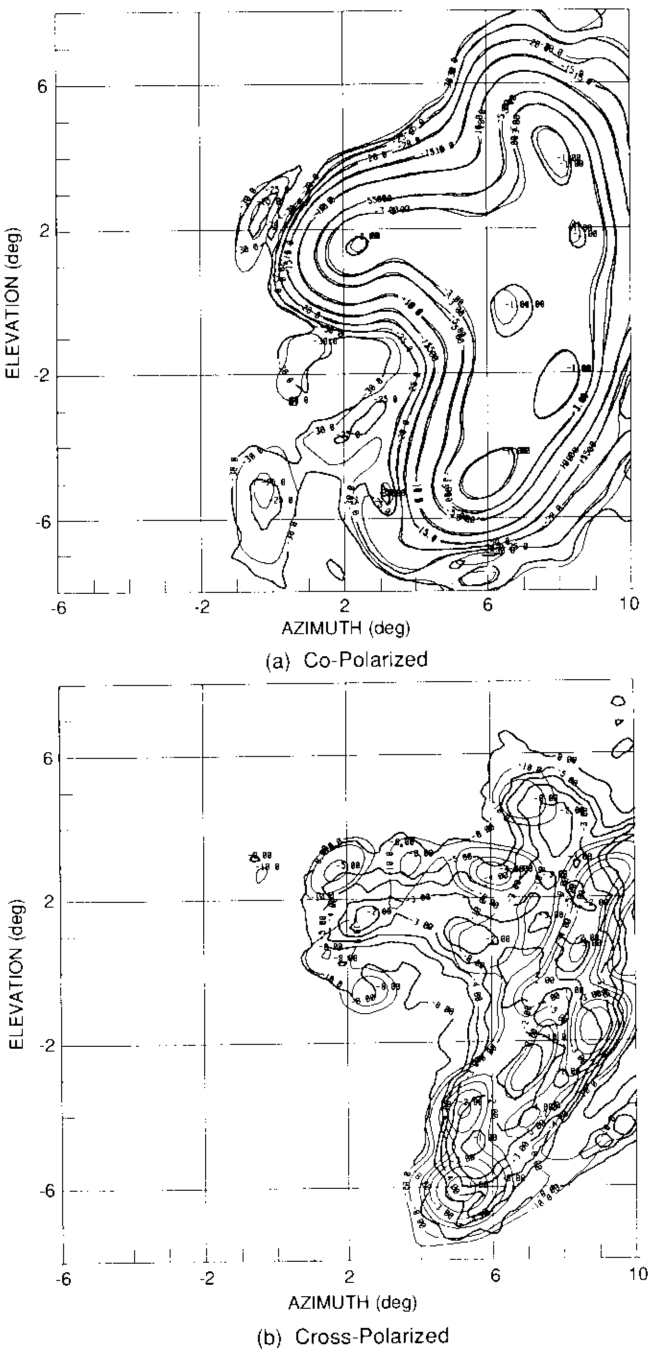


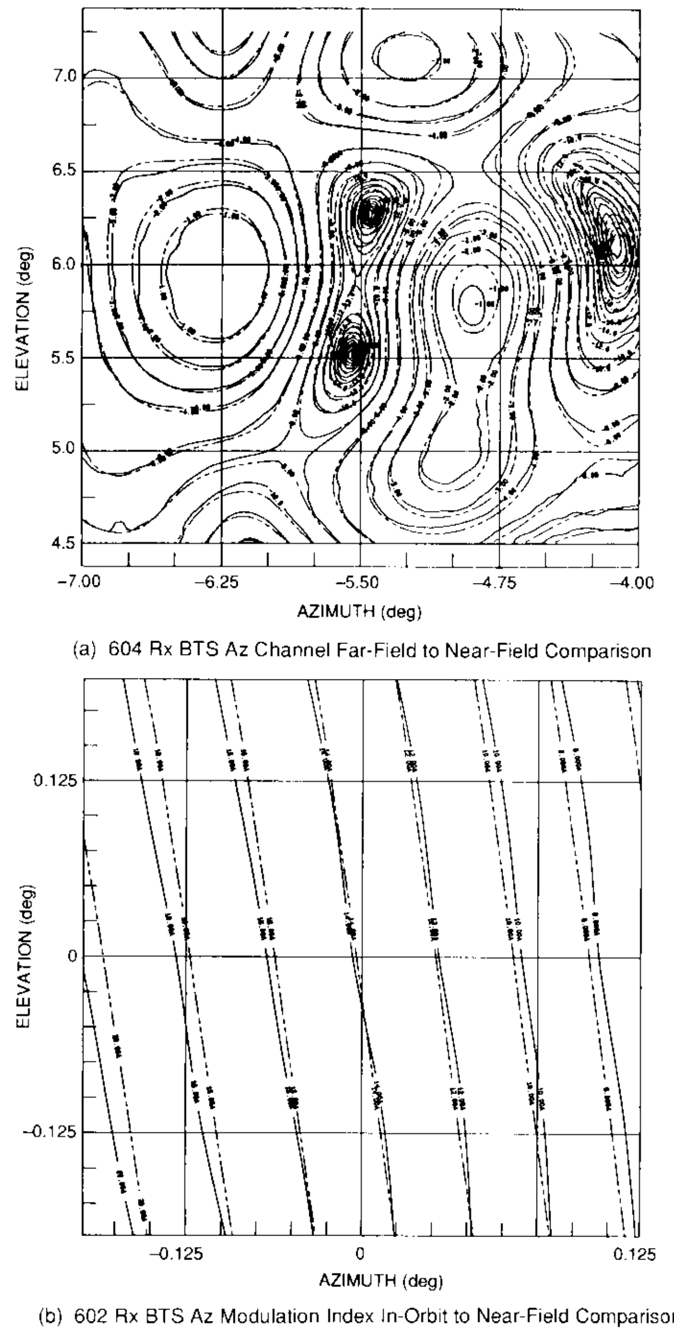
Figure 2. *Far-Field-to-Near-Field Measurement Comparison: Zone 3*



(a) Co-Polarized

(b) Cross-Polarized

Figure 3. *Far-Field-to-Near-Field Measurement Comparison: Zone 4*



(a) 604 Rx BTS Az Channel Far-Field to Near-Field Comparison

(b) 602 Rx BTS Az Modulation Index In-Orbit to Near-Field Comparison

Figure 4. *Near-Field BTS Calibration*

satellites. Persinger *et al.* [4] discusses the design and implementation of the INTELSAT VI antenna subsystem, while Rosell *et al.* [3] elaborates on in-orbit measurements.

Off-loaded 1-g deployments

The size and complexity of the INTELSAT VI deployable appendages and solar array required a unique approach to off-load deployment. During C-band antenna reflector deployments, a group of up to five 3-m-diameter helium-filled balloons was used to compensate for the 1-g gravity effects. Figure 5 shows six inflated balloons ready for deployment testing of the INTELSAT 605 despun section at the Centre Spatial Guyanais (CSG), French Guiana. Because of the large deployment angles (see Table 5), the balloon lift cables must pass from the back of the reflectors to the front, requiring whiffletrees and swivels. Since it was not possible to maintain a position exactly at the center of gravity, a method based on equal moment compensation (*i.e.*, a smaller lift force at a greater moment arm) at the hingeline was used.

The test philosophy was based not only on verification that a mechanism could deploy an appendage, but also on the ability to measure a state of health (*i.e.*, a torque margin) in order to detect any degradation due to environmental exposure or wearout. It quickly became apparent that small errors in the balloon lift force could significantly affect the fluid-damped deployment times. A zero-kinetic-energy methodology was developed to determine the friction torque and motor torque, and also to provide balloon lift force error information. In this approach, the force required to move the appendage back and forth very slowly is recorded. The difference between the "pull" force and "push" force is a measure of twice the friction torque, and the average is the net motor torque from the mechanism. Data from actuator unit-level torque tests is compared to system-level data to determine off-load errors. A study of three or more positions along the deployment arc can lead to the proper combination of lift point geometry and lift force. The balloon deployments, while cumbersome and time-consuming, did provide an acceptable method for deploying the large reflectors and booms safely, while allowing for the measurement of meaningful deployment parameters.

The Ku-band antennas used a side-mounted spring element to partially compensate the overturning moment on the elevation drive mechanism. The azimuth drive mechanisms on both Ku-band antennas and the global antenna cluster did not require gravity-compensation devices, since their hingelines are parallel to the gravity vector. The solar panel off-load system employed a concept used on previous HAC spin-stabilized spacecraft, scaled up to accommodate the 113-kg INTELSAT VI solar drum. Three off-load devices collocate

Figure 5. *Inflated Balloons During INTELSAT 605 Deployment Testing at CSG*

TABLE 5. C-BAND AND OMNI DEPLOYMENTS

APPENDAGE	DEPLOYMENT ANGLE	APPENDAGE MASS (kg)	EQUIVALENT LIFT FORCE[a] (kg)	GROUND DEPLOYMENT TIME IST-2 (s)	602 ON-ORBIT DEPLOYMENT	
					TIME (s)	TEMPERATURE (°C)
Omni 1st Stage	47°	5.3	4.0	9.7	NA[b]	NA[b]
Omni 2nd Stage	164°	7.4	NA[c]	26.0	42.8	5°
Transmit 1st Stage	225°	39.9	26.3	57.0	31.2	19°
Receive Reflector Boom	87°	24.2	24.2	20.1	23.1	8°
Transmit 2nd Stage	119°	51.2	51.2	52.8	40.1	16°

[a] Lift force includes compensation for ground support equipment mass.
[b] Not available, since deployment occurs out of ground station view.
[c] Off-loading not required, since omni azimuth hinge axis is vertical.

with the solar drum positioner (SDP) mechanisms consisted of coiled negator springs with a metal tape and pulley system. These provided nearly constant force over the 413 cm of deployment travel.

The spacecraft was tested in the fully assembled configuration (less reflectors) in the IRTV facility, with the spun section spinning, and the despun platform pointing controlled by the on-board attitude determination and control system (ADCS). This required an off-load system to compensate for the majority of the gravity load on the 1,080-kg platform, in order to protect the bearings on the bearing and power transfer assembly (BAPTA). A suspended-mass pulley system was used which incorporated a ball-bearing swivel to allow rotation of the despun shelf.

The off-loader incorporated a two-axis lateral positioner and whiffletree, which allowed the swiveled lift point to be repositioned to compensate for changes in geometry within the vacuum chamber, and for center of gravity shifts due to deployment of the Ku-band and global antennas. Early problems with this off-loader were overcome once it was determined that the alignment of the three shelf pick-up cable attachment brackets was critical to its performance.

Electrostatic discharge testing

To demonstrate the immunity of INTELSAT VI spacecraft to ESD, a comprehensive test program was performed on both the protoflight and one flight spacecraft. A lumped-element computer model developed by HAC for predicting INTELSAT VI currents and voltages induced by ESD events made it possible to predict responses to ground-based ESD environments.

One problem with ESD testing has been that test instrumentation is often affected by the discharges, leading to uncertainty in the test results. For the INTELSAT VI program, INTELSAT developed a fiber-optic-based instrumentation system which allowed monitoring of induced voltages and currents during controlled energy injections from a capacitive discharge pulser simulating discharges expected in orbit, thus permitting comparison of measured data with model predictions. The fiber optic link provided electrical isolation with bandwidth to accurately transmit high-frequency components of ESD events in excess of 50 MHz. The INTELSAT TDHS offered the capability to capture all spacecraft telemetry during the tests and allowed examination of all channels for upsets during the injections.

More than 160,000 pulses were injected into the prototype spacecraft, with a maximum energy level of 10 mJ. The INTELSAT 604 flight spacecraft was exposed to less than 100 pulses at a maximum energy of 3 mJ. This is believed to be the first direct-injection ESD test on a commercial flight spacecraft.

The test results showed that the induced currents and voltages agreed well with the model. When the prototype spacecraft was exposed to higher energy levels, many upsets of telemetered status and telemetered memory content were observed; however, actual spacecraft configuration and memory content were not altered, as evidenced by the fact that telemetered status returned to normal in subsequent telemetry frames. Clearing of the prototype spacecraft command processing unit command registers was observed at the higher energy levels. This phenomena had been observed during unit qualification testing when 25-mJ pulses were injected into the box corners. It was interesting that the same phenomena surfaced during prototype spacecraft testing at a lower energy level.

None of the ESD-induced upsets were judged mission-critical. No permanent damage was sustained, and no evidence of latent damage has been observed. In addition, no upsets were observed during the flight spacecraft ESD testing.

The fiber optic instrumentation was again used to determine the magnitude of voltages induced in the spacecraft harness during welding of propellant lines. The induced voltages measured on the Y1 spacecraft during welding were an order of magnitude less than those observed during ESD testing. Therefore, it was decided that welding could be safely performed on a flight spacecraft without disconnecting or removing units. One delta pressure transducer was removed from the INTELSAT 603 spacecraft, and the propellant line was welded closed. The fiber optic instrumentation was used to measure induced harness voltages, which were again verified to be substantially less than INTELSAT 604 had been exposed to during ESD testing.

Program-unique problems

Unique problems were encountered during the INTELSAT VI program due to the large size of the spacecraft and the need to add compatibility with a third launch vehicle after all spacecraft structures had been fabricated.

Size of the spacecraft

The massive size of the INTELSAT VI spacecraft presented constant challenges during integration, testing, and transportation. Each spacecraft was extensively disassembled after environmental testing, and was shipped to the launch site in five containers holding the despun section (antenna farm, repeater, telemetry, and command), spun section (power, controls, and propulsion), solar panels, batteries, and launch vehicle adapter.

The shipping container for the despun section was too large to fit within any commercial cargo aircraft. The container could have fit within one of the

modified U.S. Air Force C5A's; however, the aircraft were not available at the time required for shipment. Consequently, the containers were transported to Florida by truck. Figure 6 shows the INTELSAT 602 spacecraft despun and spun containers loaded on a trailer at HAC, just prior to departure. The INTELSAT 602, 605, and 601 spacecraft, launched on Ariane 44L vehicles, were transported to Cayenne, French Guiana, by ship. During the INTELSAT 602 shipment, water leaked into the solar panel container, causing some delamination of solar cells.

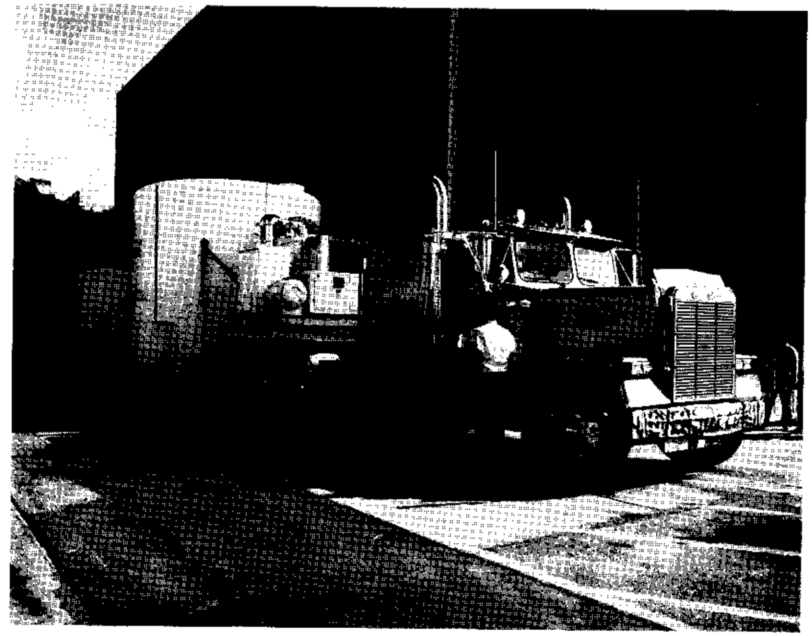


Figure 6. *INTELSAT 602 Spacecraft Spun and Despun Sections Loaded on a Trailer at HAC El Segundo Just Prior to Departure*

At the launch site, the spun and despun sections were tested separately. The sections were then joined, and the solar panels and batteries were installed prior to propellant loading. The integration and testing at the launch site was so extensive as to require 3 months for Ariane launches and 4 months for Titan launches (which require the integration of a solid perigee kick motor stage). By contrast, the INTELSAT V launch campaign required less than 2 months. Figure 7 shows the INTELSAT 605 spacecraft ready for encapsulation prior to Ariane launch from CSG.

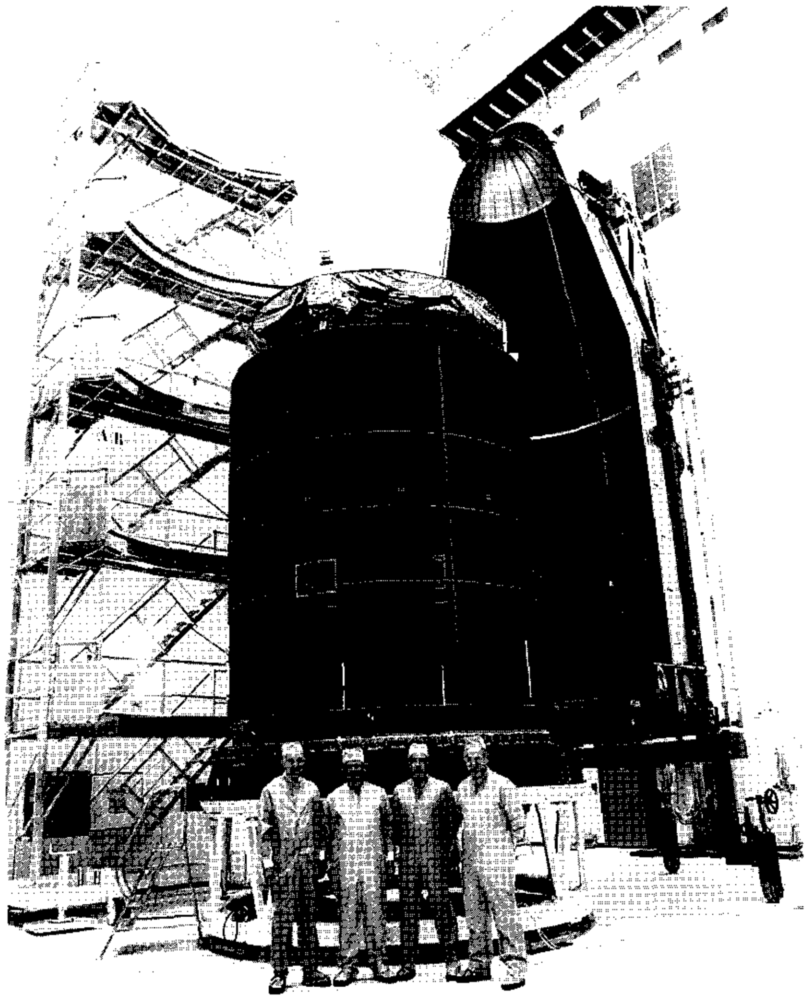


Figure 7. *INTELSAT 605 Spacecraft Ready for Encapsulation Prior to Ariane Launch From CSG*

Change of launch vehicle

The initial INTELSAT VI contract specified compatibility with the Arianespace Ariane IV and the NASA Space Transportation System (STS, the Shuttle) launch vehicles. As a result of the Shuttle *Challenger* disaster, NASA elected to cancel the INTELSAT VI contract. Subsequently, INTELSAT entered into a contract with Martin Marietta Corporation (MMC) for two launches on the Commercial Titan III vehicle. The INTELSAT VI contract with HAC was amended to provide for termination of the STS airborne support equipment subcontract with British Aerospace and disposal of the cradle hardware. The requirement for Titan compatibility, including hardware, launch vehicle interfacing, and launch site preparation, was added.

The agreement with HAC provided that any exceedences (*i.e.*, deviations in the Titan III launch conditions outside the Ariane/STS launch environment envelope) would require requalification of the INTELSAT VI spacecraft, or INTELSAT would assume responsibility for any consequences. Based on the preliminary loads analysis from MMC, an additional sine vibration qualification test was performed on the prototype spacecraft. Subsequent loads analysis and mission predictions from MMC indicated further exceedences over the Ariane/STS environment for launch acoustic and overpressure shock, as well as for post-fairing-separation free molecular heating. At considerable cost to INTELSAT, MMC extended the launch pad flame duct to reduce acoustic loads, added a water suppression system to reduce the overpressure pulse shock loads, and modified the launch trajectory to reduce free molecular heating.

Conclusions

INTELSAT procures and operates more commercial communications satellites than any other entity. For the INTELSAT IV, V, and VI series spacecraft, INTELSAT contracted for developmental, qualification, and acceptance test programs which were the most extensive in the industry. Each program included a prototype spacecraft that was not refurbished for flight. The INTELSAT record for reliability in-orbit and for operation longer than satellite design life has been outstanding.

The INTELSAT VI spacecraft series utilized large C- and Ku-band antennas which required a complex deployment scheme for this dual-spin spacecraft. Pre- and post-environmental exposure testing of the antenna farm was performed in the HAC near-field facility. Deployment testing in the 1-g environment required unique test fixture design. The fact that all deployments in-orbit have been completely successful is a tribute to the care HAC and

INTELSAT gave to the design, integration, and testing of the antenna and other deployable mechanisms.

INTELSAT uses a staff of technical specialists for extensive in-residence monitoring at the spacecraft contractor facilities, and provides these specialists with extensive test data analysis capability, including the TDHS. Since a contractor's priorities focus on developing the capability to control the spacecraft, perform the testing, and capture the test measurement data, test results are generally analyzed only to the extent required to show compliance with contract specification. Because the contractor is motivated by cost and schedule constraints to complete each test in the minimum time, hardware and software resources are not allocated for the kind of analysis conducted by the TDHS.

INTELSAT analysis is directed toward predicting in-orbit performance and suitability for the intended mission. Total spacecraft performance and subsystem interaction are considered. The INTELSAT TDHS was designed to identify changes in performance or trends during the various test phases which could foretell problems, even if current test measurements meet specification.

Acknowledgments

The authors wish to acknowledge the contributions of the following individuals to the success of the INTELSAT VI spacecraft series: HAC program managers D. Braverman, M. Merideth, G. Dutcher, T. Eakins, and G. Tadler, and HAC System Engineering headed by R. Opjordan. They also wish to acknowledge the contributions of former INTELSAT program managers S. Bennett, R. Scott, and S. Abrahamson, INTELSAT engineering managers G. Horvai and L. Dest, and COMSAT technical director, H. Holm.

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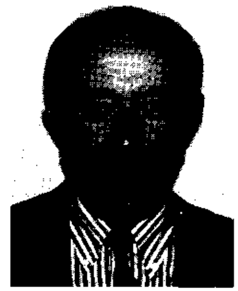

Charles E. Johnson received a Bachelor of Engineering in electrical engineering from the Johns Hopkins University. He served as the INTELSAT Program Manager for the INTELSAT VI spacecraft series during the integration, test, and launch of the five spacecraft. Prior to joining INTELSAT in 1985, he worked for 15 years in COMSAT spacecraft program offices during the integration and testing of the INTELSAT IV, INTELSAT V, COMSTAR, and MARISAT spacecraft series. Previously, he was a spacecraft test director at HAC during the Surveyor Lunar Lander and other spacecraft programs.

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James J. Lemon received a B.S.I.D.E from Purdue University in 1979 and an M.S.C.E. (Structures) from Stanford in 1980. He joined COMSAT as a summer student in 1979, and as a full-time engineer in 1980. In 1983, he moved to El Segundo, California, to begin work on system test software for the INTELSAT VI program. In 1989, he joined INTELSAT as a Senior Engineer, and in 1990 moved to Palo Alto, California, to manage software development for the INTELSAT VII/VII-A Spacecraft Program Office Test Data Handling System (TDHS).

Mr. Lemon maintains an avid interest in computer software and computer graphics, specializing in spacecraft telemetry display and antenna analysis.

Keith J. Volkert received a B.S. in aeronautical and astronautical engineering from Northrop University in 1968. He is currently Deputy Director of Space Systems Programs for COMSAT's Space Systems Engineering Group. In his 10 years with COMSAT he has supported numerous international communications satellite programs, including INTELSAT VI. Prior to joining COMSAT, he worked at JPL on the Viking Orbiter, Voyager, and Galileo programs.

Index: communication satellites, INTELSAT, planning, testing

INTELSAT VI launch operations, deployment, and bus in-orbit testing

L. S. VIRDEE, T. L. EDWARDS, A. J. CORIO, AND T. RUSH

(Manuscript received January 23, 1991)

Abstract

The planning and resources that ensured a smooth launch, post-launch operations, and in-orbit testing of the INTELSAT VI satellite series are described. The efforts over years of planning are outlined from both the launch and spacecraft operations perspectives. INTELSAT mission activities are then detailed, concentrating on launch base operations, spacecraft attitude and orbit operations, and spacecraft deployment. All new satellites launched by INTELSAT undergo extensive post-deployment bus and payload checkouts before being placed in service. The final section of the paper describes the in-orbit testing of the INTELSAT VI bus.

Introduction

The INTELSAT VI spacecraft was originally designed to be compatible with the Ariane 4 launch vehicle and the NASA Space Transportation System (STS, commonly known as the Shuttle) [1]. The initial launch arrangements for the five INTELSAT VI spacecraft included three STS and two Ariane 4 launches INTELSAT 601 and 605]. However, as a result of the tragic Shuttle *Challenger* accident in January 1986, the INTELSAT VI program was restructured and the launch arrangements were modified to include a third Ariane 4 launch (INTELSAT 602) and two Titan III launches (INTELSAT 603 and 604). During the several-year schedule extension, two of the five spacecraft were modified for compatibility with the Commercial Titan launcher.

Mission operations are functionally identical for both the Ariane and Titan launch vehicles, once the spacecraft is in geosynchronous transfer orbit (GTO).

The first INTELSAT VI spacecraft, INTELSAT 602, was launched atop an Ariane 4 on October 27, 1987. The mission involved difficult prelaunch operations, a complex series of maneuvers, spacecraft dynamics movements, and deployments. Each phase of the mission was accomplished successfully, largely due to detailed planning, exhaustive prelaunch spacecraft testing, and comprehensive mission rehearsals. The following discussion focuses on that mission, which was typical of all INTELSAT VI launches.

The actual launch of INTELSAT 602 was completed in just over 22 minutes after lift-off; however, the launch was really the culmination of a process that had begun over 7-1/2 years earlier. The efforts during development of the launch vehicle and spacecraft programs had resulted in a spacecraft design that was compatible with the Ariane launch vehicle. Meticulous launch campaign planning laid the groundwork for launch site operations. The 3-1/2 month launch campaign ensured that a fully integrated and tested INTELSAT 602 spacecraft was ready for launch. All of these efforts resulted in the successful launch of the first INTELSAT VI spacecraft.

Following separation of the spacecraft from the launch vehicle, the focus of activities shifted to the INTELSAT Launch Control Center (LCC) in Washington, D.C. This was the beginning of 3 weeks of intensive and demanding work for the LCC and the telemetry, tracking, command, and monitoring (TTC&M) site personnel. Transitioning the spacecraft from the launch configuration in GTO to an operational configuration in geosynchronous earth orbit (GEO) at a specified station longitude is a complex interdisciplinary process that requires several years of planning, procedure generation, software development, training, and rehearsals. A large team of experts from INTELSAT, COMSAT, and Hughes Aircraft Company (HAC) were actively involved in all phases of preparation and execution of the mission. Three weeks after lift-off, INTELSAT 602 was providing international service for the U.S./U.S.S.R. Summit in Malta.

INTELSAT 602 is now serving the Indian Ocean Region (IOR), and the four additional satellites have also been launched. At the time of this writing, INTELSAT 603 has failed to achieve the desired orbit because of a launch vehicle problem, while INTELSAT 601 and 605 have been successfully commissioned and are in service in the Atlantic Ocean Region (AOR). INTELSAT 604 was successfully launched and is currently undergoing in-orbit testing (IOT).

INTELSAT VI launch and mission planning

Planning for the launch and mission operations of any spacecraft is inherently part of the design process. Within INTELSAT, launch vehicle activities

and spacecraft activities are the primary responsibility of different groups. Launch-related activities consist of ensuring the compatibility of the INTELSAT VI spacecraft with its associated launch vehicle, while simultaneously preparing for and managing the complicated logistics of the launch campaign. Spacecraft activities involve detailed planning of the sequence of events, and compiling and automating the hundreds of thousands of commands that must be sent to the spacecraft.

INTELSAT VI launch planning

The overall effort entailed in preparing for a launch generally takes a period of approximately 3 years—somewhat less than the time required to produce the first spacecraft of a typical INTELSAT spacecraft program. Although not formally defined as such, the wide variety of activities performed over this period can be divided into two phases: an integration phase and a launch campaign planning phase.

INTEGRATION PHASE

The integration phase includes the formal definition and documentation of all requirements and interfaces between the spacecraft and the launch vehicle during the launch phase, and all requirements and interfaces between the spacecraft, launch vehicle, spacecraft test equipment, and launch site support facilities during prelaunch operations. The term "integration" is used since the requirements and interfaces of the spacecraft contractor and the launch services supplier must be combined, or integrated, to provide compatibility. The integration phase generally covers the first 2 years of the 3-year launch planning period.

One aspect of INTELSAT VI Ariane launch planning is particularly noteworthy. At the time the contract was signed, it was not possible to develop a detailed definition of compatibility with the Ariane 4 because the Ariane 4 program had only been approved in January 1982. The only compatibility item specifically identified in the INTELSAT VI spacecraft contract was that the spacecraft static envelope must be no more constraining than that described in two telexes from the launch vehicle contractor, Arianespace. The complete definition of all interface and launch requirements had to evolve as the spacecraft and launch vehicle designs were developed. It was remarkable that this was achieved without significant technical and programmatic problems.

The definition of requirements and the detailed documentation of interfaces was orchestrated by INTELSAT through a combination of ad hoc technical meetings, telephone conferences, and written correspondence. As the requirements and interfaces were identified and agreed to, they were formally documented in an interface control document. For Ariane launches, this document is called the "Dossier de Controle d'Interface" (DCI). Development of the DCI was an evolutionary process which continued as the spacecraft design requirements matured. After the DCI was formally approved by INTELSAT, HAC, and Arianespace, it was maintained under configuration control.

In conjunction with the development of the DCI, a series of mission analyses were conducted by Arianespace. A coupled launch vehicle/spacecraft structural loads analysis is of critical importance to the spacecraft contractor, since results are used to verify the adequacy of the structural design. In addition, an integrated thermal analysis was used to assess the compatibility of the spacecraft thermal design with the intended launch operation. Other analyses included trajectory and mission sequence, flight mechanics (*e.g.*, spacecraft reorientation after orbit injection, spin-up, and clearance during separation), and RF compatibility studies. The results of these analyses and supplemental analyses completed by the spacecraft contractor ensured that the spacecraft and launch vehicle could fulfill their intended missions.

LAUNCH CAMPAIGN PLANNING PHASE

Approximately 1 year prior to launch, specific planning for the launch campaign was initiated. A preliminary schedule was developed encompassing the spacecraft assembly and testing tasks that had to be completed to prepare the spacecraft for launch. Where necessary, procedures specifically tailored to the launch site were developed. Plans were devised for shipment of the spacecraft itself, as well as the large amount of mechanical and electrical support equipment necessary for the launch operations. Arrangements were also initiated for shipment to the launch site of the hazardous propellants to be loaded into the spacecraft.

In parallel with the planning that had to be done by the spacecraft contractor, joint planning with the launch services contractor was also necessary. Detailed utilization plans for the facilities at the launch site were developed, including such items as layouts for the spacecraft and related mechanical ground support equipment (MGSE) in the high-bay facilities, and layouts for the electrical ground support equipment (EGSE) in a control room adjacent to the high-bay facilities. In addition, a detailed list of support services was compiled so that the launch services contractor could properly prepare for the launch campaign. Typical support services include interfacility transportation, supply of miscellaneous fluids, provision of various office equipment and supplies, and arrangements for telephone service.

Also during this time, combined discussions were held with the spacecraft and launch services contractors to define the testing to be conducted at the launch site, in order to verify the electrical interfaces defined in the interface control documentation. These discussions defined the scope of testing, described the methods used, and identified the test equipment required.

By necessity, activities during the launch campaign planning phase are iterative in nature. Schedules and plans developed by the spacecraft and launch services contractors must be combined and coordinated. Literally hundreds of details must be worked out which are varied in nature, ranging from detailed technical discussions of interface testing to more pragmatic issues such as the number of desks to be provided in the office areas. The success of the launch campaign itself depends on the thoroughness of preparations during the planning phase. Once the campaign has begun, activities that have not been properly preplanned and coordinated between the spacecraft and launch services contractors can adversely impact the launch schedule.

INTELSAT VI spacecraft mission planning

Planning for the first INTELSAT VI launch began in 1984. Activities slowed considerably when the first launch was delayed due the Shuttle *Challenger* accident, and resumed in earnest in early 1988. A multidisciplinary team of INTELSAT, COMSAT, and HAC engineers actively defined the detailed sequence of events, developing and documenting procedures and contingency plans. These efforts culminated in the first comprehensive launch mission rehearsal in December 1988. The early rehearsal identified numerous shortcomings in procedures, processing software, and mission team protocol and discipline, which were corrected over the period leading to the first launch.

Certain aspects of mission, orbital, and spacecraft operations underwent significant changes during the planning and development phase. The lead in these planning and implementation activities was taken by INTELSAT's Spacecraft Engineering Department and Flight Operations Section. The original sequence was considerably altered as more information on the spacecraft capabilities and constraints was established during the course of spacecraft unit- and system-level testing. As a result, the final mission profile bore little resemblance to the initial profile.

ORBITAL OPERATIONS PLANNING

The mission profile after launch is depicted in Figures 1 and 2. The Ariane 44L provides the GTO injection, reorients the spacecraft to telemetry coverage injection attitude, spins the spacecraft, and separates it from the launch vehicle.

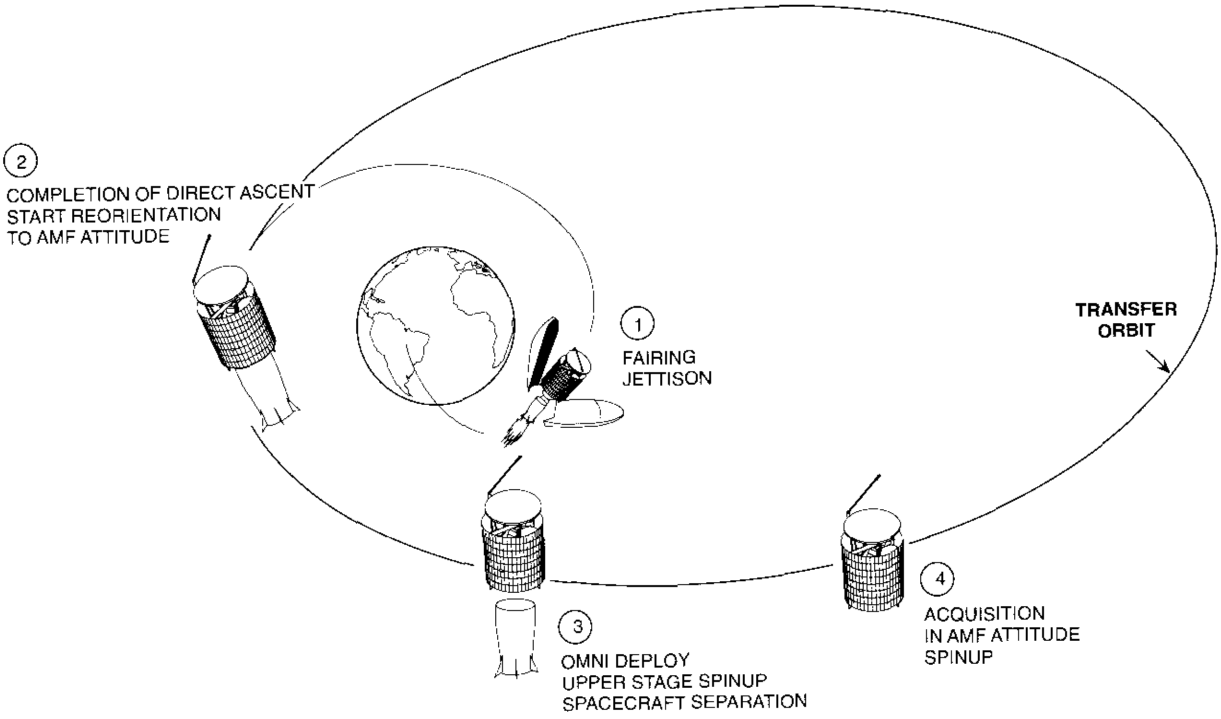

Figure 1. *Transfer Orbit Injection*

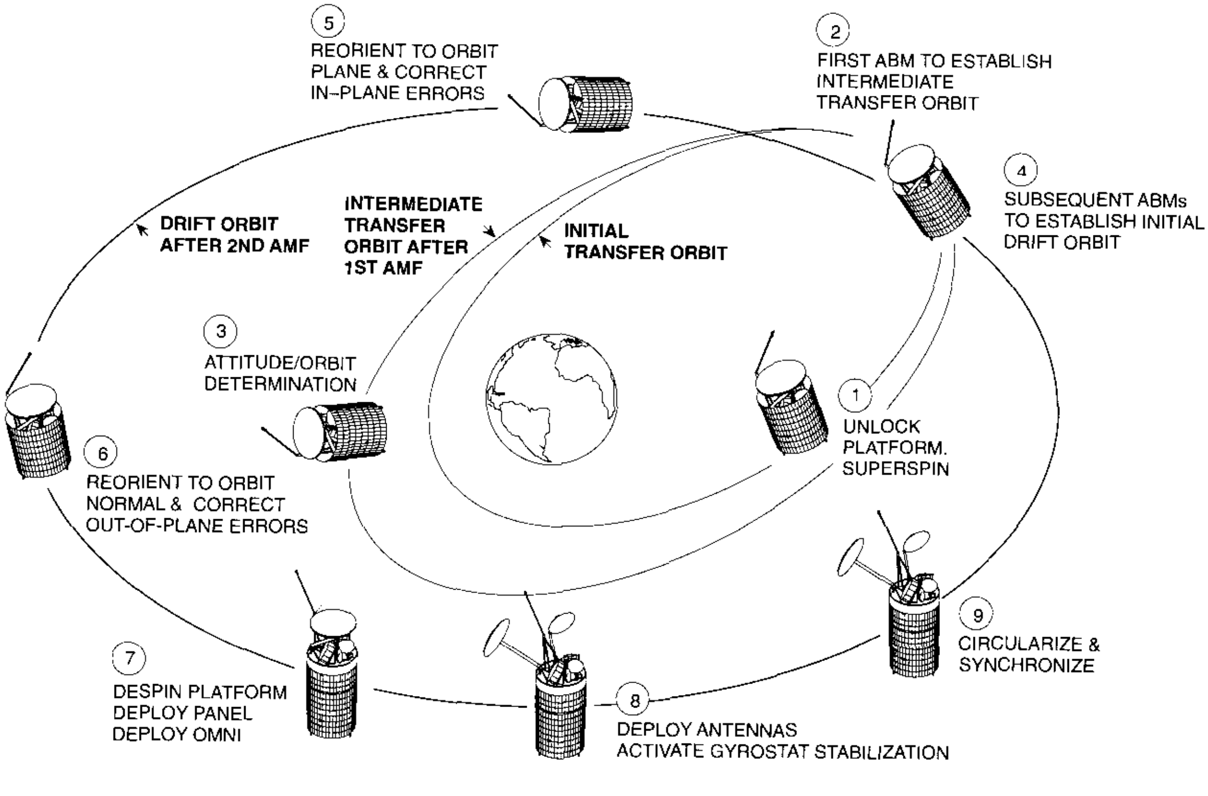

Figure 2. *Synchronous Orbit Acquisition*

Following acquisition by an INTELSAT TTC&M station, spacecraft status is verified and a series of operations is undertaken to prepare for the subsequent orbit-raising maneuvers.

An INTELSAT VI series satellite is placed into geosynchronous orbit in several steps. The Ariane-injected GTO is highly elliptical, with apogee and perigee aligned with the equatorial plane at altitudes of 35,786 and 200 km, respectively. The orbit plane is inclined to the equatorial plane by 7°. One large maneuver at apogee can simultaneously raise perigee to synchronous altitude and rotate the orbit plane into coincidence with the equatorial plane, placing the satellite into geosynchronous orbit.

The orbit-raising maneuver impulse is supplied by two liquid apogee motors (LAMs) mounted on the aft end of the spinning spacecraft, parallel to the spin axis and diametrically opposite each other. More details regarding the satellite bus design can be found in a companion paper by Dest *et al.* [2]. Previous spacecraft have used fixed-size, solid rocket motors to impart this maneuver velocity in a single burn lasting about 1 minute. The INTELSAT VI restartable LAMs require about 1-1/2 hours of burn time because of a lower thrust level. Propellant efficiency is maximized when the maneuver velocity is applied in an infinitesimally short period of time, as with a solid rocket motor. Such efficiency is nearly achievable by executing a sequence of shorter LAM maneuvers at several appropriate apogee occurrences, since the principle of superposition applies. The evolution of the LAM maneuver mission profile for INTELSAT 602 [3] is presented in Table 1. The following paragraphs discuss the reasons for the changes.

TABLE 1. INTELSAT 602 LAM MANEUVER MISSION PROFILE

	ORIGINAL NOMINAL		ORIGINAL BACKUP		PRELAUNCH NOMINAL	
LAM MANEUVER NO.	APOGEE NO.	DURATION (min)	APOGEE NO.	DURATION (min)	APOGEE NO.	DURATION (min)
0	2	0.75	2	0.75	1	0.75
1	4	42	5	42	2	15
2	6	42	8	42	3	22
3	8	3	10	3	5	27
4	–	–	–	–	7	18
5	–	–	–	–	8	3

The original mission profile for INTELSAT 602 was defined early in 1989. The orbit-raising sequence called for two large apogee boost maneuvers (ABMs), each of which involved firing the LAMs for about 42 min. Prior to these, a 45-second burn of the LAMs was scheduled to determine the amount of rotor spin rate change imparted during a burn. Finally, a 3-minute vernier burn completed the sequence. To allow for the possibility of postponement of the first large maneuver, a backup sequence was also developed.

The above maneuver sequence was selected to minimize the effect of thrust attitude errors. Sufficient time was allowed to determine and correct such errors between maneuvers, thus minimizing the amount of propellant expended for error correction. Additionally, the sequence and sizing of maneuvers were selected so that the last maneuver would place the satellite in geosynchronous orbit at 322°E longitude for IOT from the TTC&M earth station at Fucino, Italy.

Several months before launch, the mission profile was revised to use shorter maneuvers. Based on thruster test-firing data and in-orbit data from similar thrusters, there was concern over a possible thermal runaway condition which might lead to catastrophic thruster failure. The first major ABM was to be limited to 15 minutes. Subsequent maneuvers could be longer, but not nearly as long as in the original plan. A backup profile was judged unnecessary because the increased number of ABMs provided more flexibility in devising a maneuver sequence to meet the mission objectives once the LAM performance was known.

SPACECRAFT ATTITUDE CONTROL OPERATIONS PLANNING

Planning of spacecraft attitude control operations is necessary to provide the proper spacecraft attitude during orbit-raising maneuvers, while maintaining an acceptable thermal configuration and power energy balance. Throughout transfer orbit, orbit-raising maneuvers are executed using LAMs. Since the direction of thrust is parallel to the spin axis, the spacecraft maneuver planning process defines the inertial orientation of the spin axis required for the maneuver. To achieve the correct orientation, it must be possible to both determine and change the spin axis attitude. The spacecraft attitude control system, including that portion used during orbit-establishing maneuvers, is described in detail in a companion paper by Slafer and Seidenstucker [4].

Spin axis attitude is determined by using data from sun and earth sensors. The sensors are mounted in the rotor and scan the sun and earth as the spacecraft rotates. The sun sensor is a V-slit design that measures the angle between the spin axis and the line of sight to the sun. The earth sensor is an infrared horizon scanner with a narrow field of view. It measures earth chordwidth, which defines the angle from the spin axis to the earth center. The spacecraft has four earth sensors. Two, designated north earth sensors, are mounted with the optic axis at an angle of 84.5° to the spin axis, while two south earth sensors are mounted with the optic axis at an angle of 95.5° to the spin axis.

Data from the sensors are collected for a period of 4 to 5 hours centered around apogee. During this time, at least one earth sensor scan intercepts the earth to provide chordwidth data. The data collected are processed with a least-squares batch processor to compute an accurate estimate of the inertial attitude of the spin axis.

The attitude data are corrupted by noise on the measurements, as well as by the complicated rotation of the spacecraft. In transfer orbit, the rotor and platform spin at different rates. The rotor is both statically and dynamically balanced, while the platform is balanced statically but has non-zero products of inertia. Because of this dynamic imbalance, the principal axis of rotation of the platform does not coincide with the spin axis of the rotor, but intersects the spin axis at a slight angle. With both rotor and platform rotating, the spin axis cones around the inertial angular momentum vector, and the sensor field of view does not sweep out a right circular cone as it would for pure, simple spin. This irregularity of the sensor scan causes a further corruption of the sun and earth sensor data, which is taken to be additional random noise in the least-squares batch processor. The higher noise level can be tolerated as long as the data collection interval is sufficiently long—preferably, 4 to 5 hours. For the first launch, this effect was minimized by almost completely balancing the platform dynamically with balance weights.

Reorientation of the spin axis (actually, the angular momentum vector) to the LAM maneuver attitude is another aspect of spacecraft attitude control. This is accomplished by spin-synchronous pulsing of a LAM or a 22-newton axial thruster. Synchronization is provided by detecting the sun in the meridian slit of the sun sensor. Once every rotor spin period, the thruster is pulsed at a constant angular delay relative to sun detection. The angular delay is calculated by knowing the starting and desired final inertial attitudes, the inertial orientation of the sun, and the location of the thruster relative to the sun sensor. The LAMs and axial thrusters are parallel to the spin axis but displaced outboard from it. Therefore, synchronous thruster pulses provide only transverse torque, which precesses the inertial angular momentum in the desired direction.

Spacecraft attitude control dominates mission operations during the several LAM firings, until GEO is achieved. Attention then focuses on deployment of the spacecraft appendages.

PLANNING SPACECRAFT DEPLOYMENTS

For compatibility with launch vehicle envelopes, spacecraft appendages must be stowed for launch. Deployable appendages include the omni, C-band, and Ku-band antennas; the antenna support structure (monopod and auxmonopod); and the telescoping solar drum. INTELSAT VI separates from the launch vehicle by releasing a V-band clamp using three pyrotechnic bolts fired by the launch vehicle. Initial deployment of the omni antenna to the intermediate transfer orbit position occurs just after this separation and is commanded outside of ground station coverage by the Ariane launch vehicle. Release of the spun-to-despun interface is also accomplished in transfer orbit prior to orbit raising. Remaining INTELSAT VI deployments are completed after achieving GEO. The deployment sequence is depicted in Figure 3.

The stowed and deployed configurations of INTELSAT VI are shown in Figure 4. The telescoping outer solar drum is freed from the inner drum by individually commanding three pyrotechnic bolt cutters. The deployable outer drum is then deployed 63.8 cm by three stepper-motor-driven rack and pinion mechanisms called solar drum positioners (SDPs). During deployment, the output of the SDP motor is limited by selecting a motor current pulse-width dependent on temperature telemetry. This limitation of output ensures that more force is available to back out of a stuck condition than was available to get into it.

The complex antenna subsystem (described by Persinger *et al.* [5]) is deployed to its final on-orbit configuration by using both spring-driven and stepper-motor-driven mechanisms. A series of pyrotechnic events is commanded, cutting locking bolts and pulling locking pins, until all antennas are released. The commanded sequence of release is shown in Table 2. The commanded stepping sequence required to move the Ku-band and global antennas from the stowed to fully deployed state is illustrated in Figure 5. The spacecraft deployment scenario was another part of the mission planning that was changed frequently as a result of information learned during ground testing. Special software was developed to aid in detecting and relieving a potential jam condition during solar drum, Ku-band, and global horn deployments.

