COMSAT LABORATORIES

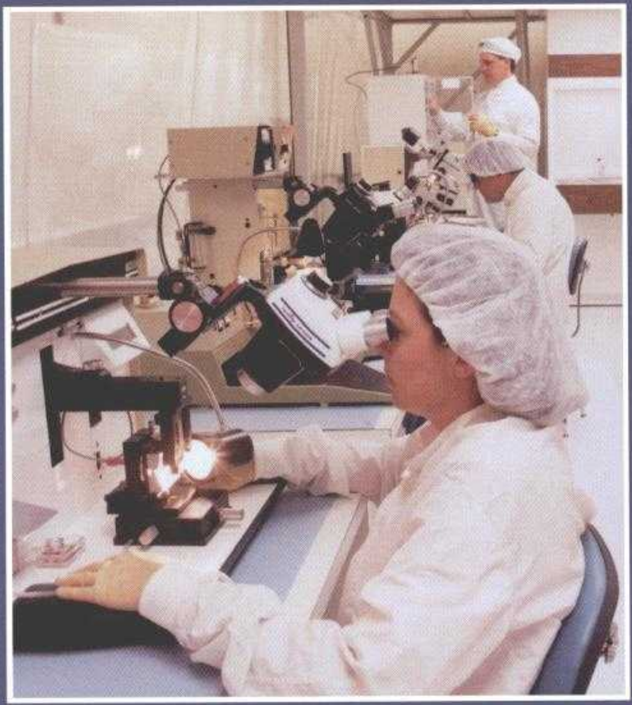
ANNUAL REVIEW

1990

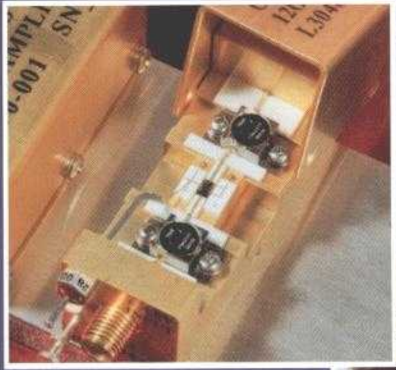
COMSAT

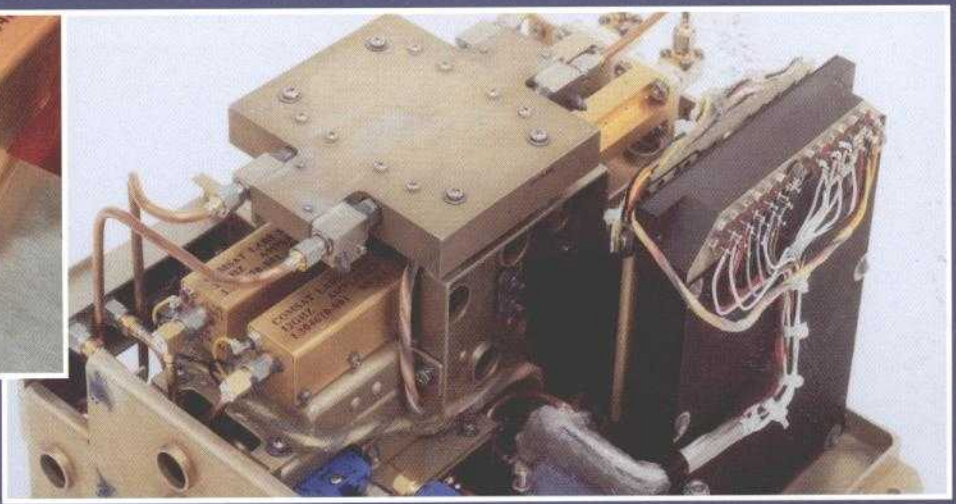
COMSAT Laboratories • 22300 COMSAT Drive • Clarksburg, MD 20871 • Telephone 301-428-4000 • Telex 440696

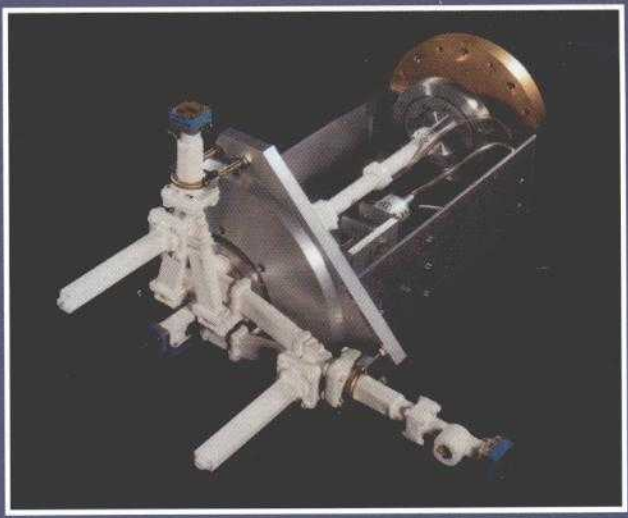
Microwave Technology and Systems Division



The Microwave Technology and Systems Division (MTSD) of COMSAT Laboratories is responsible for developing state-of-the-art hardware for communications satellites and earth stations, defining future satellite architectures, and providing technical support for ongoing satellite programs. MTSD has a clean-room assembly and test facility (left) to produce space-qualified components and subsystems. Recently delivered hardware includes the in-orbit test transponder for ITALSAT (below right), a 30/20-GHz diplexer for the Advanced Communications Technology Satellite (ACTS) Program (bottom right), and gain-standard horns for the National Institute of Standards and Technology (bottom left).

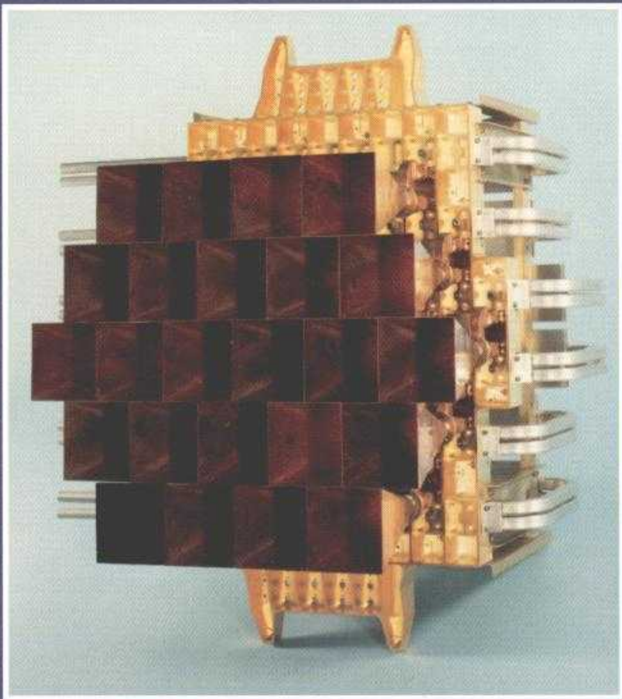


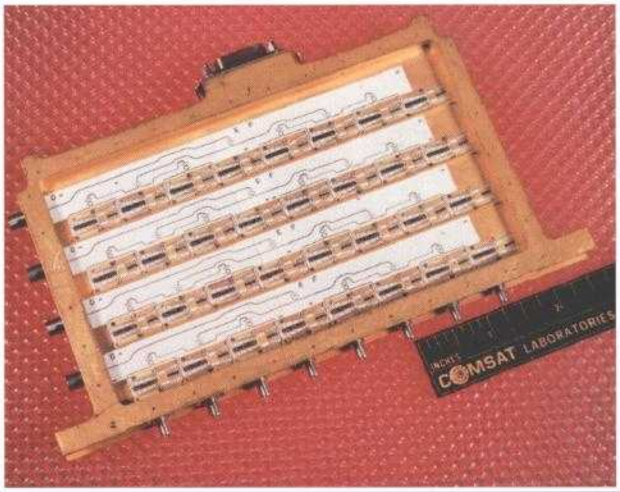


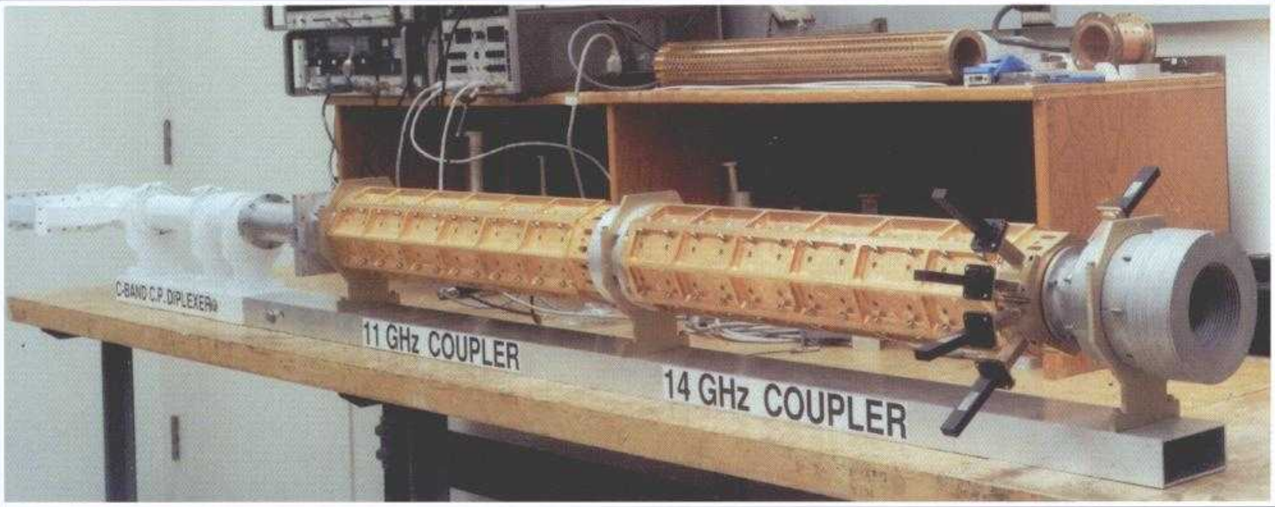


MTSD

MTSD's research and development is directed toward the realization of key technologies for implementing low-cost, power-efficient, reliable communications satellite systems. Technologies under development include a 24-element high-power phased array (right) capable of generating four independently steerable beams using a beam forming matrix (below right), a C-band multibeam phased array, a dual circularly polarized flat plate antenna, (below left), and a dual C- and Ku-band feed (bottom) for earth station antennas. Recently demonstrated technologies using MMICs include a C-band microwave switch matrix and a Ku-band, 64-element, low-power transmit array which can produce a steerable and/or a shaped beam.