MISSION DOCUMENTATION

One of the most significant mission planning efforts involved generating the documentation required for executing a nominal mission and for coping with contingency situations that could occur during transfer orbit operations. The documentation identified early in the planning stage included a detailed

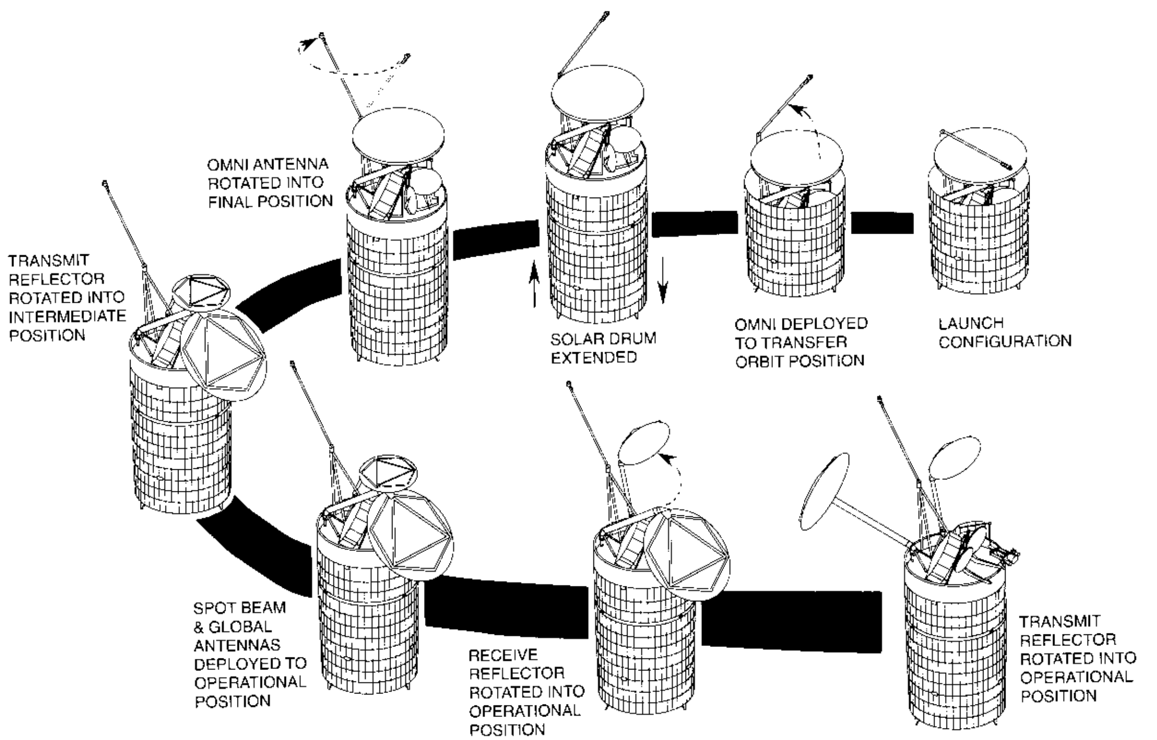

Figure 3. *Deployment Sequence*

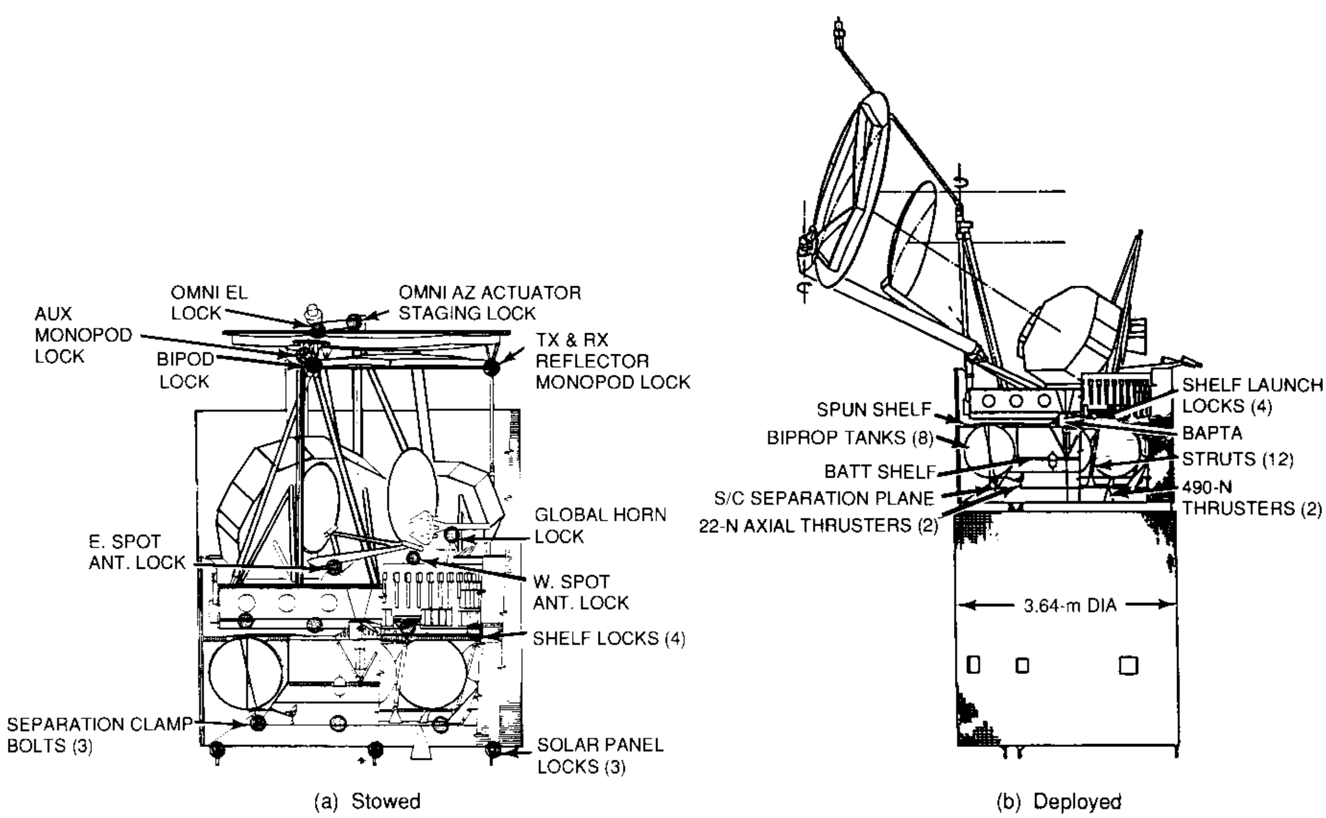

Figure 4. *INTELSAT VI Antenna Configurations*

TABLE 2. ANTENNA DEPLOYMENT RELEASE SEQUENCE

LAUNCH LOCK	PYROTECHNIC DEVICES	DESCRIPTION
Omni Elevation	Bolt cutter	Actuator is fired by the sequencer and deploys omni antenna 47.3°.
Omni Azimuth	Pin puller	Deploys omni azimuth actuator 164.5° to final on-orbit position.
Auxiliary Monopod (auxmonopod)	Bolt cutter	Deploys auxmonopod support structure 87° out of RF field.
Monopod	Bolt cutter	Releases transmit and receive C-band reflectors at monopod interface.
Tripod	Bolt cutter	Releases transmit C-band reflector. Transmit dish actuator deploys reflector 224°.
Global Horn and E/W Ku-Band Spot Beam Antennas	Bolt cutters (3)	Releases launch supports so that stepper motor mechanisms can deploy global horn and E and W spots to nominal earth-pointing positions. Specific stepping sequence used to avoid contacting other structures.
Bipod	Bolt cutter	Releases receive C-band reflector. Receive boom actuator deploys boom and reflector 84.7° to final on-orbit position. Monopod deploys out of RF field.
Transmit Boom Actuator	Pin puller	Transmit boom actuator deploys C-band reflector and boom 119.5° to final on-orbit position.

sequence of events, contingency plans, an operations handbook, telemetry and command lists, a computer timeline, and TTC&M station coverage plots.

Development of these documents required considerable time and effort by INTELSAT and HAC personnel. The most important document, the detailed Sequence of Events, will serve as an example of this effort. This document provides the following:

- Command sequences in the correct order to achieve the mission goals.
- Each command number, full command text, command type, and details of the ground command generator setup.
- Telemetry display requirements, together with the changes in the displays produced by execution of the command.
- Command authorization details.

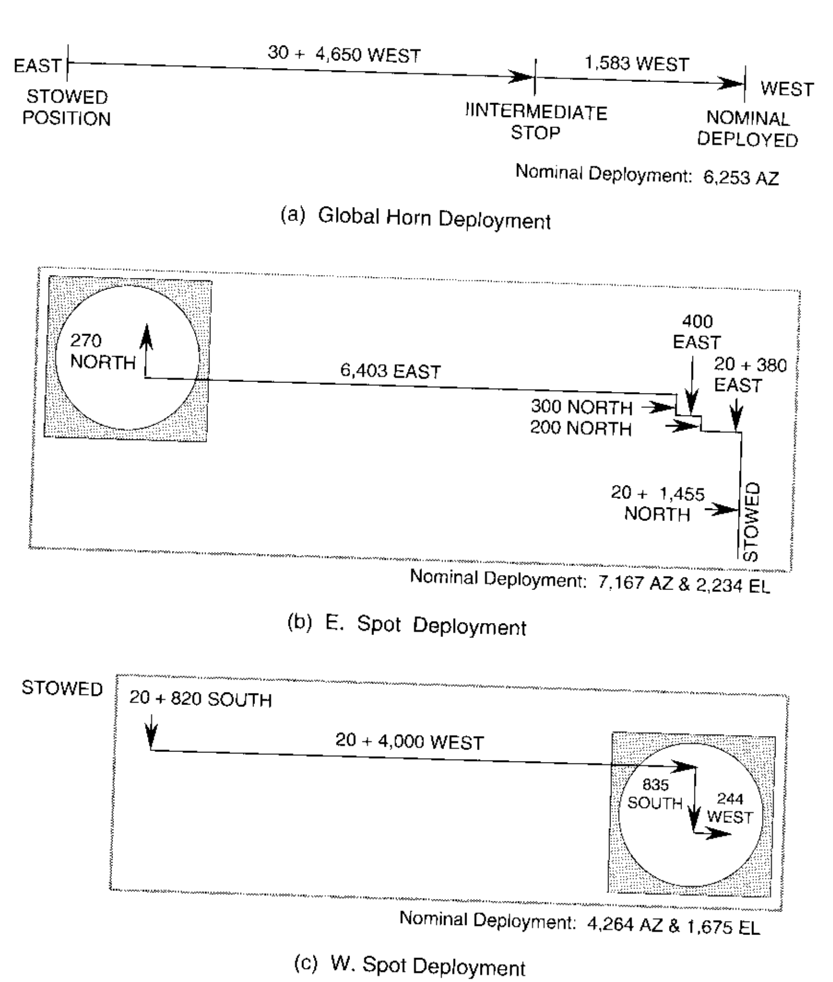

Figure 5. *Stepper-Motor-Driven Deployment Sequence*

- TTC&M station visibility details.
- Perigee, apogee, and eclipse passage details.
- Operational constraints for each operation.
- Computer and strip-chart setup requirements.
- Command verification requirements.
- Contingency plans applicable to specific operations.

The document development procedure began by defining the orbital operations required to place the spacecraft into GEO from GTO. Information was then obtained on the requirements of each subsystem for each phase of the transfer orbit. The most demanding subsystems were the attitude determination and control subsystem (ADCS) and the mechanisms subsystem. Their requirements were very dynamic, changing significantly from one interface to another. After the main elements of the mission were understood, an outline sequence was defined. A near-final version of this outline is shown in Table 3. The details were generated by engineers assigned to specific subsystems, through interface meetings and from the results from the spacecraft ground tests program and prelaunch rehearsals. The final 195-page Sequence of Events document was not complete until about 1 week before the first launch.

TABLE 3. NOMINAL ARIANE TRANSFER ORBIT SCHEDULE OF EVENTS

TIME	EVENT
1st Apogee	Zamengoe Acquisition Omni deployment Ariane separation
	Jatiluhur Acquisition Omni first-stage deployment check Spacecraft attitude checks
	Yamaguchi Acquisition Health checks T&C checks ACE initialization Thermal configuration Battery thermal configuration LBS thermal configuration ADCS functional checks
	Perigee Pass Configuration
2nd Perigee	Enter Perigee Shadow
2nd Apogee	Exit Perigee Shadow Post-perigee configuration
	Superspin Sequence Platform release Motor drivers superspin spacecraft Spinup/radial preburn
	Attitude Adjustments LAM/RCS touch-up orientation
	LBS Pressurization
	Perigee Pass Power and Thermal Reconfiguration

TABLE 3. NOMINAL ARIANE TRANSFER ORBIT SCHEDULE OF EVENTS (CONT'D)

TIME	EVENT
3rd Perigee	Enter Perigee Shadow
3rd Apogee	Post-Perigee Pass Power and Thermal Reconfiguration Station acquisition Attitude determination
	LAM Test Fire (3rd apogee) RCS touch-up orientation
4th Perigee	Pre-Perigee Pass Power and Thermal Reconfiguration
	Enter Perigee Shadow
4th Apogee	Post-Perigee Pass Power and Thermal Reconfiguration Station acquisition Attitude determination
	First Major LAM Fire (4th apogee) RCS touch-up orientation
5th to 8th Perigee	Pre-Perigee Pass Power and Thermal Reconfiguration
	Entering Perigee Shadow
5th to 8th Apogee	Post-Perigee Pass Power and Thermal Reconfiguration Station acquisition Attitude determination
9th Perigee	Pre-Perigee Pass Power and Thermal Reconfiguration
	Enter Perigee Shadow
9th Apogee	Post-Perigee Pass Power and Thermal Reconfiguration Station acquisition Attitude determination
	Second Major LAM Fire (9th apogee) RCS touch-up orientation
10th Perigee	Pre-Perigee Pass Power and Thermal Reconfiguration
	Enter Perigee Shadow
10th Apogee	Post-Perigee Pass Power and Thermal Reconfiguration Station acquisition Attitude determination
	Third Major LAM Fire (10th apogee)
	Orbit Normal Reorientation LAM/RCS touch-up orientation

MISSION REHEARSALS

From its very first spacecraft launch, INTELSAT has placed great value on prelaunch mission rehearsals. Preparation for the first INTELSAT VI launch involved several mini-rehearsals, as well as full team rehearsals. The mini-rehearsals were used to verify specific transfer orbit operations and/or to assess LCC and TTC&M station hardware and software readiness. The objectives of the full team rehearsals ranged from practicing critical operations to training the launch team in subsystem interaction and LCC protocols. Three such rehearsals were held.

Availability of INTELSAT VI ADCS and telemetry simulators enabled high-fidelity simulations to be conducted for the first time in preparation for launch of a new generation of INTELSAT spacecraft. The flexibility built into these simulators allowed failures to be introduced and contingency operations to be verified. The lessons learned during these simulations proved valuable during the mission. In addition, the merit of high-fidelity simulators became quite apparent, and plans have been made to provide similar facilities for future generations of INTELSAT satellites.

MISSION TEAM

The success of a spacecraft launch is highly dependent on the ability, knowledge, and cohesiveness of the mission team. The INTELSAT approach was to form a single team, integrating specialists from INTELSAT, HAC, and COMSAT. The team structure is similar to that used successfully in previous INTELSAT launches. The Mission Director is in charge of the overall mission and is aided by a systems team and specialist subsystems teams in the areas of ADCS, propulsion, mechanisms, TTC&M, astrodynamics, power, and thermal. A Flight Director is in charge of implementing the details of the mission, taking overall direction from the Mission Director. Computer hardware and software specialists, LCC and TTC&M ground station controllers, and data technicians also provide valuable support to the launch team. More information on the management and operation of the LCC and of TTC&M ground stations may be found in companion papers by Smith [6] and Skroban and Belanger [7], respectively.

The composition of the launch team changed over time as a result of interface meetings, where the need for specialists in various areas became evident. Selection of the subsystem team leaders was somewhat more difficult; however, the integrated team concept and cooperation from COMSAT and HAC allowed satisfactory resolution.

INTELSAT 602 launch base operations

The INTELSAT 602 spacecraft was shipped from El Segundo, California, to Kourou, French Guiana, using a combination of truck and ocean vessel transportation. Shipment to the launch site was done earlier than normal to allow for an earlier launch date, if one became available.

The shipment that left El Segundo on March 27, 1990, included four major items: the spun section, the despun section, the solar arrays, and the Ariane adapter, each in its own shipping container. The truck transport from El Segundo, California, to West Palm Beach, Florida, carried the spacecraft spun and despun sections on a special air-conditioned transporter which maintained the spacecraft within its temperature limits. However, during the trip it was discovered that the system was incapable of maintaining proper control of the humidity inside the containers, which necessitated en route modifications to the environmental control system.

The Astrotech spacecraft processing facilities in Titusville, Florida, were used to inspect for possible damage. Upon arrival at Astrotech on April 7, the spacecraft was inspected as thoroughly as possible through access ports and air-conditioning duct openings. No evidence of moisture condensation could be found, and the decision was made to continue with the shipment. The spacecraft was trucked to West Palm Beach on April 17 and subsequently loaded on the cargo ship *Kirstin* bound for French Guiana.

The ship arrived at the harbor in Cayenne, French Guiana, on May 2, and the spacecraft and other elements of the shipment were trucked by Arianespace to Centre Spatial Guyanais (CSG), approximately 65 km from Cayenne. All of the shipment elements except the solar array container were taken to an air-conditioned storage facility at CSG. The solar array container was taken to a clean-room area at CSG, where the container cover was removed and the panels were inspected. It was determined that rainwater had leaked into the container, but no damage to the panels was visible. Later, after the launch campaign had begun, detailed inspections revealed that some disbonding of the solar cells from the panel substrate had occurred, which necessitated repair of the solar panels at CSG.

Subsequent shipments (via both air and sea) brought the remainder of the MGSE and EGSE necessary to support the launch campaign. The spacecraft and related support equipment consisted of the equivalent of fifty-six 2.44 $\times$ 3.05-m pallets—a considerable amount of equipment.

INTELSAT 602 launch campaign

The INTELSAT 602 launch campaign began on July 10, 1989. The EGSE was unpacked, and setup of the equipment was initiated in a control room adjacent to the high bay in Building S1B, where the spacecraft would be assembled and tested. In parallel, preparation of the MGSE began in the high bay.

Activities over the next 5 to 6 weeks included performance testing and final assembly of the spun and despun sections as separate items. The major activities on the spun section included functional testing of the attitude control subsystem, propulsion subsystem tests (*e.g.*, maximum expected operating pressure demonstration, helium leak tests, and valve performance tests), and verification of the alignment of the thrusters and sensors. Testing on the despun section included functional tests of the communications and telemetry and command subsystems, removal of RF test plates and couplers, finalization of the thermal control blankets on the despun shelf, and deployment tests of the communications antennas. On August 22, the spun and despun sections were joined, and on August 25 the flight batteries were installed.

The major activities from August 26 to September 8 focused on the solar panels. Following installation and electrical performance testing of the fixed and deployable panels, the spacecraft was moved to a tall support stand so that solar panel deployment tests could be performed. During the deployment tests, numerous measurements are made to verify that adequate clearances were maintained in critical areas (Figure 6).

On September 10, the spacecraft was moved to Building S3B for propellant loading and encapsulation of the spacecraft in the launch vehicle fairing. While the spacecraft was still undergoing nonhazardous operations in Building S1B, activities were initiated in Building S3B (located near the launch pad) to prepare for propellant loading. These preparations included the checkout of special fuel and oxidizer loading carts and the transfer of propellants from storage containers into the carts.

Once the spacecraft arrived in Building S3B, propellant loading operations were initiated by specially trained personnel wearing protective clothing, with air supplies, due to the toxic nature of the propellants. From September 11 through 15, 1,432 kg of oxidizer and 873 kg of fuel were loaded into the spacecraft propellant tanks and pressurized to flight levels. On September 16, the spacecraft pressurant tanks were pressurized with helium to their flight pressure of 4,200 psia.

Following propellant loading, the spacecraft was joined to the HAC-provided Ariane adapter, and electrical testing was conducted to verify that the interfaces between the spacecraft and adapter were functioning properly. On September 22, the spacecraft and adapter were coupled to the external cone of the Ariane 4 vehicle equipment bay (VEB) and electrical testing of these interfaces was performed.

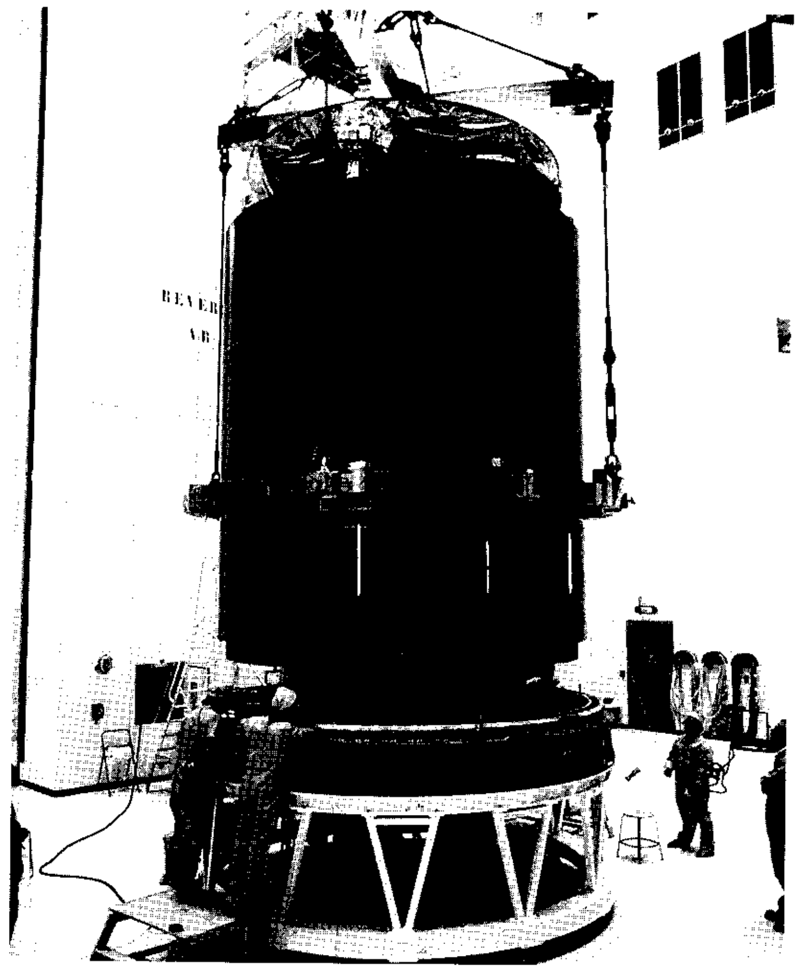

Figure 6. *INTELSAT 602*

Installation of the Ariane 4 fairing halves around the spacecraft was initiated on September 25 and completed on September 26. Following encapsulation, the spacecraft was powered-up to verify the ability to communicate with the spacecraft through the RF window in the fairing.

On September 27, the composite (spacecraft, adapter, VEB external cone, and fairing) was moved to a transporter, transferred to the launch pad, and hoisted to the payload level. (The launch vehicle had been transferred to the launch pad from its assembly building on September 14.) On September 28, the composite was joined to the launch vehicle.

Shortly after the spacecraft was coupled with the launch vehicle, the INTELSAT 602 campaign was interrupted by discovery of a problem with the command relay unit of the launch vehicle. The command relay unit contains approximately 186 relays which control the activation of numerous launch vehicle functions. Since there had been unexplained failures in acceptance testing of similar relays, the command relay unit was declared non-flightworthy. The spacecraft was secured in a safe configuration, and the campaign was suspended on October 2.

The command relay unit problem was subsequently resolved, and the campaign was restarted on October 18. The umbilical lines between the equipment in the LCC and the spacecraft were revalidated and reconnected to the spacecraft. The spacecraft was then powered up, and the telemetry was checked to verify that the spacecraft was still in good health. On October 20, tests to verify spacecraft command functionals were performed, and battery charging was initiated to prepare for launch.

INTELSAT 602 launch

Spacecraft activities on launch day began 8 hr 35 min prior to launch. At this time, the spacecraft was powered-up, telemetry was checked, and high-rate charge of the batteries was initiated. At 6 hr 35 min prior to launch, the spacecraft was commanded into the safe launch configuration.

In parallel, launch vehicle personnel carried out final preparations of the launch vehicle. At 5 hr 50 min prior to launch, the launch vehicle service tower was rolled back. At 3 hr 35 min prior to launch, filling of the Ariane third stage with liquid hydrogen and liquid oxygen was initiated. (The first and second stages had been filled with their storable propellants on the previous day.)

At 2 hr 15 min prior to launch, the spacecraft was commanded into the armed launch configuration. Pressurization of the launch vehicle third-stage helium tanks was initiated 1 hr 35 min prior to launch, and filling of the third stage with propellant was completed by T – 45 min At T – 30 min, there was a 24-min "margin" period for completion of any activities that were running late, so that the automatic sequence could begin at T – 6 min.

At T – 15 min, spacecraft battery charging was terminated and the spacecraft was operating on internal power. A final check of the spacecraft telemetry parameters verified that the spacecraft was ready for launch.

At T – 6 min, the launch vehicle automatic sequence was initiated. At T – 4 s, the cryogenic propellant loading arms used to fill the third stage were released, and at T = 0 the ignition signal was given to the engines of the first stage and to the liquid boosters. Computers monitored the performance of the engines and, since everything was nominal, the launch vehicle release signal was issued and lift-off occurred at T + 3.4 s (Figure 7).

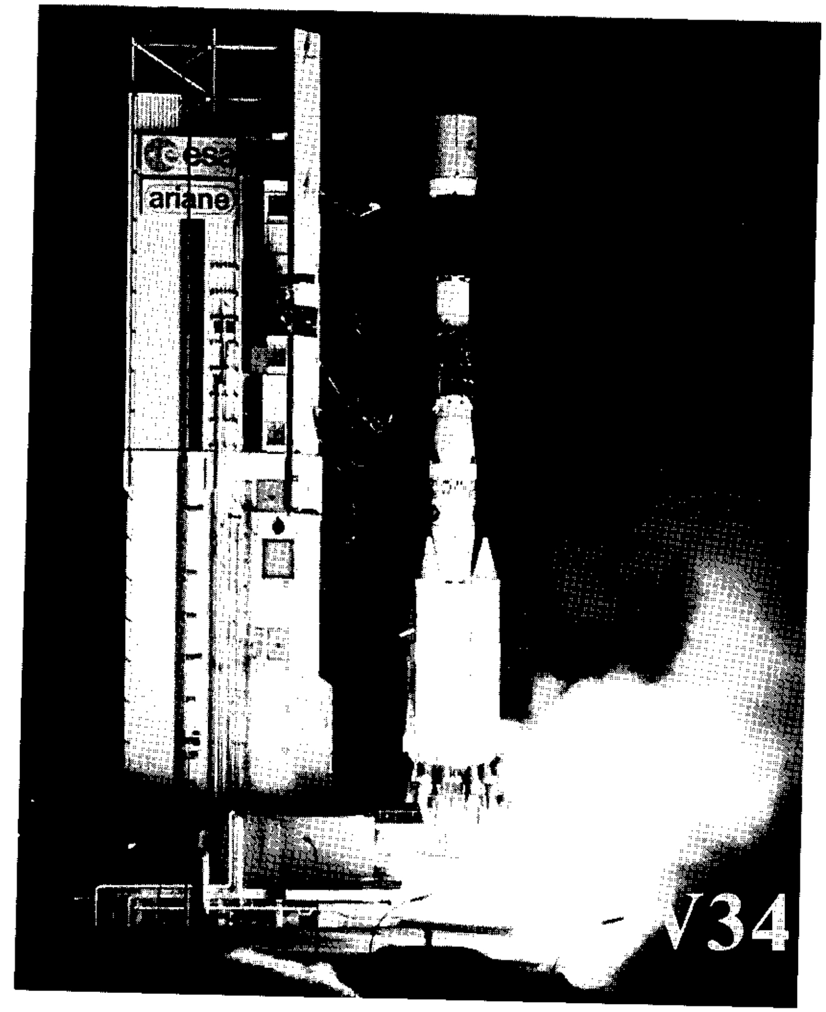

Figure 7. *INTELSAT 602 Lift-Off*

Thrust for the initial portion of an Ariane 44L launch is provided by the four engines of the first stage and the four liquid propellant boosters attached to the first stage. Approximately 2.5 min after lift-off, the liquid boosters were jettisoned, and the first stage continued burning until approximately T + 3.5 min The first stage was then separated, and the second stage was ignited. During second-stage flight, the payload fairing was separated once the free molecular heating rate had decreased to less than the specified value. The single engine of the second stage continued under on-board guidance until approximately T + 5.5 min. Following separation of the second stage, the Ariane third-stage engine was ignited to provide 12 min of thrust to inject the spacecraft into transfer orbit.

Following shutdown of the third stage, the spacecraft was in transfer orbit; however, the launch vehicle still had several important functions to perform. The spacecraft was reoriented to the proper attitude and the command was given to deploy the omni antenna. Next, the spacecraft was spun-up to 5 rpm and the command was given to fire the separation band releasing the spacecraft from the Ariane adapter.

All of these events occurred without incident on the evening of October 27, 1989. The launch vehicle performed flawlessly, and INTELSAT 602 was injected into the proper transfer orbit. The spacecraft was acquired by the INTELSAT tracking network and, following a review of its telemetry by spacecraft engineers at the LCC, it was confirmed that the spacecraft was in good health. The launch was a success.

INTELSAT 602 spacecraft operations

Following separation of the spacecraft from the launch vehicle, the focus of activities shifted to the INTELSAT LCC in Washington, D.C. While the launch site personnel celebrated their success, it was the beginning of 3 weeks of intensive and demanding work for the LCC and the TTC&M site personnel.

The INTELSAT 602 transfer orbit injection by Ariane placed the satellite in an inertial attitude about 10° south of the ABM attitude. This increases contact time for the earth station when the spacecraft is first acquired by the ground network. Exactly on the timeline at 2335 UTC (Universal Time Code), the INTELSAT TTC&M earth station in Zamengoe, Cameroon, acquired the telemetry signal. All launch vehicle separation events had occurred satisfactorily, and the satellite was acquired with a spin rate of 4.92 rpm, with the telemetry omni antenna properly deployed. Following the acquisition of command and telemetry RF links by Jatiluhur, Indonesia, and Yamaguchi, Japan, the nominally 7-day mission sequence of events began to use the INTELSAT TTC&M monitoring network [7] to place INTELSAT 602 in a geosynchronous orbit and to transform the satellite from its compact 6.4-m launch configuration to its extended 11.8-m deployed on-orbit configuration.

The first major event in the mission was to prepare the propulsion subsystem for transfer orbit operation. The system was pressurized by commanding open a series of valves. There was an unexpected transient gurgling evident in telemetry when the valves were opened. Once propulsion experts had reviewed the telemetry data and signified that their subsystem was operating nominally, a brief test firing of the LAMs was commanded.

The next phases of the mission entailed unlocking the despun platform from the spun section. The four shelf locks were released one at a time by ground-commanded pyrotechnic bolt cutters. Based on spacecraft telemetry, the mechanisms group verified that the platform was truly released and superspin could be initiated. Superspin—an inertial state where the normally despun platform is commanded to 11 rpm—is necessary to ensure stable operation while depleting fuel during subsequent orbit-raising maneuvers.

Orbits are determined based on range, azimuth, and elevation measurements from two or more earth stations. Several hours of data are processed with a least-squares batch processor to obtain the orbital elements. The processor is capable of fitting data through a LAM thrust acceleration profile and solving for LAM performance and thrust orientation as state variables. The determination of thrust orientation complements the attitude determination process described above. This estimate of LAM thruster performance is used to improve the accuracy of the next LAM firing.

During the mission, the first two LAM maneuvers were executed according to the nominal prelaunch mission plan. Thermal and performance data from the 15-min LAM burn on second apogee indicated that the thrusters both reached thermal steady-state with normal performance and temperatures. A decision was made to revise the mission plan to allow longer maneuvers, which reduced the planned number of maneuvers by one and completed the sequence of maneuvers one orbital revolution (and 1 day) earlier.

After the revised mission profile was developed, an analysis of local heating in the vicinity of the LAM thrusters showed temperatures that were higher than predicted. While this did not pose a problem for the thrusters, it did for the parts of the spacecraft absorbing the heat. To be conservative, a burn duration limit of 45 minutes was imposed on subsequent LAM burns and a final revision of the mission profile was adopted. The revised and actual mission profiles are shown in Table 4.

On November 1, 1989, the fifth and final LAM firing sequence (150 s of firing followed by a 39-s firing 47 minutes later) resulted in the attainment of

TABLE 4. INTELSAT 602 LAM MANEUVER MISSION PROFILE

	REVISED		ACTUAL	
LAM MANEUVER NO.	APOGEE NO.	DURATION (min)	APOGEE NO.	DURATION (min)
0	1	0.75	1	0.75
1	2	15	2	15
2	4	15	4	43
3	6	52	5	7
4	7	3	7	21
5	–	–	8	3

GEO. The satellite attitude was then reoriented to its nominal orbit-normal attitude. The critical transformation from the superspin dynamic state to the nominal gyrostat spin-stabilization state then ensued without any problem, and much more smoothly than in all simulations.

The next event was solar array drum deployment. Each step of an SDP moves the solar drum approximately 0.0184 mm; therefore, deployment over the full range required about 225,000 step commands. There are several occasions during deployment where potentially disastrous critical clearances must be maintained. Both manual and automatic methods are employed during SDP operation to ensure that all three mechanisms operate in unison to prevent even the slightest misalignment of the deploying drum. Once the outer drum is sufficiently deployed to uncover the radiator surface on the inner drum, deployment is suspended while a thermal reconfiguration is performed to ensure that payload temperatures remain within appropriate limits. In addition, if the temperature of any of the three mechanisms' motors rises above 93°C, deployment will be halted until the motor cools or the redundant motor is activated. The continuously critical slow telescoping of the 3.6-m-diameter external solar array over the internal solar array extended for more than 3-1/2 hours without incident. The solar array was now perfectly positioned and began generating 2,252 W of power.

Following deployment of the drum, the omni antenna azimuth deployment was performed. As the solar drum deployed, the omni actuator was exposed to space and its temperature dropped to 2°C. Initially, there was some concern about deploying at this temperature, since all ground testing had been performed at room temperature. However, the omni azimuth actuator nominal cold operation design temperature was -11°C, and an additional 5°C margin had been added to the acceptance temperature of -16°C. Deployment was initiated and successfully completed in 43 seconds.

On November 2, the despun platform was pointed at the earth and then placed in a slow "rotisserie" mode to create uniform thermal conditions for the entire antenna assembly in preparation for deployment. The remaining deployments occurred without incident.

The motion of the spacecraft is monitored with an accelerometer and provides a "signature" for each deployment. A comparison of the actual signature to the predicted signature is shown in Figure 8. A summary of the actual deployment times *vs* the predictions is given in Table 5.

Spacecraft in-orbit tests

Following successful acquisition of GEO, INTELSAT 602 was subjected to a lengthy series of tests to check the entire satellite prior to commissioning it for service. The purpose of this checkout was twofold. First, to verify that all units, subsystems, and systems survived the launch environment; and second, to identify any generic defects and corrective measures that might be required for subsequently launched spacecraft.

No major anomalies were encountered during the IOT. It is rare that the first satellite of a new generation as complex as INTELSAT VI can go through the launch environment and the mission and still exhibit such a high level of integrity in orbit.

The IOT of the satellite involved a complete checkout of the spacecraft bus and payload subsystems. The bus subsystem tests were performed from the INTELSAT LCC by subsystem teams composed of specialists. Testing of the payload subsystem, and of the RF performance of the telemetry, command, and ranging (TC&R) subsystem, were interleaved with checkout of the space and ground segments of the satellite-switched time-division multiple access (SS-TDMA) system. These tests were performed from the IOT facility at the INTELSAT TTC&M station at Fucino, Italy, and the TDMA reference stations at Etam, West Virginia, and Tanum, Sweden, and are described in a companion paper by Rosell *et al.* [8].

Spacecraft bus

The primary purpose of the spacecraft bus tests was to verify that all units and functions of the bus, including all redundant units, were functioning properly. The bus subsystem testing was completed in 14 days.

The beacon tracker subsystem (BTS) and the ADCS underwent the most extensive tests. INTELSAT VI is the first INTELSAT satellite to employ a BTS

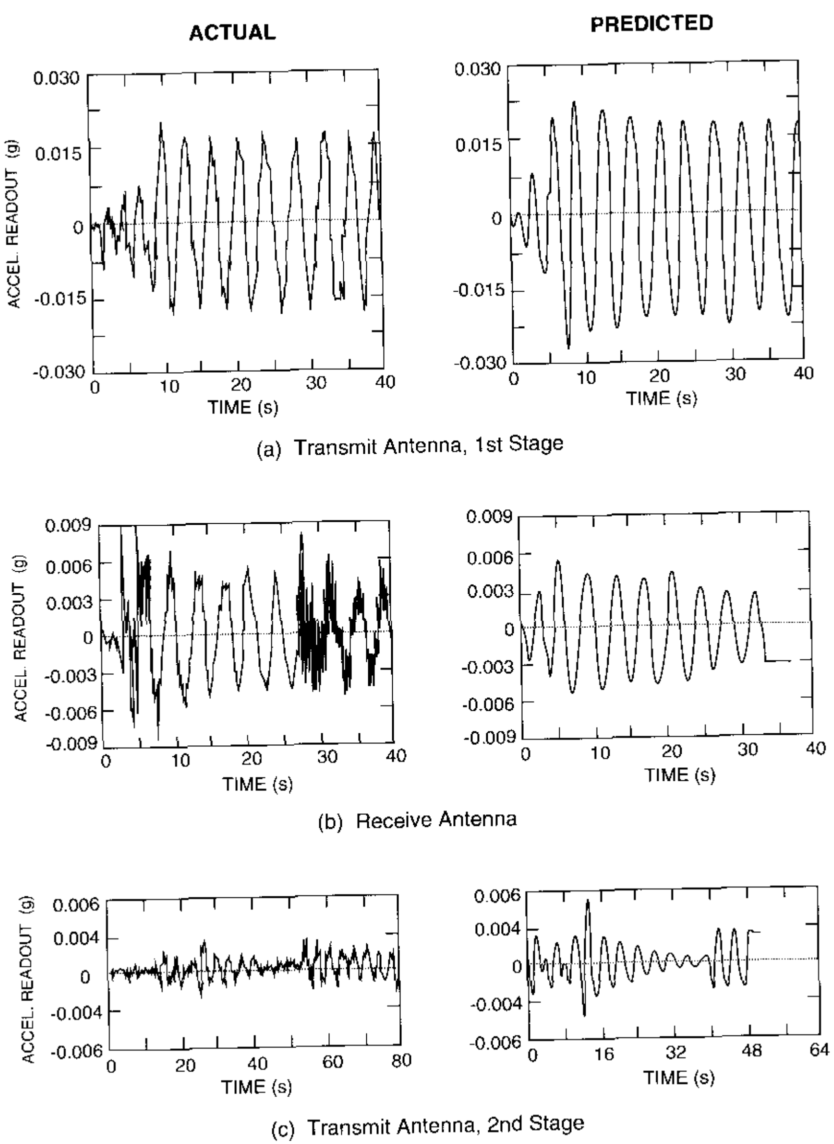

Figure 8. *INTELSAT 602 C-Band Antenna Deployment: Actual vs Predicted Accelerometer Signatures*

TABLE 5. INTELSAT 602 DEPLOYMENT TIMES

DEPLOYMENT ACTUATOR	ACTUATOR TEMPERATURE (°C)	MEASURED DEPLOYMENT TIME (s)	PREDICTED DEPLOYMENT TIME (s)
Omni Azimuth	2	43	*
Auxmonopod	**	1.4	*
Transmit Dish	19	31	25
Monopod	**	2.3	*
Receive Boom	8	23	24
Transmit Boom	16	40	35

* Predictions for deployment not applicable or not available.
** Temperature telemetry not available for this location.

for pointing the large deployable C-band receive and transmit antennas. The beacon reference was supplied by the Fucino TTC&M station. The tests involved measuring the characteristics of the beacon tracker receiver (BTR) over its operating regime and determining the biases and diurnal variations in the boresight pointing of the two large C-band reflectors. The latter involved use of a sophisticated ground-based Kalman filter software program. This software uses the BTR error outputs, in conjunction with the satellite attitude and orbit ephemerides, to compute the pointing biases and magnitude of the diurnal variation due to thermal distortion. The thermal distortion was found to be in close agreement with ground predictions. These tests are repeated once the operational station is acquired, and periodically thereafter to determine the seasonal and long-term variations of thermal distortion.

The ADCS functional tests included checkout of the normal-mode control loops with all sensors and gains, calibration of the stationkeeping modes, and verification of satellite stability and the integrity of the automatic safety system. Some performance parameters, such as the safety system limits, were checked during the transfer orbit phase. The INTELSAT VI ADCS has an automatic attitude control function called the spin axis controller (SAC). Verification of its performance was extremely encouraging, with the SAC able to control the spin axis to within the selected 0.05° deadband. However, an anomaly was experienced after several weeks of operation, when a specific combination of operational parameters caused erroneous control thruster firings. The anomaly is understood, and new operating procedures have been successfully implemented. No other anomalies were observed in any of the tests, and the ADCS has since performed well within the specifications.

Calibration of the orbit inclination mode of operation involved a series of maneuvers using an extensive library of new ground software. Inclination maneuvers are now routinely undertaken, keeping spin axis perturbations to less than 0.03°. The effective performance during the maneuvers is within 1 percent of ground predictions. The main component of the measured performance loss is plume drag on the inside surface of the deployed solar drum. Based on the results so far, it can be concluded that HAC has fairly high-fidelity plume drag prediction models.

To verify the thermal design of the INTELSAT 602 spacecraft, a four-phase test program was undertaken, with each phase lasting 48 hours. The tests were designed to allow comparison with the development-phase infrared thermal vacuum (IRTV) tests, and to provide a basis for evaluating the effects of aging later in the mission. Such a database has allowed INTELSAT to operate INTELSAT V satellites successfully beyond their design life. The four tests involved the following:

- Replication of one of the IRTV configurations to provide a cold operation case (*i.e.*, the repeater subsystem was off, and replacement heaters were used on the rim shelf).
- Hot case, with the repeater subsystem turned on and the Ku-band traveling wave tube amplifiers (TWTAS) at full RF drive.
- Intermediate case, with the repeater subsystem turned on and the Ku-band TWTAs at zero RF drive. (This is also a hot condition for the spacecraft.)
- A configuration representative of the operational configuration.

A total of 176 temperature sensors were monitored during the tests, and good correlation between predictions and in-flight observations was noted in all the tests. A substantial margin exists for most units, to cover the inevitable increase in temperature over life. The thermal IOT has thus provided an excellent database that will help determine and track the thermal health of the satellite. It will also allow the impact of new operational configurations to be assessed. INTELSAT plans to repeat such tests during the course of the mission at equinoxes and solstices.

Since there is much redundancy in some parts of the power subsystem, it was decided to limit testing to a primary and a redundant path for each function. Thus, the power subsystem IOT involved measuring the current draw of nearly all of the units on the satellite. (This was facilitated by the satellite

having current monitors on most units.) The currents were noted whenever a unit was turned on or off during the transfer orbit phase, and during the reconfigurations for thermal tests. Some units not used during these phases were checked out during the bus IOT phase. The relays in the battery charge and reconditioning unit (BCRU) were fully exercised during these tests. A minor telemetry anomaly, which was attributed to the grounding scheme used, occurred during testing the BCRU. All subsequent INTELSAT VI spacecraft have been modified to correct for this anomaly, and the problem has not recurred. Apart from this, the power subsystem checked out satisfactorily.

As part of the TC&R subsystem tests, the operation of all commands utilizing both redundant systems was verified, mostly in conjunction with other subsystem testing.

The INTELSAT VI spacecraft incorporates several mechanisms. Most of the positioner mechanisms were used in deployment of the solar drum and antennas during the launch phase. The primary objective of the post-launch IOT of these mechanisms was to verify the positioner range of travel and to check operation of the redundant hardware. The SDPs were moved in unison and individually, in both the deploy and retract directions. The range of travel encompassed the full range required for adjustment of spin axis wobble during the course of the mission. Following checkout, the wobble was reduced to less than 0.002° with the aid of the BTS. The Ku-band antennas were stepped in a profile that verified their ability to move the antenna boresight to any point on the earth's disk. The C-band reflectors, which had been stepped in closed loop during BTS IOT, were stepped in open loop via ground command. All of the primary and redundant mechanisms performed satisfactorily.

Upon satisfactory completion of all IOTs, INTELSAT 602 was placed in service. It is now stationed at 63°E serving the IOR.

Acknowledgments

Numerous HAC and INTELSAT publications, which are unavailable in the public domain, were used to compile this paper. The authors wish to acknowledge all the contributors to these publications. The sections describing the INTELSAT 602 mission and bus IOT are extracted from Reference 3.

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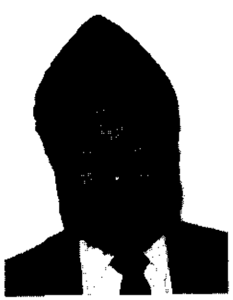

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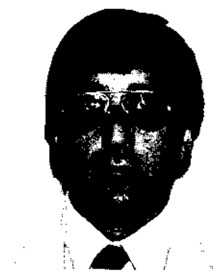

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Index: communication satellites, INTELSAT, transmission, transponders, testing

In-orbit RF test of an INTELSAT VI spacecraft

G. E. G. ROSELL, B. TEIXEIRA, A. OLIMPIEW, B. A. PETTERSSON, AND S. B. SANDERS

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Abstract

When a new spacecraft is launched for INTELSAT, a number of tests are routinely performed to verify that the stress loads imposed by the launch have not affected the onboard subsystems. An RF in-orbit test (IOT) is conducted to verify the performance of the communications payload (antennas and transponders) and telemetry, command, and ranging subsystems. This paper describes the new measurement methodologies developed and implemented at INTELSAT's Fucino, Italy, IOT station to accomplish the RF IOT of INTELSAT VI series spacecraft. Also presented are the test results obtained from IOT measurements performed on INTELSAT 602, which have proved to be in good agreement with prelaunch data.

Introduction

A series of RF in-orbit tests (IOTs) is performed on newly launched INTELSAT spacecraft to verify that no damage has been incurred by the spacecraft's communications payload and telemetry, command, and ranging (TC&R) subsystem components from launch to geosynchronous orbit. These tests also offer the first opportunity to test the spacecraft antennas on an ideal test range.

The IOTs are conducted to assure INTELSAT that the satellite is capable of supporting the traffic and services it was designed to carry. Thus, it is necessary to verify the correct operation of all units of the RF subsystems in orbit, as well as the performance of other subsystems which have direct impact on the RF system performance. This can only be accomplished by performing an IOT before the satellite is put into service.

The IOTs are performed using a facility at one of INTELSAT's IOT sites, and the results are compared with data from ground-based tests performed by the manufacturer, under INTELSAT supervision, during spacecraft construction. The IOT sites provide for in-orbit measurement of the satellite payload RF performance to a high level of accuracy. They are also used for anomaly investigations and routine checks of the spacecraft payload subsystems performance. INTELSAT currently has an operational IOT station at Fucino, Italy. Two additional IOT stations are under construction: one at Beijing, China, and the other at Clarksburg, Maryland, U.S.A.

The IOT system at Fucino was developed by INTELSAT using experience gained through numerous IOT campaigns. Measurement speed, accuracy, and relative ease of operation have greatly improved since the first IOTs were performed on the *Early Bird* (INTELSAT I) satellite. The first IOTs were performed using spectrum analyzers and XY recorders, all manually controlled, under very cramped conditions in the antenna feed room. The first fully automated IOT was built for the INTELSAT V series spacecraft [1]. It used signals injected and measured at the antenna feed flanges to accurately calibrate the earth station losses, allowing the IOT measurement equipment to be located remotely in a convenient, consolidated facility.

Planning Concerns

The major concerns in planning an IOT campaign are spacecraft fuel consumption and the total duration of the testing. The usable lifetime of an INTELSAT spacecraft such as those in the INTELSAT VI series is generally determined by the amount of propellant fuel onboard the spacecraft—because the mean time between failures (MTBF) of the payload electronics is significantly longer than the fuel-determined life. During an IOT, the spacecraft is maneuvered to allow the IOT station access to all the antenna beams. Because these maneuvers consume precious fuel, it is important that platform position changes be limited to those that are justifiably necessary, and that the test sequence be carefully determined to keep fuel consumption to an absolute minimum.

When a new spacecraft is launched, there is usually a backlog of demand for new capacity and great urgency to put the spacecraft into operation as soon as possible. Disregarding any potential revenue from an earlier initiation of service, the straight-line depreciation cost of an INTELSAT VI spacecraft in

orbit is such that a few days (or weeks) of delay can represent a significant loss of income.

Experience gained from the IOT of 13 of the INTELSAT V series spacecraft was used as a reference for the initial planning of the INTELSAT VI IOT campaign. However, the INTELSAT VI series spacecraft are much larger than the INTELSAT V series, and also require substantially more reconfiguration commands. Specifically, a typical INTELSAT V series spacecraft has two zone beams, two hemi beams, two spot beams, one global beam, and 29 channels (comprising 16 receivers and 45 traveling wave tube amplifiers [TWTAs]). In comparison, an INTELSAT VI series spacecraft has four zone beams, two hemi beams, two spot beams, two global beams, and 50 channels (comprising 20 receivers, 77 power amplifiers, and two 10×6 dynamic satellite-switched time-division multiple access [SS-TDMA] switch matrixes).

Since an INTELSAT VI series spacecraft is about twice as large as a typical INTELSAT V, its IOT would be expected to take twice as long. A typical INTELSAT V series spacecraft IOT lasted 3 to 4 weeks; therefore, an INTELSAT VI IOT using the same procedures and test methodologies would have taken 7 to 8 weeks. This was considered excessive, and an effort was undertaken to reduce the time required for an INTELSAT VI IOT by improving the speed of the test techniques and equipment.

Commanding the spacecraft during an IOT is another major time-consuming task. INTELSAT VI configuration control commanding is more complex than that for previous spacecraft series, and automation is necessary to prevent commanding from becoming the dominant contributor to total IOT duration. Automation of spacecraft configuration control allowed automatic command queue execution using the command coordination system (CCS). A PC-based command generation software package called RCAP (Repeater Command Assistance Program) was developed to allow faster and more reliable generation of reconfiguration commands.

This paper focuses on payload IOT. Companion papers cover monitoring of the launch and spacecraft bus IOT [2]; operation of the satellite during IOT [3]; and the telemetry, tracking, command, and monitoring (TTC&M) network [4], of which the IOT earth station is a part.

IOT systems

The system used for in-orbit testing of INTELSAT VI was built based on experience with the IOT of the INTELSAT V series, and shared some of the same equipment and software. As noted above, the INTELSAT V IOT equipment (IOTE) is not sufficiently fast or accurate for use in the INTELSAT VI era. The basic characteristics of the IOTE for both INTELSAT V and VI are reviewed here.

INTELSAT V IOT system

All INTELSAT V spacecraft were tested from Fucino, Italy, which was also selected for the IOT on the INTELSAT 602 spacecraft, based on geographical and geosynchronous considerations. The INTELSAT V IOTE at Fucino was installed in early 1980 and used for IOT of the first INTELSAT V spacecraft (502), launched in December 1980 [5].

The INTELSAT V IOT system operated by generating the up- and down-link local oscillator (LO) signals simultaneously, as well as an injected tone whose frequency was approximately 170-kHz higher than the received frequency (looped back through the spacecraft). The injected and received signals were then down-converted to 10.0 and 10.17 MHz, respectively. The 10.17-MHz signal was further converted to 10 MHz and phase-locked to the injected signal. Both signals were then applied to the inputs of a vector network analyzer.

The measurement method was based on a classical point-by-point technique, whereby the signal uptime and downtime delays of approximately 260 ms were incurred for each frequency step being measured. Signal fluctuations were reduced by averaging several measurements; however, this method was not very effective for correcting propagation-induced signal fluctuations (particularly tropospheric scintillation), for which rapid fluctuations of up to 2 dB/s and more than 6 dB peak-to-peak are not uncommon for Ku-band signals at low earth station elevation angles. A typical frequency response sweep of a 72-MHz transponder took up to 5 minutes. This system functioned reasonably well over the years and its software and hardware were upgraded to encompass new data processing equipment and new frequency bands—namely the International Business Service (IBS) bands (11.7 to 11.95 GHz and 12.5 to 12.75 GHz) and the Maritime System L-band (1.5 and 1.6 GHz). The RCAP RF instrumentation remained essentially the same during the 10-year span of the INTELSAT V IOT program.

New INTELSAT VI IOT system

The goal for the new INTELSAT VI series spacecraft was to upgrade the IOTE in order to significantly reduce the duration of an IOT compared with that expected if INTELSAT V-era IOTE were used. A major improvement in IOT accuracy was also considered highly desirable.