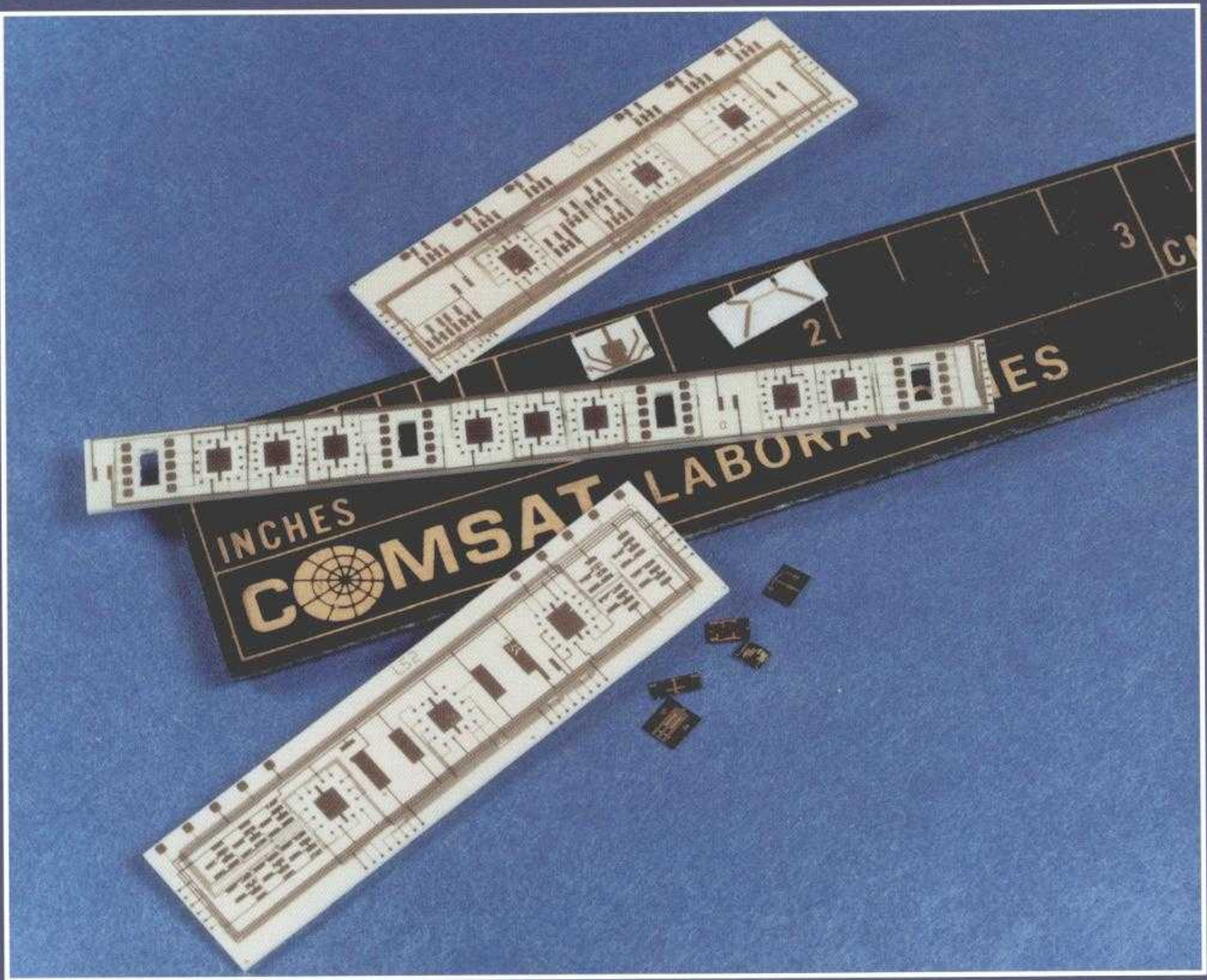




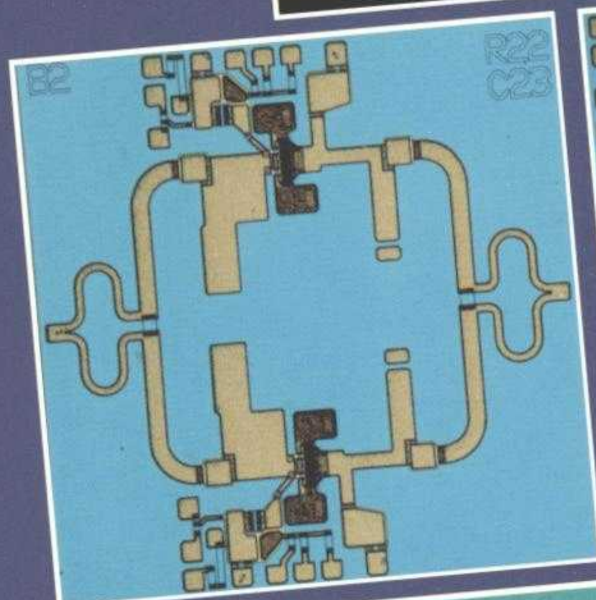


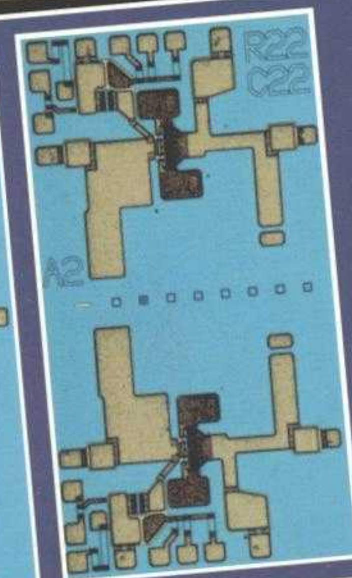
Microelectronics Division

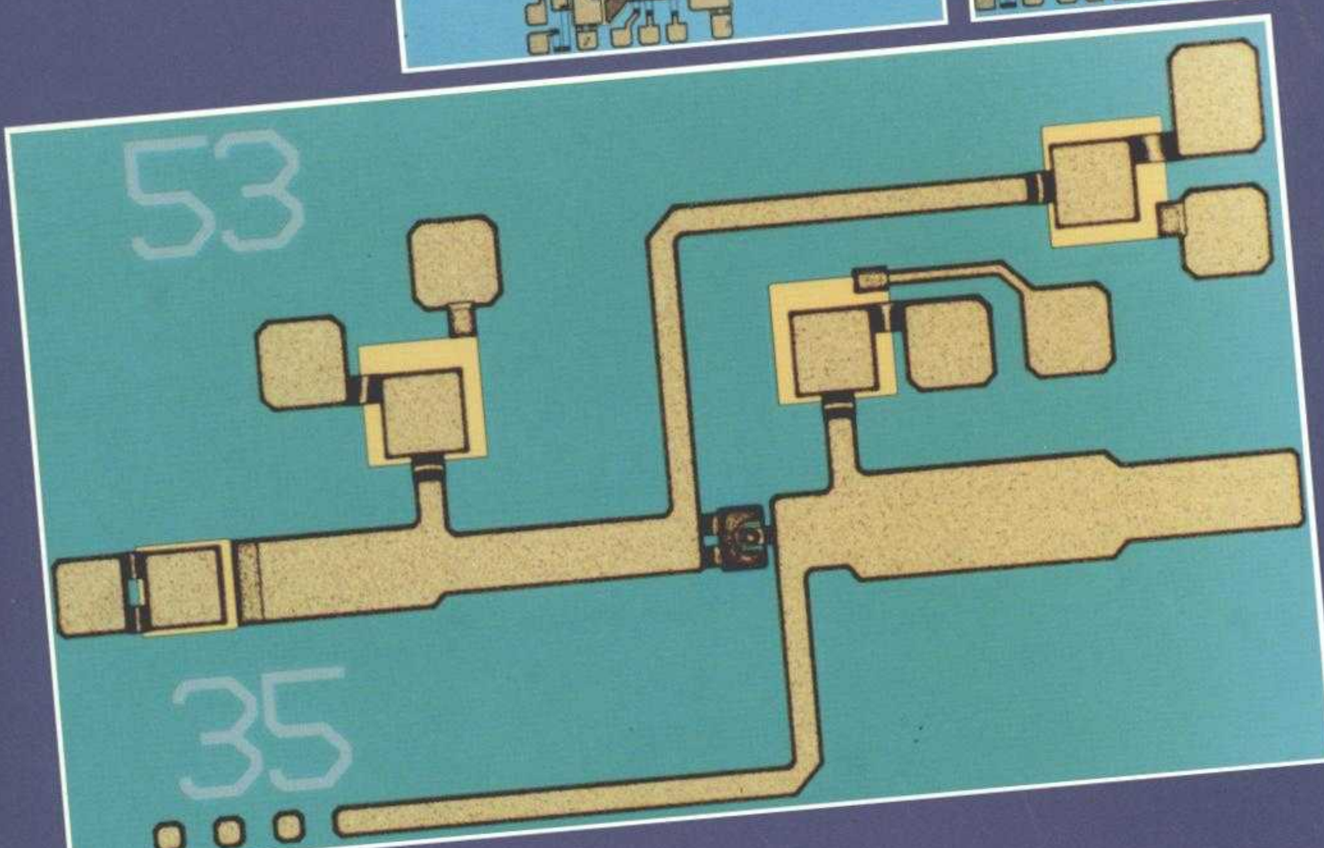
A micro-world of monolithic microwave integrated circuits (MMICs) is being developed by the Microelectronics Division (MED) at COMSAT Laboratories. MED designs, fabricates, assembles, and tests microwave components for internal applications in future communications satellites and ground stations, radar, missile seekers, communications systems, and electronic countermeasures for external customers. MMIC insertion is expected to improve system affordability, performance, and



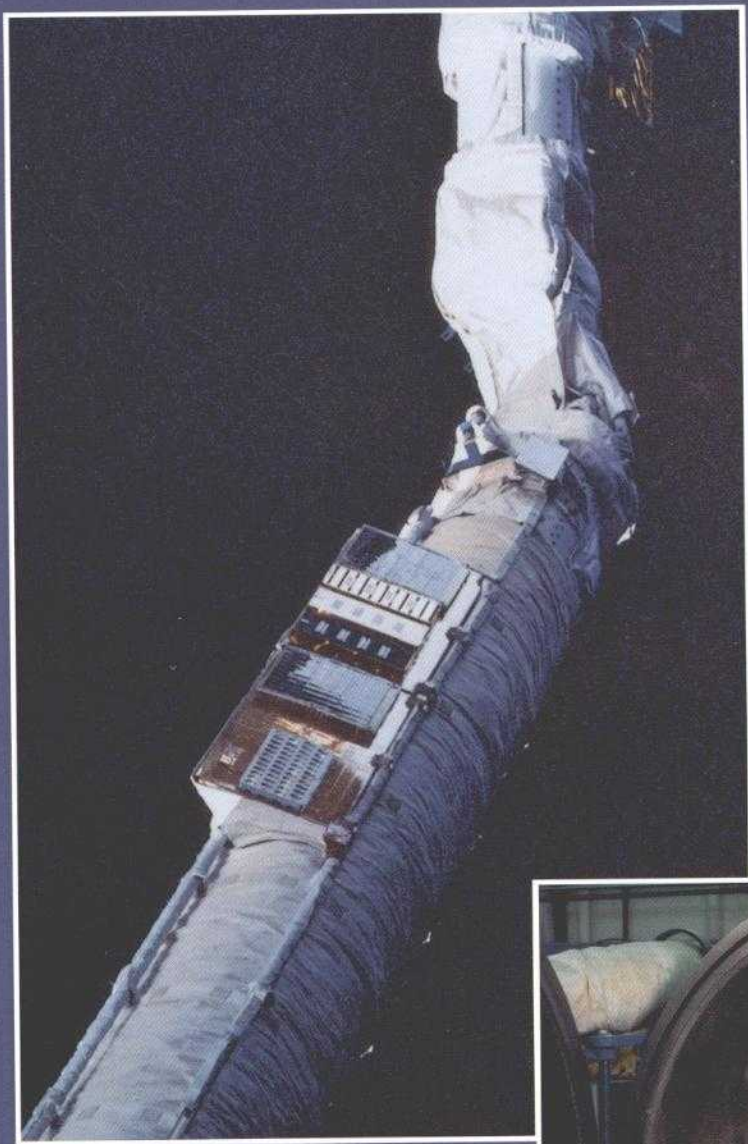
reliability while retaining the form and function of hybrid circuits. MED supports a number of subsystems through MMIC insertion, including the 64-element Ku-band phased-array antenna, switch matrixes, and active monolithic filters for satellite communications. In addition, MED has developed transmit/receive modules for advanced tactical radar, and Ka-band power amplifier modules for millimeter-wave seeker applications.