The new IOT test methodologies described here were conceived after evaluating several different measurement methodologies that had the potential to minimize the duration of IOT measurements and improve their accuracy. The INTELSAT VI IOT uses off-the-shelf, state-of-the-art equipment with extensive internal signal processing capabilities. The new measurement concepts were verified at INTELSAT using spacecraft simulators. The Fucino IOTE was then upgraded in September 1989, prior to launch of the first INTELSAT VI spacecraft (602).

The new test methodology departs from previous techniques in the following respects:

- Modular, synthesized digital spectrum analyzers provided with internal calibration routines are used to measure the main relative level and absolute frequency.
- Fast frequency switching synthesizers with level predistortion eliminate the need for cumbersome and unreliable leveling loop equipment.
- Two independent synthesizers are employed—one to generate the up-link signal and the other the down-link LO and injection signals. This allows independent sweeps on the up- and down-links, which, with proper synchronization, provides swept measurements in less than 1 s.
- A dual pulse generator controls the timing for all measurements. It is also used to synchronize the up- and down-link measurement steps.
- An RF pilot signal compensates for up- and down-link level fluctuations [6] during swept frequency response measurements. This signal is also used as a reference for the group delay measurements, in order to cancel out spacecraft movement relative to the station.
- Automated power meters with internal averaging are used to measure absolute power.
- The transponder saturation point is automatically determined by software. This reduces the time required to find the saturation point, and improves measurement repeatability.
- The measured data are automatically tagged with the predicted position in the beam for the IOT antenna. This reduces operator workload and eliminates errors in the entry of these parameters. It also allows antenna pattern measurements to be performed in any spacecraft orbit plane.

To minimize the software effort, it was decided to retain the existing instrument control computer (Hewlett-Packard HP 9845) and the existing test data handling computer (HP A900).

Figure 1 is a simplified block diagram of the INTELSAT VI Fucino IOT station. The function of the test instruments is best illustrated by describing the new test methodologies implemented in the INTELSAT VI IOT system.

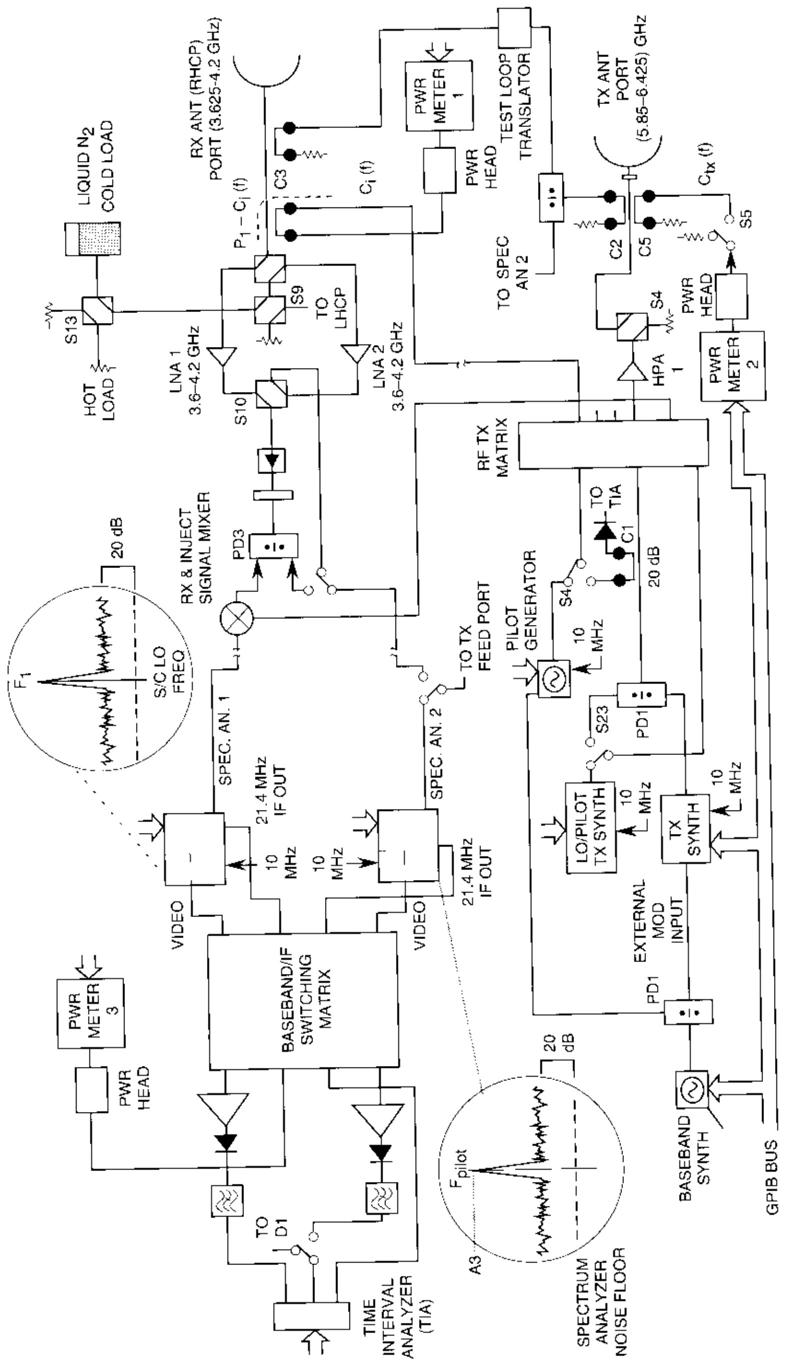

Figure 1. *Fucino IOTE Simplified Block Diagram*

INTELSAT VI RF payload subsystems

The RF IOT of the INTELSAT VI payload checks the performance of two categories of subsystems: communications payload subsystems involving the transponders and antennas, and the TC&R subsystems. The INTELSAT VI spacecraft communications payload subsystem is described in detail in companion papers. Horvai *et al.* [7] discusses the payload; Persinger *et al.* [8] examines the antenna subsystem; and Gupta *et al.* [9] addresses the onboard SS-TDMA subsystem.

The IOT of the TC&R subsystems is described here. Figure 2 is a functional schematic of these subsystems, while Figure 3 shows the location of the TC&R components on the INTELSAT VI spacecraft.

Telemetry subsystem

INTELSAT VI carries two redundant central telemetry units (CTUs) and four pairs of redundant remote telemetry units (RTUs). Only one unit from each redundant pair (RTU and CTU) can be on at any given time. These telemetry units are cross-strapped to two 4-GHz telemetry transmitters, which provide the two telemetry beacons for the INTELSAT VI spacecraft.

INTELSAT VI has two pairs of commandable C-band telemetry beacon frequencies and two tracking (continuous-wave [CW]) Ku-band beacons, as listed in Table 1. Beacons 1 and 2 (for telemetry transmitters 1 and 2, respectively) are the primary beacon frequencies on the spacecraft. C-band beacons 1A and 2A are alternate beacon frequencies used during launch and spacecraft relocation. The Ku-band beacons 1K and 2K are used for tracking and propagation studies only, and do not carry any telemetry data. They are transmitted by dedicated right-hand circularly polarized (RHCP) global coverage horns. The IOTE antenna is linearly polarized at Ku-band; hence a 3-dB loss is incurred in Ku-band beacon reception.

Independent from the selectable beacon frequencies, each C-band telemetry transmitter has two transmission modes: an earth coverage mode when on-station (in geosynchronous orbit); and an omnidirectional coverage mode employed during transfer orbit and obtained from a vertically polarized, dual toroidal beam antenna using one of three selectable TWTAs (shared with the zone 4 beam) per telemetry transmitter. Once on-station, one telemetry beacon is operated in the omnidirectional mode to ensure maximum telemetry coverage should the spacecraft lose earth lock.

Each telemetry transmitter can be phase-modulated by up to three different baseband frequencies which carry different telemetry information, as summarized in Table 2. Each transmitter can operate in any combination of the three selectable modes: normal pulse code modulation (PCM), ranging, and PCM

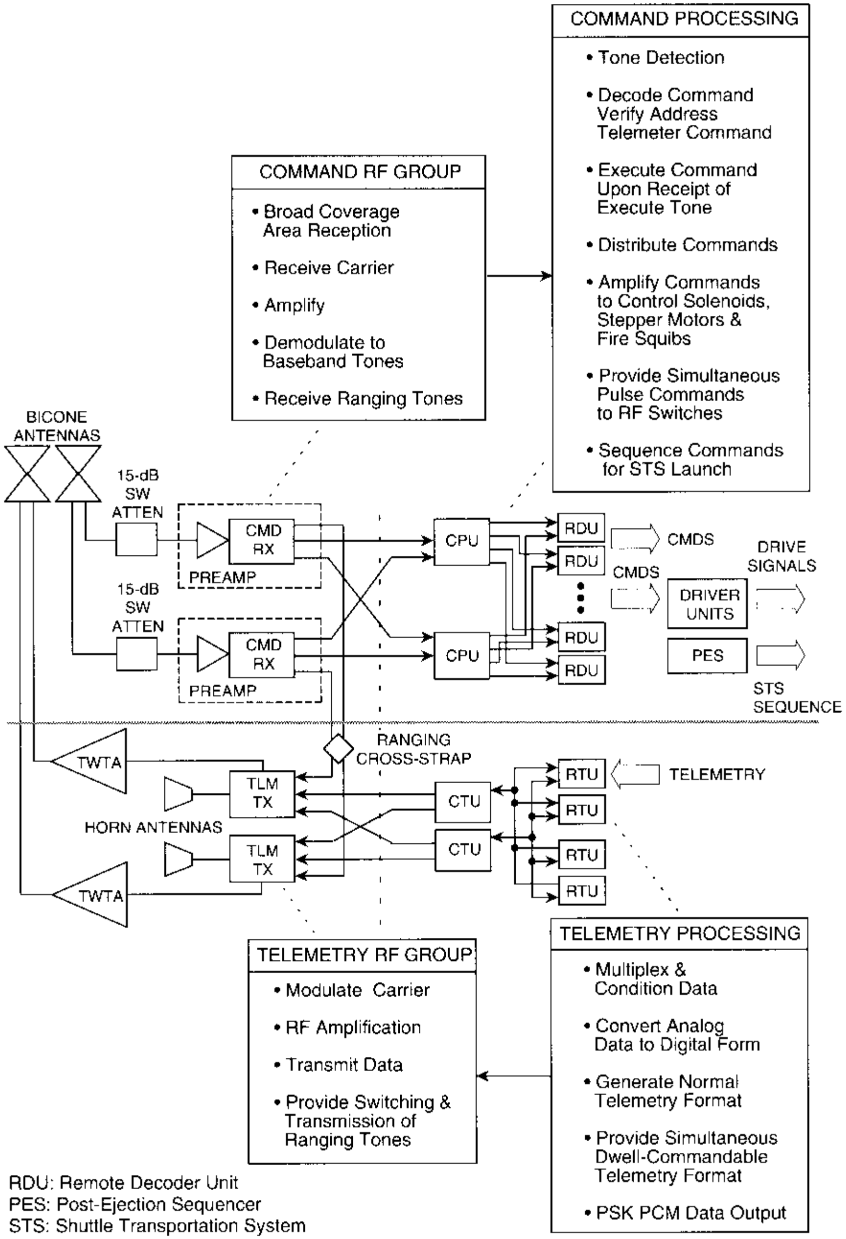

Figure 2. *INTELSAT VI Telemetry, Command, and Ranging Functional Schematic*

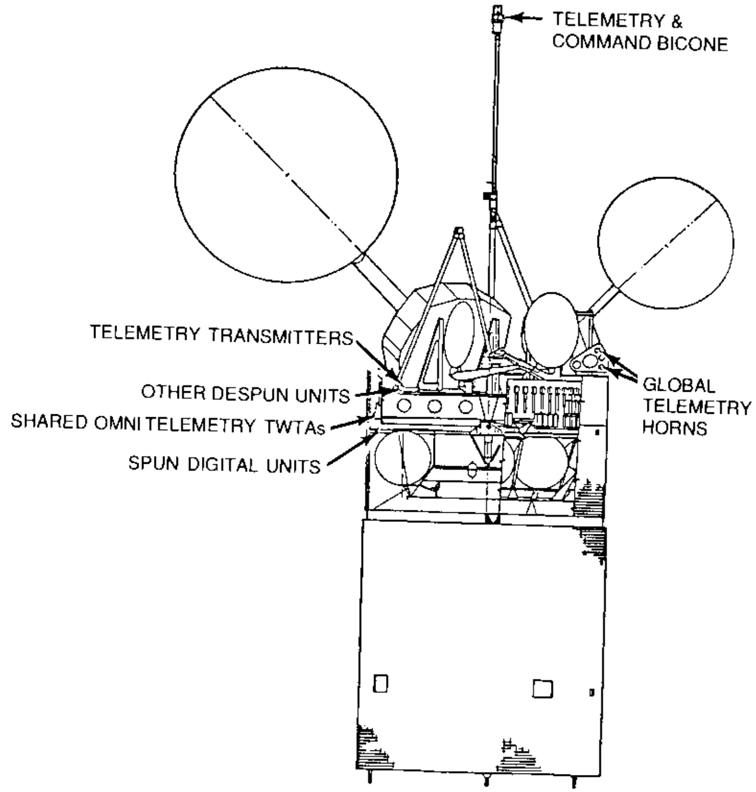

Figure 3. *INTELSAT VI Deployed Configuration Showing Location of Some TC&R Subsystem Components*

TABLE 1. INTELSAT VI BEACON FREQUENCIES

BEACON NO.	FREQUENCY (MHz)
1	3,947.5
1A	3,948.0
2	3,952.5
2A	3,952.0
2K	11,198.0
1K	11,452.0

TABLE 2. INTELSAT VI TELEMETRY SUBCARRIER FREQUENCIES

BASEBAND INPUT NUMBER	FUNCTION	FREQUENCY (kHz)
1	Normal PCM	48.0
2	Range	≤27.8
3	PCM Dwell	72.0

dwell. Different modulation indexes are selected by the telemetry transmitter in response to status signals from the CTU, which in turn depend on the number of subcarriers selected (*i.e.*, 1.0 for one source, 0.7 for two, and 0.6 for three sources).

The bit rate of the biphase-level encoded PCM telemetry bit stream (4.8 kbit/s, normal and dwell) phase shift keying (PSK)-modulates a 48-kHz subcarrier, which in turn phase-modulates the telemetry transmitter beacon signal. The PCM dwell mode data are modulated onto a 72-kHz subcarrier.

Command and ranging subsystems

The command subsystem provides for ground control of all commandable spacecraft functions. Commands can be transmitted to the spacecraft by PCM return-to-zero (RZ)/FM modulation of two different command carriers in the 6-GHz range, which are received by a horizontally polarized dual-mode toroidal bicone omnidirectional antenna. The antenna outputs are directed to two separate redundant receivers. Redundancy is achieved by hard-wiring the two receivers' prime power inputs to one of the two spacecraft power buses (one on each bus), such that both receivers are always on. The up-link carrier frequency will determine the choice of command receiver, since the receivers are tuned to two different frequencies. Thus, only three separate tone frequencies are needed (corresponding to 0, 1, and execute) to frequency-modulate the command carrier.

The selected command receiver down-converts the RF signal to IF (70 MHz), where it is amplified, limited, and passed to an FM discriminator whose tone outputs are amplified and fed to each of the two redundant CPUs. The CPUS filter and sum the tones, and feed the data (in the form of a PCM-RZ data stream) to the digital section of the CPU for decoding. The CPU selection information is contained within the command message, and the receivers and CPUs are fully cross-strapped. The command receiver also provides a separate video output to a selected telemetry transmitter for ranging, which is available when any C-band beacon is operated in range mode.

Communications payload subsystem IOT measurement methodologies

With the INTELSAT V system, the measurements of longest duration were typically the gain transfer and in-band/out-of-band frequency response measurements. With the old step-by-step approach, an individual test could easily take up to 5 minutes of active test time. During this time span, changes in atmospheric propagation parameters could affect the measurement, making it difficult to determine if variations in the frequency response of a transponder were caused by an abnormality in the transponder, or by atmospheric propagation variations. With the new instrumentation and measurement methodologies, the same tests have been shortened to as little as 1 s of "on-the-air" test time, in most cases. Examples of typical test methodologies possible with the new system are given below.

Gain transfer measurements

TEST OBJECTIVE AND RESULTS

This test determines the power transfer curve of a communications transponder, including the saturation points of all solid-state power amplifiers (SSPAs) and TWTAs. The effective isotropically radiated power (e.i.r.p.) *vs* flux density and gain *vs* flux density transfer curves are measured. Representative data for INTELSAT 602 saturation flux density and corresponding e.i.r.p., along with the measured and prelaunch transfer curves, are presented in Figures 4 and 5. The vertical line ("SAT") across the traces indicates the saturation flux density point, and the intercepted e.i.r.p. value on the transfer curve corresponds to the saturated e.i.r.p. The solid line corresponds to measured data, while the dashed line corresponds to prelaunch prediction. The double-dashed line corresponds to the measured transponder gain for the range of flux densities used.

TEST PROCEDURE

The measurements are made with a digitally stepped power sweep, using the test equipment configuration shown in Figure 6. This method consists of generating a fast, power-stepped ramp on the up-link signal (curve C), comprising N steps of 0.1 dB each. Prior to execution of this test, the transmit synthesizer sends CW signals in 5-dB steps (with adaptive reduction close to the target gain compression point) until a target gain compression corresponding to the average gain compression for the particular type of transponder power amplifier in use is reached. The average target gain compression values used for the INTELSAT VI series are as follows:

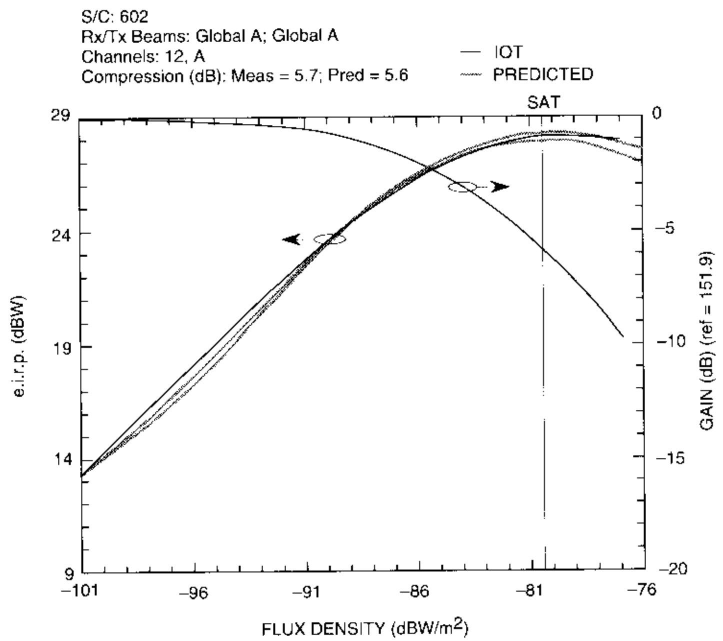

Figure 4. *Example of Spacecraft TWTA Gain Transfer Characteristics Data*

- C-Band TWTA : 5.0 dB (This reference value is also used for all other satellite series transponders.)
- Ku-Band TWTA : 7.5 dB
- SSPA : 2.5 dB

Once the up-link signal reaches a level that produces the target gain compression specified, the transmit synthesizer output level is reduced by 21.0 dB and the synthesizer is programmed to produce a power-stepped ramp up to 3 dB above the reference level for SSPAs, or 6 dB above the reference level for TWTAs, controlled by trigger pulse A from the pulse generator. Therefore, the power ramp will contain a maximum of either 241 or 271 steps of 0.1 dB for an SSPA or a TWTA, respectively.

Trigger pulse B, produced by the pulse generator approximately 260 ms later, triggers spectrum analyzer 1, which records the power ramp signal returned by the spacecraft. The recorded ramp is then compared to the injected signal level at each measurement point, and the down-link e.i.r.p. is calculated. The up-link e.i.r.p. is calculated using the recorded power ramp on spectrum analyzer 2 and the up-link power meter reading at the saturation point.

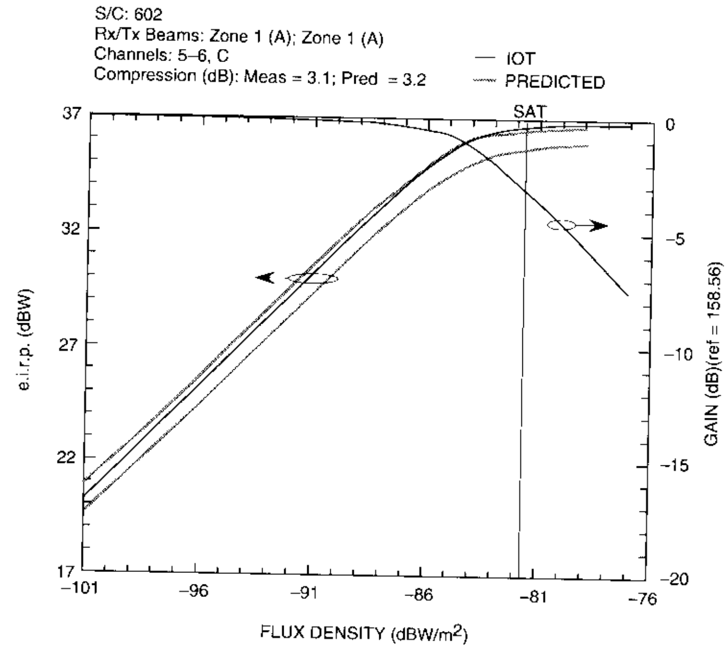

Figure 5. *Example of Spacecraft SSPA Gain Transfer Characteristics Data*

The saturation point is determined by software evaluation of the gain transfer measurement results, taking into consideration the type of power amplifier used in the transponder under test. For the INTELSAT VI spacecraft, two methods are employed to determine the saturation point. For TWTAs, the saturation point is automatically determined by searching for the first input power point on the stepped power ramp at which the saturated output level is reached. In general, for TWTAs, the down-link e.i.r.p. remains flat for a range up to 1.5 dB above the saturation point. For the INTELSAT VI SSPAs, the saturation point is defined as the point where a 1.5-dB reduction in the up-link flux density produces a 0.25-dB reduction in the down-link e.i.r.p. The software determines the measured point with the lowest power level which meets that criterion.

Flux density/e.i.r.p. measurements

TEST OBJECTIVE

The objective is to measure the flux density needed to saturate a particular transponder, and the corresponding down-link e.i.r.p. The results are

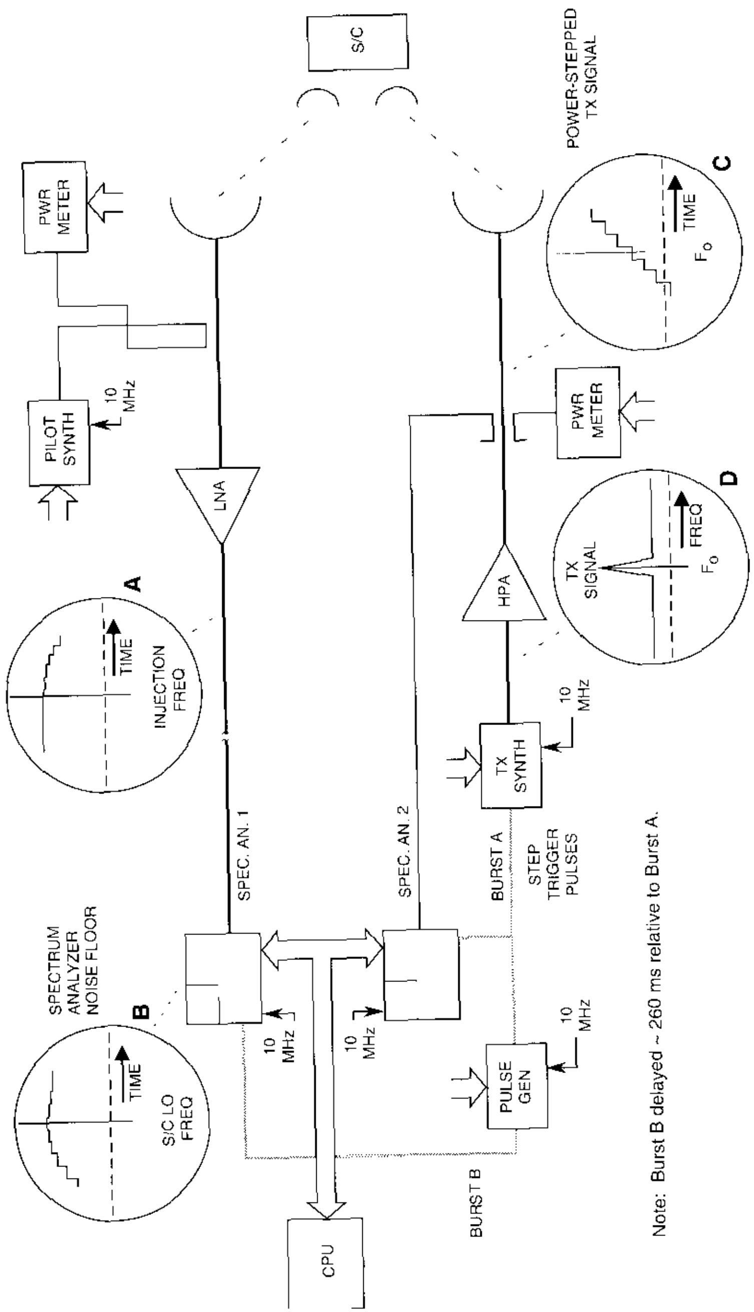

Figure 6. *Gain Transfer Measurement Setup Simplified Diagram*

automatically compared with prelaunch performance test data from hot, cold, and ambient test phases. The prelaunch data are stored in the test data handling system (TDHS), and the IOT system automatically retrieves the relevant data. Typical test results are given in Figures 7 and 8, where the prelaunch data for hot, cold, and ambient test conditions are shown, along with the IOT-measured data (*). This test is also used to determine the transponder's linear gain in a loopback mode, and can be used to measure the down-link e.i.r.p. of CW signals transmitted by other stations.

The test is performed through all spacecraft receivers and power amplifiers. To ensure thermal equilibrium, a minimum number of receivers and power amplifiers are left on during the testing.

TEST DESCRIPTION

A CW signal is radiated at either the saturation or linear operating regions of the transponder, and the up-link flux density received and e.i.r.p. transmitted by the spacecraft are calculated based on measurements referenced to the IOT antenna feed. When transponder saturation is determined automatically, a procedure similar to the gain transfer test is used, with the only difference being that the power sweep ramp begins from a level 6 dB below the reference up-link power level.

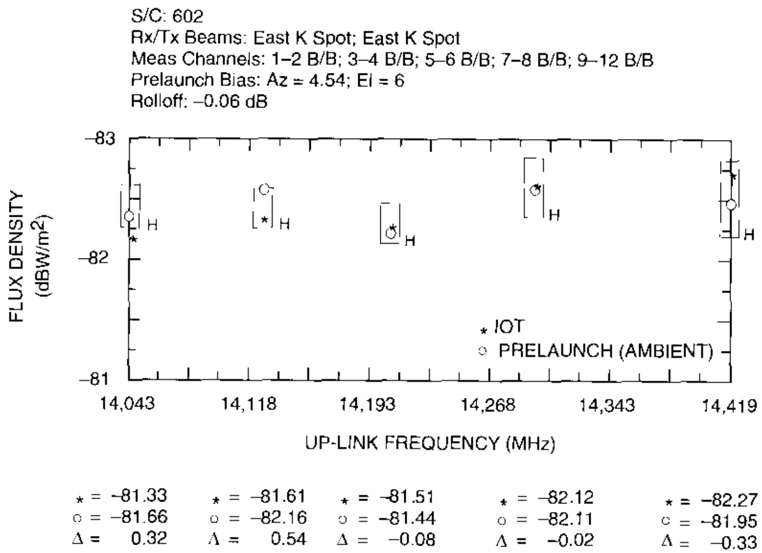

Figure 7. *Typical Flux Density Graphical Test Results*

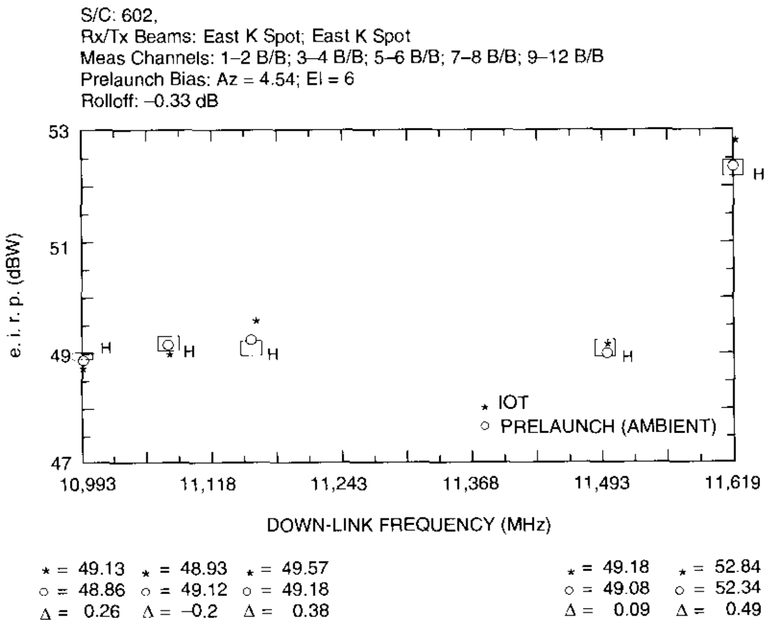

Figure 8. *Typical e.i.r.p. Graphical Test Results*

Once the saturation point is found, the up-link signal is maintained at that level while the down-link level is monitored on spectrum analyzer 2 for a period of 1 s for C-band or 10 s for Ku-band beams. The difference between the injection level and the maximum down-link signal level recorded on the spectrum analyzer is used to calculate the down-link e.i.r.p. The maximum down-link signal monitor on the analyzer removes errors arising from station antenna tracking inaccuracy, as well as most atmospheric propagation fluctuations.

The test setup shown in Figure 9 is similar to the one used for gain transfer measurements. An additional power meter connected to the spectrum analyzer IF output is used to perform the optional carrier-to-noise power density ratio, C/N_0, measurements.

Gain vs frequency response

TEST OBJECTIVE

The frequency response tests determine the gain *vs* frequency characteristics of the communications transponders on any INTELSAT spacecraft by

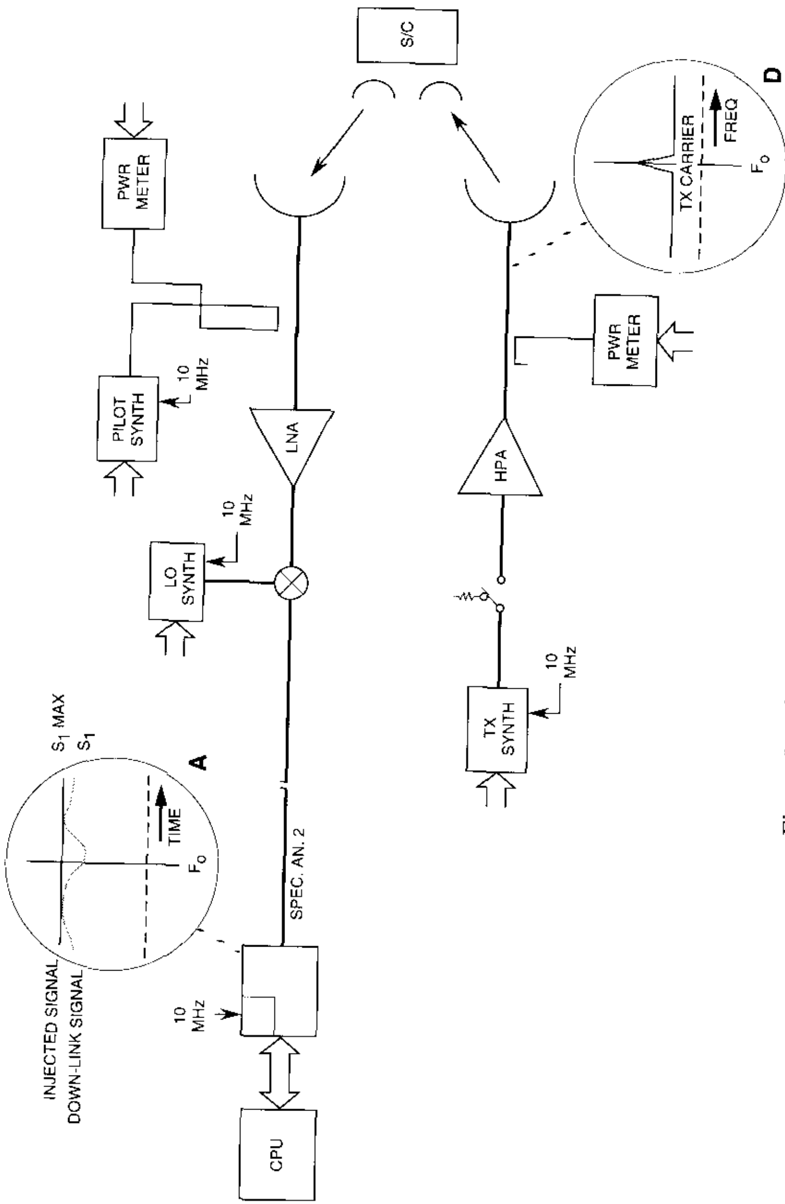

Figure 9. *Flux Density/e.i.r.p. Test Setup*

performing in-band and out-of-band measurements. The results are automatically compared with prelaunch performance test data from hot and cold test phases, as shown in Figures 10 and 11.

TEST DESCRIPTION

The gain *vs* frequency measurements are generally performed using carrier levels that keep the test transponder within its linear operating region. Thus, a combined input and output multiplexer frequency response is obtained. Saturated frequency response tests are only performed during anomaly investigations when the transponder frequency response is being investigated and the transponder input section needs to be isolated.

The test setup for this measurement is shown in Figure 12. The total propagation time for the RF signals to and from the spacecraft under test is calculated prior to the test, using spacecraft orbital data. The output power of the transmit synthesizer is leveled by using a power meter and a sensor situated at the respective feed transmit monitor port, so that predistortion techniques can be employed. The transmit synthesizer is then used to send a digitally directly synthesized frequency burst (triggered by pulse A from the

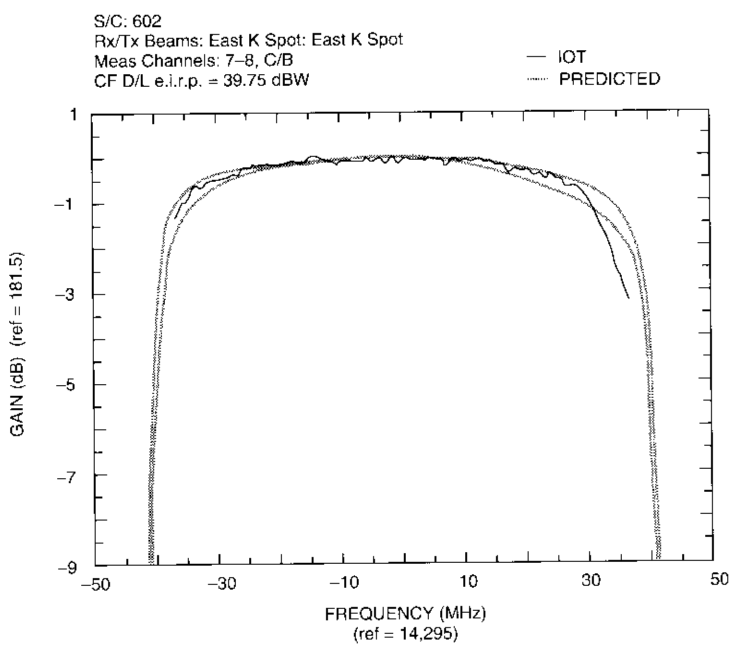

Figure 10. *Example of In-Band Frequency Response Results*

pulse generator) that spans the transponder bandwidth to be measured in 1-MHz steps.

Optionally, to obtain the linear frequency response, a pilot synthesizer radiates a CW pilot signal (near the center of the swept frequency band) at a level equal to or less than -10 dB relative to the swept signal. The total combined power of the pilot plus the down-link signal is adjusted to avoid any compression on the transponder power amplifier.

The RF-swept signals and (if applicable) the pilot are translated in frequency by the spacecraft transponder and arrive at the station receive feed flange about 260 ms after transmission. They are then synchronously down-converted to the spacecraft LO frequency via a broadband RF mixer and the LO synthesizer. A burst of frequencies identical to the burst sent by the transmit synthesizer—but displaced by the transit time (approximately 260 ms)—is then sent by the LO synthesizer.

Immediately after the looped-back signal measurements (to and from the spacecraft), the same frequency burst is locally injected at the earth station low-noise amplifier (LNA) input to subtract the contribution from the earth station down-link frequency response. The injected signals are identical (in

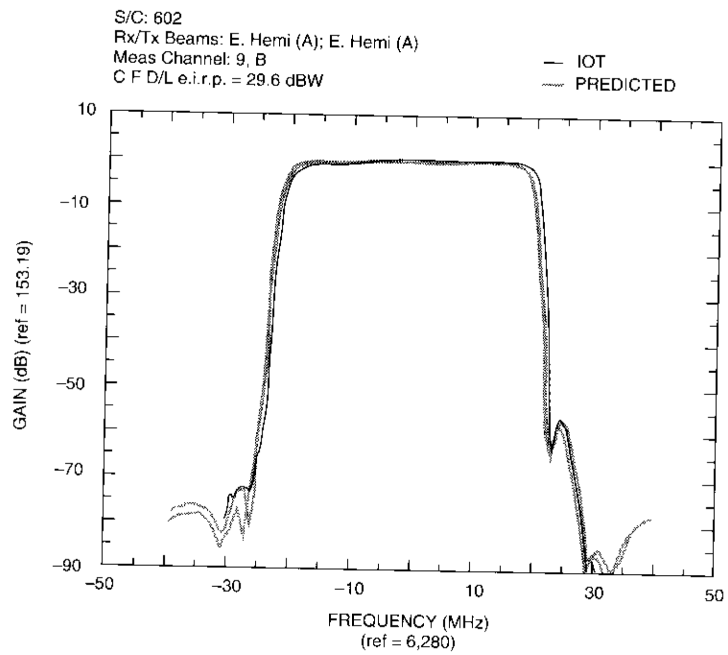

Figure 11. *Example of Out-of-Band Frequency Response Results*

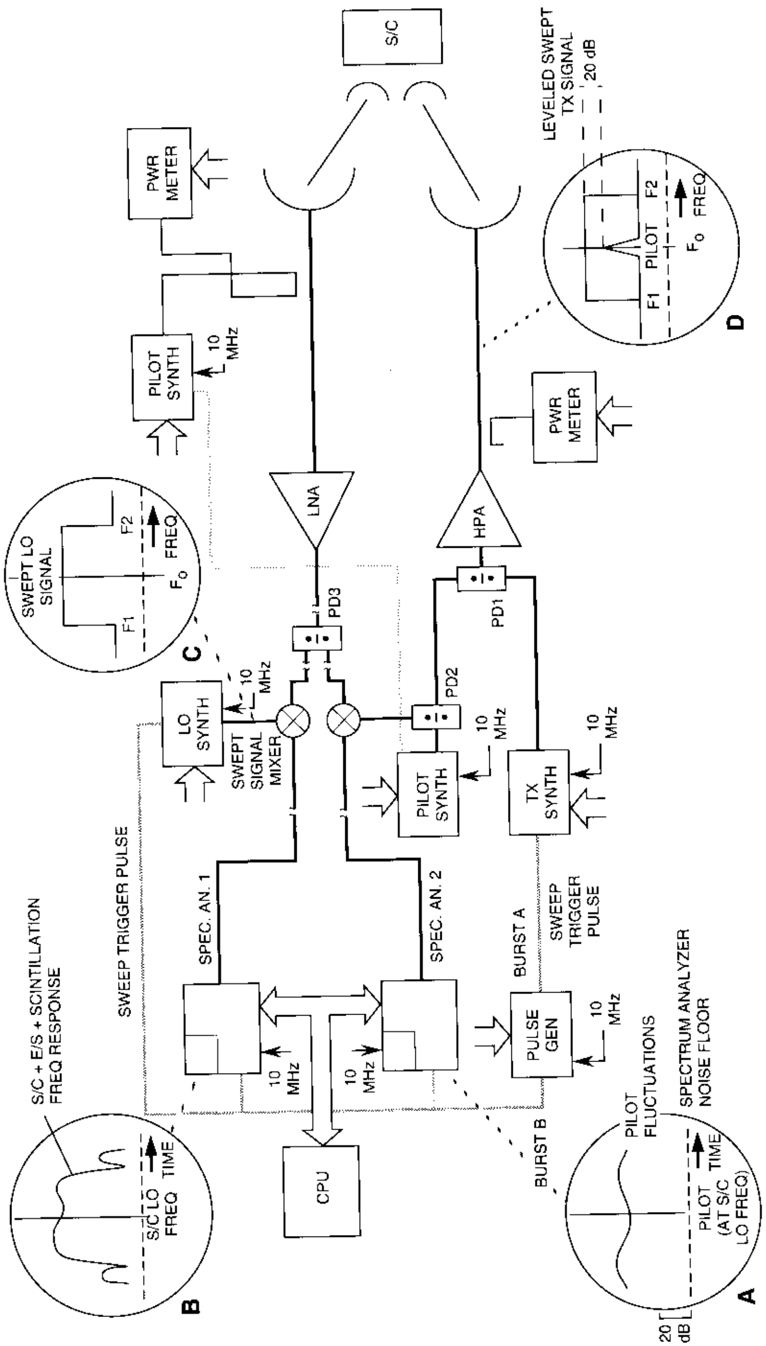

Figure 12. *Gain vs Frequency Measurement Simplified Diagram*

frequency, step size, duration, and number of steps) to the received signal burst, and are at a level close to that measured when the down-link signal frequency was at the center of the frequency band of the transponder under test. This technique assumes that the earth station down-link frequency response is stable during the short time period (approximately 5 s) between execution of the looped-back and injected measurements.

G/T measurements

TEST OBJECTIVE

The purpose of this test is to verify the ratio between the spacecraft receive antenna gain and the total transponder noise temperature referenced to the same receive interface point for all available channels (gain-to-noise temperature ratio, *G/T*). The results are automatically compared with prelaunch performance test data from hot, cold, and ambient test phases, as shown in Figure 13.

TEST DESCRIPTION

The Y-factor measurement method described in Reference 1, using hot and cold loads mounted just ahead of the earth station LNA, was the method used

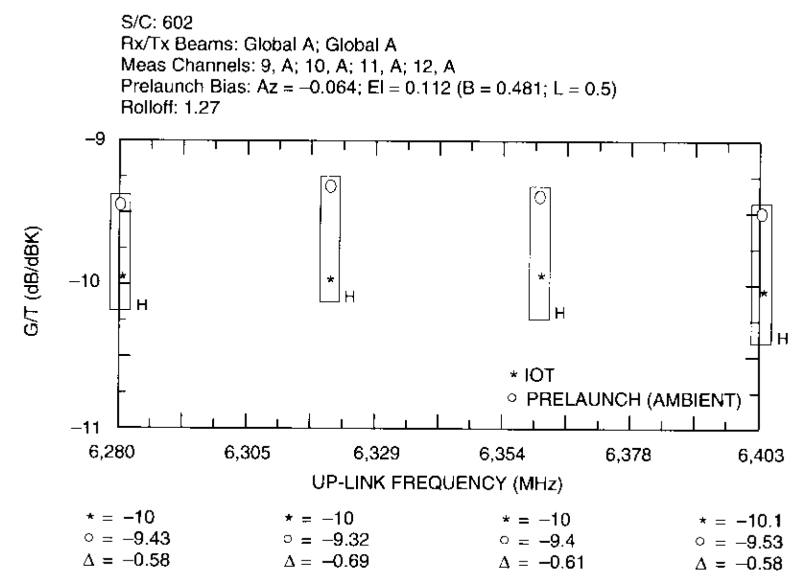

Figure 13. *Example of G/T Graphical Test Results*

to measure *G/T* on the INTELSAT V series IOT stations to determine the test equipment noise bandwidth. For INTELSAT VI, a new test procedure was devised to eliminate the need for the hot/cold loads [10], which are expensive and difficult to maintain accurately calibrated.

The IOT on the INTELSAT VI series spacecraft is based on knowledge of the earth station equipment noise bandwidth, which can be determined prior to the *G/T* measurement using either a technique which integrates the spectrum analyzer trace or a frequency response measurement referenced to the *G/T* power meter readings. The test setup (Figure 14) uses the noise bandwidth of the IF filter of the spectrum analyzer, which is calibrated immediately prior to a sequence of *G/T* measurements. The IF output of the analyzer (set to zero span) is connected to a power meter sensor. The measured values are then inserted into the following equation:

$$G/T = \left(\frac{L_{up} \bullet L_{sky} \bullet B_{IF}}{\text{e.i.r.p.}} \right) \bullet \left(\frac{C}{N} \right) \bullet \left(\frac{Y}{Y-1} \right) \qquad (1)$$

where k = 1.38044×10^{-23} W/HzK (Boltzmann's constant)
L_{up} = Up-link path loss ratio
L_{sky} = Up-link atmospheric attenuation ratio
B_{IF} = Calibrated noise bandwidth of the IF output of the analyzer (Hz)
C/N = Carrier-to-noise ratio
Y = (Spacecraft + earth station noise)/(earth station noise) = Y-factor
e.i.r.p. = Equivalent isotropically radiated power (W)

TEST SEQUENCE

The earth station antenna is pointed off the spacecraft, and earth station noise is measured on the spectrum analyzer IF power meter (P1) for all channels selected for measurement. The earth station antenna is then repointed to the spacecraft, and the spacecraft transponder noise plus earth station noise are measured on the IF power meter (P2). The ratio P2/P1 corresponds to the Y-factor used in equation (1). A linear carrier is then brought up, and the up-link level is adjusted to the minimum level that can be accurately measured on the up-link power meter. The spacecraft transponder noise plus earth station noise plus linear test carrier are measured on the IF power meter (P3). The ratio P3/P2 corresponds to $(C+N)/N$, which is used to derive the C/N variable used in equation (1). All other constants and calculated values are then used to determine the spacecraft *G/T*.

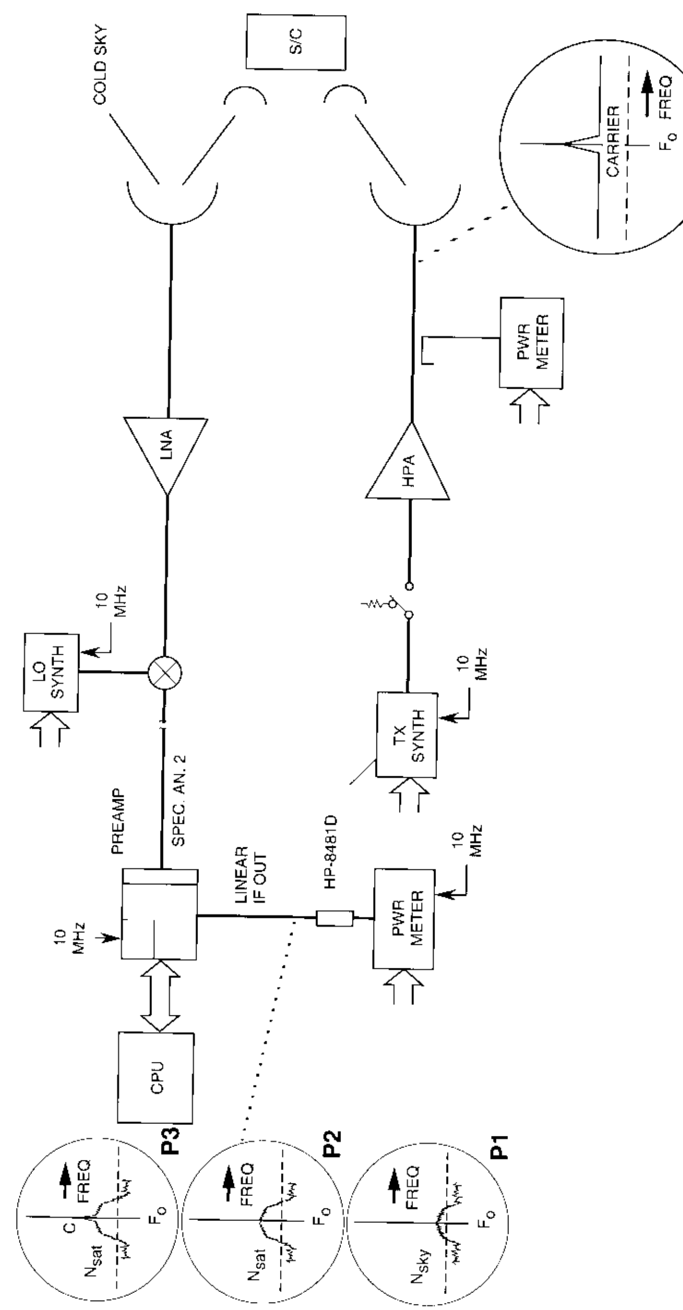

Figure 14. *Satellite/(G/T) Test Setup*

The predicted G/T is calculated based on prelaunch data for the spacecraft receive beam gain and the repeater noise figure, as follows:

$$G/T_{pred} = G_{Rxant} - 10 \log (T_{eff}) \tag{2a}$$

$$T_{eff} = [10^{(NF/10)} - 1] \bullet T_o + [(1 - B) \bullet T_{space} + B \bullet T_{earth}] \bullet L_{wg} + T_{amb} \bullet (1 - L_{wg}) \tag{2b}$$

where T_{eff} = Effective noise temperature of the spacecraft transponder

NF = Repeater noise figure referred to the spacecraft receive antenna interface (prelaunch data)

B = Ratio of spacecraft antenna beam volume covering the earth *vs* the total antenna beam volume. Table 3 gives an example of the B factors used for INTELSAT 602. Figure 15 shows an example of spacecraft antenna pointing during IOT.

T_o = 290 K (reference for NF calculation)

T_{space} = 10 K (average sky noise temperature as seen by the spacecraft antenna)

T_{earth} = 290 K (average earth noise temperature in the region covered by the spacecraft antenna). Season- and hemisphere-dependent.

L_{wg} = $10^{-L(dB)/10}$ (waveguide loss from the antenna to the receive interface point, in linear units). Ratio between power at interface point and power at receive antenna.

T_{amb} = 300 K (average receive antenna waveguide temperature).

TABLE 3. B FACTORS AND RECEIVE ANTENNA LOSSES USED FOR INTELSAT 602 IOT

BEAM	B FACTOR	ANTENNA WAVEGUIDE LOSS, L (dB)
East Spot	0.654	1.0
West Spot	0.534	1.0
Zone 1	0.345	1.8
Zone 3	0.468	1.2
Zone 2	0.577	1.4
Zone 4	0.973	1.6
East Hemi	0.300	1.3
West Hemi	0.495	1.3
Global A	0.460	0.5
Global B	0.460	0.5

Equation (2b) was developed by INTELSAT to better represent the thermal noise level present at the transponder input. The generic equation used in previous (INTELSAT I through V) IOTs was

$$T_{eff} = [10^{(NF/10)} - 1] \bullet T_o + T_{earth} \tag{3}$$

This equation does not compensate for the lower earth noise contribution from the spacecraft receive antenna when part of its pattern is not covering the earth. When it is used instead of equation (2), the predicted G/T tends to be

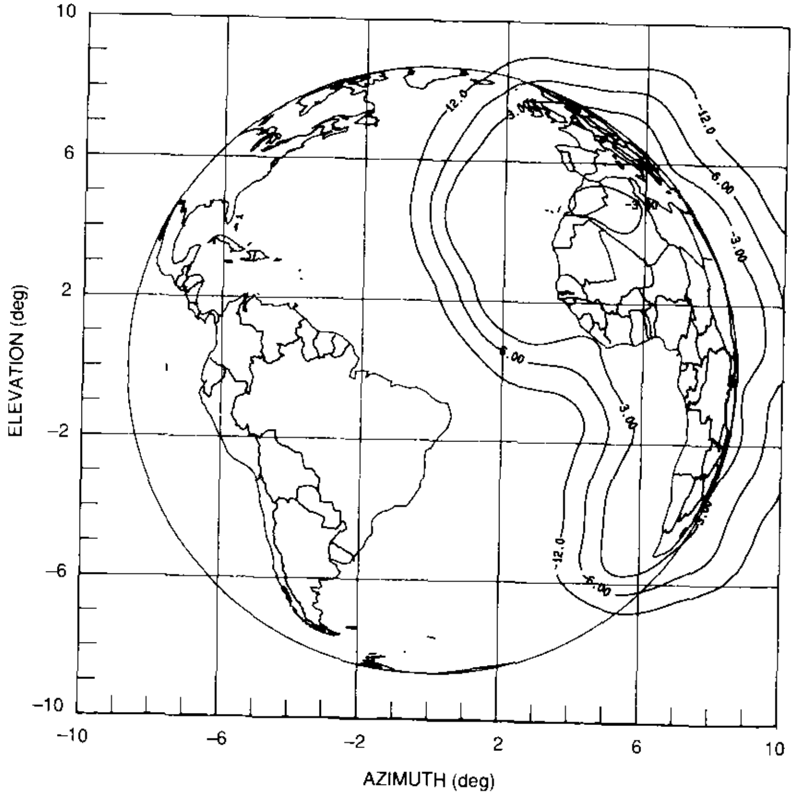

Figure 15. *Typical East Hemi Beam-Pointing During IOT Tests*

lower than the actual measured value (differences of more than 3 dB can be observed).

Translation frequency measurements

TEST OBJECTIVE

This test is conducted to measure the translation frequency and offsets of the various LOs used for the receive-to-transmit band translations in INTELSAT spacecraft. The measurement can also be used to determine the down-link frequency of CW signals transmitted from other stations. The test results are recorded as a table containing measured high, low, and middle LO frequency steps.

TEST DESCRIPTION

The test setup for this measurement is shown in Figure 16. A CW RF signal is radiated toward the spacecraft, and the same signal is used as an LO to beat against the looped-back received signal. The resulting IF equals the transponder translation frequency plus Doppler shift.

The spectrum analyzer IF output is connected to a counter, which is used for frequency measurement. In case of failure of the counter, or low down-link e.i.r.p., the spectrum analyzer can also be used for the LO measurement, with little impact on measurement accuracy and with the added advantage of extending the measurement dynamic range to a level close to the system noise floor.

Antenna pattern measurements

Antenna pattern measurements (main lobe transmit and receive co-polarization and cross-polarization patterns, and transmit and receive co-polarization sidelobe patterns for hemi/zone, spot, and global beams) define coverage and isolation (cross-polarization and pattern) for the particular INTELSAT VI satellite and for the system.

Most spacecraft antenna pattern tests are performed by moving the spacecraft antennas in the east/west direction, which requires only a temporary change in the electromagnetic torque of the despun section of the spacecraft (orbit-normal attitude). However, some tests do involve moving the spacecraft antennas in the north/south direction, and thus require the firing of thrusters to introduce a precession angle between the spacecraft's coordinate system and its orbit plane. This creates a diurnal movement of the IOT station relative to the spacecraft coordinates and allows for measurements through beams not normally visible from the station.

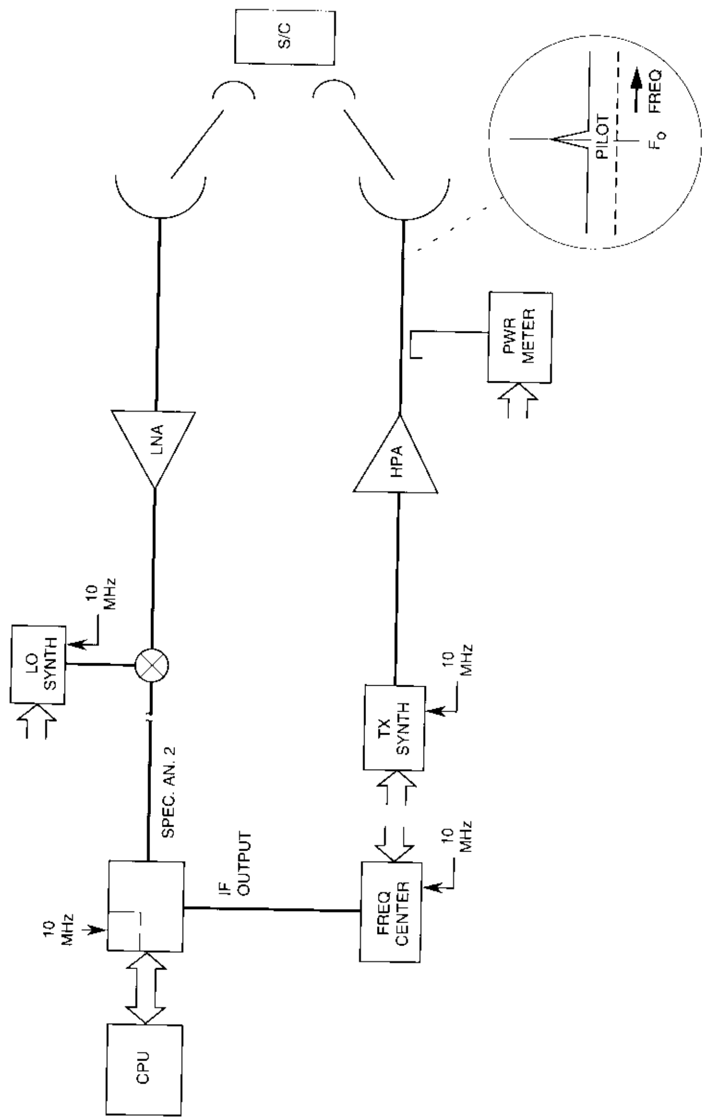

Figure 16. Satellite Transponder Translation Frequency Measurement Setup

Antenna pattern tests are usually performed for each 0.5° step for the hemi/zone beams, each 1.0° step for the global beams, and each 0.3° step for the spot beams. Total azimuth range depends on the beam coverage and IOT station transmit e.i.r.p. capability. Each antenna pattern point measured is properly time-tagged, and the corresponding spacecraft attitude data are retrieved, thus allowing antenna pattern measurements to be performed in any plane (azimuth, elevation, or inclined). The spot beams are normally pointed toward the testing station to perform the antenna pattern measurements.

MAIN LOBE ANTENNA PATTERNS

Test Objective

This series of tests verifies all the co-polarized and cross-polarized radiation characteristics of the main lobe of the spacecraft beams. The test setup is shown in Figure 17.

Test Description

Main lobe antenna pattern measurements can be classified in four main categories as described below:

- *Co-Polarized Spacecraft Receive Antenna Pattern Test.* This procedure is used to obtain the flux density necessary to saturate the spacecraft transponder at discrete angular offsets in relation to the testing station. The different flux density values required to saturate the transponder at each antenna offset provide the data for the relative antenna receive directivity. The saturation test methods used for the flux density/e.i.r.p. test are repeated for each discrete offset. The predicted flux density to achieve saturation at each measured position is calculated using prelaunch ambient test phase results, as shown in Figure 18.
- *Co-Polarized Spacecraft Transmit Antenna Pattern Test.* This test is conducted at the same time as the receive antenna pattern test. The saturated down-link e.i.r.p. values achieved at each discrete angular offset are directly proportional to the spacecraft transmit antenna directivity, since the transponder output power is kept constant by ensuring that the transponder is saturated. The saturated down-link e.i.r.p. is determined using the same procedures as for the flux density/e.i.r.p. tests. The predicted e.i.r.p. at saturation for each measured position is calculated using the prelaunch ambient test phase results, as shown in Figure 19.

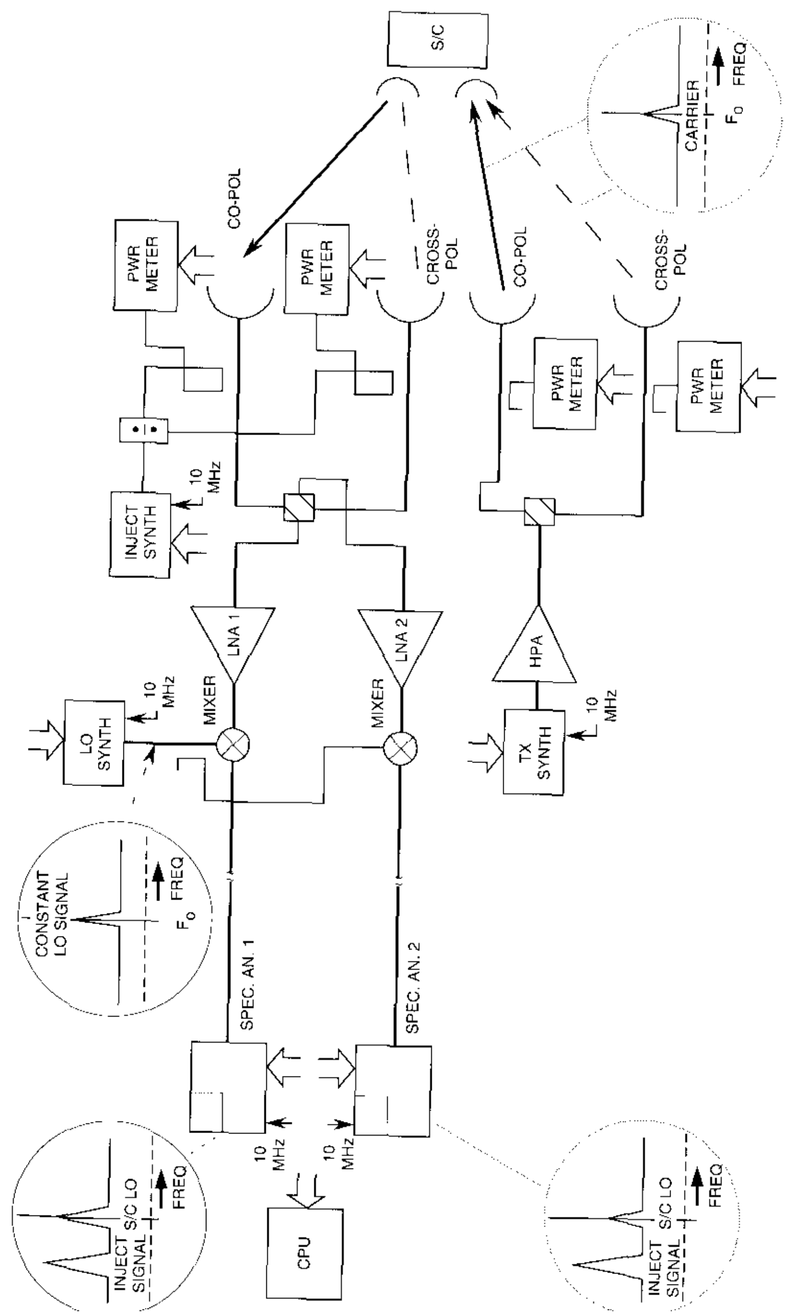

Figure 17. *Satellite Antenna Pattern Test Setup*

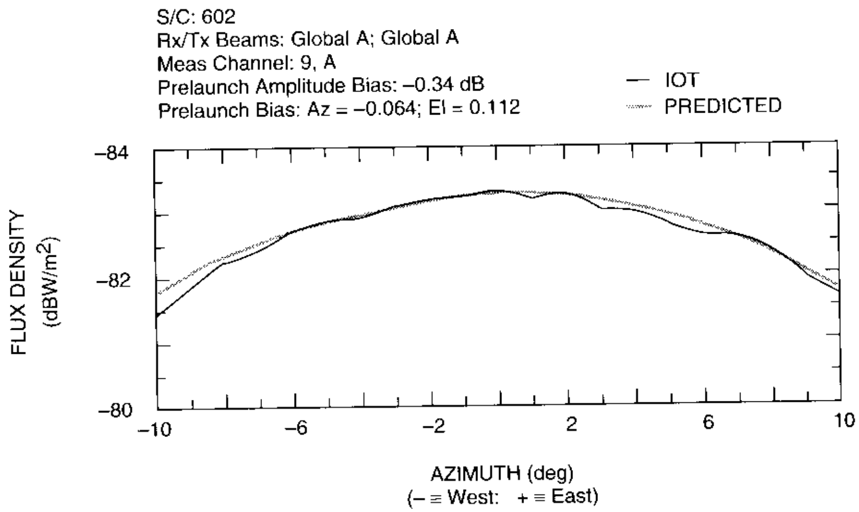

Figure 18. *Example of Co-Polarized Receive Antenna Pattern Graphical Result*

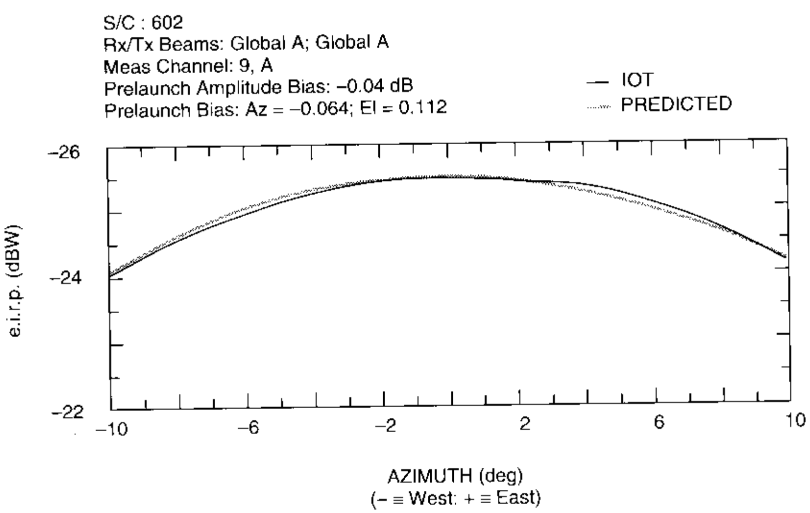

Figure 19. *Example of Co-Polarized Transmit Antenna Pattern Graphical Result*

- *Cross-Polarized Spacecraft Receive Antenna Pattern Test.* For this test, all orthogonally polarized transponders visible from the IOT station must be switched off. A linear co-polarized signal is transmitted first, followed by switchover of the station high-power amplifier (HPA) to the cross-polarized transmit port, while maintaining the same up-link e.i.r.p. level. The receive signal is measured before and after the switchover on the same down-link port. The transmit e.i.r.p. must guarantee that the spacecraft transponder under test is sufficiently backed off and operating in the linear region. The difference between the linear gains is the spacecraft receive antenna cross-polarization isolation. The flux density required to saturate the transponder when using the cross-polarized test signal is calculated based on the measured linear gain delta and the saturated co-polarization flux density. Figure 20 shows the measured and predicted receive cross-polarization isolation (upper traces), and the predicted and measured flux density to saturate (lower traces).

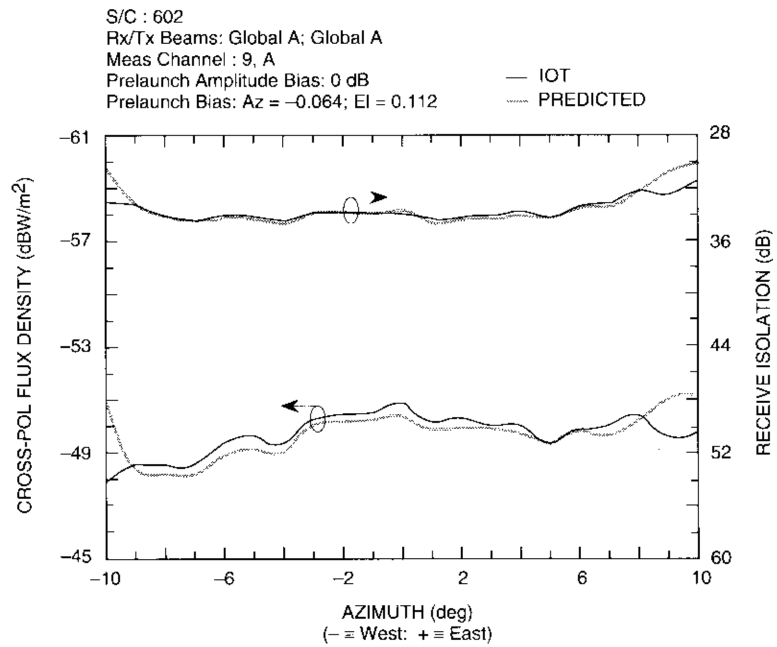

Figure 20. *Example of Receive Cross-Polarized Antenna Graphical Result*

- *Cross-Polarized Spacecraft Transmit Antenna Pattern Test.* For this test, all orthogonally polarized transponders visible from the IOT station must be switched off. The spectrum analyzers, which simultaneously monitor both the co-polarized and cross-polarized received signals, are set to the same frequency, and the earth station e.i.r.p. is brought up to the level used to measure the saturated co-polarization e.i.r.p. The cross-polarization down-link e.i.r.p. is measured, and the spacecraft antenna transmit cross-polarization isolation is calculated. Figure 21 shows the measured and predicted transmit cross-polarization isolation (upper traces), and the predicted and measured e.i.r.p. at saturation (lower traces).

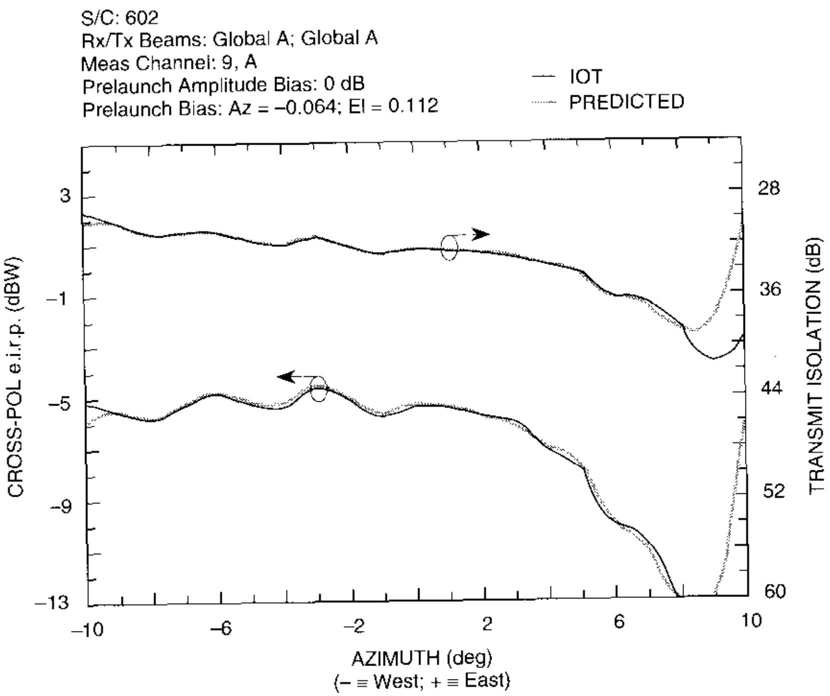

Figure 21. *Example of Cross-Polarized Transmit Antenna Pattern Graphical Result*

SIDELOBE PATTERNS

Test Objective

This test verifies the co-polarized sidelobe performance of the spacecraft antennas. It is normally performed on those beams that use a beam-forming network (BFN) of horns, and verifies that the sidelobe cancellation horns are performing as measured in the ground tests. The test is also used to check for any reflections from RF-reflecting surfaces located near the antenna under test. The sidelobe pattern tests are normally conducted to check the performance of hemi and zone beams. The test setup is the same as for the main lobe antenna pattern tests.

Test Description

The receive and transmit sidelobes are measured separately. When the receive sidelobe is measured, the spacecraft is configured to receive the IOT test signal through the beam for which the sidelobe is to be measured. The transponder output is then routed to the main lobe of the opposite beam, which illuminates the test station. The linear gain is measured for each antenna pointing offset that was used for the transmit antenna main lobe pattern tests. For example, to measure the east hemi receive sidelobe, the spacecraft is configured to receive the test signal through the east hemi antenna and then transmit it using the west hemi antenna. (The spacecraft receiver, power amplifier, and gain setting must be the same as for the main lobe tests, to minimize errors.)

To calculate the flux density necessary to saturate the transponder through the receive sidelobe, the flux density used to saturate the main lobe receive beam is added to the linear gain differences between the sidelobe measurements and the main lobe measurement used as a reference. The results are presented as shown in Figure 22, where the upper trace is the calculated difference between the sidelobe and main lobe antenna gains, and the lower traces are the calculated and predicted flux density needed to saturate the transponder through the sidelobe of the antenna under test.

When the spacecraft antenna transmit sidelobe is measured, the spacecraft is configured to receive the IOT signal through a beam that has its main lobe over the IOT station. The transponder output is then routed to the beam for which the transmit sidelobe is to be measured. (The spacecraft receiver, power amplifier, and gain setting must be the same as the main lobe tests, to

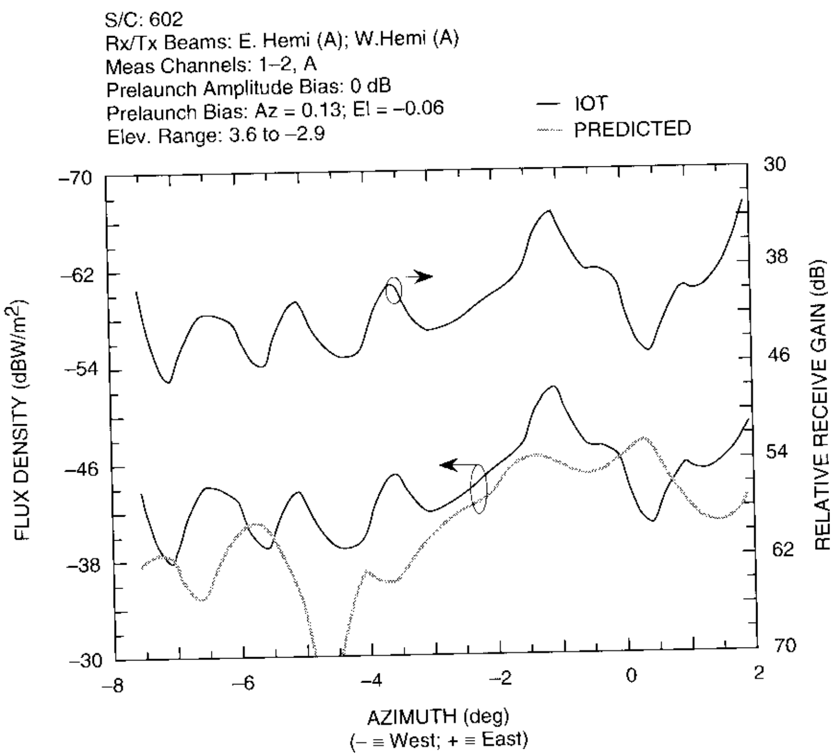

Figure 22. *Receive Sidelobe Graphical Test Result*

minimize errors.) The test transponders are saturated at each antenna pointing offset that was used for the receive beam main lobe pattern, and the saturated sidelobe transmit e.i.r.p. is measured directly. The results are presented in Figure 23, where the upper trace is the measured saturated gain difference (the carrier-to-interference ratio, *C/I*), and the lower traces are the measured and predicted saturation e.i.r.p. produced by the spacecraft sidelobe.

TC&R subsystems IOT measurement methodologies

The in-orbit RF measurements of the TC&R subsystems consist of telemetry subsystem measurements, command subsystem measurements, and ranging subsystem measurements, as described below.

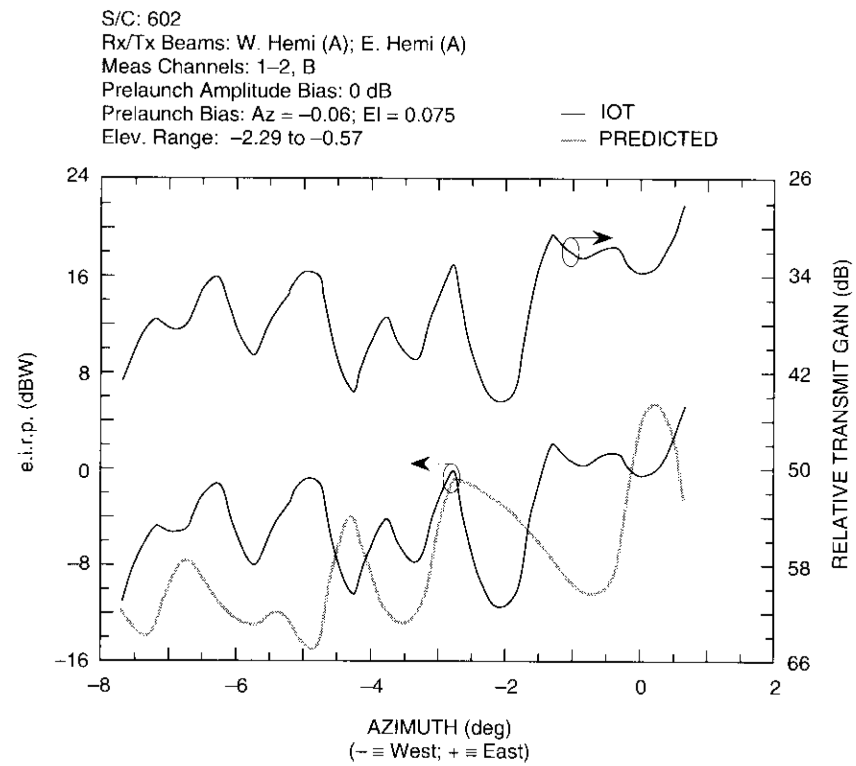

Figure 23. *Transmit Sidelobe Graphical Test Result*

Telemetry/range subsystem measurements

The telemetry subsystem measurements comprise beacon e.i.r.p., beacon frequency, beacon modulation indices and baseband frequencies, telemetry antenna patterns, and telemetry horn axial ratio.

BEACON e.i.r.p.

To determine the e.i.r.p. of a modulated beacon, a calibrated HP71210 spectrum analyzer is used to measure the levels of the beacon fundamental, the first two sidebands, the inject signal (placed between the fundamental and the first sideband), and the noise floor. The total beacon power is calculated by adding the power of the sidebands to the power of the fundamental. This total power is then compared with that of the injected signal to compute the beacon e.i.r.p. The e.i.r.p. of the RHCP 11-GHz beacons (1K and 2K) is measured using the linearly polarized Ku-band IOT antenna, and then transformed to an equivalent circularly polarized e.i.r.p. by adding 3 dB to the measured value.

BEACON FREQUENCY

The "Autozoom" feature of the calibrated spectrum analyzer is used to measure the beacon center frequency to a resolution of 1 Hz. The accuracy of the synthesized analyzer frequency measurements is ±5 Hz. Use of the spectrum analyzer considerably increases the dynamic range over which frequency measurements can be taken.

BEACON MODULATION INDEXES AND BASEBAND FREQUENCY

The modulation index of the telemetry beacon is measured for both single-baseband and multi-baseband inputs. Single-baseband input consists of PCM or range mode. In the PCM mode, the spectrum analyzer is used to measure the power of the carrier and of its first two sidebands. The ratio of the carrier and the first-order sidebands is then used to compute the modulation index. In the range mode, a 27.777-kHz ranging tone is continuously transmitted to the spacecraft, and the modulation index is measured in a manner similar to that used for the beacon in PCM mode. The only difference is that the modulation index is measured for various up-link carrier power levels. Figure 24 shows an example of a beacon measurement printout.

TELEMETRY ANTENNA PATTERN

The azimuth antenna patterns for the beacon horn and omni antennas are measured by slewing the spacecraft ±20° in pitch and measuring the e.i.r.p. of the beacon fundamental at each angle increment. At C-band, the beacon under test is configured in range mode only, and a clean command carrier is transmitted to remove any beacon sidebands. Since the telemetry horn antenna provides coverage over 40°, the horn antenna pattern for both beacons is relatively flat (see Figure 25). The C- and Ku-band beacon antenna patterns are measured concurrently to save test time.

TELEMETRY HORN AXIAL RATIO

A technique that exploits the ability of the IOT antenna to perform co-polarization and cross-polarization measurements and then derive the