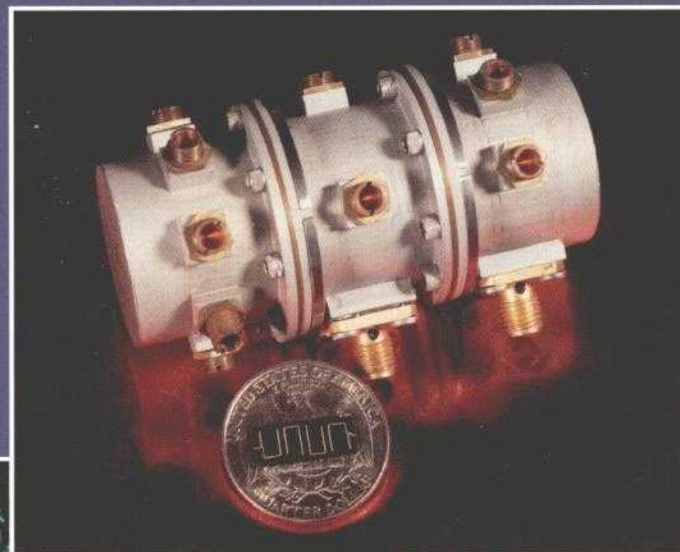




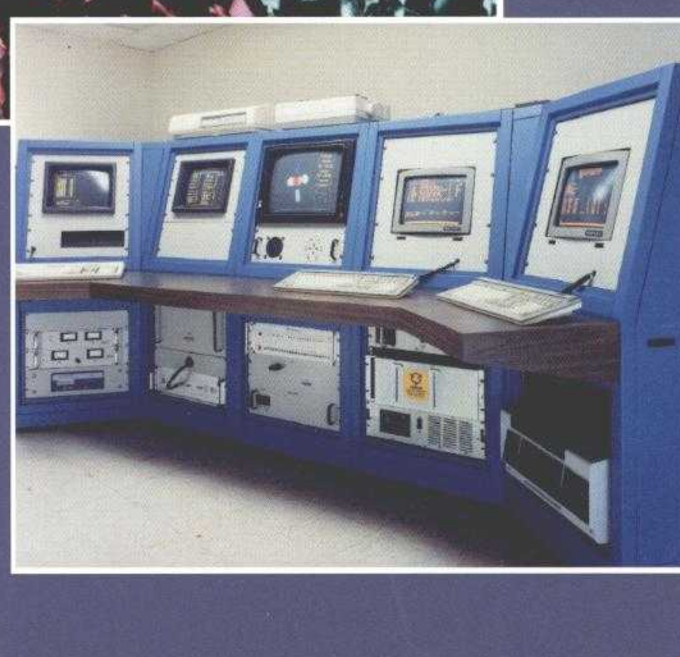
Satellite Technology Division



The Satellite Technologies Division (STD) of COMSAT Laboratories conducts research, development, and support activities in a number of technical areas important to the Corporation, including the technological development of advanced communications satellite concepts that employ multibeam and on-board processing. STD also provides a broad range of engineering skills in disciplines related to satellite attitude control and dynamics, structures, telemetry and command, mechanisms, thermal control, power systems, energy conversion and storage, and environmental and qualification testing.

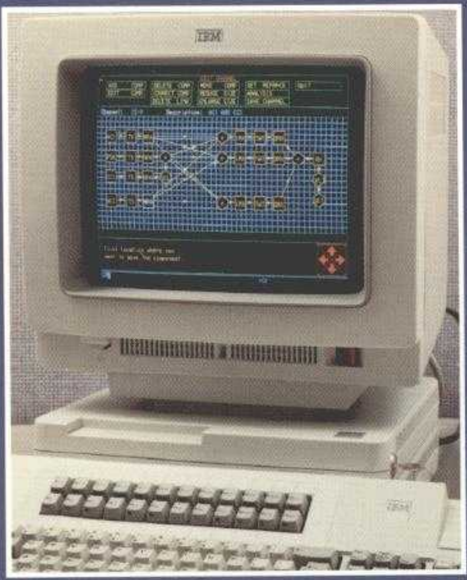


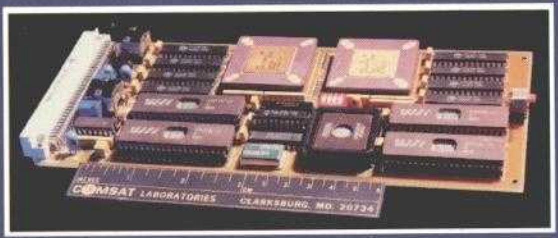

COMSAT



Communications Technology Division

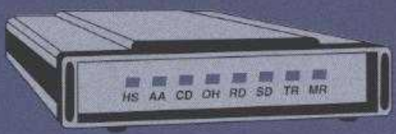
COMMUNICATIONS SYSTEM DESIGN, EN



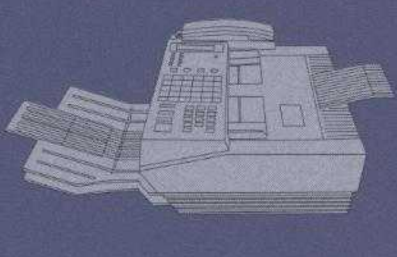


AUDIO
- Voice
- DCME
- TMUX
- Fax Compression
- Fax/Data Interfacing
- Echo Control
- Digital Broadcast Audio

VIDEO
- Time-Compressed TV
- Digital TV
- Mod. NTSC
- HDTV
- N-MAC



TERRESTRIAL INTERFACE

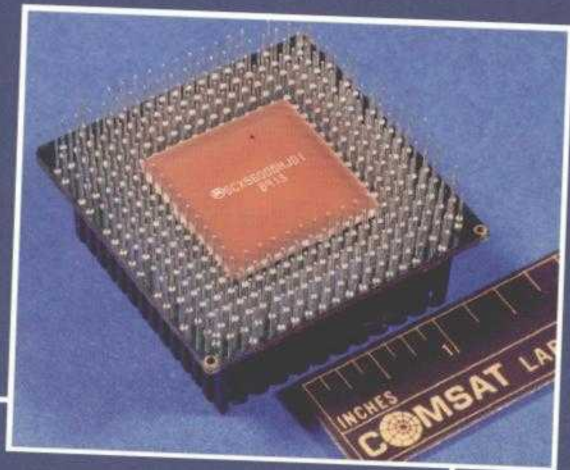


SIGNAL PROCESSING TECHNOLOGY

MOBILE AND PERSONAL T

CTD

N, ENGINEERING, SIMULATION AND TESTING

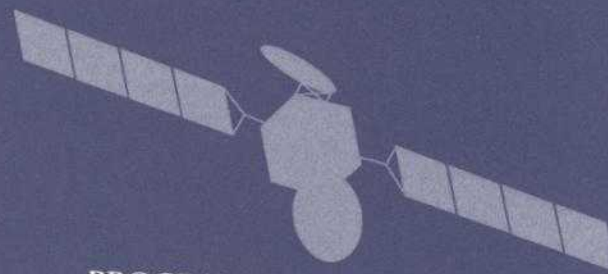


CODECS
- Block
- Viterbi
- Reed-Solomon

MODEMS
- µP and DSP Based
- Programmable, Digitally Implemented
- High-Speed Burst
- Trellis Coded
- COPSK

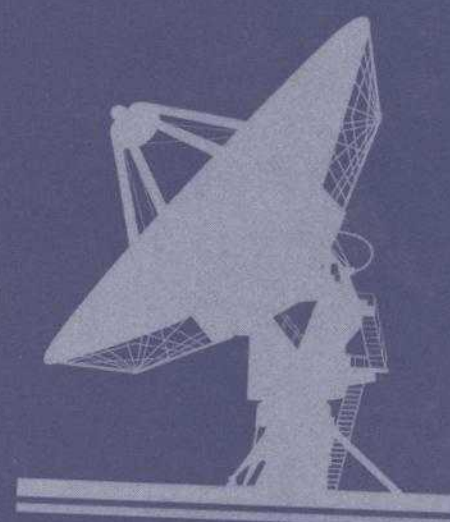
ENCRYPTION

CDMA



PROGRAMMABLE ON-BOARD DEMUX/DEMOD

ADAPTIVE EQUALIZATION



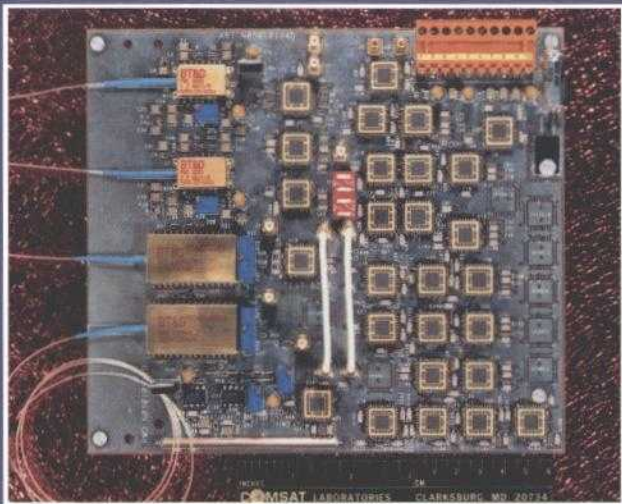
The Communications Technology Division (CTD) efforts encompass all communications aspects of the end-to-end circuit connection. CTD conducts research and development and provides technical support for transmission, video, and voice frequency band processing; systems simulation; and systems analysis and synthesis. Advanced communications system architectures and technologies are used extensively to achieve the lower equipment costs and improved transmission efficiency necessary to maintain the competitiveness of satellite communications. The widespread application of digital signal processing techniques is required to support these advanced architectures and technologies.