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Beacons ,  Reprint

                S/C   : 602
Rx/Tx Beams   : BEACONS;BEACONS
Date  : 24 Jan 1990
Time UTC-(SLT)  : 22:28:05-(19:56)
Sub sat. pnt (Long-Lat)  : 322E;0
TLM Receiver : 1
TLM Receiver Temp (C)  :
PA ID  : 1|A;2|C
Path Numbers :
E/S  : Fucino
Position from Boresight (Az-Elev)  : 4.430E; 6.160N
Weather  : CLOUDY
Comments : BOTH BEACONS ON HORN
File : /IOT_TESTS/I602/BCEBCNBCN1158.2
```

24 Jan 1990 22:28:05-(19:56)

Bcn	Bcn Freq [MHz]	F Pwr [dBm]	S1 Dlt [dB]	S2 Dlt [dB]	Mod [Rad]	S Pwr [dBm]	B Pwr [dBm]	I Pwr [dBm]
1	3947.501836	-44.4	-6.3	-17.2	.872	-47.30	-42.57	-22.47
2	3952.489255	-43.3	-6.3	-17.1	.870	-46.22	-41.48	-22.60

Bp-Ip [dB]	Pinj [dBm]	Cal dn [dB]	P.L [dB]	EIRP [dBW]	Time [UTC]
-20.10	-16.10	-155.16	+196.45	+5.09	22:30:44
-18.88	-16.23	-155.18	+196.46	+6.17	22:33:25

Figure 24. *Example of Beacon e.i.r.p., Frequency, and Modulation Index Test Result*

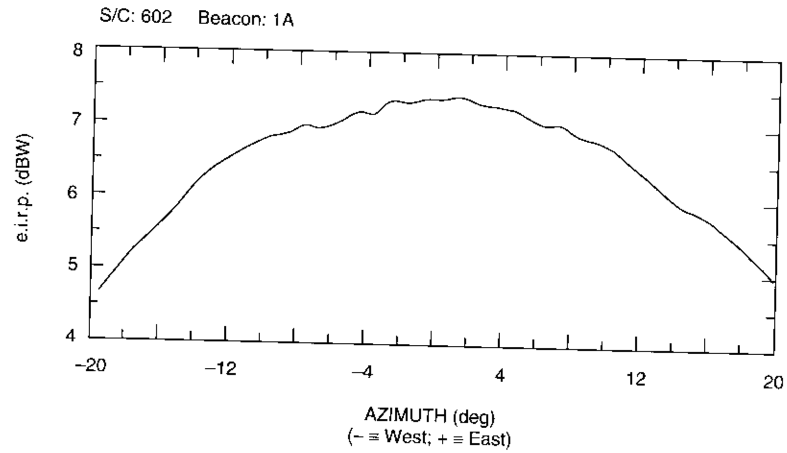

Figure 25. *Example of Beacon Co-Polarized Antenna Pattern IOT Result*

isolation is used to determine the telemetry horn axial ratio. The isolation is translated into the axial ratio, AR, by the formula

$$AR = 20 \cdot \log \left(\frac{10^{(R/20)} + 1}{10^{(R/20)} - 1} \right) \quad (4)$$

where R = COPOL(dBW) – XPOL(dBW).

The above measurement is performed over a range of ±20° in 2° steps, with the beacon configured for range mode only. Due to the location of the Fucino earth station, the axial ratio of the telemetry horns is measured at an elevation of 6.15°N. The IOT system calculates the axial ratio based on the measured cross-polarization isolation. The isolation and axial ratio for each measured position are then plotted on the same graph, as shown in Figure 26. These plots of measured data do not contain any prelaunch information, which is available only in hardcopy format for the TC&R subsystem.

Command subsystem measurements

The command subsystem measurements are basically flux density measurements. The 6-GHz up-link command signal is fed through a TWT HPA to the LHCP port of the IOT antenna. At the antenna feed, the up-link signal is monitored via a calibrated waveguide coupler, using the transmit power meter. The reading from this meter is then used to calculate the command carrier flux density level received by the spacecraft. The command subsystem measurements consist of command/execute sensitivity, command deviation sensitivity, command bandwidth response, and command antenna pattern.

COMMAND/EXECUTE SENSITIVITY

Sensitivity is determined for both receivers and processors by measuring the threshold up-link power level for the command and execute functions. The execute threshold is measured by transmitting and continuously executing a spare command. Up-link power is then decreased until only one of two execute returns is noted. The flux density corresponding to the up-link power is the execute threshold.

The command threshold is measured by transmitting and clearing a spare command while decreasing the up-link power level. The threshold is defined as that flux density for which two out of three commands transmitted enter the spacecraft CPU, as verified in the telemetry return. The value from the up-link power meter is then used to compute the up-link threshold flux density.

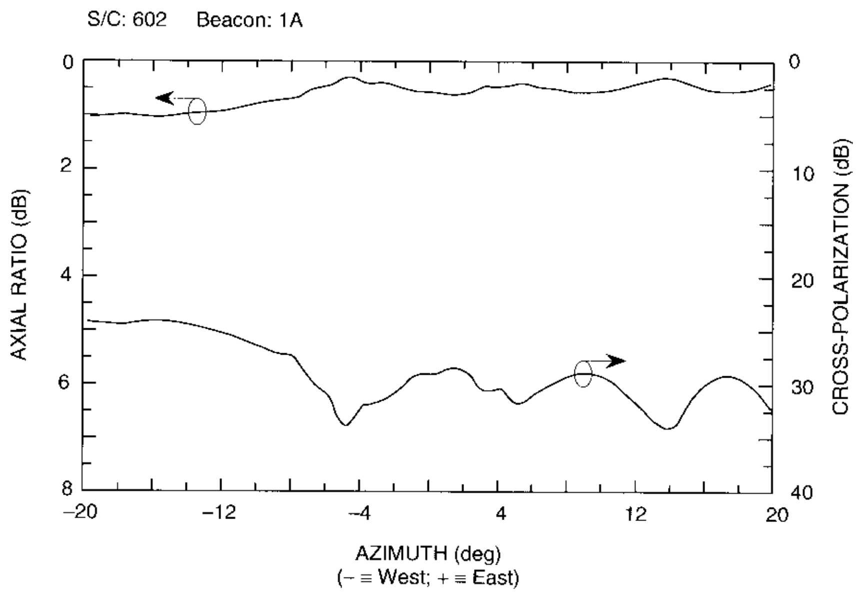

Figure 26. *Example of Beacon Cross-Polarized Antenna IOT Result*

The above tests are performed for both command frequencies—first without, and then with, the alternate command carrier active, to assess any desensitization.

COMMAND DEVIATION SENSITIVITY

Command deviation sensitivity is measured by varying the modulation index of the command frequency and then adjusting the up-link power level and measuring the command threshold. The deviation of the command frequency is changed by adding attenuation between the command generator and the IF modulator.

COMMAND BANDWIDTH RESPONSE

Command bandwidth response is measured by varying the command frequency over a ±3 MHz range in 0.25-MHz steps and measuring the command threshold. The command frequency is selected by setting the frequency of the synthesizer, which determines the frequency of the up-converter. This test is performed for both receivers and CPUs.

COMMAND ANTENNA PATTERN

The command antenna pattern is measured at the command threshold for both receivers and CPUs over a range of ±20° off the pitch axis. The command threshold is measured as the spacecraft is pitch-biased in 2° steps.

INTELSAT VI IOT planning

The test plan for an INTELSAT VI spacecraft comprises two basic elements: antenna pattern testing and RF matrix testing.

Antenna pattern testing

Antenna pattern tests include main lobe co-polarization transmit and receive, main lobe cross polarization transmit and receive, receive sidelobes, and transmit sidelobes. Figures 27 and 28 illustrate the hemi zone and beam

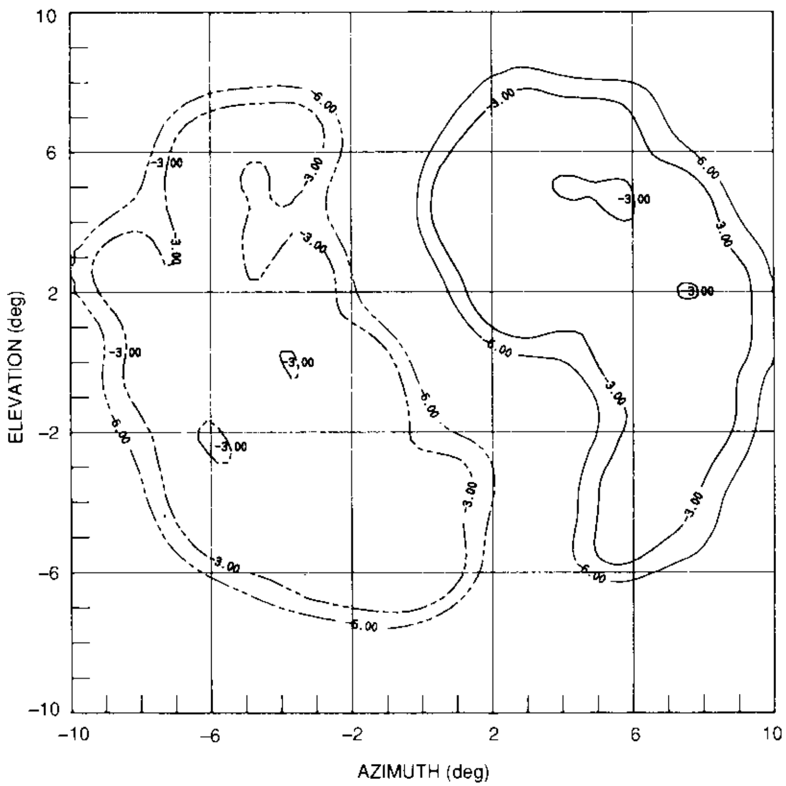

Figure 27. *INTELSAT VI Hemi Beams*

prelaunch measured coverages, respectively. One concern for the antenna testing, and also for testing of the RF matrix for zones 2 and 4, is that the Fucino IOT station is located at 6.15°N in spacecraft coordinates (cut 1 in Figure 28). The antenna coverage from the hemi and zone beams ranges from 8°N to 7°S in spacecraft coordinates. Consequently, the southern zone beams (zones 2 and 4) are not visible from Fucino, as shown in the figure.

The only way for the zone 2 and 4 beams to be visible from Fucino—in order to test the complete antenna pattern of the hemi and zone beams—is to position the southern beams over the Fucino location by inducing a spacecraft roll bias offset. To enable Fucino to access the southernmost part of the hemi/zone beams, an offset of up to 13° was required. It was decided that azimuth cuts at five different elevation angles would be sufficient to evaluate all of the 147 horn elements that form the hemi/zone beams. Table 4 summarizes the test sequence for all five cuts. It can be seen that cut 2 is performed by moving

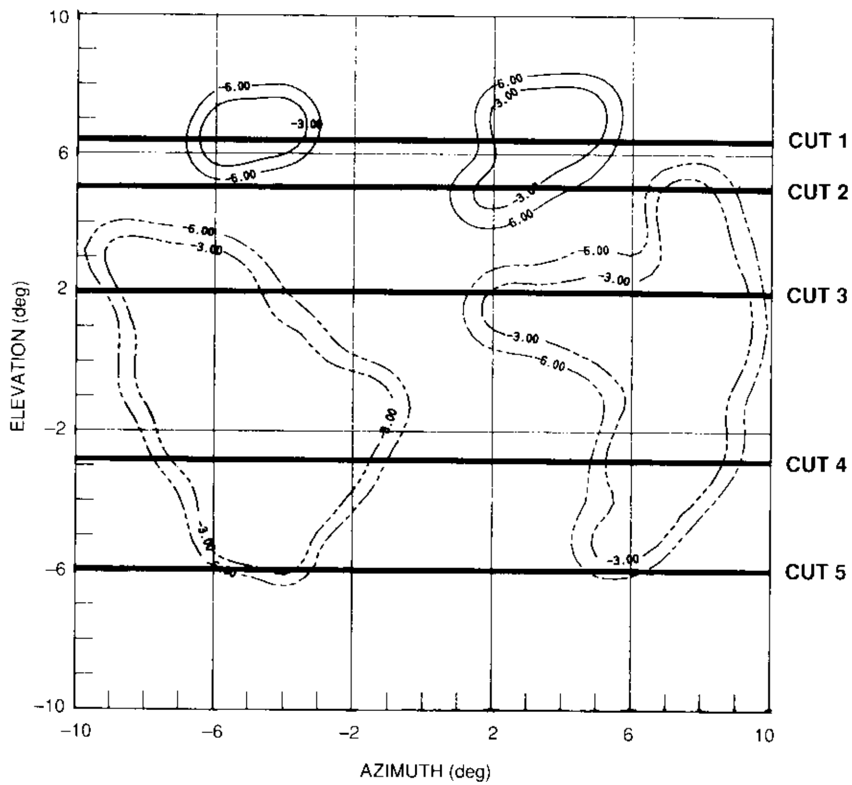

Figure 28. *INTELSAT VI Zone Beams*

TABLE 4. ANTENNA PATTERN TEST SEQUENCE SUMMARY

BEAM	SQUAREAX POSITION	"S" SWITCH POSITION	ROLL BIAS*	ANTENNA BIAS (APM)**
Cut 1--(Elevation = 6.15°N)				
Global A			0	0
Global B			0	0
E. Spot			0	6.15°N, 4°E
W. Spot			0	6.15°N, 5°W
Zone 1	AOR	SSM	0	0
Zone 3	AOR	SSM	0	0
E. Hemi	AOR	SSM	0	0
W. Hemi	AOR	SSM	0	0
WH/Z1/EH/Z3	AOR	MSM	0	0
Zone 1	IOR	SSM	0	0
Zone 3	IOR	SSM	0	0
Cut 2--(Elevation = 5.00°N [optional])				
Zone 3	IOR	SSM	0	1.15°N
Zone 4	IOR	SSM	0	1.15°N
Zone 4	AOR	SSM	0	1.15°N
Zone 3	AOR	SSM	0	1.15°N
E. Hemi	AOR	SSM	0	1.15°N
W. Hemi	AOR	SSM	0	1.15°N
Cut 3--(Elevation = 2.00°N)				
Zone 2	AOR	SSM	1.15°N	0
Zone 4	AOR	SSM	1.15°N	0
E. Hemi	AOR	SSM	1.15°N	0
W. Hemi	AOR	SSM	1.15°N	0
WH/Z2/EH/Z4	AOR	MSM	1.15°N	0
Zone 4	IOR	SSM	1.15°N	0
Zone 2	IOR	SSM	1.15°N	0
Cut 4--(Elevation = 3.00°S)				
Zone 2	IOR	SSM	1.15°N	0
Zone 4	IOR	SSM	1.15°N	0
Zone 4	AOR	SSM	1.15°N	0
Zone 2	AOR	SSM	1.15°N	0
E. Hemi	AOR	SSM	1.15°N	0
W. Hemi	AOR	SSM	1.15°N	0
Cut 5--(Elevation = 6.00°S)				
West Hemi	AOR	SSM	1.15°N	0

AOR = Atlantic Ocean Region; IOR = Indian Ocean Region; POR = Pacific Ocean Region

*The roll biases indicated for cuts 3, 4, and 5 are 1° higher than the minimum required, in order to provide more time for measurements.

**The APM bias for the hemi/zone antennas is the electrical offset required. To calculate the equivalent mechanical offset, the electrical offset is divided by 1.81 (i.e., 1.19°N electrical offset equals 0.657°N mechanical offset).

the hemi/zone antenna positioner mechanism (APM) to obtain a 1.15°N beam-pointing bias.

Due to the relatively static attitude of the satellite spinning axis as it moves around the earth, a roll bias offset will not remain constant. An initial offset of 13°N roll, 0° yaw will in 6 hours become 0° roll, 13° yaw, and in 12 hours become 13°S roll, 0° yaw. This drastically limits the time available for the Fucino IOT station to make azimuth cuts of the central/southern hemi/zone beams. For a roll bias offset of 5.15°, Fucino can perform the cut 3 measurements for 5 hours per day (±1° window); at 10.15° roll bias, cut 4 measurements can be performed for 4 hours; and for a 13.15° roll bias, cut 5 measurements can be performed for only 3 hours per day in order to check the respective row of feed horns in the hemi/zone BFN.

RF matrix testing

The RF matrix tests comprise the following:

- Flux density to saturate
- e.i.r.p. at saturation
- *G/T*
- In-band frequency response
- Out-of-band frequency response
- Step attenuator value
- LO frequency.

All transponders and receivers are tested. In addition, all alternate paths through the various switch combinations in the static switch matrix (SSM) and microwave switch matrix (MSM) are verified such that every switch is exercised and every switch contact is used at least once. A typical test plan for one beam is shown in Table 5. The test results are presented as shown in the respective measurement description modules.

Before an RF matrix test can begin, it is desirable to have the Fucino antenna positioned at the beam peak. Thus the first step in conducting the RF matrix tests is to perform the main lobe antenna cut. This defines the required beam location for the remainder of the RF matrix test for that beam.

Spacecraft reconfiguration

As is evident from the test plan, quite a large number of payload and spacecraft reconfigurations are required during an IOT. Although in principle the test schedule is predefined, the sequence of tests can change dynamically due to many factors. This, coupled with possible requirements for anomaly

TABLE 5. IOT TEST PLAN FOR THE INTELSAT VI ZONE 3 BEAM: INTELSAT VI PAYLOAD VERIFICATION MATRIX (BEAM: ZONE 3 (NE); COVERAGE: AOR; POLARIZATION: UP-LINK RHCP, DOWN-LINK LHCP; CUT 1)

RECEIVER NO.	RECEIVER ATTEN.	MUX ATTEN.	SWITCH MUX CONFIG.	SSPA ATTEN.	CHANNELS 1–2	3–4	5–6	7–8	9	DATA TO BE MEASURED
4	Out	Out	P	In	B	B	B	B	B	Antenna Pattern Rx/Tx Co-pol/Cross-pol Mainlobe
8	Out	Out	P	In	B	B	B	B	B	Z4 (SE) Rx Sidelobe Co-pol Pattern
4	Out	Out	P	In	B	B	–	B	B	Z4 (SE) Tx Sidelobe Co-pol Pattern
4	Out	Out	P	In	B	B	B	B	B	Flux/e.i.r.p. (linear) (Rx attn)
4	In	In	P	In	B	B	B	B	B	Flux/e.i.r.p. (linear) (mux attn)
4	In	Out	P	Out	B	B	B	B	B	Flux/e.i.r.p. (linear) (SSPA attn)
4	In	Out	R1	In	B	B	B	B	B	Flux/e.i.r.p. (linear) (alt. path 1)
4	In	Out	R2	In	B	B	B	B	B	Flux/e.i.r.p. (linear) (alt. path 2)
4	In	Out	V/V-A1	In	B	B	B	B	B	Flux/e.i.r.p. (linear) V/V-A Config. 1
4	In	Out	V/V-A2	In	–	–	B	–	–	Flux/e.i.r.p. (linear) V/V-A Config. 2
4	In	Out	V/V-A3	In	B	B	B	B	B	Flux/e.i.r.p. (linear) V/V-A Config. 3 (SW 5–10 check)
4	In	Out	P	In	B	B	B	B	B	Flux/e.i.r.p. (sat. lin), G/T, Transfer, (G.D. 1–2, 3–4)
4	In	Out	P	In	B	Off	B	Off	B	In/Out-of-Band: 1–2, 5–6, 9
4	In	Out	P	In	Off	B	Off	B	Off	In/Out-of-Band: 3–4, 7–8
4	In	Out	P	In	B	–	–	–	–	LO (receiver high ref. osc. freq.)
2	In	Out	P	In	B	–	–	–	–	LO (receiver low ref. osc. freq.)
2	In	Out	P	In	B	–	–	–	B	Flux/e.i.r.p. (sat), (LO: 1–2) (receiver mid ref. osc. freq.)
2	In	Out	P	In	B	–	–	–	–	LO (receiver high ref. osc. freq.)
3	In	Out	P	In	B		–	–	–	LO (receiver low ref. osc. freq.)
3	In	Out	P	In	B	B	B	B	B	Flux/e.i.r.p. (sat), LO: 1–2 (receiver mid ref. osc. freq.), G/T
3	In	Out	P	Out	C	–	C	–	C	Flux/e.i.r.p. (linear) (SSPA attn)
4	In	Out	P	In	C	–	C	–	C	Flux/e.i.r.p. (sat, lin), In-Band, Transfer
4	In	Out	P	In	–	C	–	C	–	Flux/e.i.r.p. (sat), In-Band, Transfer
4	In	Out	P	In	B	–	–		–	LO (receiver low ref. osc. freq.)
4	In	Out	P	In	B	B	B	B	B	Flux/e.i.r.p. (sat), LO: 1–2 (receiver mid ref. osc. freq.)

investigations, makes it impossible for all of the necessary commands to be predefined. Rather, reconfiguration commands will need to be generated to support the requirements of the test director as the testing proceeds. Commands are generated by using the PC-based RCAP software, which presents a representation (graphical or tabular) of the spacecraft payload (transponders) that can then be manipulated by the operator to the desired configuration. The RCAP program produces the appropriate command lists, in a format recognizable by the spacecraft, to enable this configuration to be achieved. A file of commands, referred to as a command queue, can then be electronically transferred to the CCS at the INTELSAT Satellite Control Center (ISCC) in Washington, D.C., for future execution.

Due to the speed of the new IOT equipment, performance of the necessary reconfigurations is a continuing process that requires the full-time participation on the IOT team of a spacecraft commanding specialist from the INTELSAT Flight Operations Section (FOS). To minimize the stress on the payload, it is desirable to keep the switching and power-cycling of units as low as possible. It is the responsibility of the FOS engineer, in close coordination with the test director, to recommend the most efficient command sequence for the testing.

The complexity of the INTELSAT VI payload makes the number of reconfigurations required, and hence the number of commands sent to the spacecraft, very large—considerably larger than was necessary on earlier INTELSAT spacecraft. For instance, during the 4 weeks of INTELSAT 602 IOT (including SS-TDMA testing), approximately 17,000 commands were sent. With the inherent command intensity of the INTELSAT VI spacecraft, the speed of commanding has now become the dominant factor governing the duration of the IOT.

Prior to the INTELSAT VI era, commanding was always accomplished "manually," that is, by verbally passing commands to an operator at one of INTELSAT's telemetry, tracking, and command (TT&C) stations. The station operator would then manually enter the commands in the command generator for transmission to, and execution in, the spacecraft. In day-to-day operations, a command list was routinely sent to the TT&C station beforehand so that the station operator could visually verify that the correct command had been loaded into the command generator before proceeding. This is not possible during an IOT because the order and breakdown of the test schedule are often determined rapidly, in real time. While manual commanding is still available, the probability of mistakes is increased by the lengthy serial commands used for INTELSAT VI.

With the advent of the INTELSAT VI era, the philosophy of commanding was reviewed. The primary change was to centralize and automate commanding within the CCS, which offers a flexibility that greatly improves the speed and ease of commanding. Commands can be sent via the TTC&M network to the satellite individually by keyboard entry in the ISCC, or by running predefined data files (queues) containing a list of commands. The former method, referred to as individual interactive commanding (IIC), provides flexibility because the order of command does not have to be predefined. Queue commanding, while relatively inflexible because the command order is predefined, allows for a very fast change from one spacecraft configuration to another, which is ideal for IOT. Hence, IIC would be used to configure the spacecraft to a "starting" configuration, and then a queue would be introduced. By using flags, each command in the queue can be processed in a different manner, and prompts to the operator can be set or not, as required. For example, after processing a command, the next command can be automatically transmitted to the spacecraft, or the operator can be asked for "permission to transmit." Thus, by using flags, the queue can be broken down into blocks such that the execution of a block will set up a certain required test configuration on the spacecraft. Each command sent is automatically verified by the software prior to execution to ensure against corruption; thus, security is not impaired to achieve faster commanding. The use of command queues through CCS has been invaluable in testing the INTELSAT VI series and has allowed completion of the IOT in much less time than was previously required.

INTELSAT 602 IOT results

The IOT of INTELSAT 602 began on December 7, 1989, and was completed on January 18, 1990, with breaks for the Christmas/New Year holidays and for traffic interruptions (the satellite was pressed into service for the Panama invasion and for the Malta summit). The actual test duration was 24 working days (12 to 14 hr/day).

RF matrix testing

When the RF tests are performed, the measured data are automatically compared against data taken during factory testing of the spacecraft (prelaunch data). These data are stored in the TDHS, and the IOT system automatically retrieves them for the measured configuration, adjusts the antenna gain for the position of Fucino in the antenna pattern, performs the comparison, and then prints out the test results in a table. The system plots the data in a graphical format. Actual test results for INTELSAT 602 were presented previously in the descriptions of the respective measurement techniques.

All in-band and out-of-band frequency responses, step attenuator values, and LO frequency measurements showed good agreement with the prelaunch data. Dynamic ranges of up to 90 dB (measured) were achieved on the out-of-band frequency response tests, which for the first time allowed actual measurement of filter flank responses during an IOT.

Table 6 shows the average deviations between measured and prelaunch data for e.i.r.p., saturation flux density, and *G/T*. For the *G/T* comparison, it should be noted that the prelaunch data are calculated, not measured, values.

TABLE 6. AVERAGE DEVIATIONS BETWEEN IOT MEASURED DATA AND PRELAUNCH REFERENCE

BEAMS	e.i.r.p. (dB)	FLUX DENSITY (dB)	G/T [a] (dB)
Global A	-0.1	+0.3	-1.1
Global B	+0.1	+0.2	-0.8
E. Ku-Band Spot	+0.2	+0.2	0.0
W. Ku-Band Spot	+0.2	-0.1	+0.1
E. Hemi	0.0	+0.1	+0.4
W. Hemi	0.0	-0.8[b]	+0.5
Zone 1	+0.2	-0.4	+0.2
Zone 2	-0.3	-0.0	+0.4
Zone 3	+0.3	+1.0[c]	+0.2
Zone 5	+0.2	-0.4	+1.0

[a] Prelaunch data for *G/T* represent calculated, not measured data.
[b] Suspected high gain-setting from factory.
[c] Suspected low gain-setting from factory.

Antenna pattern testing

A total of 23 different antenna patterns (cuts) were taken for the hemi and zone beams during IOT of INTELSAT 602. The antenna patterns closely matched the prelaunch measurements from the far-field and near-field test ranges. The extremely close agreement between the IOT measurements and the near-field in-plant measurements verified the performance of both the upgraded IOT station and the near-field test range.

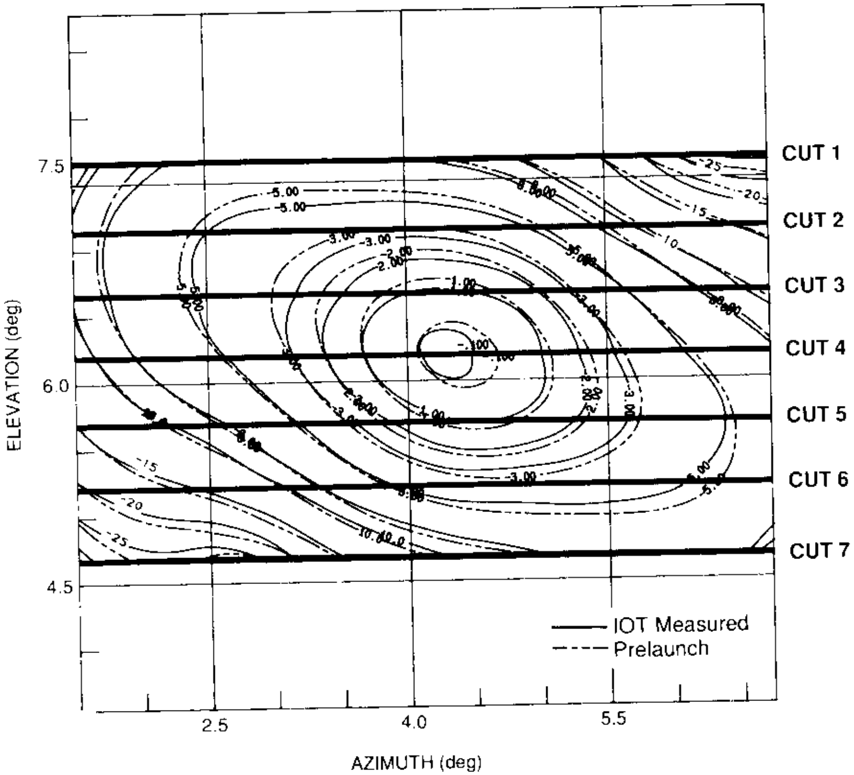

Figure 29. *INTELSAT VI East Spot Beam Contours*

In addition to performance measurement of the Ku-band antennas, the pointing of the two Ku-band spot beams was also verified by centroid measurements. Seven azimuth cuts were taken, 0.5° apart in elevation, as shown in Figures 29 and 30 for the east and west spot beams, respectively. The test results indicated a 0.4°E offset on the east spot beam. The west spot beam pointing agreed with the prelaunch data.

Conclusions

The upgrade of the Fucino IOT station has significantly improved the precision and speed of payload IOT measurements. The IOTs of INTELSAT 602, 604, 605, and 601 were performed in half the expected time (4 weeks instead of the predicted 8 weeks). The test data, when compared with the prelaunch

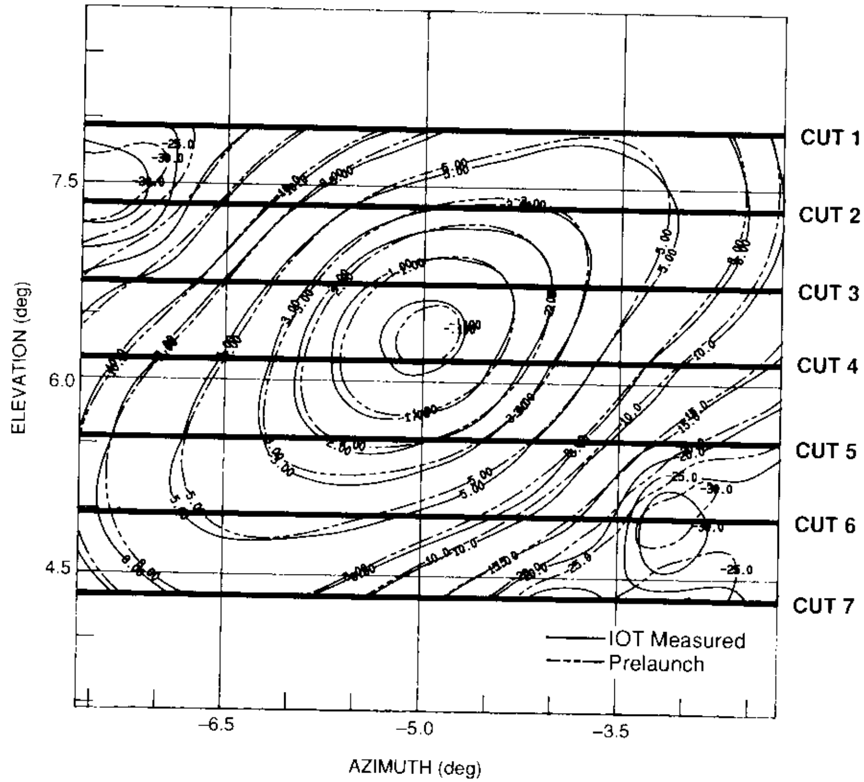

Figure 30. *INTELSAT VI West Spot Beam Contours*

data, indicated that all of the INTELSAT VI satellites tested with date were unaffected by launch and in-orbit injection stresses. INTELSAT 602, 604, 605, and 601 are now in service, having been accepted on the basis of the IOTs.

Acknowledgments

The design, installation, and testing of the upgraded IOT station at Fucino, Italy, as well as the performance of the INTELSAT VI IOT, was a team effort. The authors would like to express their gratitude to many of their colleagues at INTELSAT, and in particular to D. Sachdev, E. Magnusson, M. Battikha, K. Betaharon, and P. Neyret for their support and helpful discussions throughout development of the new IOT methodology. At COMSAT, they would particularly like to thank R. Persinger and G. Hambleton for their contribution to *the spacecraft testing at the factory and to IOT sequence planning. Thanks are also due to G. Horvai and J. Lemon of INTELSAT for support on the TDHS data interface with the IOT system; to K. Lindqvist of INTELSAT for support at the IOT site; and to the FOS and ISCC staff for the support at INTELSAT Headquarters in Washington, D.C. Further, the support from the Telespazio staff at the Fucino site, and particularly G. Moretti, C. Ambrogi, and F. Moretti, is appreciated.*

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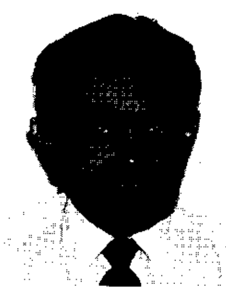
Basilio Teixeira is a Senior Engineer with the INTELSAT Space Segment Engineering Programs Department, Payload Section (SSEPD-PAY). His primary functions include development of payload concepts and performance specifications for future satellites, specification and selection of new test equipment and measurement methodologies for the IOT stations, and participation as Software Engineer and Payload Specialist in the IOT of new INTELSAT satellites. He was responsible for integrating and testing all of the new equipment installed at the Fucino IOT station, as well as all of the software upgrades in support of the INTELSAT VI IOT.

Mr. Teixeira has been involved with in-orbit testing of satellites since 1982. He was stationed at the Fucino IOT station for 1-1/2 years, and at the Yamaguchi TTC&M/IOT station for 5 years as IOT Engineer and Senior Technical Representative, respectively. In 1988, he moved to Washington, D.C., to join INTELSAT's New Spacecraft Program (NSP) section, where he remained until moving to his current section in 1991.



Alexandre Olimpiew is a Senior Engineer with INTELSAT's Ground Network Engineering Projects Department (GNEP). His primary functions are the specification and implementation of hardware upgrades (including new measurement techniques) to the CSM and IOT stations. He specified all of the new test equipment installed at the Fucino IOT station in support of the INTELSAT VI payload IOT.

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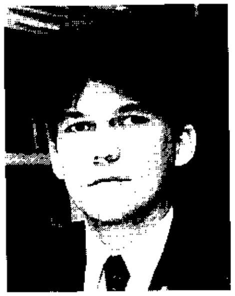

Stewart B. Sanders joined British Telecom International in 1981 and worked at BTI's earth station at Madley, England. He attended Worcester Technical College and gained an HNC in electronics in 1986, also attending a number of courses at BTI's engineering colleges. During his time at Madley, he worked on a number of different earth station systems, although primarily on the activation and support of the first fixed TDMA service. He 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. During his time 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 FOS as an RF Systems Engineer, where he provides day-to-day and on-call support of the INTELSAT satellite network. He has helped to define and test software for INTELSAT VI and future satellite operations, and has been a team member for all of the INTELSAT VI launches, bus IOTs, payload IOTs, and SS-TDMA testing. His primary role during the payload IOTs includes responsibility for satellite safety and the provision of command support.

Index: earth stations; INTELSAT; tracking, telemetry, control (command) TT&C

Design and operation of a post-1989 INTELSAT TTC&M earth station

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Abstract

The design and operation of tracking, telemetry, command, and monitoring (TTC&M) earth stations implemented by the U.S. Signatory as part of INTELSAT's Post-1989 TTC&M Network are discussed. Past experience in providing TTC&M services to INTELSAT is presented, and implementation of two of the new special-purpose complexes is described. The U.S. Signatory's design approach and implementation are then presented as they relate to TTC&M earth station operation in the INTELSAT VI era. Finally, the functions performed in support of INTELSAT V/V-A and VI spacecraft operations are reviewed.

Introduction

In 1987, the INTELSAT Executive Organ developed a plan for what came to be known as the Post-1989 TTC&M Network. At that time, the imminent expiration of existing contracts for telemetry, tracking, command, and monitoring (TTC&M) services, coupled with the timing of the INTELSAT VI implementation, presented an opportunity for the Executive Organ to review future TTC&M requirements. This review, subsequently endorsed by the INTELSAT Board of Governors, gave rise to the Post-1989 TTC&M Network configuration. As envisioned, this network would consist of six TTC&M earth stations at signatory locations around the world, replacing the existing network of eight TTC&M stations and two communications system monitoring (CSM) stations.

A key feature of the post-1989 network is its extensive use of limited-motion antennas (LMAs) for dedicated telemetry, command, tracking, and ranging. Prior to 1989, these functions were performed largely through collocated communications antennas. That is, the existing communications antennas at the facility were used for TTC&M, in addition to their primary function of carrying communications traffic. The antennas were thus limited to supporting one satellite. In the event of a problem affecting the payload, the communications antenna would likely be required to point-over to a spare satellit at precisely the time when the antenna was required for TTC&M activities, necessitating reconfiguration of the telemetry, tracking, and command (TT&C) antenna network to establish TT&C coverage of the satellite in trouble.

Utilizing relatively low-cost LMAs to perform these functions provides a number of benefits, including lower cost of operation, simultaneous ranging from two sites for more accurate orbit determination, and foremost, a dedicated antenna which retains access to its assigned spacecraft during a spacecraft anomaly. As new satellites are placed into orbit, LMAs can be added to the existing TTC&M facilities to maintain dedicated coverage. Table 1 is a matrix of the current INTELSAT Post-1989 Network antenna complement, by earth station.

This network of INTELSAT TTC&M earth stations has as its hub the INTELSAT Satellite Control Center (ISCC), located at INTELSAT Headquarters in Washington, D.C. Overall control of the satellite network is exercised by the ISCC, which utilizes the TTC&M earth stations to perform the functions necessary to support launch and synchronous orbit operation, including spacecraft acquisition, tracking, telemetry reception, commanding, ranging, in-orbit testing (IOT), and communications monitoring. These operations are described in detail in companion papers by Wheeler [1] on communications operations; Smith [2] on satellite operations and the ISCC; Virdee *et al.* [3] on launch operations and bus IOT; and Rosell *et al.* [4] on payload IOT.

In early 1988, 16 INTELSAT signatories responded to the INTELSAT RFP for TTC&M earth stations, with proposals for 21 different facilities. COMSAT World Systems, the U.S. Signatory, was awarded contracts for two of the six TTC&M stations, to be constructed in Clarksburg, Maryland (a suburb of Washington, D.C., approximately 25 miles north of INTELSAT Headquarters) on the grounds of the existing COMSAT North facility, and in Paumalu, Oahu, Hawaii, at an existing COMSAT earth station complex. Figure 1 shows the Clarksburg TTC&M complex.

This paper describes the COMSAT facilities implemented under the post-1989 TTC&M program and discusses the functions they perform in support of INTELSAT V/V-A and INTELSAT VI spacecraft operations.

TABLE 1. INTELSAT POST-1989 TTC&M CONFIGURATION

EARTH STATION	REGION(S)	INTELSAT ANTENNA DESIGNATIONS								COLOCATED COMMUNICATIONS ANTENNAS FOR CSM
		CFPA	KFPA	CLMA 1	CLMA 2	CLMA 3	CLMA 4	CLMA 5	KLMA	
Clarksburg, MD, U.S.A.	AOR	CKT-1T	CKT-2T	CKT-3L	CKT-4L	CKT-5L	CKT-6L	CKT-7L	–	0
Fucino, Italy	AOR, IOR	FOT-3T	FOT-9T	FOT-7L	FOT-8L	FOT-10L	FOT-11L	–	FOT-12L	3
Raisting, Germany	AOR, IOR	RAT-1T	–	RAT-2L	RAT-3L	RAT-4L	–	–	–	3
Beijing, China	IOR, POR	BET-1T	BET-2T	BET-3L	BET-4L	BET-5L	–	–	–	2
Perth, Australia	IOR, POR	PET-1T	–	PET-2L	PET-3L	PET-4L	–	–	–	2
Paumalu, HI, U.S.A.	POR	PAT-1T	–	PAT-2L	PAT-3L	PAT-4L	PAT-5L	–	–	0

CFPA : C-band full-performance antenna.
KFPA : Ku-band full-performance antenna.
CLMA : C-band LMA.
KLMA : Ku-band LMA.
Note: Antennas which are part of the INTELSAT Control Coordination Circuit (CCC) network are shown in Figure 2.

Figure 1. *Clarksburg TTC&M Earth Station Complex*

Earth station design requirements

The COMSAT World Systems earth stations at Clarksburg, Maryland, and Paumalu, Hawaii, were designed to meet the definitive specifications approved by the INTELSAT Board of Governors. While they incorporate state-of-the-art hardware and software for the RF systems, monitor and control (M&C), and power generation, the earth stations feature simple and functional building design and civil works, employing pre-engineered construction and above-ground cable and waveguide interfacility links (IFLs). This section describes the major earth station components.

Antenna systems

To meet INTELSAT TTC&M requirements, a number of different antenna systems were implemented by COMSAT. The C-band full-performance antenna (CFPA), which was the cornerstone of the entire earth station complex, was located at Clarksburg due to that site's proximity to the Washington, D.C., area. The CFPA was erected at the lowest elevation on COMSAT property to minimize radio frequency interference (RFI) to the significant number of microwave links in the area operating in the 6-GHz transmit band. Once the location was determined to be satisfactory from an RFI standpoint, the control building and other antenna structures were positioned to complement the antenna.

At Paumalu, an existing 16.5-m-diameter TTC&M antenna was retrofitted to 19 m, resulting in the same electrical performance as the Clarksburg CFPA. As at Clarksburg, the other antennas and new buildings were then positioned to complement the upgraded CFPA.

The CFPAs at Clarksburg and Paumalu perform every function required of a TTC&M antenna—synchronous orbit TT&C, launch support, CSM, and IOT of newly launched spacecraft. COMSAT used a TIW Systems, Inc., 19-m Cassegrain antenna and 80-K low-noise amplifiers (LNAs) to achieve the required 35-dB/K gain-to-noise temperature ratio, *G/T*, for a Standard A antenna in the INTELSAT system. A dual polarization feed, with an axial ratio better than 0.4 dB (cross polarization isolation of 33 dB) was employed. To meet the strenuous effective isotropically radiated power (e.i.r.p.) requirements of 93 dBW across the 575-MHz band in both polarizations, MCL, Inc., air-cooled, 3-kW, traveling wave tube amplifier (TWTA), helix-type high-power amplifiers (HPAs) were used. These HPAs were installed above the azimuth axis to minimize losses. Thus the e.i.r.p. requirement was met without the need to combine the HPA outputs. It should be noted that the extended bandwidth of 575 MHz includes the 1', 2' transponders introduced on the INTELSAT VI series of satellites.

The CFPA is the only antenna in the complex that employs monopulse autotracking to track satellites in transfer orbit during launch missions. A backup step-track capability exists for synchronous orbit operations.

Figure 2 is a block diagram of the CFPA's RF system. An HPA hybrid combiner network is provided in the event that two high-power command carriers must be radiated simultaneously from the CFPA. Each command carrier would be amplified exclusively from one HPA and combined in the hybrid. The resulting e.i.r.p. per carrier would be approximately 90 dBW, which is greater than that obtainable by radiating both carriers through one HPA. Receive couplers ahead of the LNAs allow for the injection of calibration signals for CSM and IOT, and a separate waveguide run is provided to transmit the IOT injection signals from the control room to the feed coupler. A test loop translator is employed for zero-range calibrations, and a similar translator is used on all TT&C antennas.

Clarksburg also utilizes a TIW 14.2-m Ku-band full-performance antenna (KFPA), equipped with step-tracking, primarily for CSM and IOT. Although not equipped with monopulse, the KFPA can support INTELSAT K-type spacecraft launches by using program tracking with offset correction interacting with the step-track mode.

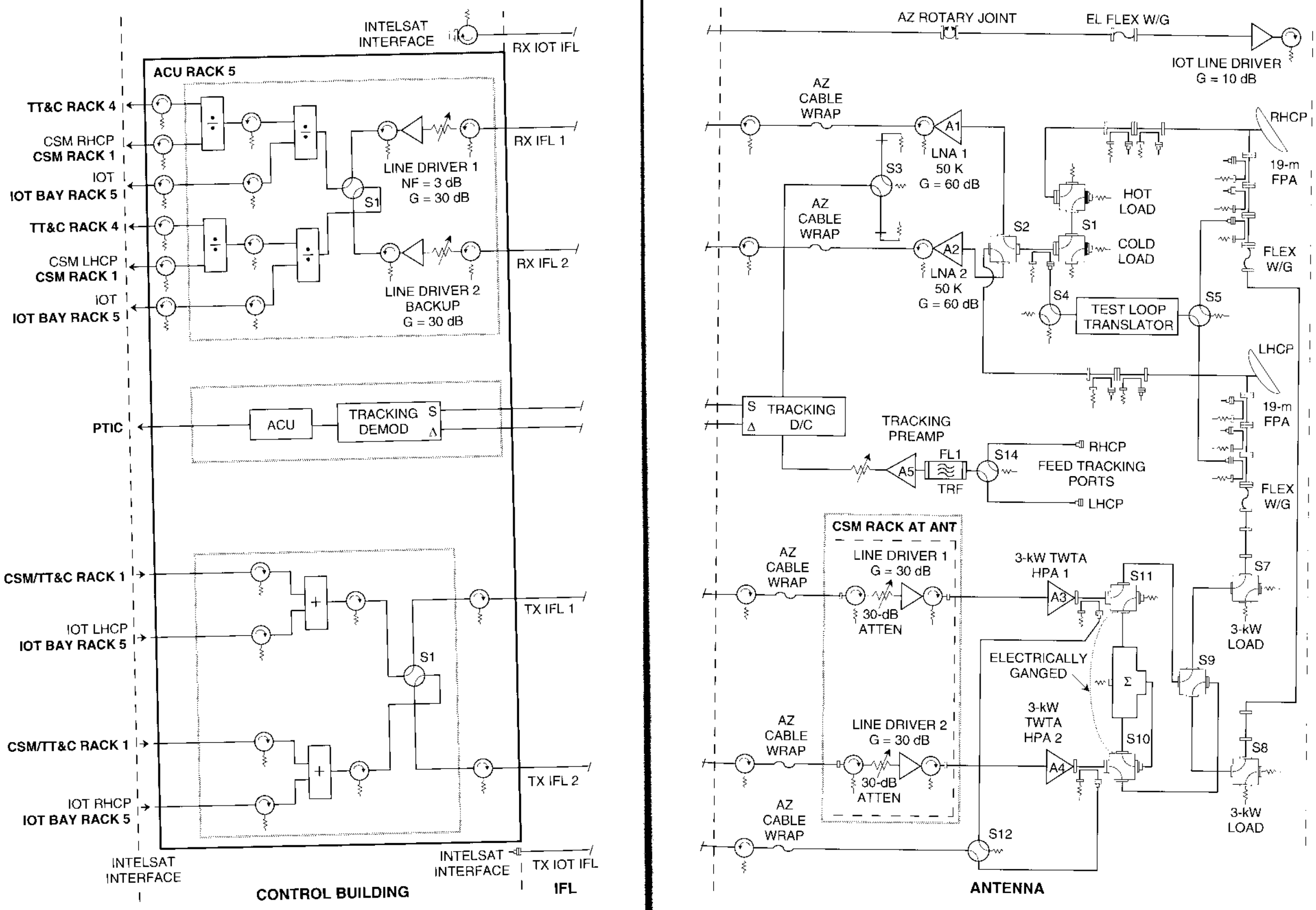

Figure 2. *CFPA Block Diagram*

The choice of a 14.2-m antenna allows the use of air-cooled MCL 600-W traveling wave tube HPAs to meet the required e.i.r.p. of 87.0 dBW anywhere in the transmit band of 14.0 through 14.5 GHz. These HPAs are housed in the antenna pedestal base. INTELSAT Standard C performance is achieved with 220-K LNAs, providing performance well above the G/T of 34 dB/K called for in the specification.

The LMA requirements were met with Vertex 9-m jackscrew antennas, which provide a limited operating azimuth range of 110° per segment. The antennas can be physically repositioned on their pedestal to allow operation in two 110° segments. With this size antenna, the required G/T of 27.0 dB/K is easily met with redundant 80-K LNAs.

Because LMAs are not required to have instantaneous bandwidth covering the entire satellite band, MCL air-cooled 3-kW klystron HPAs were chosen to meet the 83-dBW e.i.r.p. requirement. The LMA HPAs are installed in an HPA room in the main control building, and are provided on a 1-for-N backup basis, where N is the number of LMAs to a maximum of five. The HPA room also houses the high-power multiplexer used to switch the backup HPA to any LMA.

Four LMAs are employed at Paumalu, and five at Clarksburg. However, two of the five at Clarksburg are upgraded LMAs which are also used for CSM and TDMA reference and monitoring services (TRMS). These TRMS/LMAs are Vertex 15-m antennas of a design similar to the smaller LMAs. They are equipped with 45-K LNAs to achieve the Standard A G/T specification of 35 dB/K required for CSM and TRMS operation. The LNA configuration is "tridundant"; that is, one LNA operates on each polarization, with one backup LNA supporting both polarizations.

The transmit system of the TRMS/LMAs requires that command and ranging transmissions (which are primary LMA functions) be accommodated, in addition to the TDMA reference burst transmissions. The TDMA functions require facilities sufficient to operate on both polarizations, and one antenna (on the 335.5°E satellite) must be capable of operating in transponders 3-4, in addition to transponders 1-2. Therefore, each TRMS/LMA employs three additional dedicated HPAs in a 1-for-2 backup configuration—in one case using 3-kW air-cooled MCL 80-MHz klystron HPAs, and in the other using 3-kW air-cooled MCL TWTAs identical to those in the CFPA.

To accommodate the command and ranging requirements of an LMA, the output of the narrowband (TT&C) klystron is filter-combined on the left-hand circular polarization with the TRMS HPA output. Thus, the outputs of the two different HPAs (TT&C and TRMS) can be transmitted over the same polarization path. All of these HPAs are housed in the HPA room and switched to their respective antennas through the high-power multiplexer and IFLs.

Completing the TTC&M antenna complement are two 9-m Vertex antennas of the same type as the LMAs, which are part of the INTELSAT Control Coordination Circuit (CCC) network (depicted in Figure 3). This network consists of International Business Service (IBS) carriers linking all TTC&M earth stations with INTELSAT Headquarters via INTELSAT and U.S. domestic satellites. It is over this CCC network, as currently implemented, that all telemetry, command, ranging, monitoring (CSM), and station remote M&C signals are transmitted. The CCC network is more fully described in a companion paper by Smith [2].

The two antennas, known as small communications antennas (SCAs), employ MCL 700-W air-cooled TWTAs (also housed in the HPA room) configured in a 1-for-2 arrangement with their own high-power multiplexer and IFLs. The SCAs, equipped with 80-K LNAs, meet the requirements of an INTELSAT Standard F3 antenna and employ redundant up- and down-converters, INTELSAT-provided modems, and a digital multiplexer to transmit and receive the IBS carriers of the CCC network.

Antenna control and tracking

The antenna control and tracking system developed by TIW for this program consists of an antenna control unit (ACU), a program track interface computer (PTIC), and the antenna tracking down-converter. All of the antennas employ the same basic antenna control system.

The ACU is a microprocessor-based unit that provides all the operational modes and displays necessary to operate the antenna. There is one ACU for each antenna, mounted in the antenna control bay in the control room, and each antenna system (CFPA, LMA, *etc.*) has an antenna control bay and an associated M&C bay. The ACU allows selection of the antenna mode, tracking frequency, and receiver automatic phasing through a straightforward operator interface via the front panel.

The PTIC adds a dimension of control and capability beyond that of the ACU. The PTIC is an external computer, configured one for each antenna group, which interfaces with the ACUs (if there is more than one in the antenna group) to provide program track modes. The PTIC can calculate satellite and star positions at any given time and determine the azimuth and elevation angles that will point the antenna in the proper direction. It can also determine satellite angles from NORAD-supplied element sets or INTELSAT-provided satellite ephemeris data, and pointing angles to four radio stars from data

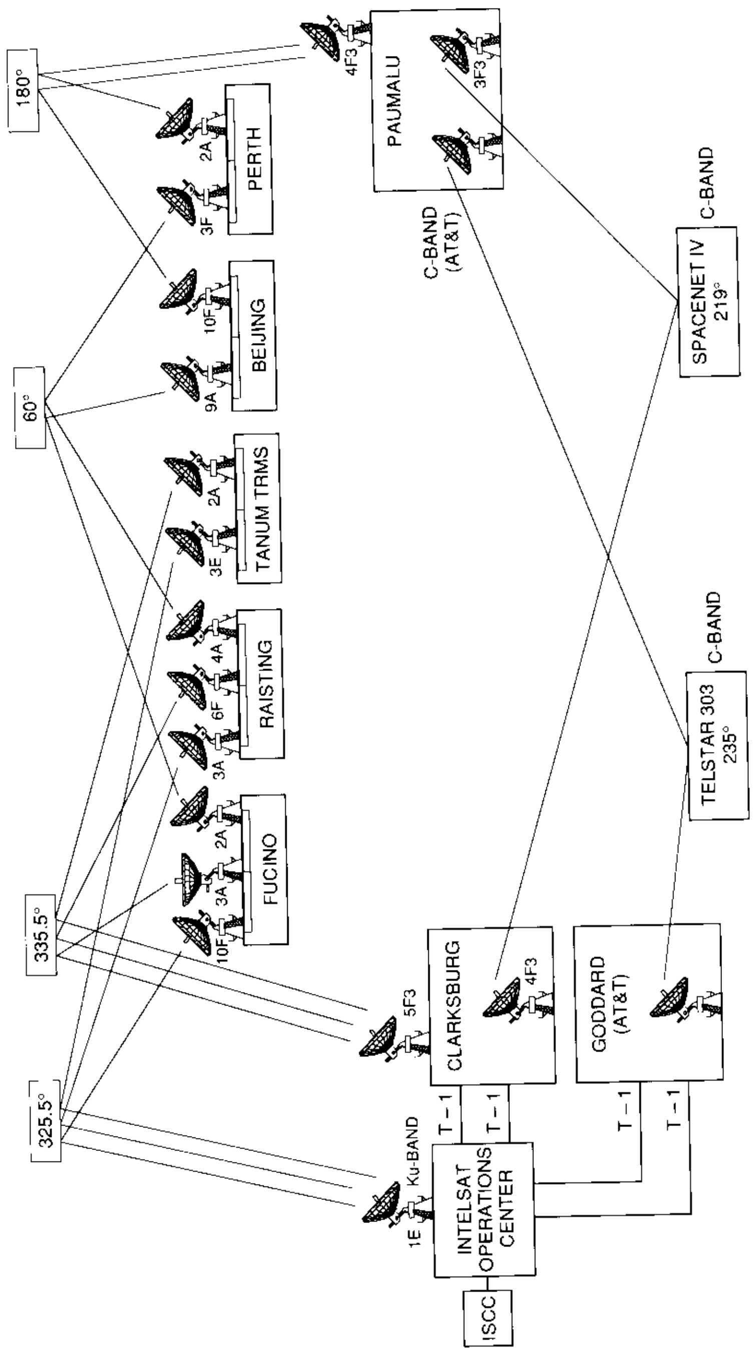

Figure 3. *CCC Network*

stored within the computer. The PTIC also offers a means of commanding (via the M&C system) azimuth and elevation angles that have been determined by other methods and stored in the PTIC. This would typically consist of pointing data from INTELSAT during launch operations (transfer orbit) and low earth orbit (LEO) satellite tracking.

In addition to performing all the normal ACU functions, the PTIC provides a remote interface to INTELSAT Headquarters which allows INTELSAT to control the antenna through the M&C system.

Monitor and control system

The COMSAT M&C system (also developed by TIW for this program) provides a graphical remote interface to the RF antenna systems and the site facility. Individual computers are dedicated to each RF antenna system and to the site facility system. Figure 4 is a block diagram of the M&C system for the TRMS, and is representative of the configurations used in the other RF systems.

The RF M&C computers employ an intelligent processor board to transfer information over a high-speed serial bus connected to various sensor blocks, which interface to the RF switches and alarm conditions. The sensor blocks are capable of detecting a wide range of inputs, including contact closures and transistor-transistor logic (TTL) signals. The blocks may also be used to provide a contact closure or the voltage to drive a motor-driven switch.

The operator thus has a graphical representation of the RF and facility configuration of each system, including HPAs, LNAs, all RF switches, and (where applicable) up- and down-converters, and can command individual switches to select a desired configuration, or select equipment to be switched on or off line—in which case the M&C system commands the appropriate switches automatically. The operator can also select an individual HPA window display, which allows full control of the HPA functions, including RF power.

All of the various M&C computers (and PTICs) of the antenna groups, as well as the facility computer, interface with a main control computer that connects INTELSAT Headquarters with the site, allowing remote monitoring and control of all major subsystems. This system takes the Clarksburg and Paumalu earth stations to a level above that of COMSAT's earlier TTC&M stations. Electromechanical mimic control panels have been eliminated in favor of a computer-controlled system that provides the added capability of controlling the station remotely from INTELSAT Headquarters.

Facilities systems

The facilities systems at Clarksburg and Paumalu were designed and implemented to provide a secure, reliable environment for TTC&M and TRMS

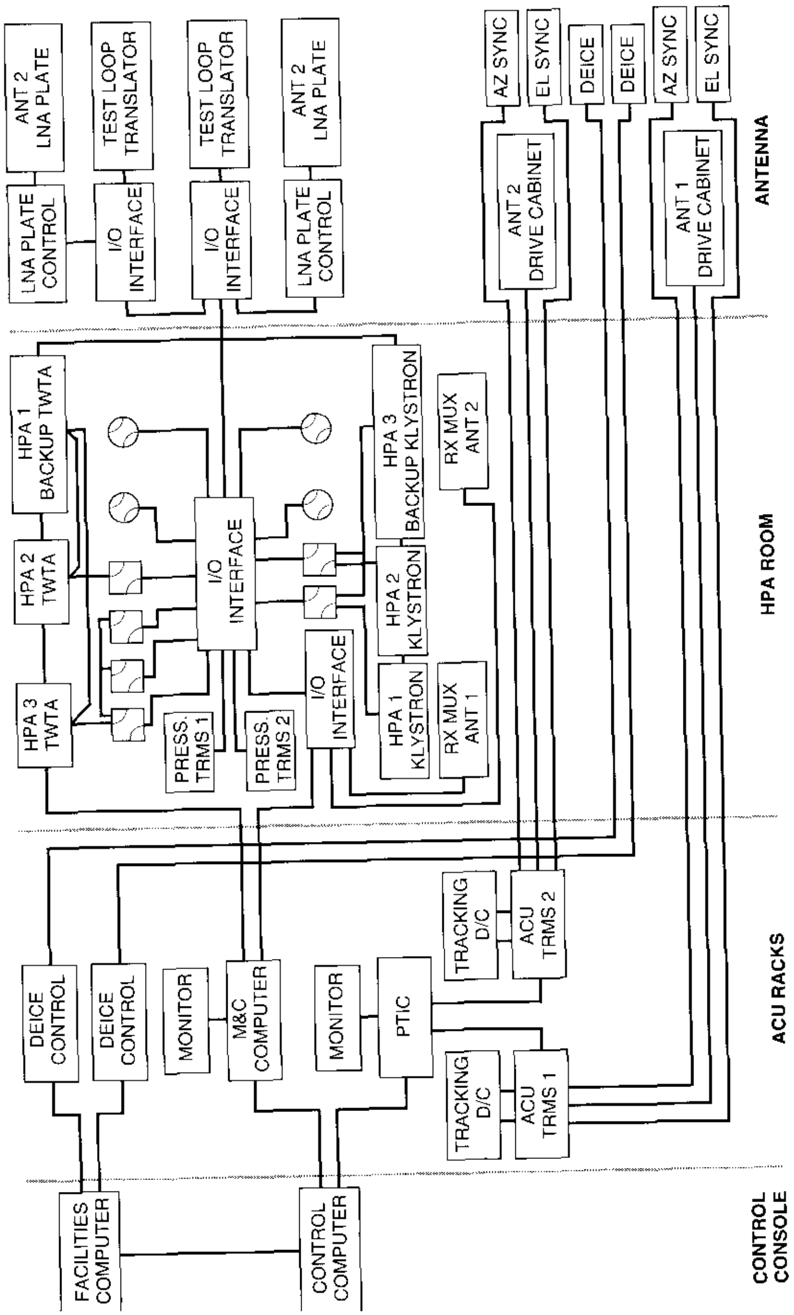

Figure 4. *Monitor and Control System Block Diagram*

operations. The INTELSAT civil works and facilities specification was intentionally kept very general to allow the signatories to determine the types of buildings and power systems most compatible with their respective sites and antennas. Uninterruptible power and backup power generation were mandatory. Given the broad guidelines of the specification, COMSAT developed a civil works and power design that was both cost effective and reliable.

Figure 5 is a site plan layout of the Clarksburg site. (Paumalu is similar.) The layout of the buildings provides for future expansion of the control building as required. The antennas were placed in north-south lines to allow an unobstructed view of the INTELSAT-occupied segment of the synchronous arc. Above-ground cable and waveguide trays were used to reduce cost and allow for easy interfacing of future antennas with the control building.

Two pre-engineered buildings were constructed at each site. One is the main control building housing the INTELSAT-furnished equipment (IFE) and the major COMSAT-provided systems, including the HPA systems; control bays; heating, ventilation, and air conditioning (HVAC) system; and uninterruptible power systems (UPS). The second, smaller building houses two diesel generators and the high-voltage switchgear.

The generators are configured to automatically start and supply power after sensing a commercial power failure via the high-voltage switchgear. The UPS provides an uninterruptible source of power to critical station systems (including all IFE) during loss of commercial power, while the generators are starting and coming on-line. At both sites, one generator can supply the full station load. A second generator is used at Clarksburg for deicing the antennas.

The control room equipment is mounted on a floor of the type used for large computers, where the area between the floor and the subfloor is a cooled-air plenum that provides upward-flowing cool air to the control room equipment. The HPA room is cooled with separate units, and the temperature of the office spaces is controlled with heat pumps. The control room and generator building are fire-protected with sprinkler systems activated from smoke alarms and rate-of-rise temperature detectors.

Earth station operation

The COMSAT earth stations were designed to be operated around the clock by a contingent of Senior Electronic Communications Technicians, performing all the functions associated with TTC&M (and at Clarksburg, TRMS as well).

Having two technicians per shift is mandatory. At Clarksburg, because of the TRMS function performed on two spacecraft time-division multiple access

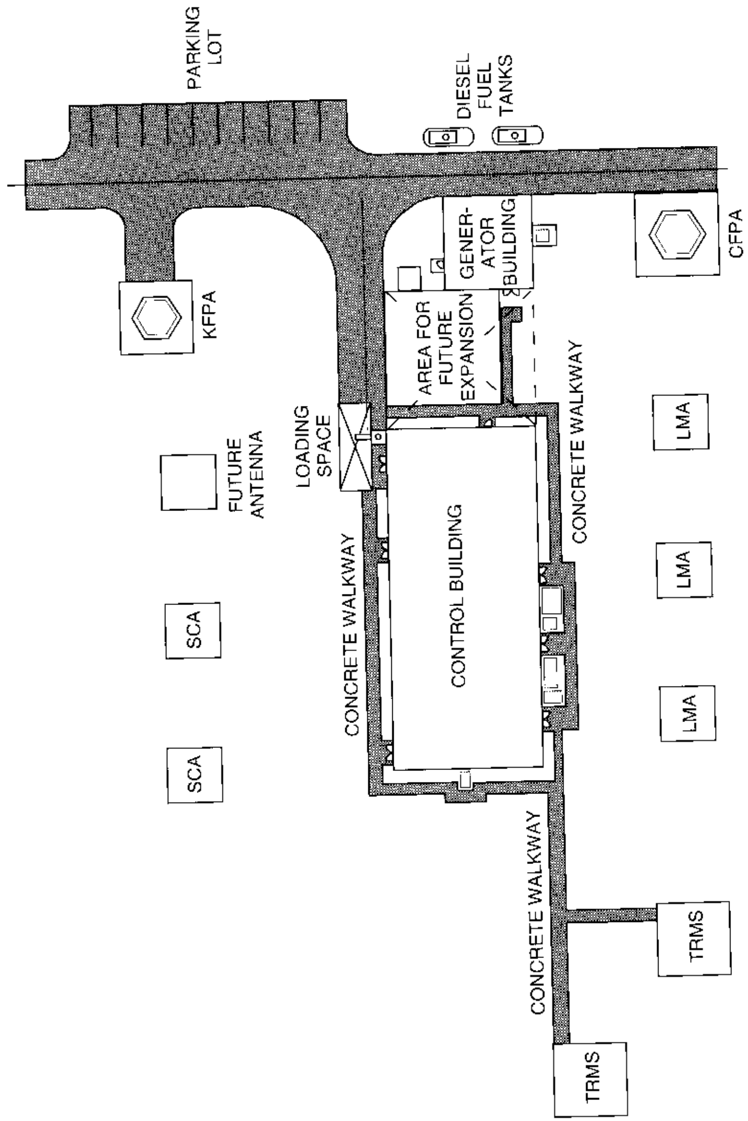

Figure 5. Clarksburg Site Plan Layout

(TDMA) systems, a third technician was added. Two Senior Electronic Technicians who are assigned to Maintenance Shop duties consisting of extraordinary equipment repair and modification, and routine maintenance, are also available to complement shifts that are short-handed. In this way, adequate coverage is maintained for all required functions. Additionally, Senior Facilities Mechanics assigned to the Maintenance Shop have responsibility for the entire earth station facilities plant, including the power systems, HVAC, antenna mechanical systems, and fire detection and control.

The key functions performed at the earth stations in support of TTC&M operations are described below.

Telemetry reception

Each station can process telemetry from four INTELSAT V/V-A satellites and four INTELSAT VI satellites. Telemetry information is transmitted to the receiving ground station from the spacecraft beacon antennas, on the beacon signals. On the ground, these data are routed to the appropriate receiver by the receive IFL and the down-link select switch. The data, comprising any combination of normal telemetry 32/48-kHz phase shift keying (PSK), dwell 72-kHz PSK, and ranging data, are routed to PSK demodulators via a baseband matrix switch and jack fields. The output of the PSK demodulators is routed to INTELSAT Headquarters through the CCC network, and also to the command generators and to site data processing computers by using appropriate frame synchronizers.

The Hewlett-Packard A900 minicomputers used in the system enable the ISCC to control and monitor the status of all INTELSAT spacecraft, providing status, alarms, printouts, and graphical representations of events detected by the software. Earth station personnel use this telemetry information to verify system performance, make operational decisions, and monitor network response to INTELSAT remote command queues.

Commanding

The most critical network activity involves changes in spacecraft configuration, attitude, and orbital position. Command sequences may be performed either automatically using the Command Coordination System (CCS)—in which commands are generated without station operator intervention—or manually by station personnel under the direction and coordination of the ISCC. Launch and emergency scenarios sometimes rely on station-originated manual commanding, whereas routine events such as eclipse battery and sensor switching are normally performed by the ISCC operator or an autonomous (computer-controlled) queue.

The TTC&M stations are equipped with several different command units to accommodate the different spacecraft series. All supply a tone burst to FM-modulate the station up-link. The command carrier is directed to the correct up-link path by the up-link select switch, under control of the CCS.

Ranging

The station range processor supplies a very stable sequential tone pattern (35-Hz, 283-Hz, 3.96-kHz, and 27.7777-kHz sine waves) to an FM modulator, and thence to the up-converter. The up-link path for ranging is also controlled by the up-link select switch. The received ranging signal, looped through the spacecraft, is routed to the range processor from the telemetry receivers and down-link select switch. The phase delay of each tone is measured, and the resultant data are routed to the data processing computers.

Each ranging data record consists of the phase angles and azimuth and elevation coordinates from the tracking system computer, the time of measurement, and the satellite identifier, and is stored in a database file in the station computers. When sufficient data have been accumulated, the ISCC requests the station computer to transmit the data via the CCC network for reduction. Station personnel monitor status and alarm information from the CCS and station M&C systems to ensure that ranging data frames are properly acquired and of high quality.

Communications system monitoring

The CSM, developed at COMSAT Laboratories [5], is a subsystem resident at the earth station which is used to make highly accurate measurements of the emissions from the satellite communications payload. The CSM operates through the station Standard A antennas, which at Clarksburg include the two TRMS/LMAS, as well as the CFPA. The CFPA may access any spacecraft to perform CSM measurements, as required. Clarksburg also has a second CSM system working with the KFPA to monitor Ku-band transponder emissions.

At the time of their construction, the antennas for CSM were calibrated using a radio star to receive and transmit gain, in order to establish these antennas as secondary reference standards for CSM measurements.

Using frequency plan data tables stored in its computer, the CSM measures each carrier emission, including beacons, for e.i.r.p., frequency offset, and deviation. The data are used by the INTELSAT Operations Center and monitoring staff to ensure that the satellite transponders are being operated properly, that each carrier is being properly maintained by the transmitting earth station, and that consequently the network is being operated in the most efficient manner.

In addition to routine measurements conducted at least daily, the CSM performs the following functions:

- *Small-Signal Gain Measurements.* The CSM controls the radiation of a low-level carrier to measure the gain of individual satellite transponders, in order to detect any degradation over time.
- *Antenna Verification Measurements.* To be accepted into the INTELSAT network as an operating communications earth station, a candidate station must pass various antenna tests, such as transmit sidelobe patterns, transmit gain and receive *G/T*, e.i.r.p. stability, and cross-polarization purity. The CSM is the measuring instrument for these tests, requiring heavy involvement of the TTC&M earth station staff in calibrating the CSM and conducting the tests. The staff works closely with the earth station under test to ensure accurate and timely measurements, with the goal of expeditious entry into the INTELSAT system and activation of communications carriers from the new station.

The CSM system is also used with the CFPA to investigate anomalous satellite performance, as directed by INTELSAT Space Segment Engineering and the ISCC staff.

Earth station maintenance

The COMSAT TTC&M earth station staff is responsible for both the COMSAT systems equipment and the IFE. At COMSAT's discretion, certain IFE can be (and generally is) contracted to the manufacturer for preventive and problem maintenance, usually on a same-day or next-day basis, depending on the criticality of the system.

The vast majority of the subsystems are maintained by the station staff. Guidelines for maintenance are compiled into locally generated preventive maintenance instructions (PMIs). The PMI program includes a scheduling calendar by which each system is checked at prescribed intervals and histories are maintained.

The station staff is competent to troubleshoot down to the component level for most equipment. In addition, spare cards and modules for both IFE and COMSAT-furnished equipment allow for rapid replacement at that level as well, resulting in minimum subsystem down-time.

Reporting

To assist INTELSAT in system administration, numerous reports are generated on a daily and weekly basis, addressing such issues as inventory control, test completion, calibration, and system problems (hazardous condition or outage reports). The COMSAT stations are linked to both the INTELSAT and COMSAT electronic mail systems, allowing real-time transfer of information. Facsimile and teletype transmissions are also employed as required.

Summary

The design, performance characteristics, and operation of COMSAT's Clarksburg and Paumalu INTELSAT TTC&M earth stations, activated in the INTELSAT VI era, have been described. Major differences between these stations and COMSAT's previous TTC&M earth stations were addressed, including the state-of-the-art antenna systems, tracking, and M&C systems employed. The new stations were implemented around the concept of dedicated TT&C antennas, employing simplicity of design while maintaining adequate redundancy for critical subsystems. It is anticipated that the Clarksburg and Paumalu TTC&M stations will continue to serve the INTELSAT organization for many years to come.

Acknowledgments

The design, implementation, and successful commissioning of the Clarksburg and Paumalu earth stations was the direct result of an excellent blending of talent from numerous organizations. TIW Systems, Inc., had overall turnkey responsibility under contract to COMSAT World Systems (CWS). CWS worked closely with TIW and the staff of INTELSAT's Director General, drawing on specialized engineering skills resident in COMSAT Systems Division and COMSAT Laboratories. This resulted in a station design and implementation which successfully met the stringent requirements of the INTELSAT TTC&M network.

Special thanks must go to R. Luik, President of TIW Systems, and R. Malitzke-Goes, CWS Technical Officer of the Post-1989 TTC&M Program, for their tireless efforts in support of the program.

Finally, to the management and staff of the Clarksburg and Paumalu earth stations, a grateful thanks for their extensive efforts in bringing the stations on line and operating them in a dedicated and professional manner.

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Index: communication satellites, earth stations, INTELSAT, networks, systems monitoring

INTELSAT communications operations

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Abstract

To oversee the highly complex INTELSAT global communications network, the INTELSAT Operations Division has developed systems and procedures to manage the network as new technology becomes operational, to commission new earth stations and bring new carriers into service, and to cope with transitional periods. The functions and responsibilities of the INTELSAT Operations Center are presented, and its close interaction with other INTELSAT departments to provide effective, high-quality support to earth station operators is described. The support systems for voice and telegraph communications and monitoring, which aid in maintaining control of the network, are also discussed.

Introduction

Satellite communications operations have changed dramatically since the early days of INTELSAT. The number and types of communications carriers have increased, and antennas of many different sizes have been defined and have entered the system. This system growth, combined with a continuing demand for communications services, has led to the development of ever more powerful satellites. Today, INTELSAT has 15 satellites in operation serving three ocean regions, as well as two satellites undergoing in-orbit test. Of the four INTELSAT VI satellites currently in orbit, two have been in operation for nearly 2 years in the Atlantic Ocean Region (AOR), and the remaining two will begin service in the Indian Ocean Region (IOR) in early 1992. This will bring the total of in-service INTELSAT satellites to 17.

The global satellite network

The existing INTELSAT fleet consists of a mix of INTELSAT V, V-A, and VI series satellites. Table 1 gives their location, type, and flight number as of December 1991.

TABLE 1. INTELSAT SATELLITE FLEET AT YEAR-END 1991

LOCATION (°E)	COVERAGE/ FUNCTION	SATELLITE SERIES	FLIGHT NO.
57.0	IOR	V	507
60.0	IOR	V-A	515
63.0	IOR	V-A	511
66.0	IOR Spare	V	505
174.0	POR	V-A	510
177.0	POR Spare	V	503
180.0	POR	V	508
183.0	POR	V	501
307.0	AOR (IBS)	V-A	513
325.5	AOR	V	504
332.5	AOR Spare	VI	604
335.5	AOR	VI	602
338.8	AOR	V	502
341.5	AOR	V	506
359.0	AOR	V-A	512

Satellite system utilization

The current INTELSAT global network consists of approximately 123,000 equivalent voice channels. The AOR has the highest traffic density, carrying about 60 percent of the total traffic. The IOR carries 25 percent of the traffic, with the remaining 15 percent carried in the Pacific Ocean Region (POR).

The transmission channels use a variety of modulation and channelization techniques. The system is currently changing from a predominantly analog FM frequency-division multiple access (FDMA) system to a digital system of quadrature phase shift keyed (QPSK) carriers using time-division multiple access (TDMA) (both fixed and satellite-switched), QPSK/FDMA, and single-carrier-

per-channel (QPSK/SCPC) access. Analog frequency-division multiplexing (FDM)/FM carriers are steadily being replaced by intermediate data rate (IDR) digital QPSK carriers. There are more than 1,000 IDR carriers in operation today.

In addition to telephony and data services, occasional-use video services have continued to expand. Since 1976, the number of occasional-use television channel hours per year has grown from 13,000 to more than 72,000. The average number of daily television transmissions is 192, and increases significantly when major events occur. The largest number of transmissions per day was recorded in January 1991, when 430 transmissions occurred.

Another growing segment of broadcast services has been teleconferencing via the occasional-use International Business Service (IBS). The IBS was introduced utilizing QPSK/FDMA carriers for point-to-point and point-to-multipoint communications; however, it is not intended for use via the public-switched network.

INTELSAT Operations Center

Real-time management of the INTELSAT communications system is the responsibility of the INTELSAT Operations Center (IOC). Its principal function is to ensure the continuity, reliability, and quality of communications service by providing continuous (24 hr per day) real-time operational direction, guidance, and assistance to all earth stations accessing the INTELSAT space segment. Special emphasis is placed on responding to earth station operators' needs, providing positive and effective network control, implementing restorations (both cable and satellite), and providing for continuity of both the ground and space segment facilities.

This system has evolved over the years into an extremely complex network. More than 7,000 individual carriers offer 123,000 equivalent channels (either 4-kHz analog or 64-kbit/s digital). These services are provided by INTELSAT earth stations now numbering more than 2,000.

Functions and responsibilities

The IOC is directly involved in establishing new carriers and providing troubleshooting assistance to earth stations experiencing carrier degradation. In addition to setting up long-term communications carriers, the IOC assists earth stations in instituting short-term carriers to provide facilities for the restoration of transoceanic cables. In the event of a satellite failure, the IOC aids earth stations in restoring communications carriers on the designated in-orbit spare satellite. These and other IOC functions are described below.

ESTABLISHMENT OF NEW COMMUNICATIONS CARRIERS

Before any communications carrier begins service, it must be established in accordance with a set of procedures detailed in the INTELSAT *Satellite Systems Operations Guide* (SSOG) [1]. The SSOG is an essential document for earth station operators. A listing of the SSOG modules, with descriptive titles, is given in Appendix A.

The procedures for carrier establishment consist of a variety of tests, including in-station tests, satellite loop tests, and tests with the distant earth station. With the conversion of the network from analog to digital, typically 30 to 40 IDR or IBS SSOG lineups are in progress on any given day.

CARRIER PERFORMANCE TROUBLESHOOTING

Once a carrier begins operation, it normally operates with high-quality performance, as defined in the *INTELSAT Earth Station Standards* (IESS) [2], which are listed, with descriptive titles, in Appendix B. However, there are times when changing conditions cause carrier performance to degrade. This may be due to intermodulation products produced in the transponder caused by improper carrier levels, interference from the co-channel carrier due to degradation in polarization isolation caused by weather or antenna tracking problems, or interference caused by inadvertent radiation of a spurious carrier due to equipment failure or operator error. Whenever carrier degradation occurs, the IOC is contacted to assist in correcting the situation. Because the IOC has the necessary information on transponder loading, as well as measuring and monitoring equipment, most problems can be resolved quickly. On average, the IOC deals with at least two interference-related events each day.

RESTORATIONS

The IOC assists earth station operators with restoration of two types of service: cable and satellite.

Cable. Transoceanic cables provide an alternative means of establishing international communications; however, they operate in a relatively harsh environment and are subject to failure. INTELSAT provides spare space segment capacity to restore traffic in the event of a cable failure. Most large cable operators have a cable restoration plan on file with INTELSAT. When a failure occurs, the cable Restoration Liaison Officer contacts the IOC to invoke the restoration plan. The IOC then works with the earth stations to bring the required communications carriers into service until cable repairs have been completed. A more detailed description of the cable restoration process is given in an INTELSAT contribution to the International Telegraphy and Telephony Consultative Committee (CCITT) [3]. Table 2, adapted from that contribution, illustrates the requirements for this restoration service.

TABLE 2. CABLE RESTORATIONS PROVIDED BY INTELSAT

YEAR	NO. OF CABLE SYSTEMS RESTORED	AVERAGE DURATION (days)	TOTAL CHANNEL-DAYS
1987	38	13	475,458
1988	23	12	459,396
1989	24	16	561,136
1990	17	14	389,738
1991 (to 12/6)	12	12	127,058

Satellite. In the highly unlikely event of an in-service satellite failure, the IOC assists earth stations in establishing carriers on the designated in-orbit spare satellite. A contingency plan exists for each major traffic-carrying satellite. If a total satellite failure occurs, the IOC establishes a broadcast channel on the spare satellite to provide instructions to the earth stations as they point-over to the spare. Prior to activating service on the in-orbit spare, the IOC must first clear any preemptible service that may be operating on the spare satellite.

Because INTELSAT satellites are highly reliable and great care is taken in their operation, contingency plans have never had to be fully implemented. There have been two occasions where anomalies occurred which disturbed the nominal pointing of the satellite antennas. The faults were quickly identified and the satellites were restored to normal operation before the contingency plan had to be invoked.

ANTENNA VERIFICATION

Before approval can be given for an earth station to operate in the INTELSAT system, it must be demonstrated to INTELSAT—through a process called verification testing—that the performance characteristics of every antenna meet the mandatory requirements for that antenna class as defined in the IESS. It is the responsibility of the Signatories to evaluate an antenna's verification test results and certify its compliance with the relevant mandatory performance requirements. The IOC assists the earth stations in accessing the space segment and making measurements using the Communication System Monitor

(CSM), INTELSAT's global monitoring network. The CSM consists of measurement equipment located at the telemetry, tracking, command, and monitoring (TTC&M) sites and is described in greater detail in a later section.

FIXED AND SATELLITE-SWITCHED TDMA

The IOC is linked to each TDMA reference station via a packet-switched data network and is provided with display equipment similar to that at the reference station. This enables the IOC to access the displays available to the local reference station operator, and allows remote network startup or burst time plan (BTP) rearrangements to be performed with commands sent over the packet-switching network. With the introduction of INTELSAT VI and satellite-switched TDMA (SS-TDMA), the IOC has begun to use the TDMA computer facility to compute the oscillator control integer (OCI) [4] for making frequency corrections to the timing source oscillator (TSO) on board the satellite. The OCI is passed to the INTELSAT Satellite Control Center (ISCC) for execution of the necessary commands to the spacecraft. Details of the INTELSAT SS-TDMA Headquarters system are contained in a companion paper by Luz *et al.* [5]. Further details on the TSO are provided by Maranon *et al.* [6], and BTP generation and implementation are described by Mizuike *et al.* [7].

OCCASIONAL-USE SERVICES

The IOC maintains positive control over access to the space segment by approving each carrier activation and deactivation. This activity is most dynamic for occasional-use service. With typically 192 television carrier transmissions per day, the IOC has contact with the television broadcast earth stations nearly 400 times per day to approve and log the carrier start and stop times. Frequently, the IOC will assist earth stations with a pre-transmission lineup.

SATELLITE TRANSITIONS

Satellite transitions occur after the launch of a satellite, when the new satellite replaces one in operation. These transitions are relatively straightforward when the satellites are of the same series, but become quite complex when a new satellite series is introduced. Newer series satellites often have more powerful transponders and additional beams or beam connectivity. This makes it more difficult to move carriers from one satellite to another without adversely affecting carrier performance during the switchover. In 1990, SS-TDMA was introduced with the first INTELSAT VI placed over the AOR at 335.5°E longitude. A detailed description of the SS-TDMA system is given by Lunsford *et al.* [8]. During the satellite transition to replace INTELSAT 515 with INTELSAT 602, the fixed TDMA network was converted to SS-TDMA by shutting down the fixed network and restoring the network with the SS-TDMA reference station [9]. Through careful planning, the traffic outage was limited to only a few minutes. The transition process is described in detail by Kullman *et al.* [10].

When satellite transitions take place, the IOC is the focal point for the process. Working closely with the ISCC as satellite receivers are switched, the IOC verifies nominal communications carrier performance during the switching sequence by using the remote spectrum analyzer network (RSAN). The RSAN system is a set of 14 spectrum analyzers located around the world and controlled from the IOC. After satellite transition is complete, using the CSM the IOC works to ensure that all carriers are operating at their nominal levels, as described later.

POINTING DATA DISTRIBUTION

After a satellite stationkeeping maneuver has been performed, antenna pointing data for all international earth stations are generated and distributed by telex through an internal voice and telegraph system called the Engineering Service Circuits (ESC) network. Two types of data are sent, based on the particular earth station's preference. The first type provides the azimuth and elevation pointing angles as a function of time, while the second consists of 11 ephemeris parameters. Given the ephemeris data, the pointing angles can be computed by the earth stations themselves. Beginning in January 1992, INTELSAT will provide pointing data in the ephemeris format only.

Support systems

The IOC has many sophisticated systems at its disposal to maintain control of all aspects of the global network. These include the ESC network for immediate contact with the earth stations, as well as monitoring and measuring equipment to maintain carrier performance.

ENGINEERING SERVICE CIRCUITS

The ESC network serves the administrative needs of the INTELSAT communications system, including the immediate needs of the earth stations and IOC for normal operational control and coordination in establishing and maintaining satellite services. These circuits are also the primary means for real-time coordination of urgent operational and maintenance actions.

ESC channels are allocated in most INTELSAT carrier types. They are incorporated in the baseband of analog channels, and in overhead framing bits for digital carriers. Each ESC channel is a speech-plus-telegraph facility, where five 50-baud voice frequency telegraph channels occupy the upper end of the voice channel bandwidth. Two ESC channels are allocated per carrier: one for earth-station-to-IOC communications, and the other for earth-station-to-earth-station communications. At the IOC, the voice and telegraph signals are separated and sent to the ESC private automatic branch exchange (PABX) and automatic message switching system (AMSS) for further call processing.

The ESC network is composed of gateway earth stations connected to the IOC via leased telephone lines. The gateway stations are selected to provide the maximum connectivity to all earth stations, using the fewest number of gateways. Currently, the gateway earth stations are at Etam, West Virginia, U.S.A.; Roaring Creek, Pennsylvania, U.S.A.; Madley, U.K.; and Jamesburg, California, U.S.A. In 1992, Jamesburg will be replaced by Triunfo Pass and Salt Creek in California. ESC access to the IOR and POR is through Madley and Jamesburg, respectively.

Using the AMSS, approximately 2,500 telex messages covering a variety of administrative needs are processed daily at INTELSAT. The Television Service Center alone accounts for about 600 messages per day, including messages for program booking, confirmations, and transmission quality reports. The Technical Operations Control Center (TOCC) issues SSOG lineup instructions and receives SSOG lineup test results via the ESC telegraph network. Antenna pointing data and TDMA satellite position data are also distributed via this network.

In addition to providing voice and telegraph communications, the ESC network is capable of carrying low-speed data. One example is the distribution of condensed time plans (CTPs) for TDMA networks. The CTP is a subset of the BTP and contains elements of the BTP that are relevant to a particular TDMA terminal.

MONITORING SYSTEMS

To effectively manage thousands of communications carriers over 400 satellite transponders, extensive monitoring and measurement facilities are required. Some of the monitoring capability is provided by selected earth stations for services such as SCPC networks and TDMA. All other monitoring and measurements are made from the IOC, which can control remote measurement equipment. INTELSAT's four major monitoring and measurement facilities are described below.

Communications System Monitor. The INTELSAT satellite system contains a very complex mix of several thousand carriers, which typically include telephony, digital data, or television video. To accommodate the maximum number of carriers in a transponder without mutual interference, and to maintain required performance, it is necessary to keep all carriers within defined limits. This requires monitoring and measuring critical parameters as often as practical. The CSM makes these measurements and records the data for further analysis.

The CSM equipment is collocated with the telemetry, tracking, command, and monitoring (TTC&M) facilities [11]. CSM equipment is now located at the following six sites:

• Clarksburg, Maryland, U.S.A.	C- and Ku-band
• Fucino, Italy	C- and Ku-band
• Raisting, Germany	C-band
• Perth, Australia	C-band
• Beijing, China	C- and Ku-band
• Paumalu, Hawaii, U.S.A.	C-band

The site equipment consists of computer-controlled communications and measuring equipment which automatically measures a number of different parameters of both the satellites and earth stations. By using the CSM, INTELSAT ensures the ongoing operation and monitoring of its satellites, and verifies that the earth stations meet the necessary performance requirements.

The CSM is a wideband receiving system with wide dynamic range instrumentation. Specific receiver frequencies and instrument configurations are operator-selected by the measurement routine requested. The CSM relies on an accurate database of satellite configuration data and relevant earth station data. Measurement data collected over long periods of time permit the analysis of trends in communications carrier performance. The resulting trend data allow satellite usage to be optimized and provide information concerning the performance of satellite receivers and transponders.

The CSM is also designed for use during earth station commissioning. In particular, it has the ability to measure antenna patterns while the earth station antenna traverses the orbital arc, which permits measurement of near-in sidelobes as well as sidelobes many degrees out from the main beam. The CSM is also capable of measuring cross-polarization isolation.

The current CSM is over 10 years old and is becoming difficult to maintain. A requirements document and specification have been developed and approved for the procurement of a new CSM. The new monitor will consist of two major components: a carrier and spacecraft performance measurement system called the CSM data collection equipment (CSME), which will be collocated at the TTC&M sites; and a CSM data processing network (CSMN) located in the IOC.

The CSME will perform all measurements requested through the CSMN. The equipment will offer greater measurement flexibility and speed than the current system. The CSMN will provide network connectivity and processing capability. Its increased processing power will greatly enhance the measurement analysis and reporting portion of the monitoring system. The CSMN will also interface with the operational frequency planning system (OFPS), which will provide all the information necessary to make a measurement on any carrier in the global network. The OFPS is a local area network (LAN) database application which is maintained in real time by the TOCC and IOC.

Data transfer between the CSME and CSMN will take place through the existing Control Coordination Circuit (CCC) network. This is an all-digital IBS communications network providing highly reliable data transmission for all data applications operating at the TTC&M sites. More detail on the CCC network is provided in companion papers by Skroban and Belanger [11] and Smith [12].

Remote Spectrum Analyzer Network. The INTELSAT RSAN provides centralized monitoring, display, and analysis of carriers operating in the INTELSAT global network. Spectrum analyzers are situated at all CSM sites, and at selected other locations to supplement the CSM where beam coverage does not exist. These additional RSAN sites are currently located at New York City, U.S.A., and Thamesside, U.K., for INTELSAT 513/307°E Ku-band spot beam coverage, and at Roaring Creek, U.S.A., and Rambouillet, France, for INTELSAT 504/325.5°E Ku-band spot beam coverage. Additional sites are planned for South America and Africa, primarily to obtain southern zone beam coverage consisting of additional beams provided by INTELSAT VI.

The RSAN system consists of a system controller and up to eight graphical display stations (GDSs) located in the IOC. Each GDS uses a Hewlett-Packard series 9000, Model 310 computer with a 17-in. high-resolution monochrome display and keyboard. A spectrum analyzer, installed at the earth stations, is connected to the output of the LNA. Traces from this analyzer are transmitted back to INTELSAT for display and analysis.

TDMA System Monitor. The INTELSAT TDMA system currently comprises both fixed and satellite-switched networks. Each system encompasses the satellite, TDMA reference and monitoring stations (TRMSs), and a number of traffic terminals. A TRMS consists of an antenna, RF/IF equipment, reference terminal equipment (RTE), and the TDMA system monitor (TSM). All TRMSs are connected to the INTELSAT Operations Center TDMA Facility (IOCTF) via a packet-switched network. The IOCTF [5] monitors and controls all of the TDMA networks.

A TSM is collocated with each RTE, and this equipment is used to monitor system performance, diagnose system failures, and assist users in executing their traffic terminal lineups. (A description of the TSM is given by Barnett *et al.* [13].) The TSM is designed to measure relative burst power levels, burst carrier frequency and position, pseudo bit error rate, and transponder input backoff. The system monitor data are displayed locally at the RTE and the IOCTF. Control of the monitor can also be exercised locally or at the IOCTF.

The TSM can measure relative burst power levels to within ±0.25 dB, the reference burst center frequency to within ±3.0 kHz, and traffic bursts to within ±0.2 kHz. Burst position error is measured within ±1 symbol (17 ns). The pseudo bit error rate is accurate to within 20 percent in the 10^{-2} to 10^{-6} range, and the transponder operating point is measured to within ±1.0 dB.

SCPC Network Monitoring. INTELSAT has 11 transponders which carry SCPC services in the AOR, IOR, and POR. There are four network monitoring stations (NMS) in the three regions which monitor and control the carrier levels and frequency offsets of nine of the networks. Three networks (at 63°E, 325.5°E, and 359°E) are currently monitored by the IOC and the INTELSAT Communications System Monitoring and Analysis (CSMA) group. By mid-1992, the IOC will monitor and control all SCPC networks.

Each NMS monitors SCPC carriers 24 hours a day, 7 days a week. In addition to monitoring carrier power and frequency, operators must rid the network of spurious and unauthorized carriers. It is also necessary to periodically reduce carrier levels to prevent intermodulation noise buildup in the transponder, and to advise stations when carrier frequency corrections are necessary.

The four NMSs use the INTELSAT-provided network monitoring and reporting equipment (NMRE) to automatically monitor all transponders assigned to them. The NMRE automatically measures SCPC carrier levels and frequency and reports those that are radiated outside the preset limits. The operator can then take action by calling, via ESC, those stations operating outside the nominal.

IOC organizational relationships

While the IOC manages the real-time aspects of global network operation on a 24-hr basis, it receives direction and support from many other groups in the INTELSAT Operations Division. The interdepartmental relationships are described below.

Operations Plans

Operations Plans is responsible for developing the transponder loading plans for every satellite. These plans are developed through several meetings that are held annually. One of the most important is the Global Traffic Meeting, which produces the traffic database that forms the basis for detailed planning. This database not only impacts satellite loading, but also aids in planning for additional satellite procurement, if necessary.

The final details of transponder loading are resolved at Operations Representative Conferences. The AOR conference is large enough to be held separately, while the IOR and POR meetings are combined. These meetings agree upon the final plans for the loading of each transponder in the global network. These loading plans are represented in a graphical form known as "sawtooth" diagrams, in which analog FM carriers are shown as triangles, IDR carriers are shown as trapezoids, and IBS carriers are shown as rectangles. Typical sawtooth diagrams are shown in Figure 1. The width of these icons is proportional to the bandwidth of the carriers. The final agreed-upon plans are forwarded to the TOCC for implementation planning.

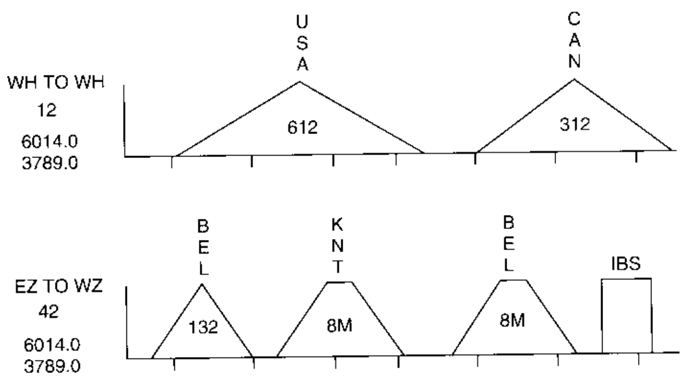

Figure 1. *Example Sawtooth Diagrams*

Technical Operations Control Center

The function of the TOCC is to ensure the provision of reliable satellite service of the highest quality to all users. The TOCC develops satellite contingency plans, coordinates space segment for ad hoc cable restorations, and assists Signatories in establishing short-term temporary carriers for special events.

The TOCC is also responsible for implementing the transponder loading plans received from Operations Plans. Before an approved plan is forwarded to the TOCC, it has been analyzed by the Satellite Transmission Impairments Program (STRIP) [14] software to ensure that the desired carriers can be accommodated once the entire plan is implemented. The program analyzes the effects of all impairments (such as co-channel interference and intermodulation products) and produces sufficient link margins to account for rain margin and terrestrial and adjacent satellite interference.

To implement the transponder loading plan, the TOCC develops SSOG lineup instructions for bringing the carrier into service. First, the TOCC has a link budget drawn up to determine the up-link effective isotropically radiated power (e.i.r.p.) of the transmitting station, and other relevant link parameters. The STRIP program is then run again with the new carrier operating in the existing plan. In this way, the TOCC manages the transition from one plan to the next. The IOC assists the TOCC by executing all instructions prepared by the TOCC and issued in the SSOG telex lineup message.

Communications Systems Monitoring and Analysis

The CSMA group has two primary functions. The first is to assist the TOCC in establishing new carriers through link budget analysis and running the STRIP program. Second, the group collects, processes, and analyzes the measurement data provided by the CSM equipment.

After transponder analysis is completed, the CSMA staff prepares transponder balancing worksheets that are provided to the IOC for implementation. In the heavily loaded INTELSAT system, monitoring of transponder performance is essential to maintain high-quality performance of all carriers.

Television Service Center

The Television Service Center (TVSC) is responsible for managing the operations of all occasional-use services. TVSC staff book all programs, confirm space segment availability, resolve billing issues, and track program quality. Schedules for all confirmed occasional-use services are provided to the IOC for controlling access to the space segment.

INTELSAT Satellite Control Center

The ISCC is responsible for managing the day-to-day functions necessary to maintain proper operation of the spacecraft. The IOC and ISCC work closely in coordinating all spacecraft activities that affect communications carriers. Beginning with the INTELSAT V series, satellite configuration switching has become commonplace, with nearly 200 configuration changes being devised and executed annually. These changes typically include beam pointing and transponder connectivity switching. The IOC also uses its available monitoring facilities to assist the ISCC in isolating transponder or receiver failures. Excellent descriptions of the ISCC and its functions are provided in companion papers by Smith [12] and Pettersson *et al.* [15].

Orbital Mechanics

Orbital Mechanics plans all spacecraft maneuvers and generates both pointing data for antenna tracking, and satellite position data for the TDMA networks. Pointing data are generated weekly and transferred to the IOC's AMSS for telex distribution. Satellite position data are provided to the IOC on magnetic tape, which is loaded into the IOCTF computer and distributed to the TDMA network.

Conclusions

Each new satellite series brings new challenges to the IOC. The INTELSAT V series created a dynamic new environment with frequent spacecraft reconfigurations, and closer relations and coordination among spacecraft operations evolved. INTELSAT VI brought SS-TDMA, with the attendant responsibility for maintaining the frequency corrections of the onboard TSO. Introduction of the next satellite type, INTELSAT K, will further increase the dynamics of system operations. In addition to the current dynamic nature of providing video services in a fixed, occasional-use capacity, INTELSAT K will add a new dimension by allowing frequent spacecraft reconfigurations to provide broadcasters with even greater flexibility. To meet the challenges of the future, INTELSAT has developed a highly integrated and flexible Operations Division to assist earth station operators in establishing new technology services and maintaining the high quality of existing services.

Acknowledgments

Operation of the INTELSAT network is a major team effort involving all the departments described in this paper. Many thanks to those who reviewed this paper for accuracy, and in particular to H. Keel for many inputs on the monitoring systems, C. Kullman for assistance with sections dealing with TDMA, and M. Robusto for help with antenna verification and overall review.

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Appendix A. Summary of Satellite Systems Operations Guide Documents

The SSOG documents contain essential information on all technical aspects of operating in the INTELSAT system. The entire SSOG series is being reissued in a set of self-contained modules that are aligned with the number scheme of the IESS documents described in Appendix B. The reissued SSOG does not materially alter the content of the original SSOG documents, but updates the material and presents it in better order.

The following is a brief description of the SSOG documents.

SSOG 100 Series: Introductory

100 Current Version Master File—A listing of the latest version of SSOG modules.

101 Introduction and Document List—A brief introduction to the SSOG series of documents, including cross-references to the IESS, *INTELSAT Service Manual*, and International Telecommunication Union (ITU) documents.

102 Glossary of Terms, Definitions, and Abbreviations

103 Satellite Operational Management, Coordination, and Control—A description of how the INTELSAT system is managed, the elements involved in the process, and their relationships.

104 Formats for Ordering, Amending, and Reporting of Service

SSOG 200 Series: Verification and Approval of Earth Stations

200 Entry and Operation of Earth Stations into the INTELSAT System—Procedures to bring an earth station into operation.

210 Earth Station Verification Test Procedures

SSOG 300 Series: Test, Lineup, and Maintenance Procedures for Modulation/Access Schemes

301 FDM/FM/FDMA

302 CFDM/FM/FDMA

303 QPSK/SCPC/FDMA

304 QPSK/SCPC/DAMA: SPADE

305 CFM/SCPC: VISTA

306 TV/FM

307 QPSK/TDMA: TDMA

308 QPSK/FDMA: IDR

309 QPSK/FDMA: IBS

SSOG 400 Series: Supplementary Test, Lineup, and Maintenance Procedures

403 Engineering Service Circuits: ESC

SSOG 500 Series: Lineup and Maintenance Procedures for Baseband Processing Equipment

501 Digital Circuit Multiplication Equipment: DCME

502 Frequency Division Multiplex Equipment: MUX

SSOG 600 Series: Transmission Plan Approval

A description of the formats to be used for submitting a leased or purchased transponder transmission plan for approval, with explanatory notes and examples.

Appendix B. INTELSAT Earth Station Standards Documents

The IESS documents provide earth station owners with a common reference for performance characteristics required from the earth station and its associated equipment. These technical requirements ensure standard performance of earth stations accessing the INTELSAT space segment.

Documents which comprise the IESS are listed below.

Group 1: Introductory

101 Introduction and Approved IESS Document List

Group 2: Antenna and RF Equipment Characteristics

201 Standard A—Antenna and Wideband RF Performance Characteristics of Earth Stations Having a G/T of 35.0 dB/K (6- and 4-GHz Frequency Bands)

202 Standard B—Antenna and Wideband RF Performance Characteristics of Earth Stations Having a G/T of 31.7 dB/K (6- and 4-GHz Frequency Bands)

203 Standard C—Antenna and Wideband RF Performance Characteristics of Earth Stations Operating in the 14/11- and/or 14/12-GHz Frequency Bands

204 Standard D—Antenna and Wideband RF Performance Characteristics of Earth Stations for Low Density Services (VISTA) (6- and 4-GHz Frequency Bands)
205 Standard E—Antenna and Wideband RF Performance Characteristics of Earth Stations Accessing the INTELSAT Space Segment (14 and 11/12 GHz)
206 Standard F—Antenna and Wideband RF Performance Characteristics of Earth Stations Accessing the INTELSAT Space Segment (6- and 4-GHz Frequency Bands)

Group 3: Modulation and Access Characteristics

301 Performance Characteristics for Frequency Division Multiplex/Frequency Modulation (FDM/FM) Telephony Carriers
302 Performance Characteristics for Companded Frequency Division Multiplex/Frequency Modulation (CFDM/FM) Telephony Carriers
303 SCPC/QPSK and SCPC/PCM/QPSK System Specification
304 SPADE System Specification
305 SCPC/CFM Performance Characteristics for the INTELSAT VISTA Service
306 Performance Characteristics for Television/Frequency Modulation (TV/FM) Carriers and Associated Sound Program (FM Subcarrier)
307 INTELSAT TDMA/DSI System Specification
308 Performance Characteristics for Intermediate Data Rates (IDR) Digital Carriers
309 QPSK/FDMA Performance Characteristics for International Business Service (IBS)

Group 4: Supplementary

401 Performance Requirements for Intermodulation Products Transmitted From INTELSAT Earth Stations (6- and 14-GHz Frequency Bands)
402 Earth Station e.i.r.p. Adjustment Factors to Account for Satellite Antenna Pattern Advantage and Path Loss Differential With Elevation Angle (K1 and K2)
403 Engineering Service Circuits
404 (INTELSAT IV-A module no longer used)
405 INTELSAT V Satellite Characteristics
406 INTELSAT V-A Satellite Characteristics
407 INTELSAT V-A (IBS) Satellite Characteristics

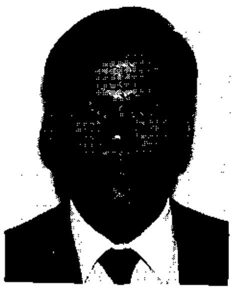
408 INTELSAT VI Satellite Characteristics
409 INTELSAT VII Satellite Characteristics
410 INTELSAT Space Segment Leased Transponder Definitions and Associated Operating Conditions
411 Requirements for Earth Stations Accessing INTELSAT V Satellites Operating in a Contingency Mode by Having Higher Than Nominal Orbital Inclination
412 Earth Station Pointing Data
413 Requirements for Access to TDRS Satellites (Supplementary Earth Station Characteristics, Leased Transponder Definitions, and Satellite Characteristics)

Group 5: Baseband Processing

501 Digital Circuit Multiplication Equipment Specification 32-kbit/s ADPCM With DSI

Group 6: Generic Earth Station Standards

601 Standard G—Performance Characteristics for Earth Stations Accessing the INTELSAT Space Segment for International Services Not Covered by Other Earth Station Standards
602 Standard Z—Performance Characteristics for Domestic Earth Stations Accessing the INTELSAT Leased Space Segment



Michael E. Wheeler received an M.S.E.E. from the Florida Institute of Technology in 1979. He is currently Manager of the INTELSAT Operations Center. From 1972 to 1980, he worked on the development of UHF FLEETSATCOM radio equipment, including the UHF DAMA TDMA system. As Associate Director of Small Terminal Development at MACOM/Linkabit, he was responsible for development and production of transportable X-band satellite terminals. Prior to joining INTELSAT, Mr. Wheeler was with Satellite Business Systems (SBS)/MCI where he was responsible for installing the Ku-band earth stations used for the INTELSAT Business Service (IBS). While at SBS in Modem Development Engineering, he worked on development of the 48-Mbit/s TDMA burst modem.

Index: communication satellites; INTELSAT; networks; systems monitoring; tracking, telemetry, control (command)

INTELSAT VI spacecraft operations

G. S. SMITH

(Manuscript received April 15, 1991)

Abstract

The INTELSAT Satellite Control Center (ISCC) is the focal point for INTELSAT satellite operations. This paper describes the organizational structure and responsibilities of the ISCC and discusses its interaction with other sections of INTELSAT. A survey of the INTELSAT VI data systems, as well as the overall communications network being implemented in parallel with the deployment of INTELSAT VI satellites, are also presented. Of particular interest has been the introduction of telecommanding capabilities in the ISCC, and their effect on overall operations. System implementation approaches and issues are discussed and presented, with a summary of lessons learned.

Introduction

Concurrent with the addition of the INTELSAT VI satellite series, INTELSAT is upgrading satellite operations resources to efficiently manage its growing fleet of geostationary spacecraft. Emphasis has been placed on upgrading the control facilities, earth stations, and ground network, and utilizing current technology to increase the levels of automation and data processing capabilities within the satellite operations network. Major changes have included the capability to share limited earth station resources among an increasing number of spacecraft; conversion from an analog to a digital network for data transmission; transition from a manual, distributed commanding approach to a centralized, telecommanding mode; and the introduction of enhanced data processing systems. An ongoing challenge has been to make the transition to the new capabilities while fulfilling operational requirements and sustaining a high level of activity.

Satellite operations involve the interaction of procedures, personnel, the network, and facilities. The goal of the system is to maintain the INTELSAT space segment at the operating level necessary to meet worldwide telecommunications needs by ensuring spacecraft safety in a cost-effective manner.

Satellite operations network

INTELSAT is currently operating a fleet of 18 spacecraft. Seventeen are in geostationary orbit (13 three-axis INTELSAT V/V-A's and four spin-stabilized INTELSAT VI's), and one (INTELSAT 603) is being maintained in low earth orbit (LEO), at the time this paper was finalized, awaiting the outcome of a NASA Space Transportation System (STS-49) Shuttle reboost mission scheduled for the first half of 1992. To operate such a large fleet, INTELSAT maintains a network consisting of the following elements:

- The INTELSAT Satellite Control Center (ISCC), located at INTELSAT Headquarters in Washington, D.C.
- Telemetry, tracking, command, and monitoring (TTC&M) earth stations around the world.
- The INTELSAT Operations Center (IOC) in Washington, D.C.
- A communications network to interconnect all facilities and processing systems.

These elements, along with communications and spacecraft engineering sections at INTELSAT Headquarters, support continuing satellite operations.

The ISCC is the focal point for monitoring and controlling the INTELSAT spacecraft fleet. The ISCC interacts continuously with the TTC&M earth stations and the IOC.

The TTC&M earth stations are responsible for maintaining data processing, up-link, and down-link equipment on site and supporting spacecraft acquisition, commanding, ranging, and communications monitoring operations. As of April 1991, the network of TTC&M stations consisted of facilities at Clarksburg, Maryland, USA; Paumalu, Hawaii, USA; Raisting, Germany; Yamaguchi, Japan; Jatiluhur, Indonesia; Fucino, Italy; and Tangua, Brazil. These stations allow the ISCC to monitor and operate spacecraft in the Atlantic, Pacific, and Indian Ocean regions. The long-term goal of INTELSAT is to operate all spacecraft using a network of six sites. Yamaguchi, Jatiluhur, and Tangua will be replaced by Perth, Australia, and Beijing, China. The planned final configuration (Figure 1) is expected to be operational by the end of 1991.

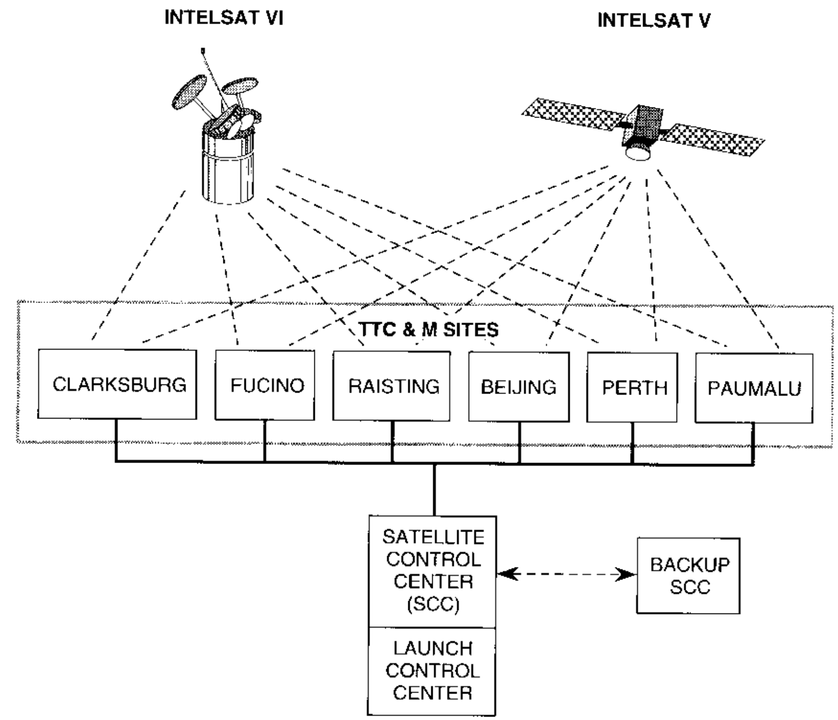


Figure 1. *INTELSAT ISCC and TTC&M Sites*

A detailed description of the design and operation of TTC&M earth stations is provided in a companion paper by Skroban and Belanger [1].

To connect the TTC&M sites with the ISCC, INTELSAT relies on a network of circuits that transfer data worldwide. INTELSAT is currently making the transition from an analog leased-circuit network to the fully digital International Business Service (IBS) network that utilizes internal resources to provide primary and alternate paths from all sites. This new IBS network—the Control Coordination Circuit (CCC) network—will be discussed later in this paper.