TRANSMISSION PROCESSING TECHNOLOGY

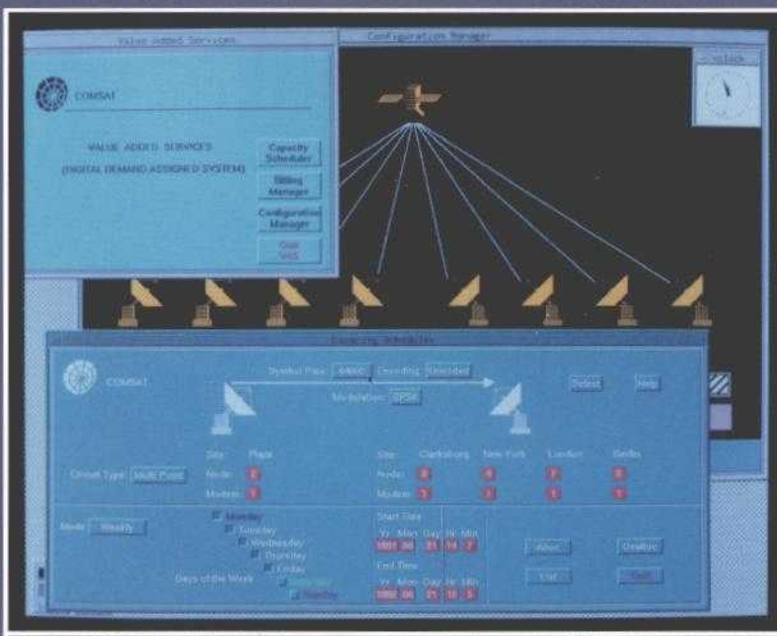
ON-BOARD PROCESSING TECHNOLOGY

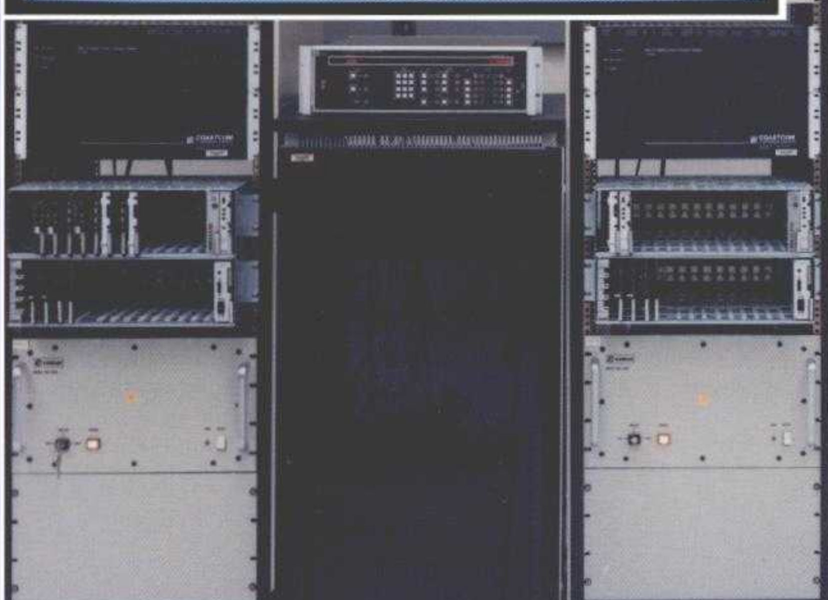
TERMINAL TECHNOLOGY

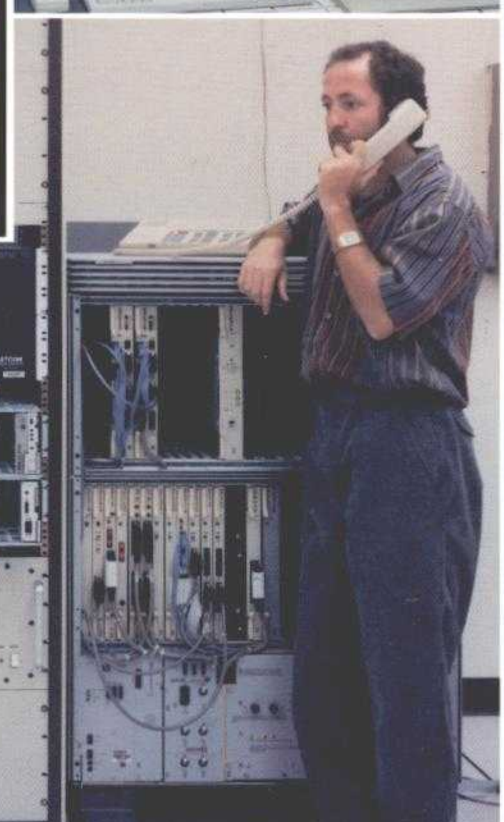
Network Technology Division



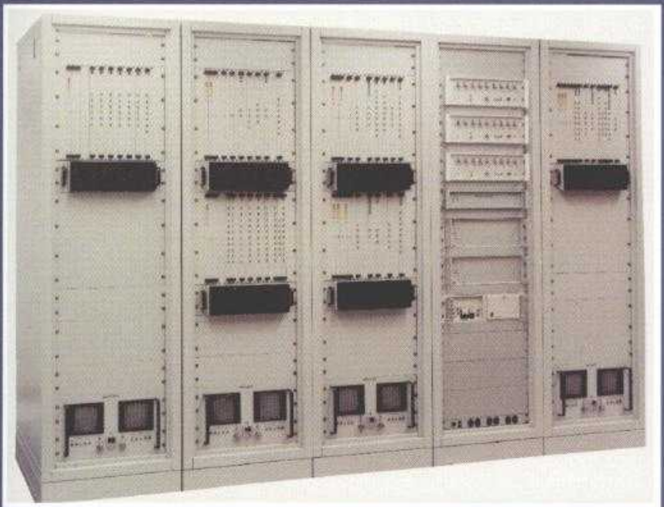
The Network Technology Division (NTD) of COMSAT Laboratories performs research and development related to the analysis, design, implementation and testing of advanced satellite- and terrestrial-based communications systems. Application areas include fixed and mobile satellite networks, on-board baseband switching and processing, integrated services digital networks, data communications and protocols, time-division multiple access, intelligent systems, and optical communications and processing.

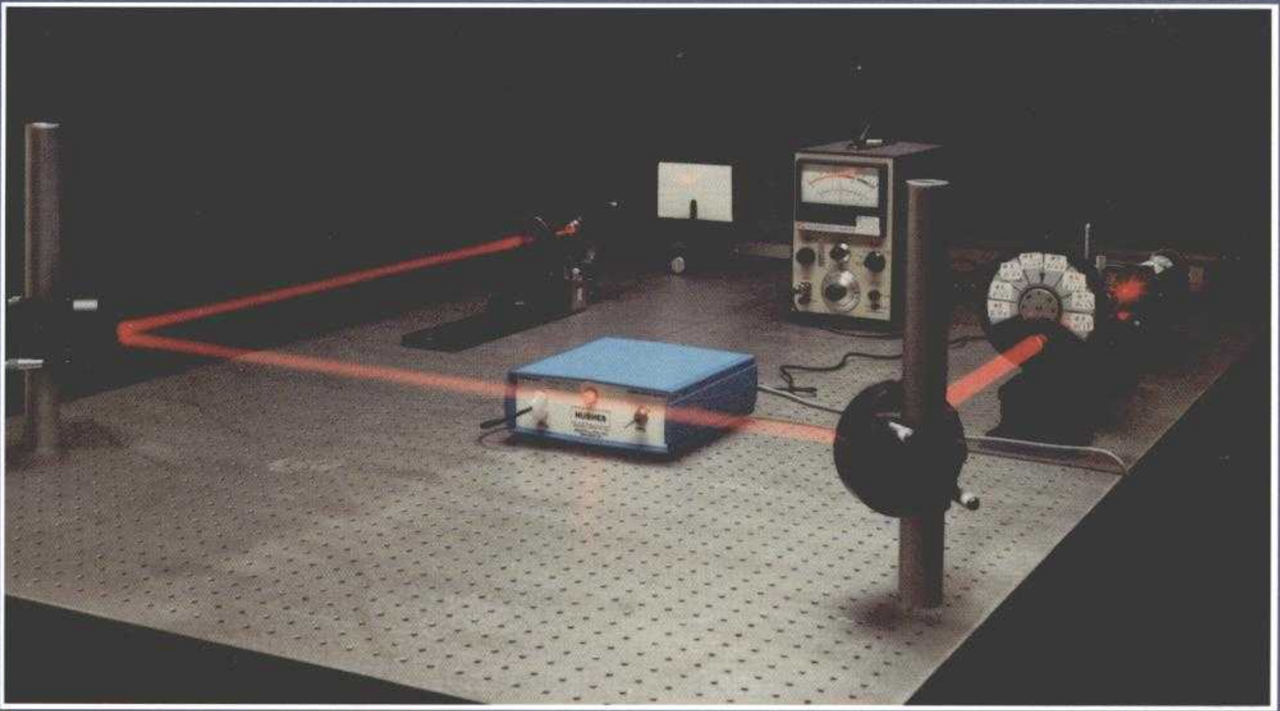




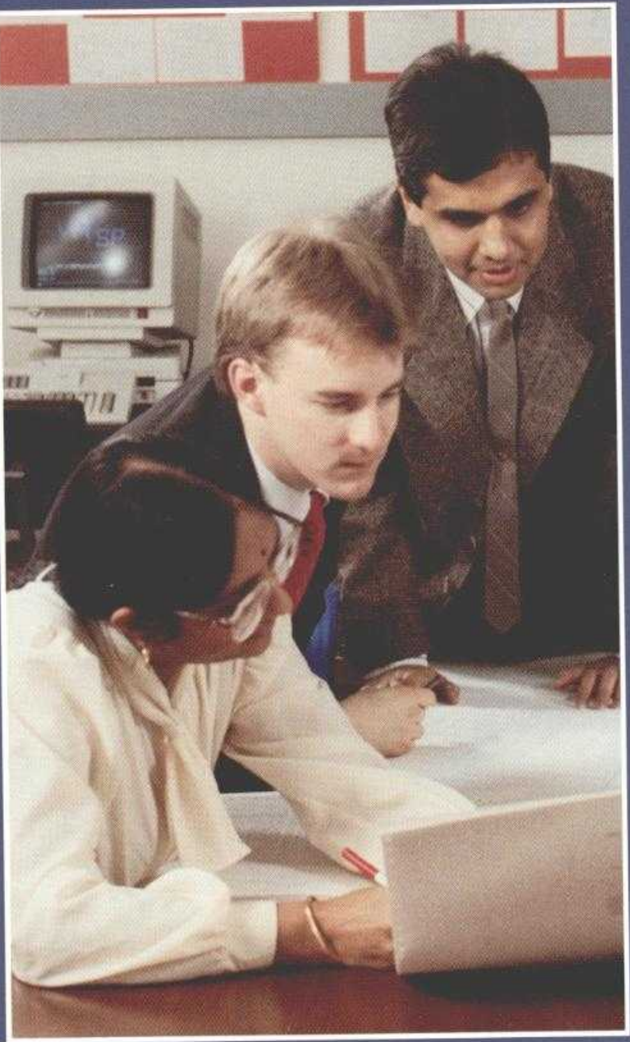


DIVISION HIGHLIGHTS

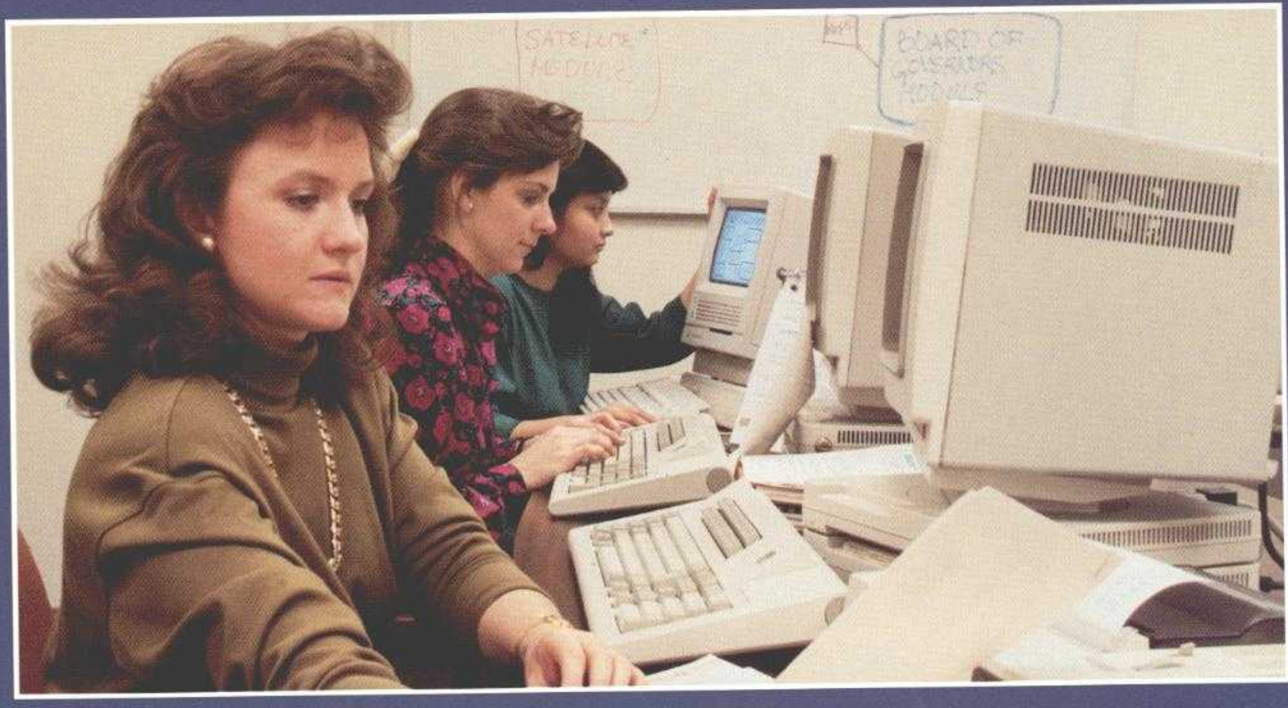



HUGHES

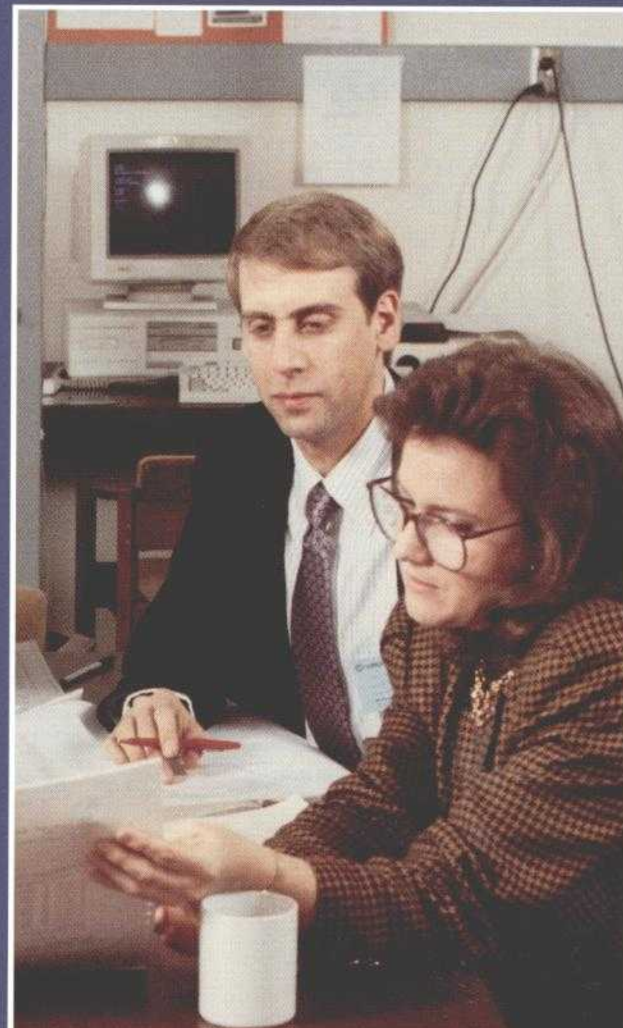
System Development Division



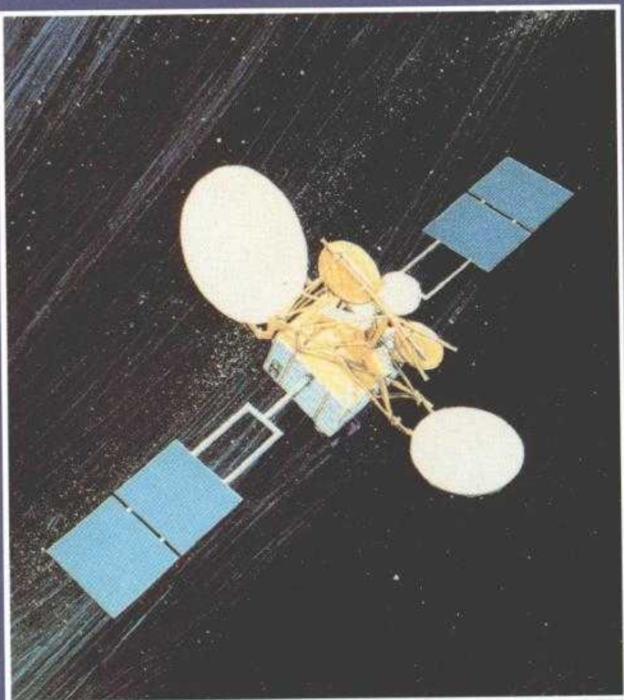
The System Development Division (SDD) performs software research and development. Activities of the division encompass the development of computer-based systems, including the design and implementation of software and the selection, acquisition, integration, and installation of hardware. The division is responsible for designing and implementing real-time systems, developing modeling and simulation tools, and establishing standards, methodologies, and tools that will improve the overall software development process within COMSAT and yield highly reliable, easily maintained software products.



Communications system monitoring and control systems and measurement systems are examples of typical real-time development applications. Modeling and simulation tools are used to evaluate and optimize satellite communications systems and subsystems and include programs that predict transmission impairments and plan the deployment of satellite resources. Research tasks explore and define new software technologies and techniques such as computer-aided software engineering tools, user interface systems, languages, operating systems, computing platforms, and development methodologies.