The IOC controls the traffic being carried in the INTELSAT space segment and performs associated duties such as monitoring the quality of service and assisting users in using the network. The interactions between the IOC and the ISCC are described in a later section, while a full description of the IOC is contained in a companion paper by Wheeler [2].

INTELSAT Satellite Control Center

The responsibilities of the ISCC begin from the moment a spacecraft separates from the launch vehicle, and end when a spacecraft is decommissioned. To fulfill the various roles required during a spacecraft's life cycle, the ISCC is divided into the following major areas:

- Launch Control Center (LCC), where missions are initially conducted and in-orbit testing of new spacecraft is performed.
- Satellite Control Center (SCC), where day-to-day operations are conducted.
- Management Observation Center (MOC), where INTELSAT management can monitor operations as needed. The MOC is also used in performing spacecraft maneuvers and other major operations, since it provides isolation from ongoing operations.

In conducting spacecraft operations, the ISCC schedules network resources to provide primary and redundant command, telemetry, and ranging coverage of all spacecraft, with a margin to support contingencies and other events. The ISCC reviews all available resources (stations, antennas, command generators, and processors) and operating requirements (ranging, commanding, telemetry monitoring, and maneuvers) and creates a plan that is then implemented within the TTC&M network.

To satisfy mission requirements and maintain spacecraft safety, the ISCC provides and maintains command capability for all spacecraft in order to support ad hoc scheduled, emergency, and/or maneuver commanding activities. Primary and backup telemetry coverage supports the monitoring of overall spacecraft health and specific subsystems parameters, and alerts spacecraft engineers when anomalies or emergencies occur. Network operations are coordinated to support ongoing activities, including the release of TTC&M antennas to support earth station performance testing, communications system monitoring, and earth station equipment downtimes. Other network activities such as launches and missions for both INTELSAT and outside customers, are also supported. These include coordinating launch activities with routine spacecraft operations, relaying telemetry and ranging data, participating in launch rehearsals, supporting spacecraft deployment operations, in-orbit testing, and spacecraft relocations.

ISCC organization

To support spacecraft operations, the ISCC is organized into three groups: Network Operations, Data Processing Systems Maintenance, and Network Systems and Support. The Network Operations group is mainly charged with managing spacecraft operations in the ISCC. Its responsibilities include coordinating operations activities involving the ISCC by scheduling support while minimizing resource conflicts; supervising ISCC technicians working on shifts; serving as a point of contact for other INTELSAT groups that require support from the ISCC; and preparing operational plans and network schedules in support of launches and special operations. Network Operations also defines and implements spacecraft coverage plans, using predefined resources to meet operational requirements. The plans define primary and backup antennas for telemetry coverage, commanding, emergency commanding, and ranging, along with spacecraft maneuver schedules, special operational requirements and guidelines, and test schedules.

The Data Processing Systems Maintenance group works with all the systems currently operating in the ISCC. Specific tasks include maintaining all data processing systems in the ISCC, including real-time and historical telemetry processors; testing and installation of hardware and new software releases; coordinating system maintenance activities with outside vendors and other maintenance personnel; and maintaining ISCC hardware, including monitors, printers, communications terminals, and strip charts. The group also conducts circuit management and configuration activities to ensure the availability of primary and secondary data paths between the ISCC and the earth stations.

The Network Systems and Support group represents the ISCC in special and upcoming projects by performing requirement studies and participating in system design and analysis activities. It also defines and manages the training and certification program for ISCC personnel.

ISCC interactions with other sections

To support ongoing operations, the ISCC interacts with several sections within INTELSAT. Figure 2 shows the relationship and interfaces between the ISCC and other areas, including the Flight Operations Section (FOS), the Orbital Operations Section (OOS), the IOC, and the INTELSAT Ground Network Projects group (GNP). The principal task of operating the spacecraft in orbit is performed jointly with engineers assigned to the INTELSAT Engineering Division's FOS. The FOS provide the ISCC with guidelines, procedures, and the on-call support needed to conduct nominal and contingency operations and perform spacecraft reconfigurations to meet traffic demands.

The ISCC also provides support to the OOS, which has a continuing requirement for dual-station ranging of all spacecraft. Orbital data are used by the OOS and the Astrodynamics Section for orbit determination and planning of spacecraft maneuvers. This requirement is met by implementing a schedule

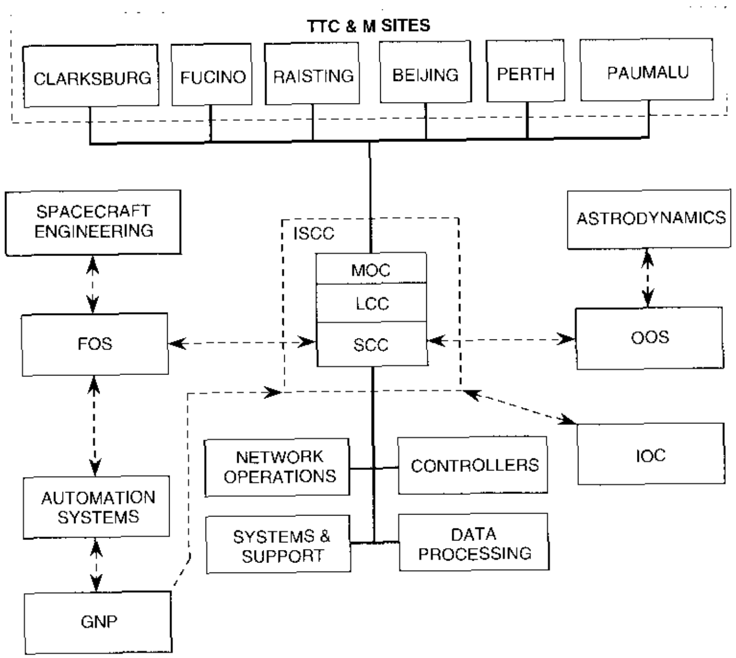


Figure 2. *Groups Supporting Spacecraft Operations*

for routine ranging and by providing coordination when additional ranging is required. The TTC&M earth stations are assigned specific spacecraft, ranging configurations (beacon ranging *vs* transponder ranging), and a scheduled time. Ranging data are collected routinely during the day (as discussed by Skroban and Belanger [1]) during the day and relayed through the ISCC to the OOS mainframe processors for analysis. The OOS uses this database to determine orbits and to schedule stationkeeping maneuvers in order to maintain the spacecraft in proper attitude and assigned orbital locations.

The ISCC continually interacts with the IOC, providing resources for carrier measurement activities and earth station verification testing. The ISCC releases the telemetry, tracking, and command (TT&C) antennas under its control to the IOC to support scheduled activities. It also works with the IOC to diagnose communications anomalies or problems affecting network users.

The INTELSAT GNP interacts with the ISCC routinely to design, develop, install, and test new systems in the network, based on operational requirements. These systems include data processing systems, hardware at the earth stations and ISCC, and applications software. The ISCC provides resources and coordination for testing and installing hardware and software within the network to support GNP needs.

Two other groups within INTELSAT interact with the ISCC on a continuing basis. The Spacecraft Engineering Department conducts spacecraft requirements and design efforts, as well as providing staffing support to the FOS for investigating spacecraft anomalies and conducting launch operations. The Satellite Operations Automation Section concentrates on defining functional requirements and formally testing software systems used to support operations. This group also maintains configuration management of software change requests affecting systems in the ISCC.

Detailed ISCC duties

The ISCC is staffed 24 hours a day by teams of four technicians per shift. Personnel come from a variety of backgrounds, mostly in military telecommunications. Operating guidelines are provided by both the Network Operations group and the FOS. The basic requirements are accomplished through the tasks listed below.

COMMAND COVERAGE

Technicians ensure that command paths are available to all satellites by performing check commands and monitoring earth station resources, such as command generators and antenna status. During contingencies, technicians implement emergency commanding using backup stations and full-performance TT&C antennas.

The ISCC also commands spacecraft in support of all maneuvers (stationkeeping and drift), battery management (eclipse and battery reconditioning), sensor management (avoidance of moon and sun interference), in-orbit testing of newly launched spacecraft, and communications payload reconfigurations (antenna steering and repeater reconfiguration) to support traffic requirements.

TELEMETRY COVERAGE AND MONITORING

Technicians ensure that prime and backup telemetry streams are provided from all earth stations via predefined paths. This includes the monitoring of communications equipment and circuits, and coordinating with common carriers when maintenance or emergency work is performed outside of normal working hours. The ISCC also coordinates the movement of TT&C antennas to provide telemetry coverage as required; and further monitors a variety of telemetry displays to determine the status of spacecraft subsystems.

RANGING OPERATIONS

The ISCC ensures that ranging requirements are met by the earth stations by reviewing summary reports provided by the system. These reports detail the number of ranging frames collected by each antenna in the network. The ISCC also coordinates the weekly calibrations of the system and the transfer of track and range data from the sites to the OOS. When the OOS detects problems with the data, the ISCC contacts stations to determine the source of the problem and schedules any support needed to verify and test the system. The ISCC also schedules support for OOS acceptance of new TT&C antennas in the network, whenever required.

NETWORK MANAGEMENT

The ISCC coordinates operations within the network in support of ongoing activities and special requests. The goal is to maintain spacecraft coverage by managing the antennas and equipment at the earth stations. Typical tasks in this area include the release and movement of antennas to support quality assurance testing of earth stations in the network, and coordinating routine and contingency operations at the earth stations during such events as equipment downtimes, outages, and hazardous conditions.

LAUNCH SUPPORT ACTIVITIES

ISCC personnel perform a variety of roles during launch campaigns to ensure that the INTELSAT network is prepared to support a mission. Tasks include scheduling and conducting readiness testing of TTC&M stations prior to launch, participating in launch rehearsals, assisting in data collection activities to support real-time decisionmaking by the launch team, exercising earth stations in such activities as spacecraft commanding and beacon signal strength measurement, and coordinating LEO spacecraft tracking exercises using the full-performance TT&C antennas at appropriate earth stations.

COMPUTER SYSTEM MONITORING

All internal processors and related communications equipment and peripherals are monitored by the ISCC. Personnel are prepared to perform minor troubleshooting of equipment or, if required, will contact on-call personnel. Other system operator duties include executing historical plots of subsystem data, performing telemetry data backups, and rebooting the processors as needed.

Satellite operations data processing systems and network

Satellite operations in the ISCC require the use of a variety of computer systems that perform specific tasks in support of daily operations. All the systems are interconnected through a network which supports the transmission of various types of data.

Control Coordination Circuit network

Currently, the ISCC is making a transition from an analog to a fully digital network in order to meet growing requirements for data transmission between the earth stations and the ISCC. In the past, connections to the earth stations were implemented through leased circuits, and operations depended on the reliability of these analog circuits. With the advent of the INTELSAT VI systems, it was decided to design a new network (the CCC) that would utilize INTELSAT resources to meet the increased requirements.

The goal of the CCC is to provide greater capacity, higher reliability, and flexibility by providing communications channels to relay all types of data (telemetry, asynchronous, and voice). The system is designed to allow circuit reconfiguration, including routing and type of traffic, to support operational needs. The CCC relies primarily on IBS connectivity over the INTELSAT network for data transmission, with certain exceptions due to lack of network connectivity. Each TTC&M earth station is configured with two small communications antennas to provide two redundant IBS paths out of the station through the INTELSAT space segment, with primary paths terminating at INTELSAT's Headquarters earth station, and secondary paths terminating at the Clarksburg TTC&M earth station in Maryland.

Figure 3 shows the connectivity between the TTC&M earth stations and the ISCC via spacecraft at the indicated orbital positions. Note the different IBS paths originating at the sites, and how the different routes are used to ensure redundancy. The goal is to have two paths from the stations over independent routes. The paths shown as dotted lines and through other satellites are those that cannot be supported by the INTELSAT network, since they require routing of data through spacecraft over North America.

Processor interconnectivity

The CCC provides the medium for interconnectivity between processors in the ISCC and the earth stations. The majority of processors in the ISCC network

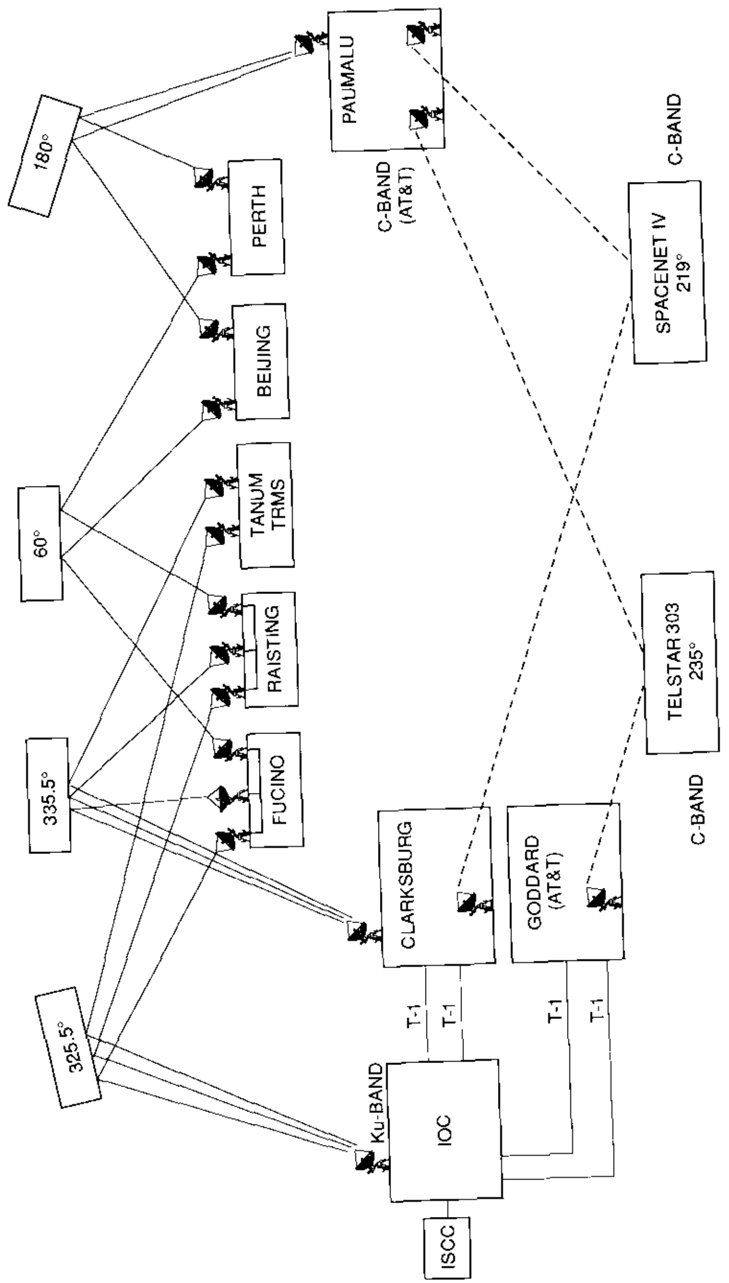


Figure 3. *INTELSAT CCC Network*

are Hewlett-Packard platforms (A900's) and the HP DS-1000 network system is used for interprocessor communications. Figure 4 shows the configuration of DS-1000 links, including the connectivity of the two spacecraft processors at the site and how these processors are linked to the ISCC. The node concentrator (NC) and the link processor (LP) are processors which serve as gateways from the earth station into the ISCC. The Communications and Control Processor (CCP) and the Command and Coordination System (CCS) processor will be described later.

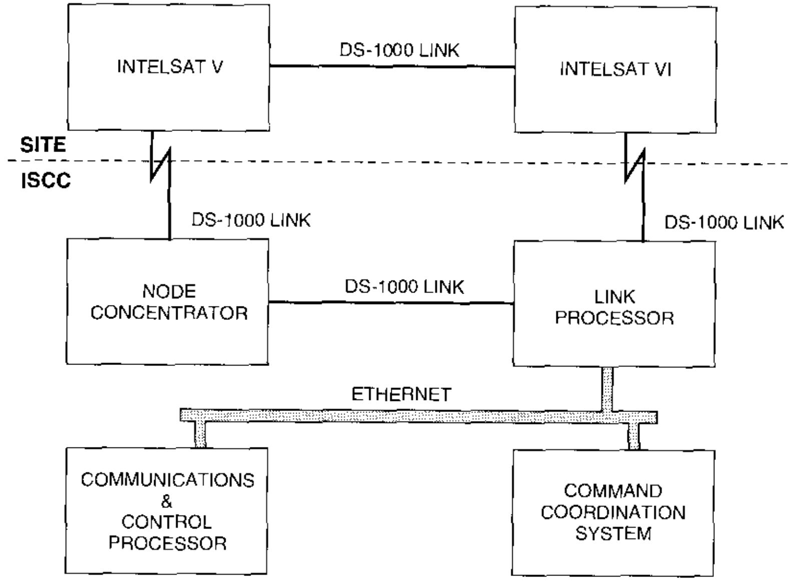
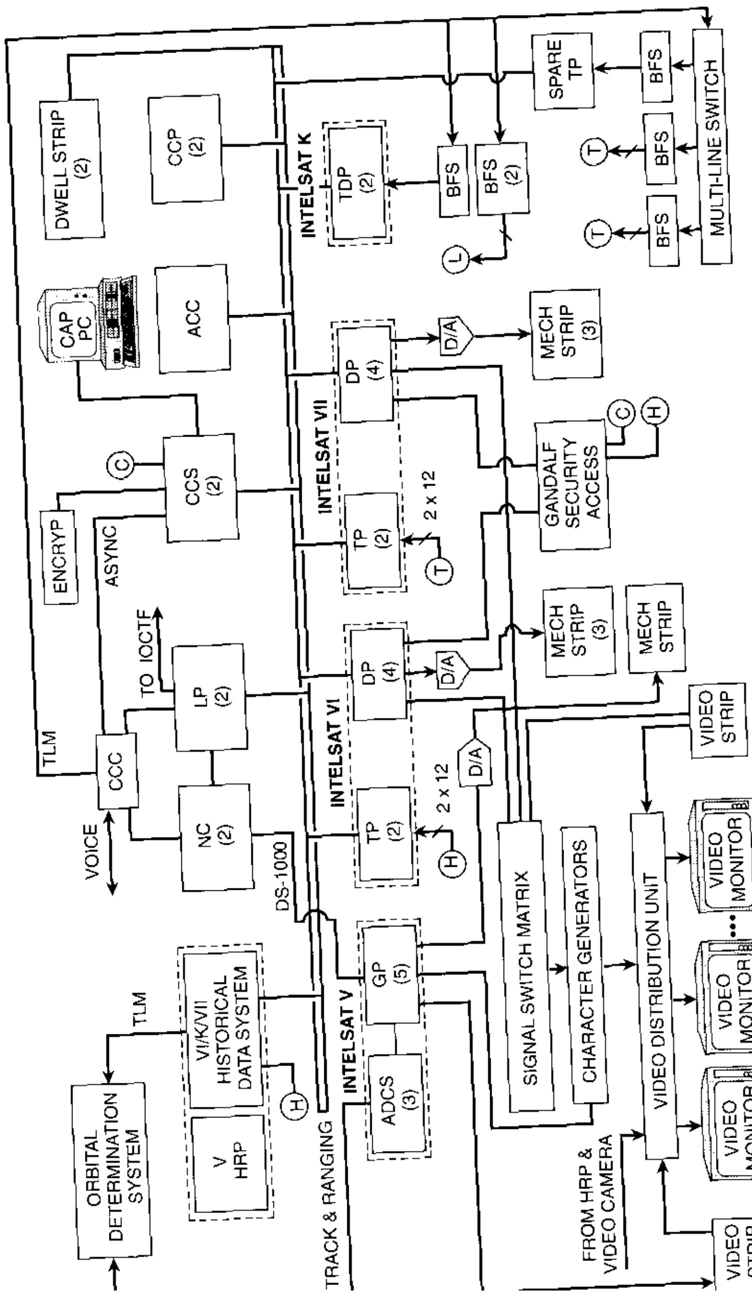


Figure 4. *Configuration of DS-1000 Links*

Satellite operations computer systems

The various tasks related to spacecraft operations are accomplished through the use of processors in the network. Several processors perform a variety of tasks, while others have specific duties. Figure 5 provides an overview of the data processing network. The three major network areas are as follows:

- *INTELSAT VI Data Systems*, which process spacecraft telemetry and provide for general functions such as data printouts, historical data plots, and telemetry video displays.



Note: Telemetry, voice, other data, and interconnectivity to TT&C sites are achieved through the CCC.

Figure 5. *INTELSAT V/VI TTC&M Data Processing Network*

- *Command and Coordination System*, which provides commanding capability for INTELSAT V and VI spacecraft.
- *INTELSAT V Data Systems*, which process telemetry data for the INTELSAT V satellite series.

All of the systems shown in Figure 5 are contained in the ISCC. Data from the TTC&M earth stations enter the system through the CCC network. Telemetry is then routed to processors for parameter checking, with INTELSAT VI data going to the bit frame synchronizer (BFS) for relay to the telemetry processor (TP), while INTELSAT V data are routed to the general processors (GPs). INTELSAT VI telemetry data are then relayed from the TP to the SCC local area network (LAN), where the data can be accessed by the other systems for display or monitoring. Other system data, such as processor messages and network events, are also received through the CCC and routed to the link processor for distribution to other processors.

INTELSAT VI DATA SYSTEMS

The INTELSAT VI systems design used a modular approach to meet all the processing requirements. The system architecture also allows for integration of the INTELSAT V systems.

The INTELSAT VI system introduced the concept of using a central processor for overall coordination of supporting processors. The main processor, located in the ISCC, is the CCP, which primarily coordinates the activities between other processors and network equipment. It also performs the following tasks:

- Control of the interprocessor DS-1000 network, including monitoring and controlling network device status, file distribution, and synchronizing time in the network.
- Generation and control (using the display processors) of INTELSAT VI telemetry displays and strip charts. The system allows controllers to generate 20 displays and control three mechanical strip charts and six video strip charts.
- Management of INTELSAT VI telemetry limit-checking files by the telemetry processors by providing functions to enter and edit limits and the capability to distribute the limits to the earth stations.
- Configuration of systems for the receipt of telemetry from the earth stations by allowing controllers to define the input channels being used to route the data, and specifying the spacecraft associated with these channels.

- Management of the power monitoring system for the INTELSAT VI spacecraft by providing functions to specify power system constants for monitoring and generating commands to support eclipse operations.
- Providing event and alarm functions for the network by generating alarms as needed for controllers to react, generating an ongoing events printout, and maintaining a log of events and alarms for later retrieval.

Several other processors are used by the CCP to support INTELSAT VI operations. Display processors, controlled by the CCP, generate the INTELSAT VI displays and control the mechanical and video strip charts. Link processors receive incoming network status messages and events from the sites for routing to the appropriate monitoring and logging systems. These processors are used to implement a wide area network (WAN), thus connecting the ISCC LAN to all of the earth station systems. Telemetry processors process INTELSAT VI telemetry against the limits or boundaries provided. Incoming telemetry is synchronized and checked, and alarms are generated as required for other systems use. Historical recording processors (HRPs) are used to store telemetry data for future studies and analyses. The system provides for the plotting of data in a variety of formats and the retrieval of data from tape storage.

Earth stations are also equipped with a dedicated INTELSAT VI processor which provides for commanding of INTELSAT VI spacecraft assigned to the site, event and alarm processing, and telemetry processing.

A planned future addition is the Alarm and Control Consolidation System (ACC). The ACC will be deployed in engineering workstations and will provide alarm and event consolidation and expert system shells to aid in diagnosing network problems and to offer alternative courses of action. ISCC personnel will use this system to monitor earth station resources and local resources, and to connect to the different processors on site, thus eliminating the need for dedicated terminals. Additional expert systems will later be incorporated to facilitate satellite operations management.

COMMAND AND COORDINATION SYSTEM

Spacecraft commanding activities for both the INTELSAT V and VI spacecraft are controlled through the CCS processor, which interacts with software at the sites to provide controllers with the capability to perform several critical operations.

Real-time telecommanding of spacecraft through man-machine interfaces allows controllers to control command generators at the site without the assistance of earth station personnel.

Command queue management provides functions for approving command queues (files containing groups of commands and parameters for execution) generated by spacecraft engineers, scheduling queues for execution, and providing the means to execute queues as required.

Activity timeline management includes resource checking in support of commanding activities, as well as conflict identification and resolution.

Autonomous commanding management is also available at all sites. The autonomous commanding system (ACS) is designed to react to specific spacecraft-related situations and send commands to place the spacecraft in a safe mode. Sample situations include Ku-band traveling wave tube amplifier (TWTA) shut-off, L-band power amplifier shut-off, and uncommanded spacecraft attitude changes caused by events such as electrostatic discharges in the attitude determination and control subsystem (ADCS). The ACS is loaded with baseline parameters and is designed to detect changes and execute the appropriate commands autonomously, responding much faster than a human controller to minimize the effect on the spacecraft. The ACS places the spacecraft in a safe mode (thrusters off) which allows engineers to analyze the situation and prepare an effective plan for returning the spacecraft to normal operation. The CCS allows controllers to activate this system for each INTELSAT V spacecraft at all earth stations. Currently there is no similar system for the INTELSAT VI spacecraft. The CCS also supports resource identification and management, which allows controllers to identify the up-link and down-link resources at each earth station and allocate them among the spacecraft in the fleet.

INTELSAT V DATA SYSTEMS

The INTELSAT V spacecraft are supported by processors both at the earth stations and at the ISCC. The processor at the earth stations provides for commanding and telemetry processing for INTELSAT V spacecraft, and for ranging of INTELSAT V and VI spacecraft assigned to the site. The INTELSAT V general processors at the ISCC are used for telemetry processing, event and alarm reporting and control, command processing and verification, and display and report generation.

The ISCC also has three INTELSAT V ADCS processors which process spacecraft attitude data and generate reports and plots. These ADCS processors also collect track and range data for the stations and provide the interface for preparing data prior to transmission to the OOS processors.

INTELSAT V historical data are stored in the HRPs, which use VAX platforms. The INTELSAT V HRPS contain several databases of telemetry, commands, and solar array current. Users have the option of plotting and displaying stored data in a variety of formats, and can access data on both disk and tape.

The combination of the CCC, the INTELSAT V and VI systems, and the CCS provides the ISCC with the tools for managing the entire INTELSAT space segment. However, this new mode of operation has placed the ISCC in a period of operational transition which will still be ongoing in late 1991.

Operational scenarios

The ISCC systems, network, and personnel described above—and their interactions—provide INTELSAT with the resources to support spacecraft operations. This section discusses activities and sample scenarios which demonstrate how the system functions overall to manage INTELSAT's space segment.

Operational activities

INTELSAT spacecraft operations activities range from routine commanding to spacecraft maneuvers and relocations. Spacecraft maneuvers include launch transfer orbit, stationkeeping, and relocation maneuvers. Stationkeeping maneuvers are performed routinely to maintain a spacecraft within its assigned location and to ease tracking by user antennas. Both orbit plane inclination (north/south) and orbit phase delta velocity (east/west) maneuvers are performed by the ISCC. Drift maneuvers are performed as needed to support spacecraft relocation. These may include drift start, drift stop, and trim maneuvers. During launch operations, transfer orbit maneuvers are also performed by the ISCC to place the spacecraft in its proper geostationary orbit.

Communications reconfigurations are conducted to support traffic requirements, and include reconfiguration of spacecraft repeaters, steering of Ku-band spot beam antennas to address changing traffic demands, and loading and activation of beam-switching plans in support of satellite-switched time-division multiple access (SS-TDMA) operations on INTELSAT V. This work is performed in conjunction with the IOC and FOS.

Battery management operations are carried out during reconditioning and eclipse periods. Eclipse operations are conducted during two periods each year, for 45 days, centered around the vernal and autumnal equinoxes. During eclipses, the spacecraft depends on the on-board batteries for power, rather than the solar arrays. Activities include placing batteries in high charge after eclipse periods and turning high charge off when required. Battery reconditioning is performed prior to eclipse season and involves discharging and recharging the batteries to ensure proper operation and extend battery lifetime.

Spacecraft maneuver scenario

An INTELSAT V maneuver scenario will be described to demonstrate how the various systems, individuals, and facilities work together to carry out such an activity. The sample spacecraft for this scenario will be INTELSAT 605, located at 335.5°E longitude and serving the Atlantic Ocean Region. SS-TDMA is currently operating in a position for which precise orbit information is necessary to ensure that traffic terminals are acquired by the SS-TDMA network without loss of traffic.

Earth stations continuously send telemetry data to the ISCC through the CCC. These data are checked at the stations (INTELSAT V processor) and at the ISCC (telemetry processor) to ensure their validity. The Fucino and Tangua TTC&M earth stations have been assigned as prime and backup stations and collect INTELSAT 605 spacecraft ranging data on a routine basis. These data are stored at the site's INTELSAT V processor before being retrieved by the ISCC (using the INTELSAT V ADCS processors) via the HP DS-1000 links supported in the CCC. At the ISCC, data from all stations are forwarded to OOS processors for analysis. The OOS reviews the track and range data and plans stationkeeping maneuvers to maintain the spacecraft in its assigned location. Once it has been determined that a maneuver is needed, the OOS prepares a maneuver message which is provided to the FOS for execution.

The FOS spacecraft engineers use the data from the OOS to create a "command instruction." The instruction requirements are entered into a PC application which creates an electronic command queue. This file is then used by the CCS for telecommanding the spacecraft. Once the queue has been electronically approved by the FOS, it is transferred via the LAN to the ISCC. Upon receipt of the queue, an approval and scheduling cycle begins in the ISCC. Using the CCS, the queue is electronically approved by ISCC operations personnel, inserted into the electronic activity timeline, and sent to both the prime and backup commanding sites (Fucino and Tangua). The activity timeline contains all the computer-assisted telecommanding activities in the network, such as automatic ranging and spacecraft commanding events.

Prior to the maneuver, the ISCC configures local systems to support this activity. The required strip charts and telemetry displays are requested through the CCP system and generated by the display processors; communications patches are established between the prime and backup commanding stations; and command up-link checks are performed. To ensure commanding, the backup site is configured for manual commanding (voice and earth station operator intervention), and the primary site is configured for telecommanding.

A few minutes prior to the maneuver, the CCS sends an alarm to the CCP to highlight the upcoming activity. In the MOC area, two ISCC technicians (the

Maneuver Coordinator and Assistant Maneuver Coordinator) await the scheduled start time of the maneuver. Maneuvers usually involve the configuration and loading of parameters on the spacecraft, firing thrusters and performing the required maneuver, and restoring the spacecraft to normal configuration. The ISCC technicians use the CCS to retrieve the command queue and execute the commands remotely with Fucino, as directed by the FOS engineer. During this time, the earth station technicians at both sites observe the telemetry displays and follow the progress of the maneuver by using the command queue listing. If any problems occur, the ISCC technician switches to the backup site for commanding and continues activities by instructing the earth station technician to manually enter, transmit, and execute commands using the command generator at the site.

Once the maneuver is completed, the ISCC technician releases the stations back to normal operation and performs a series of post-maneuver activities. Maneuver reports generated by the INTELSAT VI HRPs are filed, and copies are forwarded to the OOS for analysis. These reports contain performance data from the maneuver which are used to determine thruster performance and fuel utilization. The technician takes steps to ensure that the earth stations continue ranging on the spacecraft in order to obtain post-maneuver orbit data and verify the new orbit. Ranging activities can be verified by observing the CCS activity timeline. The OOS and IOC are notified of completion of the maneuver. The IOC in turn notifies customer earth stations to utilize the post-maneuver pointing data provided by the OOS. Finally, the ISCC is returned to normal configuration by deactivating displays and strip charts using the CCP system.

This scenario demonstrates how almost every element in the operations network is used in support of a maneuver, and that an overall team effort is essential for maintaining the INTELSAT fleet.

Current operational transition period

Development of the CCS and INTELSAT VI systems provided a new set of automated tools for performing spacecraft operations. The main task was then to implement these systems while maintaining a consistent level of operation.

Distributed and manual command and control approach

In the past, the ISCC and earth stations operated in a distributed manner, that is, the ISCC coordinated overall network activities, while the earth stations managed local resources at their sites. Commands were relayed via voice lines from the ISCC to the earth station technicians, who entered and transmitted them to the spacecraft. Commands were then executed at the ISCC's direction. Spacecraft commanding was directly related to the earth station technician's proficiency in manually commanding the spacecraft, using the command generators at the site.

Operation activities required frequent interaction between the ISCC and the TTC&M earth stations. Communications between both areas addressed such activities as time checks, relaying special ranging requirements, and checking of data and voice links. Such interactions were affected by the earth station technician's ability to understand the problem and relay information to the ISCC. At times, language barriers between technicians from different countries affected communications between the ISCC and the earth stations. In addition, the ISCC was limited in its ability to monitor activities at these earth stations. Usually, the only source of information was the earth station technician's status reports.

With an increase in the number and complexity of spacecraft expected in the INTELSAT satellite fleet, a new operations approach was needed to cope with the anticipated volume of operations and make efficient use of network and satellite operations resources.

New operations approach

The INTELSAT VI program provided the opportunity to implement a new operations approach utilizing the new systems and capabilities being developed in support of that spacecraft series. Several new or expanded capabilities were expected to have a significant impact on satellite operations.

A spacecraft telecommanding capability would allow ISCC technicians to use a man-machine interface to transmit and execute commands remotely from the ISCC, with little or no intervention by earth station technicians. Also, the ISCC would be capable of allocating defined earth station resources as primary or secondary for a spacecraft, and earth station equipment (*e.g.*, command generators) could be shared between several spacecraft, instead of using spacecraft-dedicated resources.

Earth station activity would be monitored via automated timelines, which would provide the ISCC with overall and specific summaries of commanding and ranging activities for the network or specific sites. Network management would be accomplished through master computer nodes in the ISCC, in order to coordinate activities and ensure network availability to support operations. Improved, menu-driven computer systems would also significantly affect satellite operations.

System implementation issues

As new capabilities were delivered, the ISCC staff was called upon to define the best method for implementing the new procedures without affecting day-to-day operations. For example, it was necessary to determine which of the new system capabilities would be used to support normal operations such as stationkeeping maneuvers, battery management, and telemetry monitoring. Network and earth station resources had to be effectively monitored without adding excessively to the workload of the ISCC technicians.

A combination of displays and system resources was used to provide technicians with overall network status, while reducing their response time during contingencies. New approaches and procedures were developed for recovering from outages, system failures, and other contingencies, while minimizing the effect of such events on spacecraft operations.

It was also necessary to maintain earth station awareness of operations, in an environment designed to reduce interaction between the ISCC and earth station personnel. An effective training program was designed so that ISCC personnel could quickly enhance technician proficiency on new systems and procedures. The increase in system automation (through the use of processors) had to be monitored by the technicians, who in many cases needed to raise their levels of computer literacy to assist in recovery operations as necessary.

Gradual system implementation into operations

System capabilities were introduced gradually to provide ISCC technicians with the opportunity to become proficient with basic system capabilities before additional features were implemented. Some of these capabilities significantly altered the operational environment in the ISCC, as described below.

TELECOMMANDING

This capability has greatly affected ISCC operations. Spacecraft commanding has become more efficient; however, this complex capability has also increased the need to maintain manual proficiency at the earth stations. Consequently, weekly manual commanding sessions will be performed with the earth stations to exercise the various command generator operating modes.

The ability to command spacecraft by using command queues has meant that ISCC technicians have had to familiarize themselves with the various modes available (*e.g.*, automatic execution *vs* supervised execution) and with the number of variable parameters that can be set for use during commanding activities. Telecommanding has also changed the interactions between the ISCC and the earth stations, since the majority of contacts now entail assisting ISCC personnel in troubleshooting problems in the network.

RESOURCE ALLOCATION FUNCTIONS

The capability to allocate resources to individual spacecraft, or groups of spacecraft, has provided the ISCC with an increased role in network operations. In the past, ISCC technicians depended on TTC&M earth station personnel to allocate equipment and resources at the site. In this new era, stations provide equipment configuration data which ISCC personnel input into the processing systems. Resource allocation is then performed electronically for all spacecraft, and the resulting set configuration is monitored by ISCC systems and personnel. Such activities have increased the ISCC technicians' awareness of earth station equipment and capabilities, but have also added the real-time monitoring of earth station resources to the list of daily tasks in the ISCC.

ACTIVITY TIMELINES

The new systems have provided the ISCC with timelines containing commanding and ranging activities. These timelines are assisting personnel in identifying periods of high activity and resource conflicts within the network. Various levels of timelines have been provided, from general overviews to detailed site-specific listings. The timelines are also used to verify ranging activities at the earth stations. ISCC technicians can list the ranging schedule for a station and verify that ranging is being performed at the required times and collection rates.

NETWORK MANAGEMENT

Due to the centralized approach implemented in the new systems, failures in the ISCC are more critical than they were in the past. Even though it is still possible to operate locally at the earth stations, an increasing number of operations are controlled remotely from the ISCC. Consequently, all necessary resources must be available on short notice to recover from outages and contingencies and resume normal spacecraft operations. ISCC technicians are in the process of gaining additional experience with network operations in order to quickly evaluate situations and respond efficiently.

ENHANCED COMPUTER SYSTEMS

The new computer systems are largely menu-driven, which is a change from previous systems in which operations where program-oriented. Instead of executing single programs as needed, technicians now are provided with menus and programmed function keys to access the available system features. Even though some menus have several layers, the overall consensus has been that these new systems are providing a more user-friendly environment.

IMPLEMENTATION APPROACH FOR ISCC PERSONNEL

A number of steps were taken to ease the transition to the new centralized mode of operation. A major focus has been on training personnel and defining operating procedures. Initially, technicians attended seminars that introduced them to the new operational concept and capabilities. These seminars provided theory and preliminary information to prepare controllers for the upcoming mode of operation. Additional training sessions were scheduled prior to system implementation in the ISCC. These sessions, usually provided by software and hardware engineers, involved training in basic system operations so that technicians would be capable of performing an initial set of basic tasks after system installation.

After system implementation, ISCC technicians initiated a collection of informal procedures based on their increasing knowledge base and operating requirements. These procedures in turn served as the baseline for development of formal operating procedures. After the system had been in operation for a period of time, major functional areas were identified and work commenced on producing formal procedures. Based on technicians suggestions, the best approaches for completing tasks were documented and provided to the entire ISCC. This process is ongoing as new requirements are introduced and system capabilities are enhanced.

Conclusions

Although a large portion of INTELSAT's new satellite operations and monitoring system has been installed, the ISCC is still in a period of transition. Telecommanding is a major area in which operating questions will continue to arise. While a large number of capabilities have been implemented, the system is not yet operational, and further issues will be raised as users become more familiar with the system and as additional features are introduced. Therefore, a major concern is the identification of contingency procedures to be used during commanding operations, in order to quickly recover from network outages and equipment failures. The ISCC is in the process of defining operating guidelines to accomplish this objective.

Resource and activity management have increased the workload placed on technicians. In addition to monitoring the INTELSAT spacecraft fleet, technicians also must monitor earth station resources, additional computer systems, and electronic timelines. The number of video displays that technicians are required to monitor has increased to the point that additional resources, in the form of staffing or expert systems, will be needed to adequately monitor all operations.

The process of transition has taught satellite operations personnel a number of lessons. In the future, better assessments must be made of how such new systems will affect workload, in order to adequately prepare for operational implementation. The complexity of many of the newly provided capabilities has increased technician workload, rather than reducing it. For example, overall network monitoring now involves from six to seven displays generated by two systems (CCS and CCP), as compared to two displays in previous operating modes. Additional integration analysis during system design, using realistic operational scenarios, can help identify implementation issues and redundant capabilities.

An effort should also be made to automate routine tasks, such as generating reports and telemetry plots. Some of these tasks are still being performed by technicians, rather than being generated automatically by the systems. Shifting more of these tasks to the automated systems would free ISCC personnel for other more critical tasks.

The introduction of expert systems and other advanced tools must be planned and implemented to reduce the workload in the ISCC and assist in contingency operations. Complex new networks and systems require state-of-the-art tools to assist in diagnosing problems. Currently, ISCC personnel respond to system alarms for which they must first assess the situation and then determine a course of action. The addition of expert systems would help to reduce reaction times and provide for faster recovery from equipment and system outages. Work on expert systems is currently under way at INTELSAT, especially in the areas of resource and spacecraft monitoring.

A set of contingency operations must be clearly defined to prepare for worst-case scenarios. The number of failure scenarios has increased, due to the complexity of the INTELSAT system, and efforts are being made to define a realistic set and prepare for such contingencies.

The ISCC is still in a period of transition to a new mode of operations. Efforts to ease the implementation of new systems continue to minimize adverse effects on the network. By centralizing operations, the ISCC has undertaken a more significant role in day to day activities. ISCC technicians, rather than instructing earth station personnel to perform tasks, are now directly commanding spacecraft from the ISCC and allocating resources located thousands of miles away. ISCC personnel are now becoming familiar with earth station operations, as they perform tasks that once were assigned to the sites. The ISCC will continue to provide INTELSAT with high-quality support in meeting new goals and maintaining resources into the 21st century.

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Index: digital transmission, speech processing, telephone transmission

Multilingual subjective methodology and evaluation of low-rate digital voice processors

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Abstract

The methodology and results for a multilingual evaluation of source encoding algorithms operating at 16 kbit/s are presented. The evaluation was conducted in three languages (English, French, and Mandarin), using listener opinion subjective assessments to determine whether "toll-quality" performance is possible at 16 kbit/s. The study demonstrated that toll-quality voice is indeed possible at 16 kbit/s, and that several of the methods evaluated are more robust under high bit error conditions than either 32- or 64-kbit/s encoding. Thus, 16-kbit/s voice coding technology is currently suitable for many applications within the public-switched telephone network, including the next generation of digital circuit multiplication equipment, and integrated services digital network videotelephony.

Introduction

Interest in low-rate digital voice coding is not new; however, the realization that toll-quality voice may be achievable using source encoding systems operating in the 16-kbit/s transmission range is recent. For example, a number of organizations and standards bodies have initiated approval processes for the introduction of low-rate digital encoding at 16 kbit/s in open and private networks. Most notably, the International Telegraphy and Telephony Consultative Committee (CCITT) has begun a standardization process that is expected to lead to approval of a 16-kbit/s voice encoding standard for wide application in 1992, including use in special applications within the public-switched telephone network (PSTN).

In this paper, a methodology is developed for the multilingual performance evaluation of algorithms, or codecs, operating at or near a 16-kbit/s transmission rate. The results of a subjective evaluation based on this methodology are also presented. The evaluation was conducted using eight codecs, operating in the 64- to 13.2-kbit/s transmission range, which were evaluated in three different languages: English, French, and Mandarin. The codecs included the following:

- Code-excited linear prediction (CELP)
- Adaptive transform coding (ATC)
- Continuously varying slope delta modulation (CVSD)
- Adaptive predictive coding with transform domain quantization (APC-TQ)
- Vector adaptive predictive coding (V-APC)
- Regular excited linear predictive coding (RELP)
- CCITT Recommendation G.721 adaptive differential pulse-code modulation (ADPCM)
- CCITT Rec. G.711 pulse-code modulation (PCM).

The key features of each codec are summarized in Table 1.

The performance of the above codecs, in a variety of applications, was assessed by attempting to determine whether there are distinct and substantial differences in voice quality between different types of codecs, and, if differences

TABLE 1. CHARACTERISTICS OF THE CODECS EVALUATED

CHARACTERISTIC	CODEC REFERENCE							
	A	B	C	D	E	F	G	H
Algorithm Type or Coding Method	CELP	ATC	CVSD	APC-TQ	V-APC	RELP	PCM	ADPCM
Gross Transmission Rate (kbit/s)	16	16	16	16	16	13	64	32
Net Transmission Rate (kbit/s)	16	15.5	16	16	16	13	64	32
Error Protection	No	Yes	No	No	No	No	No	No
Frame Length, if applicable (ms)	0.625	15	–	20	10	20	–	–

do exist, whether they are amplified, maintained, or eliminated with different languages and under varying channel impairment conditions.

In the following sections, the subjective assessment methodology is developed and the results of the multilingual evaluations are presented. Subsequently, general conclusions are drawn regarding the quality of the systems and type of technology evaluated. An objective measurement methodology and associated performance data for these eight codecs, with nonvoice signals, are given in References 1 and 2.

Subjective assessment methodology

The subjective assessments were conducted in English, French, and Mandarin, using eight talkers (four male and four female) in each language. The tests were designed to be administered as replicated Latin squares and to assess codec performance at different voice input levels and digital channel bit error conditions. Upon conclusion of the tests, analysis-of-variance techniques were used to determine the effect of various factors (such as talker dependence) on each codec's performance.