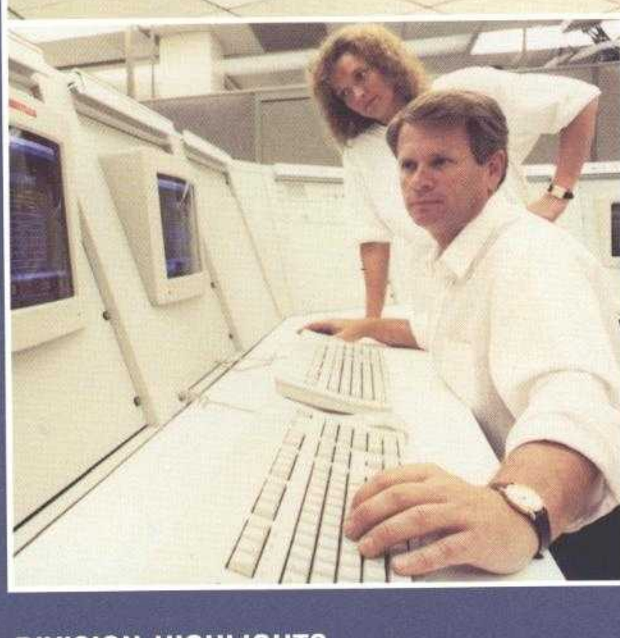


Advanced Communications Technology Satellite

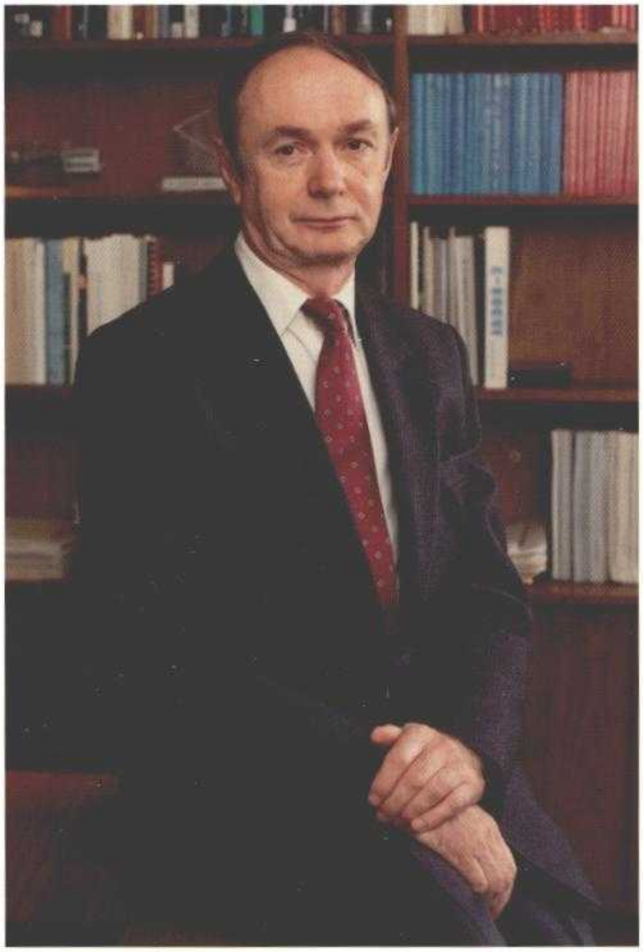


In 1984, the National Aeronautics and Space Administration (NASA), a dominant force in satellite communications technology, undertook a new research and development program: the Advanced Communications Technology Satellite (ACTS) Program. Program goals were the development of basic technologies to ensure the availability of adequate and affordable satellite communications beyond the year 1990, and the continued availability of U.S. satellite communications resources by effectively utilizing the limited resources of the geostationary orbital arc.

Under direct contract to NASA's Lewis Research Center (LeRC), COMSAT is responsible



for developing the Ground Segment equipment, including the NASA Ground Station (NGS) and the Master Control Station (MCS). This past year saw the completion of nearly all of the Ground Segment hardware and software, and major progress made in the integration and test of the NGS/MCS subsystems. Thus, the overall goal of developing basic technologies to ensure the continuing preeminence of U.S. technology in the satellite communications industry is being realized. By combining its outstanding technical resources with a highly effective program management team, COMSAT Laboratories is demonstrating that it is capable of organizing and managing a large systems development and integration program.