Overall subjective design concepts

Since the primary objective of these evaluations was to determine whether 16-kbit/s voice coding technology was capable of providing toll quality, it was assumed that most of the codecs to be evaluated would provide near-telephony-grade subjective performance. This alleviated concerns with regard to potential difficulties in communication and allowed the subjective assessment approach to be tailored to the quantification of each codec's transmission quality.

An experimental design was adopted in which each codec/condition combination was assessed using a transmission quality scale, by means of absolute category ratings (ACR) tests [2]. This scale was obtained using five-point mean opinion score (MOS) ratings, which were derived by soliciting listeners' opinions with regard to their perception of circuit quality, expressed as an *excellent*, *good*, *fair*, *poor*, or *bad* rating. These ratings were subsequently mapped isomorphically to a (5, 4, 3, 2, 1) numerical scale, with 5 corresponding to *excellent* and 1 to *bad*.

Test conditions

The experimental design, developed based on a replicated 8 × 8 Latin square, was selected to permit the evaluation of codec reference and codec test conditions, as well as to allow their mapping to a modulated noise reference unit (MNRU) framework [3],[4]. The design also permitted the performance of each low-rate codec to be compared, through subsequent analysis, with that of a predesignated control coding method (Rec. G.721 ADPCM). Furthermore, a number of relative performance assessments could be conveniently expressed with high accuracy [5].

Table 2 summarizes the conditions assessed. It can be seen that the Rec. G.721 ADPCM codec was subjected to the same circuit conditions as the low-rate codecs, thus enabling the comparative performance objective to be pursued.

Having qualitatively outlined the conditions which were to be included as part of the test, it was then possible to proceed and define the specific structure of the codec and condition combinations that were actually assessed. These conditions are summarized in Table 3. Conditions marked with an asterisk are indicative of multiple codecs. Thus, condition 1.1*a* refers to codec *a* in condition 1.1, condition 1.2*c* refers to codec *c* in condition 1.2, and so forth. Codec *h* was always defined to be the 32-kbit/s Rec. G.721 ADPCM codec, which was used as a statistical control. In this manner, each condition 1.1 to 1.4 corresponds to eight separate coding methods, yielding a total of 40 conditions for evaluation.

Experiment design

Once the test and reference conditions had been defined, eight presentation blocks were constructed (denoted by capital Latin letters A through H), with each block containing a complete set of the 40 codec/condition combinations listed in Table 3. In this arrangement, any given codec/condition combination appeared only once in each block, and every codec/condition combination appeared in any given block spoken by a different talker. A section of this blocked arrangement listing is given in Table 4.

The blocks were then arranged in the form of an 8 × 8 Latin square (Figure 1), with listeners/listening sessions forming the rows, and the order of presentation forming the columns. This design allowed the blocking of two variables: listeners and order of presentation. This was desirable, since it is known that a listener's response may substantially affect the absolute value of the quantitative opinions expressed and thus, by blocking this variation, treatment effects could be assessed with higher sensitivity. This is because a listener's response is likely to have a consistent effect on all conditions a

TABLE 2. SUMMARY OF TEST AND REFERENCE CONDITIONS

CONDITIONS	NO.	COMMENTS
Codec Factors		
Input Levels	2	15 and 25 dB below sinusoidal overload (dBm0L)
Listening Levels	1	Preferred at -25 dBm0L. -15 dBpa at the ear
Talkers	8	4 male and 4 female
Languages	3	English, French, and Mandarin
S/N	1	Better than 30-dB *S/N* for both codec input levels
BER	3	No errors, 10^{-4}, and 10^{-3}
Low-Rate Voice Codecs	6	Five 16 kbit/s and one 13.2 kbit/s
Reference Connections		
Direct	1	Source speech samples
MNRU	6	6, 12, 18, 24, 30, 36 dBQ
64-kbit/s PCM (G.711)	1	Same conditions as voice codecs
32-kbit/s ADPCM (G.721)	1	Same conditions as voice codecs

TABLE 3. DEFINITION OF TEST AND REFERENCE CONDITIONS

CONDITION NO.	CODEC EMPLOYED	BER	COMMENTS
1.1*	*a–h*	No errors	-25 dBm0L
1.2*	*a–h*	10^{-4}	-25 dBm0L
1.3*	*a–h*	10^{-3}	-25 dBm0L
1.4*	*a–h*	No errors	-15 dBm0L
1.5	MNRU	–	6 dBQ
1.6	MNRU	–	12 dBQ
1.7	MNRU	–	18 dBQ
1.8	MNRU	–	24 dBQ
1.9	MNRU	–	30 dBQ
1.10	MNRU	–	36 dBQ
1.11	Direct	–	Unprocessed speech samples
1.12	Source	–	Source speech samples

TABLE 4. EXAMPLE OF PARTIAL BLOCK COMPOSITION

BLOCK A		BLOCK B		BLOCK C		•••	BLOCK H	
CONDITION	TALKER	CONDITION	TALKER	CONDITION	TALKER		CONDITION	TALKER
1.1a	M1	1.1a	F1	1.1a	M2	•••	1.1a	F4
1.1b	F1	1.1b	M2	1.1b	F2	•••	1.1b	M1
1.1c	M2	1.1c	F2	1.1c	M3	•••	1.1c	F1
(etc.)								

ORDER OF BLOCK PRESENTATION

LISTENER/SESSION NUMBER	1	2	3	4	5	6	7	8
1	A	B	C	D	E	F	G	H
2	B	A	D	C	F	E	H	G
3	C	D	A	B	G	H	E	F
4	D	C	B	A	H	G	F	E
5	E	F	G	H	A	B	C	D
6	F	E	H	G	B	A	D	C
7	G	H	E	F	C	D	B	A
8	H	G	F	E	D	C	A	B

Figure 1. *Latin Square Layout*

listener is evaluating (*i.e.*, all conditions under assessment by a listener may be biased by the same amount, since a listener's opinion will be skewed by a preconceived notion of communications link quality). Furthermore, the experimental design contained eight presentation randomizations, thus reducing the impact of presentation order in the assessment process. Finally, the design allowed direct comparison of a specific codec's talker dependence and, for a given session, allowed each of the eight codecs to be compared against each other so that differences in performance could be quantified using appropriate analysis-of-variance methods.

Sample size

An additional issue that was addressed in the experimental design was the expected variance of the means (and indirectly the number of degrees of freedom of each circuit condition error) that was needed to obtain MOSs with a 0.2-point accuracy. Based on previous listener opinion experiments employing MNRU conditions, a sample variance of 0.7 of an MOS point was obtained for a 20-dBQ condition. This sample variance estimate, which is representative of mid-range voice quality, was used as a basis for estimating the sample size (or number of listeners) that would be required in order to attain the desired accuracy for the population means.

Since each circuit condition was included in every Latin square block (employing a different talker), and each Latin square contains a total of 64 blocks, it can be seen that each condition received 64 votes for every completed Latin square (eight listeners). As a result, the estimated MOS accuracy of the means, at a 95-percent level of confidence, for the mid-range of voice quality is equal to

$$1.96 \sqrt{s/(64 \times R - 1)} \qquad (1)$$

where s is the sample variance (0.7) and R is the number of Latin square replicates. From the above formula, it was determined that the accuracy objective could easily be met with two Latin square replications (16 listeners).

In practice, at least 24 listeners were used in each language, and subsequent data analysis revealed that the measured population errors were within 10 percent of the errors estimated using the above process.

Listener training

Listener training was divided into two parts. First, training was given with regard to the type of test to be undertaken. This training was intentionally limited, and only information that was essential to the listeners' understanding of the tasks expected of them as participants in the test was conveyed. In particular, the listeners were not told what was being evaluated, what specific characteristics of the coding techniques they should pay attention to or evaluate, or any other information that might have biased the test results. To further ensure that all subjects received the same type of training, instructions regarding the task about to be undertaken were recorded and played back in exactly the same way for each batch of listeners. Although both the instructions and the rating scales were expressed in English, the listeners were natives of the countries whose language was being evaluated.

In addition to this procedural training, listeners were asked to rate a series of processed speech samples in order to exercise their understanding of the sample playback and voting process. This exercise not only allowed participants to familiarize themselves with the vote collection procedures, but also allowed the experiment to anchor the listeners' opinions using a series of samples which spanned the high-, medium-, and low-quality ends of the voting range. The four test samples that were used in each language always corresponded to the same conditions. These anchoring conditions are given in Table 5.

As can be seen from the table, the training was conducted using reference samples only. This was done for two reasons: first, to avoid the possible introduction of listener biases arising from the specific types of codecs evaluated, and second, to provide a common, time-invariant frame of listener

TABLE 5. TRAINING SAMPLES EMPLOYED FOR ANCHORING

ORDER OF PRESENTATION	CONDITION	DESCRIPTION
1	1.7	12 dBQ
2	1.11	Unprocessed
3	1.5	0 dBQ
4	1.9	24 dBQ

training reference that would permit the results of this evaluation to be correlated with results obtained from other evaluations of low-rate digital transmission systems.

Evaluation of performance

The results obtained from the subjective test sessions were analyzed using two statistical approaches: an analysis-of-variance method and a simultaneous statistical inference technique.

Analysis-of-variance approach

Upon completion of the subjective test sessions, the votes obtained were processed using analysis-of-variance techniques by constructing a fourth-order state-variable model, whereby each observation (vote) was modeled as [5],[6]

$$y_{ijkl} = \eta + \beta_i + \tau_j + \gamma_k + \delta_l + \varepsilon_{ijkl} \tag{2}$$

where
- y_{ijkl} = voter's opinion for speech sample *ijkl*
- η = the mean (*i.e.*, a representative rating, or MOS, for a given codec for a particular condition averaged over all talkers, sessions, and listeners)
- β_i = order of block presentation effect (row effect)
- τ_j = talker dependency effect (treatment effect)
- γ_k = effect of sample positioning within a block (*i.e.*, the interaction between adjacent sample playback, or block randomization/column effect)
- δ_l = any effect due to block replication (*i.e.*, variations due to listener biases)
- ε_{ijkl} = any effect not accounted for by the model, or experimental errors.

The mapping of the talker treatment, τ_j, to the Latin square structure can be more readily observed when it is noted that, in each block, a particular condition is processed by a different talker, and that each listener (from a group of eight) hears each set of blocks in a different order.

From this fourth-order analysis, it was concluded that neither the block randomization effect nor the order of sample presentation within a block was significant. However, the effect of block order presentation *was* significant, thus indicating that the listeners' pattern of voting changed with time—an effect that was not unexpected in view of the duration of the test. However, since each block contained 40 samples, the observed variation did not adversely affect the rating of individual samples within a block.

It was also concluded that the effect of talker dependence was significant in some cases. In particular, it was found that the performance of four low-rate codecs was talker-dependent. The talker dependency results are summarized in Table 6, where each codec type is associated with an indication of its contribution to the experimental error, using the F_o variable with 7 and 231 degrees of freedom.* It should be noted that the $_{231}{}^{7}F_o$ values of most codecs (including waveform types) exceeded the critical $_{231}{}^{7}F_o$ value of 2.08, which is significant at a confidence level of 95 percent. Therefore, the listener

TABLE 6. CONTRIBUTION OF TALKER VARIATION TO CODER PERFORMANCE

CODING METHOD	$_{231}{}^{7}F_0$	TALKER DEPENDENCY
V-APC	8.70	Yes
RELP	5.35	Yes
ATC	3.75	Yes
CVSD	2.93	Yes
G.711 PCM	2.45	No
CELP	2.44	No
G.721 ADPCM	2.35	No
APC-TQ	1.93	No

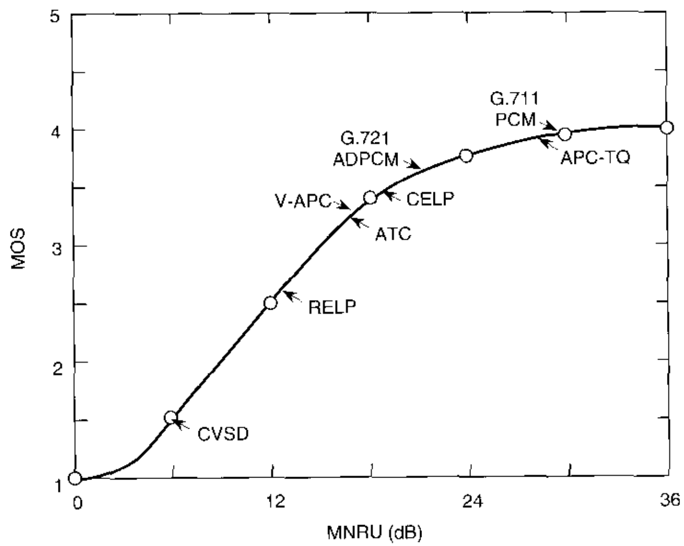
* The ratio of two sample/population variance ratios $(s_1^2/\sigma_1^2)/(s_2^2/\sigma_2^2)$ is assumed to be distributed in accordance with the *F* distribution, with ν_1 and ν_2 degrees of freedom denoted as $_{\nu 1}{}^{\nu 2}F_o$, where ν_1 is the sample size associated with s_1, and ν_2 is the sample size associated with s_2.

perception of each talker's voice quality was further investigated by computing the value of ${}_{231}{}^{7}F_o$ for the source speech material. This computation indicated that the ${}_{231}{}^{7}F_o$ variable assumed the value of 2.56 for source speech, from which it was concluded that some talkers were preferred over others, and hence only the V-APC, RELP, ATC, and CVSD codecs were likely to yield a talker-dependent performance of any statistical significance.

Finally, it was found that by far the largest component of voting variance was attributable to differences between the various codecs. As a result, the null hypothesis that all codecs performed equally well was rejected, and further processing was conducted using simultaneous statistical inference techniques [7], and employing the Dunnet method [8],[9] in particular (due to the preselection of the Rec. G.721 ADPCM method as the statistical control).

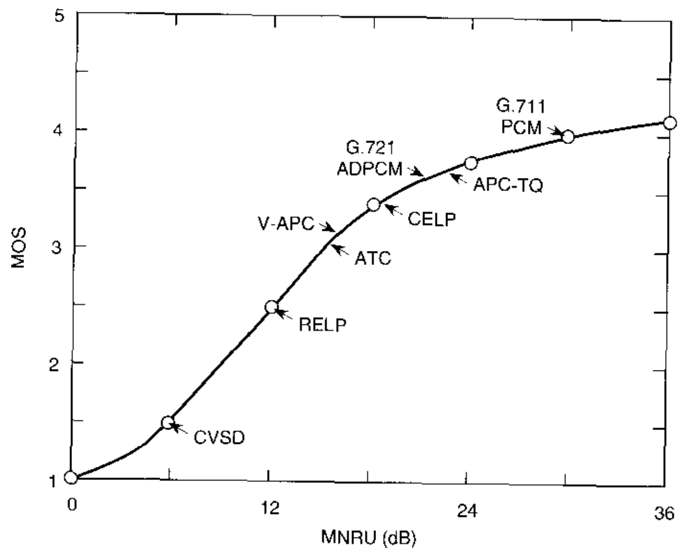
Absolute performance characterization

As indicated above, a fourth-order variance analysis for each codec/condition combination revealed that most of the differences observed between the various codecs were significant. Figures 2a, 2b, and 2c illustrate (for the English, French, and Mandarin languages, respectively) the rating of quality under nominal input speech levels and error-free conditions for the various codecs.

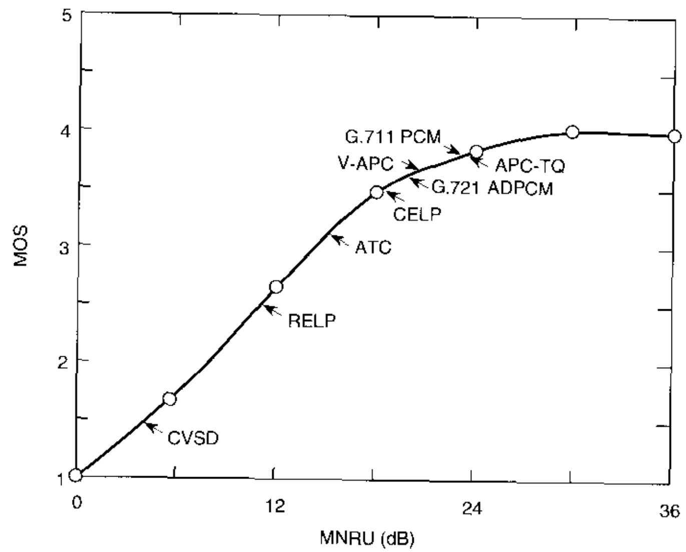


(a) English

Figure 2. *Circuit Quality MOS*



(b) French



(c) Mandarin

Figure 2. *Circuit Quality MOS (cont'd)*

A composite figure of bit-error-free performance over all three languages was computed, as shown in Figure 3. This MOS language-averaging was justified on the basis of three observations: first, because the performance ranking of the set of codecs was typically preserved between languages; second, because a significance comparison of the sample variances for each condition indicated that the observations were obtained from populations with comparable characteristics; and third, because no significant statistical variation was found in the codec interlanguage MOS variation.

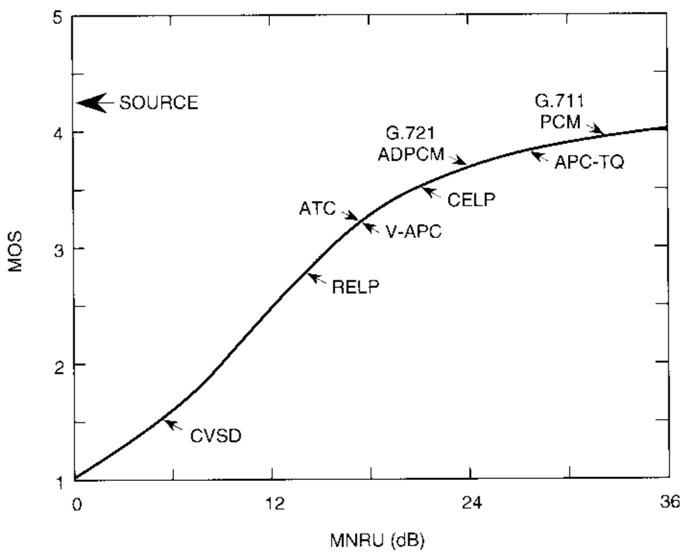


Figure 3. *Circuit Quality MOS Averaged Over All Three Languages*

The error-free condition data were then used to derive mathematical models associating MNRU, or Q values, with MOS for each language. The models were subsequently employed to obtain subjectively equivalent Q values for each test condition assessed in each language. The three models derived were as follows:

$$\begin{aligned} \mathrm{MOS}_e &= 1.0 - 3.71 \times 10^{-2}Q + 2.63 \times 10^{-2}Q^2 \\ &\quad - 1.34 \times 10^{-3}Q^3 + 2.47 \times 10^{-5}Q^4 - 1.45 \times 10^{-7}Q^5 \end{aligned} \tag{3}$$

$$\begin{aligned} \mathrm{MOS}_f &= 1.0 - 3.78 \times 10^{-3}Q + 2.16 \times 10^{-2}Q^2 \\ &\quad - 1.13 \times 10^{-3}Q^3 + 2.09 \times 10^{-5}Q^4 - 1.23 \times 10^{-7}Q^5 \end{aligned} \tag{4}$$

$$\begin{aligned} \mathrm{MOS}_m &= 1.0 + 2.08 \times 10^{-2}Q + 2.35 \times 10^{-2}Q^2 \\ &\quad - 1.53 \times 10^{-3}Q^3 + 3.79 \times 10^{-5}Q^4 - 3.41 \times 10^{-7}Q^5 \end{aligned} \tag{5}$$

where MOS_e, MOS_f, and MOS_m denote the MOS in English, French, and Mandarin, respectively, and Q denotes the Q value in dB.

Since the differences in reference condition Q ratings did not reveal significant statistical variation between languages [2], the Q ratings for each condition assessed were averaged over all three languages, and the results are summarized in Table 7. Also given are the maximum and minimum values for each mean Q rating (corresponding to a 95-percent level of confidence). These values are unequally spread over the mean Q values due to the nonlinear relationship between MOS and MNRU values.

The data in Table 7 show that the performance obtained from each codec was strongly dependent on the nature of the circuit condition assessed. For example, the 64-kbit/s PCM codec performed poorly under digital impairment conditions, as can be seen from its Q value performance at the 10^{-3} and 10^{-4} channel bit error rates (BERs). For the remaining codecs, it was generally observed that the relative performance was maintained irrespective of channel degradations (within the range of conditions evaluated). This held true even though the quality of some codecs degraded more steeply than others with increasing levels of channel impairments. It can also be seen that at least one of the 16-kbit/s codecs (APC-TQ) performed better than the CCITT 32-kbit/s ADPCM standard (Rec. G.721) for all conditions. The error performance of the voice codecs is graphically summarized in Figure 4.

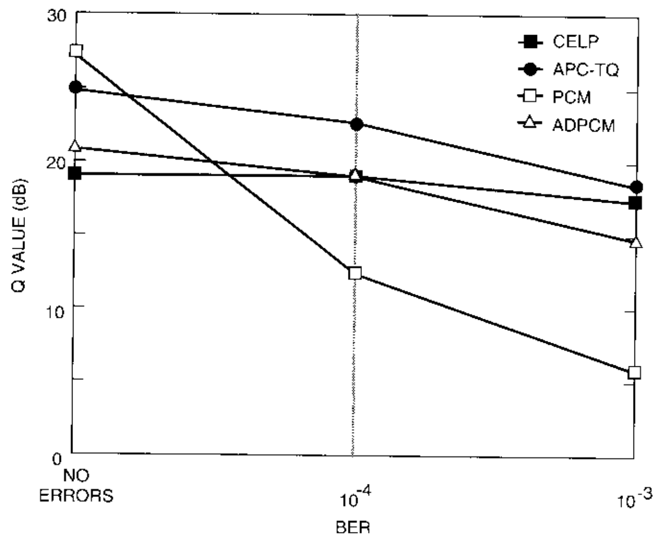
It is feasible to speculate that under error-free conditions, 16-kbit/s voice coding technology may outperform 32-kbit/s ADPCM. However, differences in subjective performance may become more evident in multi-link (or tandem) connections, where it is expected that the higher bit-rate codecs such as 64-kbit/s PCM and 32-kbit/s ADPCM will degrade less quickly with increasing tandem connections.

Conclusions

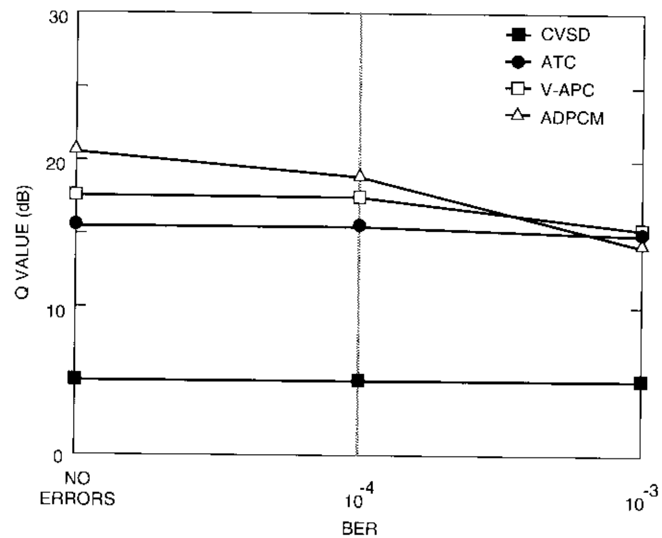
This study has shown that, on the basis of subjective performance and within the scope of the conditions evaluated, toll quality is indeed achievable with single-link 16-kbit/s coding. Furthermore, the higher quality of low-rate codecs proved to be more robust than that of 32- and 64-kbit/s coding under high bit-error conditions. While the impact of multiple interconnections on voice quality was not investigated, it is believed that with increasing

TABLE 7. Q RATINGS FOR EACH CONDITION ASSESSED OVER ALL THREE LANGUAGES

CODEC INPUT			Q VALUE (dB)		
BER	LEVEL (dB m0L)	CODEC	MINIMUM	MOST LIKELY	MAXIMUM
No Errors	−25	CELP	17.43	18.60	19.87
		ATC	15.12	16.02	16.97
		CVSD	< 6	< 6	< 6
		APC-TQ	21.67	24.60	29.07
		V-APC	16.54	17.83	19.53
		RELP	11.13	11.87	12.67
		PCM	22.87	27.07	31.80
		G.721	19.30	20.73	22.53
10^{-4}	−25	CELP	17.17	18.30	19.53
		ATC	14.67	15.60	16.57
		CVSD	< 6	< 6	< 6
		APC-TQ	19.87	21.87	26.20
		V-APC	16.07	17.32	18.77
		PCM	11.00	11.68	12.42
		G.721	17.87	19.07	20.50
10^{-3}	−25	CELP	15.13	16.03	16.97
		ATC	13.90	14.76	15.72
		CVSD	< 6	< 6	< 6
		APC-TQ	15.00	16.17	17.40
		V-APC	13.76	14.87	16.06
		PCM	< 6	< 6	< 6
		G.721	12.40	13.27	14.09
No Errors	−15	CELP	19.37	20.93	22.93
		ATC	16.00	18.63	18.19
		CVSD	< 6	< 6	< 6
		APC-TQ	23.20	28.17	> 36
		V-APC	14.53	15.40	16.49
		RELP	14.59	15.50	16.47
		PCM	29.03	34.53	> 36
		G.721	22.60	24.93	29.33



(a) Error Performance for the CELP, APC-TQ, PCM, and ADPCM Codecs



(b) Error Performance for the CVSD, ATC, V-APC, and ADPCM Codecs

Figure 4. *Voice Processor Performance as a Function of Digital Impairments*

interconnectivity, and when compared with 32- or 64-kbit/s technology, the quality offered by 16-kbit/s coding is likely to decline more steeply.

Despite this reservation, it can still be concluded that current 16-kbit/s voice coding technology is suitable for many voice applications within the PSTN, such as digital circuit multiplication equipment, packet circuit multiplication equipment, asynchronous transfer mode (ATM) networks, integrated services digital network videotelephony, store-and-forward messaging, and digital microcellular communications.

Acknowledgments

This paper is based on work performed under the sponsorship of INTELSAT. The authors also wish to thank AT&T, Pacific Communications Sciences, Inc., Extrema Corporation, Voicecraft, Inc., Philips Kommunikations Industrie AG, and COMSAT World Systems for their generous loan of the equipment needed to conduct these tests.

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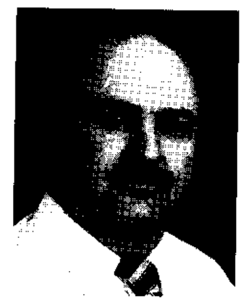

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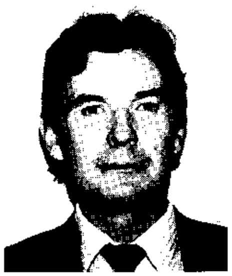

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Index: digital transmission, speech processing, telephone transmission

Objective assessment methodology and evaluation of low-rate digital voice processors

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(Manuscript received October 9, 1991)

Abstract

The methodology and results for an objective evaluation of source encoding algorithms operating at 16 kbit/s are presented. The evaluation was conducted using objective instrumentation to determine whether "toll-quality" performance with nonvoice signals is possible at 16 kbit/s. While 16-kbit/s source encoding is unable to accommodate voiceband data rates exceeding 2.4 kbit/s with acceptable quality, satisfactory performance can be obtained with signaling. Thus, 16-kbit/s voice coding technology is currently suitable for applications within the public-switched telephone network where alternative facilities for voiceband data traffic are provided, including the next generation of digital circuit multiplication equipment, and integrated services digital network videotelephony.

Introduction

The performance of algorithms operating at or near a 16-kbit/s transmission rate was investigated using nonvoice signals in order to determine whether "toll quality" is attainable with current low-rate digital coding technology. The algorithms, or codecs, evaluated included the following:

- Code-excited linear prediction (CELP)
- Adaptive transform coding (ATC)
- Continuously varying slope delta modulation (CVSD)

- Adaptive predictive coding with transform domain quantization (APC-TQ)
- Vector adaptive predictive coding (V-APC)
- Regular excited linear predictive coding (RELP)
- International Telegraphy and Telephony Consultative Committee (CCITT) Recommendation G.721 adaptive differential pulse-code modulation (ADPCM)
- CCITT Rec. G.711 pulse-code modulation (PCM).

The key features of each codec are summarized in Table 1.

The performance of the above codecs was assessed by examining whether distinct and substantial differences exist in nonvoice signal transparency capability between different types of codecs. It was then asked whether such differences would be amplified, maintained, or eliminated under different channel impairment conditions.

Objective measurements were conducted to evaluate each codec's performance with several low-speed voiceband data modems (300 to 2,400 bit/s), dual-tone multifrequency (DTMF), and CCITT Signaling System No. 5 (SS5). Also assessed was each codec's ability to preserve the phase transitions of the V.25 2,100-Hz echo canceller disabling tone. Finally, a series of measurements were made to further characterize each codec's behavior with regard to idle channel noise, nonlinear behavior, quantization noise, amplitude distortion, harmonic distortion, phase distortion, and input/output throughput delay.

TABLE 1. CHARACTERISTICS OF THE CODECS EVALUATED

	CODEC TYPE							
CHARACTERISTIC	A	B	C	D	E	F	G	H
Algorithm or Coding Method	CELP	ATC	CVSD	APC-TQ	V-APC	RELP	PCM	ADPCM
Gross Transmission Rate (kbit/s)	16	16	16	16	16	13	64	32
Net Transmission Rate (kbit/s)	16	15.5	16	16	16	13	64	32
Error Protection	No	Yes	No	No	No	No	No	No
Frame Length, if applicable (ms)	0.625	15	–	20	10	20	–	–

In this paper, voiceband data measurements, the performance of CCITT SS5, and the performance of DTMF signaling are addressed first, followed by a discussion of the distortion of the V.25 echo control tone and a description of measurement techniques for the quantification of each codec's throughput delay. Finally, further characterization of each codec's behavior with narrowband signals is described. This study also included multilingual subjective performance assessments, which are reported separately [1],[2].

Voiceband data performance

The test architecture used for the voiceband data modem measurements was centered around a bit error rate (BER) test system which provided the source data for the transmit direction of the modem under test. The codec was placed in the transmit direction of the data, in tandem with an analog impairment channel, as shown in Figure 1. The return direction provided a direct modem-to-modem, level-adjusted connection with no coding or channel impairments. In this configuration, a signal level of −15 dBm0 was provided at the input of the codec (measured with the impairment channel bypassed). During testing, the BER equipment was used to analyze the receive modem data in order to measure single errors, blocks, block lengths, block errors, test duration, and error-free seconds.

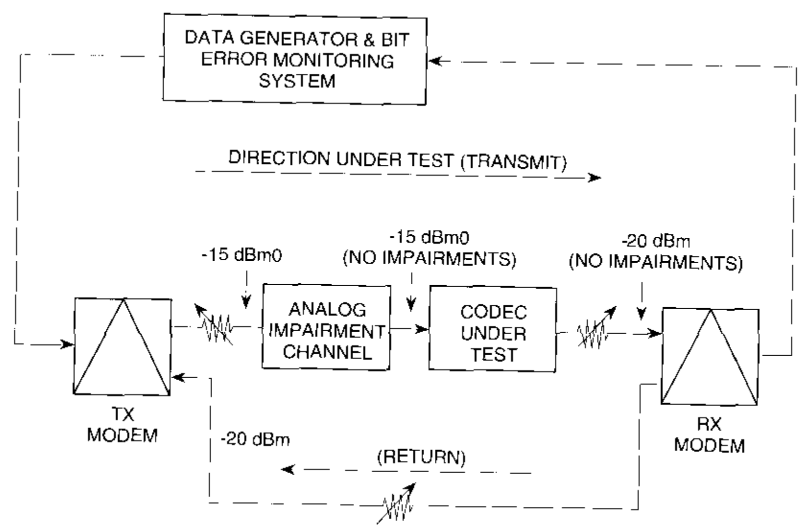


Figure 1. *Voiceband Data Modem Test Configuration*

Impairments

Two types of network impairments were employed: variable and fixed. Fixed impairments comprised group and attenuation distortion, second-order nonlinear distortion, third-order nonlinear distortion, and phase jitter. Variable impairments consisted of the linear addition of controlled amounts of band-limited white noise prior to the coder channel.

The order in which the various fixed and variable analog impairments are introduced into the analog channel affects the absolute level of all performance parameters measured. The impairments were placed in the analog channel in the transmit direction prior to the codec under evaluation, to reproduce a worst-case configuration. Noise was always added as the last impairment in this configuration, and measurements were taken as a function of the signal-to-noise ratio (*S/N*) at the input to the codec.

The characteristics of the analog channel are in agreement with the "R-28" impairments previously employed in tests that lead to the adoption of CCITT Rec. G.721 and G.723 [3]. Figure 2 is a functional block diagram of the analog channel configuration, showing the signal levels and order of impairment introduction. (Note that nonlinear distortion and phase jitter are introduced simultaneously with band-limited noise.)

Voiceband data performance measurements

Using the eight codecs under test, the performance of the following five voiceband data modulation schemes [4] was evaluated:

- V.21 operating at 300 bit/s (upper frequency band, or channel 2)
- V.22 at 1,200 bit/s
- V.22bis at 2,400 bit/s
- V.23 at 1,200 bit/s
- V.27ter at 2,400 bit/s.

In conducting voiceband data modem tests, each measurement was made until either 20,000 blocks* were received without any blocks in error; or 50 blocks were received in error; or 50,000 blocks were received with less than 50 blocks in error; or 16 hours of test time per measurement point had elapsed; or it became apparent that the modem block error ratio (MBLER) *vs* *S/N* relationship was approaching an asymptote. In practice, measurements were often allowed to continue for longer periods, permitting 100 blocks-in-error per measurement point to be collected.

* A block was defined as a contiguous series of 511 bits.

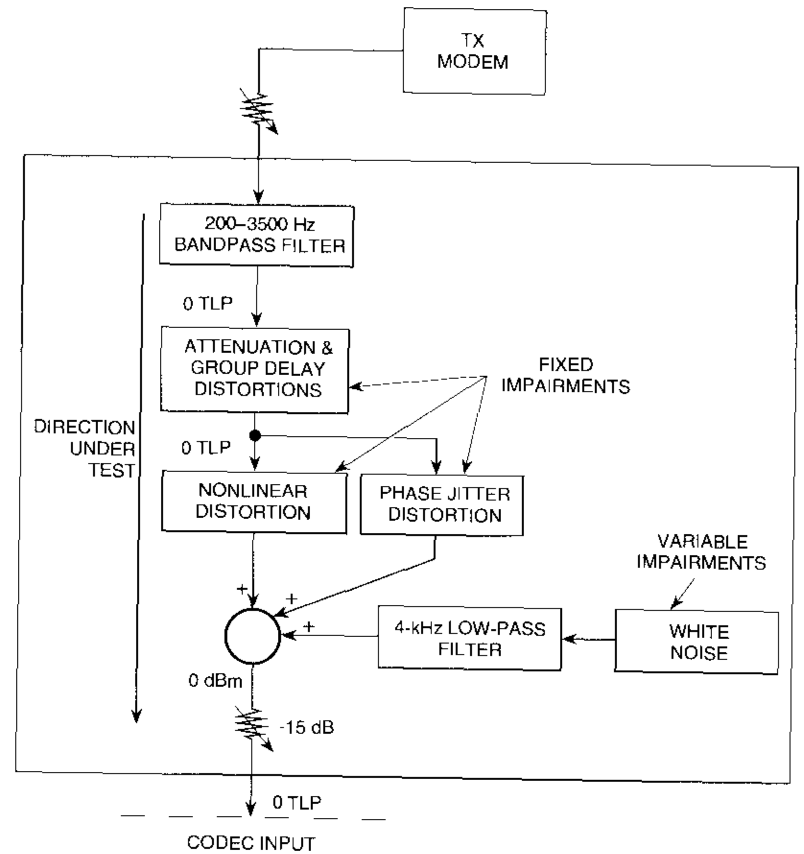
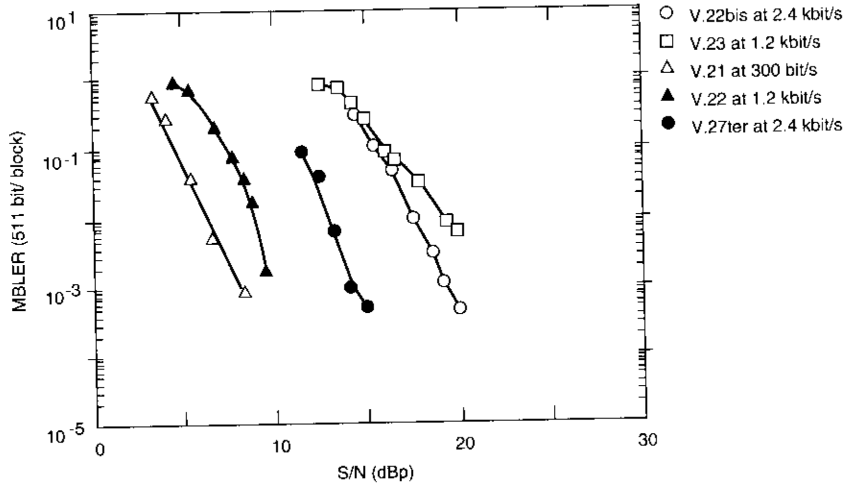


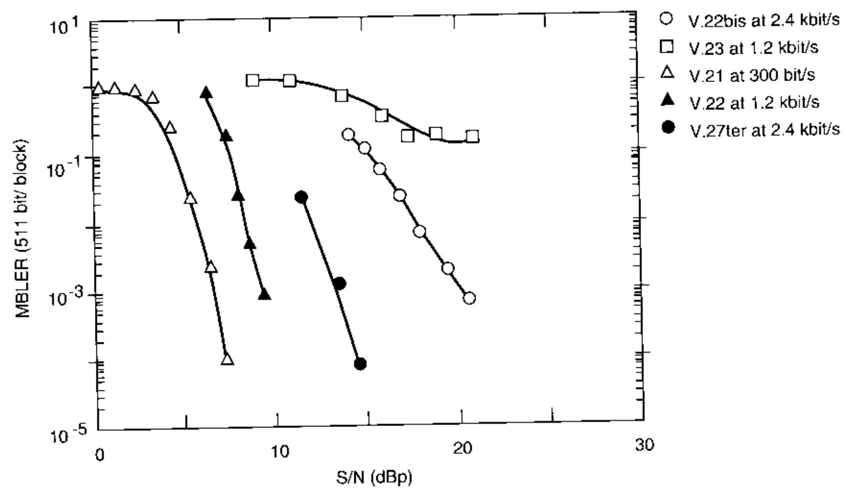
Figure 2. *Configuration of the Analog Impairment Channel*

The results obtained are summarized in the MBLER/(*S/N*) curves shown in Figure 3, for seven of the eight codecs assessed, using the five modems listed above. One of the codecs evaluated did not allow transmission of voiceband data. In all cases, the MBLER was computed based on a 511-bit block.

The evaluation revealed that most low-rate codecs (*i.e.*, coding at 16 kbit/s) offered some transparency to voiceband data transmitted at signaling rates up to 1,200 bit/s. Transparency was considered acceptable if an MBLER of less than 10^{-2} was achievable for *S/N* 30 dB. One codec (RELP) did not permit

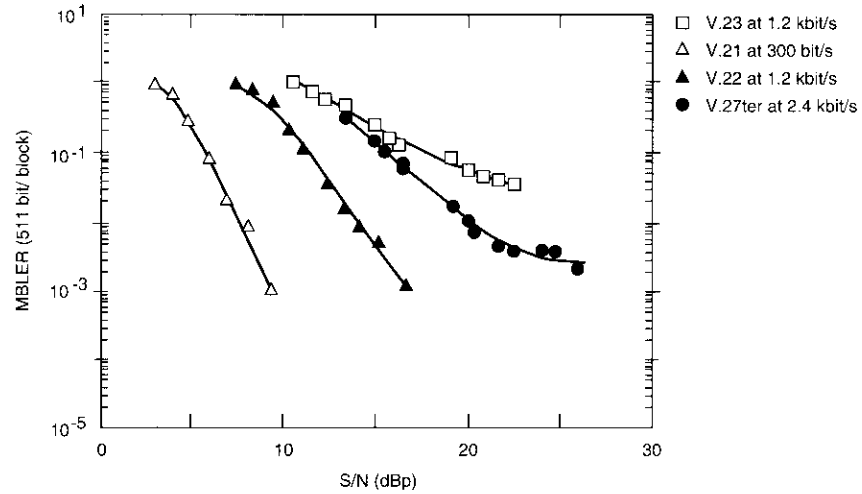


(a) CELP Codec

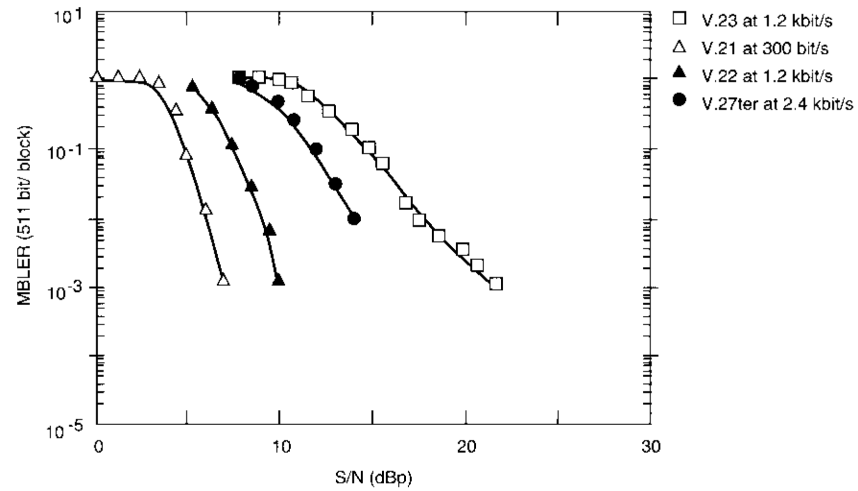


(b) ATC Codec

Figure 3. *Modem Performance*

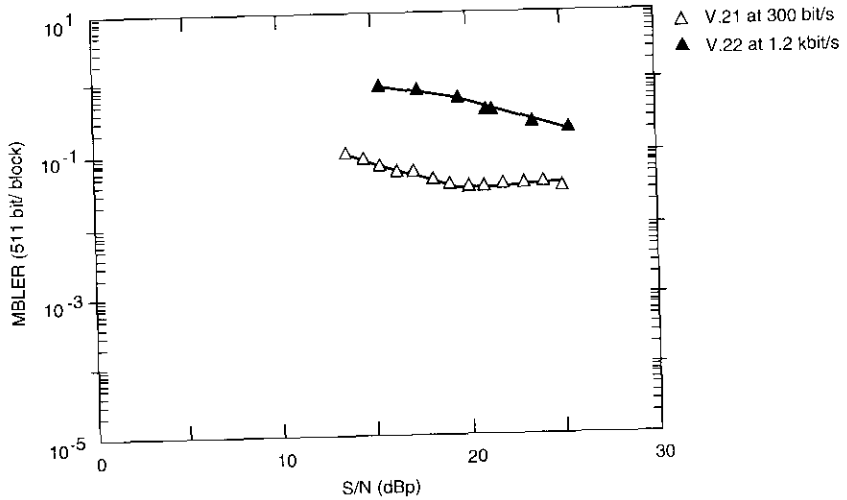


(c) CVSD Codec

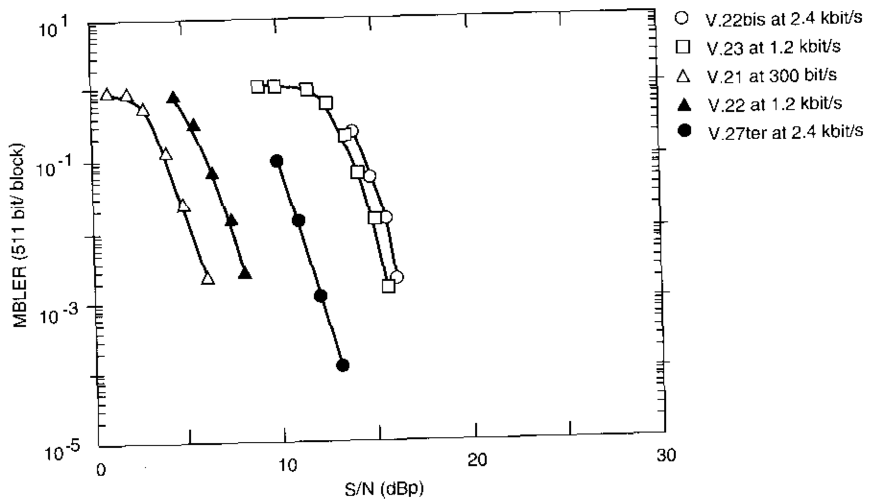


(d) APC-TQ Codec

Figure 3. *Modem Performance (cont'd)*

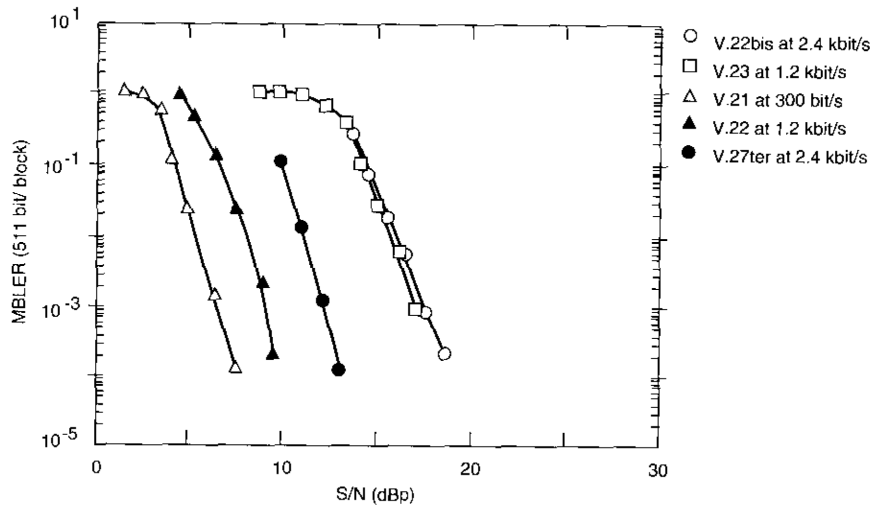


(e) V-APC Codec



(f) G.711 PCM Codec

Figure 3. *Modem Performance (cont'd)*



(g) G.721 ADPCM Codec

Figure 3. *Modem Performance (cont'd)*

any transparency to voiceband data. APC-TQ was the only codec to offer satisfactory performance with 1,200-bit/s V.23 voiceband data; the remaining low-rate codecs did not satisfactorily transmit such data.

Fewer codecs achieved satisfactory performance with the higher-speed voiceband data (*i.e.*, 2,400 bit/s). In particular, the CELP, ATC, G.711 PCM, and G.721 ADPCM were the only codecs that could accommodate 2,400 bit/s V.22bis data. The other important data—2,400-bit/s V.27ter, used in Group 3 facsimile communications—were handled satisfactorily by more codecs, as can be seen in the Figure 3 graphs for the CELP, ATC, CVSD, APC-TQ, G.711 PCM, and G.721 ADPCM codecs.

In Table 2, the circuit *S/N* condition required to achieve the selected MBLER performance threshold of 10^{-2}, where satisfactory performance was realized, is listed for each codec/modem combination. In all cases, the *S/N* ranges used in these tests were well below those that would normally be expected in the general switched telephone network (*i.e.*, *S/N* > 25 dB).

CCITT SS5 performance

In CCITT SS5, the transmitter tolerance limits of 55 ± 5 ms applicable to interregister signaling could be seriously violated by coders employing block processing frames longer than 5 ms. Since four of the codecs (APC-TQ, ATC,

TABLE 2. S/N REQUIREMENTS (IN dB) FOR VOICEBAND DATA MBLER PERFORMANCE OF 10^{-2}

MODULATION SCHEME	MODULATION RATE (bit/s)	CODEC TYPE							
		CELP	ATC	CVSD	APC-TQ	V-APC	RELP	PCM	ADPCM
V.22bis	2,400	17.50	17.00	–	–	–	–	15.60	15.80
V.27ter	2,400	12.70	11.90	20.00	13.80	–	–	10.90	11.00
V.22	1,200	8.80	8.20	14.60	9.20	–	–	7.80	7.90
V.23	1,200	19.00	–	–	17.80	–	–	15.20	15.40
V.21	300	6.00	5.70	7.60	6.00	–	–	5.50	5.50

V-APC, and RELP) were characterized by frame lengths exceeding the 5-ms tolerance, procedures were developed to assess the impact of low-rate source encoding on interregister signal recognition rates, signal pulse, and silent interval duration.

In order to assess the performance of interregister signaling as used by CCITT SS5, a test configuration similar to that used for the voiceband data measurements discussed above was employed. In this case, however, a signal level of -4 dBm (composite) was used, and the modem transmitter and receiver were replaced by a signaling generator and signaling receiver. The signaling generator provided six frequencies (700, 900, 1,100, 1,300, 1,500, and 1,700 Hz) in appropriate combinations to generate the start of pulsing KP1 and KP2 signals, the end of pulsing ST signal, the code 11 and code 12 operator response signals, and the 10 digits 0 through 9 (refer to Table 2 in Rec. Q.151 [5]). Subsequently, the signaling generator was employed so that the interregister digit whose degradation was to be assessed was repeated 10 times, preceded by the KP and followed by the ST signals. This process was repeated a minimum of 25 times for each digit and for codes 11 and 12.

The results are given in Table 3, which was constructed by summarizing the percentage of digit recognition for each circuit noise condition, as well as the interregister gap durations and pulse lengths (nominally 55 ms each) for three circuit noise conditions. However, it should be noted that the 25- and 22-dB *S/N* conditions correspond to severely degraded circuits. In most instances, a *S/N* of at least 36 dB would be expected, but at such noise levels all but one codec achieved a 100-percent recognition rate.

These results discredited the hypothesis that performance, as measured by the digit recognition rate, would be degraded by codecs with frame lengths exceeding 5 ms.

CCITT DTMF signaling performance

DTMF signaling is widely employed during call setup to transmit service addresses over the telephone network. It is also used increasingly to provide enhanced customer service, including access to remote banking, answering machine message retrieval, remote call control, and user verification. The DTMF signals consist of pairs of tones selected from a high- and low-group frequency set. The low-group frequencies are 697, 770, 852, and 941 Hz; the high-group frequencies are 1,209, 1,336, 1,477, and 1,633 Hz. Appropriate combinations of these frequencies yield the digits 1, 2, 3, 4, 5, 6, 7, 8, 9, 0 and the characters *, #, A, B, C, and D (see Figure 1 of Rec. Q.23 [6])

TABLE 3. CCITT SS5 CODEC PERFORMANCE

CODEC	RECOGNITION (%)	GAP (ms)	PULSE LENGTH (ms)
	No Noise		
CELP	100 ± 0	56.16	54.88
CVSD	100 ± 0	56.52	54.98
ATC	100 ± 0	54.68	56.77
APC-TQ	100 ± 0	55.51	55.61
V-APC	100 ± 0	55.50	56.02
RELP	97 ± 0	54.18	55.38
G.711 PCM	100 ± 0	55.52	55.57
G.721 ADPCM	100 ± 0	55.68	55.79
	***S/N* = 25 dB**		
CELP	94 ± 2	50.71	55.47
CVSD	89 ± 1	47.62	55.54
ATC	99 ± 0	52.44	57.43
APC-TQ	98 ± 0	50.01	59.51
V-APC	98 ± 0	52.63	56.66
RELP	93 ± 1	47.45	56.64
G.711 PCM	95 ± 1	50.82	55.96
G.721 ADPCM	94 ± 1	50.42	56.30
	***S/N* = 22 dB**		
CELP	83 ± 5	50.11	58.87
CVSD	83 ± 1	46.29	55.02
ATC	92 ± 1	47.45	55.59
APC-TQ	94 ± 1	47.07	59.15
V-APC	91 ± 1	49.33	55.69
RELP	79 ± 1	50.72	59.77
G.711 PCM	85 ± 1	46.80	54.83
G.721 ADPCM	78 ± 1	50.45	59.92

To evaluate the performance of DTMF signaling, a test configuration similar to the one used for the voiceband data measurements was employed. As with the SS5 measurements, a signal level of -4 dBm (composite) was used, and the modem transmitter and receiver were replaced by a DTMF signaling generator and a DTMF signaling receiver. Subsequently, the signaling generator was employed so that a sequence comprising the digits 1, 2, 3, 4, 5, 6, 7, 8, 9, 0 and the characters *, #, A, B, C, and D was repeated 100 times using a Northern Telecom Model 5900 DTMF signaling transmitter and Model 2700 universal signaling receiver. The DTMF sequence recognition percentage was then measured (with analog noise injected prior to the codec input) at a reference input *S/N* of 25 dB. Also measured were the sequence recognition percentages, with no noise injected. The results, summarized in Table 4, consist of the sequence recognition rates and gap and pulse durations (nominally 80 ms each) for the two circuit noise conditions. As with the data for CCITT SS5, the 25-dB *S/N* condition corresponds to severely degraded circuits.

From the results given in Table 4, it could be concluded that the best performance under noisy circuit conditions was not obtained by Rec. G.711 PCM or Rec. G.721 ADPCM units. However, unlike for SS5, some codecs failed to permit the error-free transmission of DTMF signaling, even under unimpaired circuit conditions. It should be noted that all codecs which prohibited error-free sequence transmission under unimpaired conditions were characterized by coding frames longer than 15 ms.

The DTMF recognition percentages were numerically lower than those realized for SS5. These differences can be attributed to three factors. First, the signal characteristics for DTMF signaling may be less suited to the voice codecs' characteristics. Second, the recognition rates measured for DTMF signaling were computed based on a 10-digit sequence, as compared to the SS5 recognition rates which were computed on the basis of a single-digit recognition success rate. Third, the measured recognition rates were dependent on the exact characteristics of the signal generators and receivers, which presumably could offer varying levels of performance.

V.25 echo control tone

It is possible that a V.25 echo control tone (with phase reversals) can be distorted due to the introduction of quantization and/or block processing distortion by the codecs. To assess this type of degradation, a modulated 2,100-Hz sine wave consisting of a sequence of 180° phase transitions inserted at 400-ms intervals was recorded through each codec. This waveform was also recorded (after phase alignment) through a direct (unprocessed)

TABLE 4. DTMF SEQUENCE RECOGNITION PERFORMANCE

CODEC	SEQUENCE RECOGNITION (%)	GAP DURATION (ms)	PULSE LENGTH (ms)
	No Noise		
CELP	100 ± 0	79.39	81.62
ATC	98 ± 3	78.07	82.93
CVSD	100 ± 0	79.48	81.55
APC-TQ	86 ± 7	77.53	81.96
V-APC	100 ± 0	79.23	81.88
RELP	40 ± 10	78.05	78.65
G.711 PCM	100 ± 0	78.89	82.15
G.721 ADPCM	100 ± 0	79.10	81.92
	***S/N* = 25 dB**		
CELP	22 ± 8	114.40	99.35
ATC	38 ± 10	101.39	95.11
CVSD	1 ± 2	144.74	179.16
APC-TQ	19 ± 8	88.57	86.97
V-APC	85 ± 7	86.12	89.16
RELP	3 ± 3	133.33	156.44
G.711 PCM	20 ± 8	114.41	99.75
G.721 ADPCM	16 ± 7	110.06	98.44

recording path. The two waveforms generated for each codec were then compared, in accordance with the functional configuration shown in Figure 4, and the settling time of the processed waveform in the neighborhood of the phase transition was measured. In all cases, the phase of the waveforms processed by the codecs was eventually reversed; that is, the 180° transition was always eventually realized. Thus, each codec's performance was not measured in terms of its ability to permit the 180° transition to occur, but rather in terms of how quickly it permitted the 180° phase transition to stabilize following initiation of the phase transition.

The settling times for each codec are given in Table 5. Most codecs were associated with settling times that met or exceeded the settling time performance of the Rec. G.711 PCM unit, which was 1.68 ms. This delay is dependent upon both the hardware implementation and the algorithm characteristics. For one codec (RELP), the settling time was 15 times greater than the next shortest settling time, for CELP. However, since there are no maximum requirements for settling times immediately following a phase transition, it was not possible to determine whether the performance obtained by the RELP codec would be acceptable.

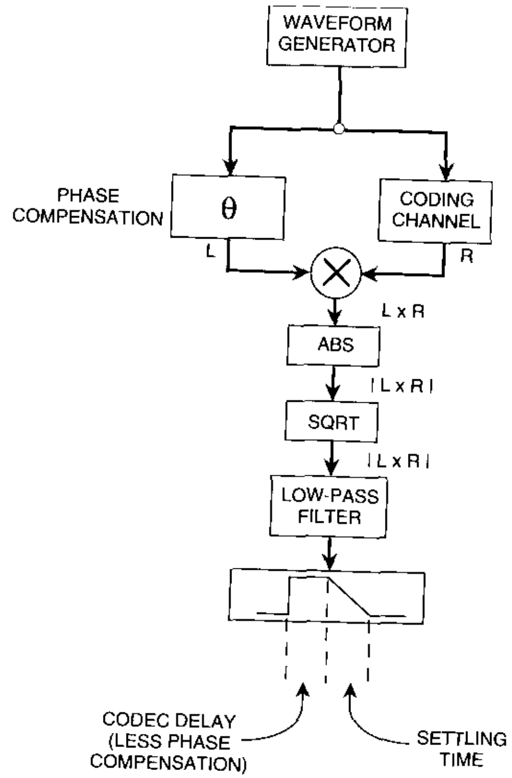


Figure 4. *Functional Diagram of V.25 Phase Distortion Measurement Configuration*

Input/output delay

Coding delay is an important parameter that must be quantified to enable appropriate network planning on an end-to-end basis. In waveform coders, measurements of delay rarely present a problem, since a direct assessment of the elapsed time between the signal onset at the codec input and the signal appearance at the codec output is possible (*e.g.*, using a modulated sine wave).

TABLE 5. SETTLING TIMES FOR EACH CODEC IN THE PROXIMITY OF A 2,100-HZ TONE 180° PHASE TRANSITION

CODEC TYPE	SETTLING TIME (ms)
ATC	1.08
CVSD	1.14
G.721 ADPCM	1.40
V-APC	1.40
G.711 PCM	1.68
APC-TQ	1.68
CELP	3.44
RELP	53.80

However, in block processing coders (or when little is known about the actual technique employed), this approach may be unreliable because codec performance could vary substantially with the nature and type of signal being encoded, as well as with the precise time at which a signal appears at the codec input (in relation to the coder's frame structure, if there is one). The technique adopted here employed an artificial voice signal to minimize narrowband signal limitations.

The method selected allowed the total delay introduced by a codec to be measured between its input and output 8-bit companded PCM interfaces. This was accomplished by observing the location of the maximum peak of the cross correlation function between the encoder input and decoder output signals. This delay consisted of the delay introduced by the algorithm encoding and decoding functions, as well as any additional delay introduced by the processing or the specific algorithm hardware implementation. The exact method used depended on an examination of the peak response of an adaptive finite impulse response (FIR) filter in a joint linear-process estimator configuration, as shown in Figure 5. An artificial speech signal was employed at a nominal codec input level of -22 dBm0 for this measurement.

In addition to the method described above, a second technique for obtaining the same information without direct observation of the filter response was applied. This approach involved measuring the energy of the signal resulting from the subtraction of the filter response from the codec output, which is a consequence of the finite width of a FIR filter. The method relied on introducing a variable amount of delay before the estimating FIR filter. Subsequently, as

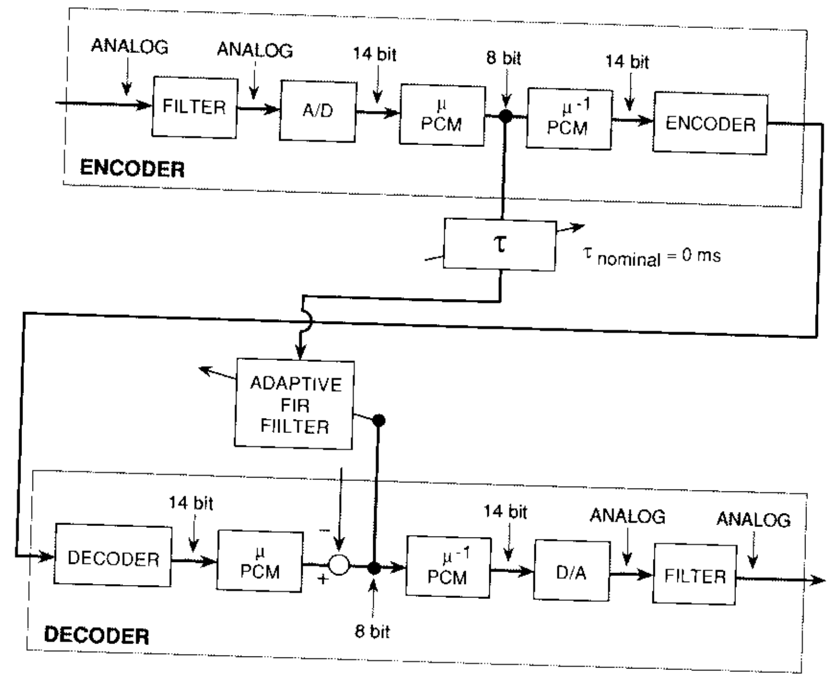


Figure 5. *Measurement of Codec Delay*

this delay was increased from zero to a value equal to the delay of the coder, the effect was to slide the FIR window into, and then past, the range in which the estimated signal contained most of its power. For example, consider a coder which introduced a delay equal to 40 ms and a FIR filter associated with a window width of 32 ms. When the variable delay is set to 0 ms, the FIR processing window will be outside the range of the response to be estimated, and consequently the error signal power will be high. When the variable delay reaches a value of 40 – 32 = 8 ms, the FIR processing window is just beginning to overlap the peak of the response to be estimated. At this point, the noise power decreases substantially, giving the first estimate of coder delay (32 + 8 ms). As the variable delay then approaches the 40-ms value, the FIR processing window is forced to move outside the response range to be estimated, resulting in another noise power increase, which gives a second estimate of coder delay (40 ms).

The delay values obtained for each codec are summarized in Table 6. The measured delay consists of two additive components: the algorithmic delay and the implementation delay.

TABLE 6. MEASURED CODEC DELAY

CODEC TYPE	DELAY (ms)
CELP	3.5
ATC	65.0
CVSD	0.3
APC-TQ	80.0
V-APC	51.0
RELP	32.0
G.711 PCM	0.1
G.721 ADPCM	0.8

Narrowband performance measurements

A number of narrowband measurements were obtained to specifically characterize the quantization, dynamic range, and nonlinear distortion performance of each of the eight codecs evaluated. In obtaining these measurements, the procedures defined in Rec. G.712 [7] were adopted. The results are summarized in Table 7. Some of the codecs evaluated offered both voice and data modes of operation. When both modes were available, the data mode of operation was used for the voiceband data measurements presented previously. The voice mode of operation was used for all other measurements (*e.g.*, signaling measurements). From these results, and by reference to Rec. G.712 [7], it was determined that most codecs met the narrowband signal performance requirements applicable to PCM encoding at 64 kbit/s.

Conclusions

None of the low-rate codecs evaluated was able to accommodate voiceband data signaling rates in excess of 2.4 kbit/s with acceptable quality. On the other hand, with signaling, most codecs (other than ATC, APC-TQ, and RELP) offered satisfactory performance at 16 kbit/s. In most cases, the narrowband signal performance requirements of Rec. G.712 applicable to PCM encoding at 64 kbit/s were met by codecs operating at 16 kbit/s.

The fact that satisfactory performance can be obtained with voice signals and network signaling indicates that current 16-kbit/s voice coding technology is suitable for special applications within the public-switched telephone network

TABLE 7. CODEC NARROWBAND SIGNAL CHARACTERIZATION

CHARACTERISTIC	CELP*		ATC*		CVSD	APC-TQ*		V-APC	RELP	G.711 PCM	G.721 ADPCM	G.712 THRESHOLDS
	VOICE	DATA	VOICE	DATA		VOICE	DATA					
Phase Jitter (deg)	±3.3	±1	±1.9	±4.8	±12.0	±0.6	±8.1	±6.6	±13.0	±0.7	±1.9	—
Amplitude Jitter (%)	±3.2	±4.7	±6.6	±5.6	±16	±0.4	±14.2	±7.0	±10.5	±1.8	±2.3	—
2nd-Order Harmonic Distortion at -4 dBm0 (dB)	-58	-61	-45	-57	-22	-49	-36	-54	-56	-63	-49	-46
3rd-Order Harmonic Distortion at -4 dBm0 (dB)	-57.5	-61	-52	-61	-25	-62	-16	-55	-57	-65	-52	-53
Nonlinear Distortion at -4 dBm0 (dB)	-29	-51.8	-27	-26	-28.0	-38.5	-13.8	-48	-49	-54	-47	-44
Nonlinear Distortion at -15 dBm0 (dB)	-29	-51.8	-27.5	-25.5	-28.4	-38.5	-13.8	-48	-49	-54	-49	-44
Single-Tone *S/Q* Noise at -15 dBm0 (dB)	35	38	29	31	16.6	56.2	15.9	42	34	40	34	33
Single-Tone *S/Q* Noise at -22 dBm0 (dB)	34	37	28	30	16.9	52.9	15.9	41	32.5	39	33	33
Idle Channel Noise (Tel. Weight) (dBmP)	-77	-77	-75.0	-75.2	-57.2	-79.2	-82.5	-72.9	-75.7	-77	-75.9	-65
Codec Input/Output Delay (ms)	3.5	3.5	65	65	0.3	40	40	51	31	0.1	0.8	—

*"Voice" and "Data" indicate the voice and data modes.

(PSTN), where voiceband data are not used, or where alternate facilities are provided to accommodate such traffic. These applications include DCME, packet circuit multiplication equipment, asynchronous transfer mode (ATM), integrated services digital network videotelephony, and digital microcellular networks. None of the 16-kbit/s voice codecs evaluated is suitable for indiscriminate use in the North American PSTN.

Acknowledgments

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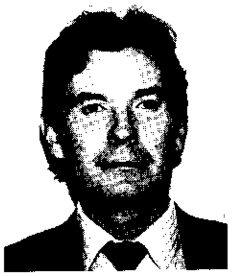

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Translations of Abstracts

Un satellite hautement fiabilisé

C. E. JOHNSON, R. R. PERSINGER, J. J. LEMON ET K. J. VOLKERT

Sommaire

Cet article décrit la méthode de surveillance extrêmement efficace et minutieuse utilisée pour tous les satellites INTELSAT depuis l'INTELSAT IV. Du fait que l'INTELSAT VI est le plus gros satellite de télécommunications commerciales mis en service jusqu'ici, il a posé maints problèmes nouveaux et complexes au constructeur. Des plans d'essai, des essais et un programme de surveillance très poussés ont été mis au point et exécutés. Les principaux éléments de ce programme sont exposés ici. L'article donne aussi un aperçu du programme d'essais au sol—du niveau unitaire jusqu'à l'aire de lancement—et fait le point sur le système de traitement de données d'essai et son utilisation. Il passe également en revue les essais particuliers au programme INTELSAT VI, qui englobent les mesures et essais d'antennes en chambre anéchoïde en champ proche, installations comprises, le déploiement du générateur solaire et des antennes à réflecteur avec compensation de la pesanteur, et les essais de décharge électrostatique. Enfin, l'article examine certains des problémes (et leurs solutions) soulevés par la taille gigantesque du satellite et le changement de lanceurs.

Lancement, mise en poste et tests sur orbite de l'INTELSAT VI

L. S. VIRDEE, T. L. EDWARDS, A. J. CORIO ET T. RUSH

Sommaire

Cet article décrit la planification et les ressources qui ont assuré le succès des lancements, des opérations postérieures aux lancements et des tests sur orbite de la série de satellites INTELSAT VI. Il rappelle les années d'efforts de planification des lancements et de l'exploitation des satellites, et relate les missions d'INTELSAT en se concentrant sur les opérations à la base de lancement et les manoeuvres sur orbite, le pilotage et la mise en poste des satellites. Une fois placés sur orbite, tous les nouveaux satellites INTELSAT subissent des vérifications complètes de la plate-forme et de la charge utile avant leur mise en service. Enfin, l'article décrit les tests sur orbite de la plate-forme des INTELSAT VI.