COMSAT Laboratories conducts a program of basic research and development to advance satellite communications technology. Elements of the program are funded by COMSAT World Systems and COMSAT Mobile Communications (formerly Intelsat Satellite Services and Mobile Communications, respectively), and are paid for from revenues derived from international communications services carried via the INTELSAT and Inmarsat organizations. Other work is funded by nonregulated components of the Corporation. Documentation concerning jurisdictional work (that is, work wholly or partially funded by the rate payer) is made available to the public through a catalog that announces the availability of published papers and reports.

During 1990, the Laboratories had an operating budget of $41 million, of which about 50 percent came from Corporate sources and the balance from outside. Approximately 30 percent of the Corporate funding (15 percent of the total) supported an applied research program with the goal of creating new technology which has the potential of improving communications systems over the long term. A further 50 percent of the Corporate funding paid for development projects, which were undertaken by the Laboratories for elements of the Corporation on a contract-like basis, and have nearer-term applications. The balance of the Corporate funding was for technical support on various projects, studies, and technical issues. The largest effort undertaken for an external customer was for the NASA Advanced Communications Technology Satellite (ACTS) program, although the Laboratories continues to perform a significant amount of development and technical support for INTELSAT.

Commencing with the calendar year 1983, we have published an Annual Report summarizing the results of our research and development program. This report, the eighth in the series, summarizes all of the R&D work undertaken with Corporate support during 1990.

John Evans

J. V. Evans

June 1991

COMSAT CORPORATION 1990

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I. Goldstein

• Corporate Staff

COMSAT LABORATORIES
J. Evans
Vice President
and Director

WORLD SYSTEMS DIVISION
B. Crockett
President

• Intelsat Satellite Services
• Mobile Communications

COMSAT VIDEO ENTERPRISES
R. Wussler
President

COMSAT SYSTEMS DIVISION
J. Alper
President

• COMSAT General

INTRODUCTION

COMSAT Corporation was created in 1963 following the passage of the Communications Satellite Act, which President Kennedy signed into law in late 1962. Subsequently, in 1964, INTELSAT was established to facilitate international communications between fixed points by satellite, and COMSAT was named U.S. Signatory. Initially, INTELSAT had 11 participants. This has since grown to 119 member countries, and the organization presently provides service to 170 nations.

Until 1979, COMSAT also acted as technical manager of INTELSAT. COMSAT Laboratories was formed in 1967 to help meet the technical challenges associated with this role. Initially located in Washington, D.C., the Laboratories moved to its present quarters in Clarksburg, Maryland, in 1969. COMSAT Laboratories presently has a staff of approximately 300 and occupies buildings which afford about 250,000 square feet of space. These facilities are located on a 230-acre tract along Route I-270 north of Gaithersburg, Maryland.

Over the years, the Corporation has undergone a number of reorganizations. In 1987, three separate operating divisions were established, namely the World Systems Division (WSD), which serves as U.S. Signatory to INTELSAT and Inmarsat; COMSAT Video Enterprises (CVE), a business that delivers TV to hotels in the U.S. via satellite; and COMSAT Systems Division (CSD), which offers private satellite communications systems and services. COMSAT Laboratories supports all three divisions as well as performing work for outside customers. The figure on the preceding page shows the Corporation's organization during 1990.

In 1990, the largest part of the work at COMSAT Laboratories was that performed for the regulated activity of international satellite communications, either directly for COMSAT or indirectly for INTELSAT. Additional work was performed for CSD and CVE, mostly with support from the Corporate Shareholders. Efforts funded entirely by sources outside of COMSAT/INTELSAT included activities for the Federal Government and the largest part of this was the work performed on the NASA Advanced Communications Technology Satellite (ACTS) program.

During 1990, there was some regrouping of some departments of the Laboratories, but the number of technical divisions remained six: Satellite Technologies, Communications Technology, Microelectronics, Microwave Technology and Systems, Network Technology, and System Development. Of these, the first five divisions participate in a research program funded by the Corporation. This program constituted about one-fifth of the Laboratories' activities and included jurisdictional business, as well as the nonjurisdictional activities of COMSAT. The former must, perforce, be made public, while the latter is held proprietary.

The balance of the Laboratories support came from projects for and directed by various Corporate elements, INTELSAT, Inmarsat, and other outside organizations. Each project is separately negotiated and has specified deliverables and delivery dates. The System Development Division, which is chiefly occupied in writing computer software, works almost exclusively on such specific tasks.

This report summarizes the Laboratories' research and development activities in 1990. It is organized by technology, as defined by the six technical areas represented by each division. The work is further subdivided into the following categories:

- jurisdictional research and development
- nonjurisdictional research and development
- support work performed for various COMSAT divisions in response to specific requests
- work performed for INTELSAT
- other work.

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During 1990, the Microwave Technology and Systems Division (MTSD) continued work on the 24-element, high-power, Ku-band, multibeam phased array, which is capable of generating four independently steerable beams. The primary effort focused on construction of the beam-forming matrix, including its 96 phase shifters. Major portions of this phased array, including the mechanical structure, horns, orthomode transducers, and cooling loop, have been completed. Initiated in 1990 was the design of a C-band phased array based on a modular element design in which a patch radiator, a polarizer, filters, amplifiers, and switches are contained in a single housing. A 25-element breadboard subarray was constructed to facilitate design of the radiating element, and a statistical analysis was subsequently performed to ensure satisfactory array performance despite element excitation errors and failures. Also during 1990, MTSD designed, fabricated, tested, and delivered an in-orbit test transponder for the ITALSAT satellite. This 12- to 20-GHz transponder, which includes 12-GHz monolithic microwave integrated circuit (MMIC) amplifiers, 12-GHz channel filters, a power supply, and telemetry and command interface circuitry, provides a means of bypassing the on-board demodulators, baseband switches, and remodulators on the satellite. Other developments in 1990 included a dual-band feed for earth station antennas and a synthesized dual circularly polarized flat-plate antenna for satellite TV reception. Work continued on earth station antennas, reflector feeds, low-noise amplifiers, and phase shifters.

COMSAT JURISDICTIONAL R&D

Ku-Band High-Power Phased-Array Antenna

In 1990, MTSD completed and extensively tested a low-power, single-beam array, thus providing the foundation for a subsequent program to demonstrate a high-power multibeam array. This high-power array (shown in the "Division Highlights," which appears at the front of this Annual Report) consists of 24 radiating elements with 2-W amplifiers integrated behind each element and is capable of generating four simultaneous, independently steerable beams while allowing for flexible power sharing among the beams. The power sharing is accomplished by a beam-forming matrix (BFM) which contains 96 MMIC phase shifters integrated within the matrix assembly. The system (Figure 1) also contains a controller and power supplies to provide bias and control functions to the phase shifters and amplifiers.

Fabrication of the array components was substantially completed during 1990. All of the feed elements and orthomode transducers (OMTs) were completed and tested. The pyramid horns and OMTs are designed for dual linear polarization over the 10.9- to 12.7-GHz band, while the feed elements demonstrate better than 18-dB input return loss and 50-dB port-to-port isolation over the band. Additionally, the array mounting structure and the thermal control system were designed, fabricated, and tested. The thermal control system consists of a liquid cooling loop that simulates the implementation of heat pipes in space.

The BFM components were fabricated and tested, and a major portion of the BFM was assembled. The BFM comprises three shelves, each containing four 1-to-8 power dividers (PDs) and eight 4-to-1 power combiners (PCs). Four 1-to-3 dividers distribute the respective inputs to each of the three shelves, thus providing 1- to-24-way power division for each beam. Within each shelf (shown in the "Division Highlights"), MMIC phase shifters (see Figure 2) are located at the junctions connecting the input power distribution networks to the power-combining networks.

The divider and combiner networks are broadband designs employing Wilkinson dividers on an alumina substrate. A 50-Ω miniature feedthrough provides the RF interconnect from the input to the output network. The phase-shifter driver and control circuits are integrated on multilayer alumina boards. Figure 3 shows the measured performance of five phase states for all 32 phase shifters in one shelf.

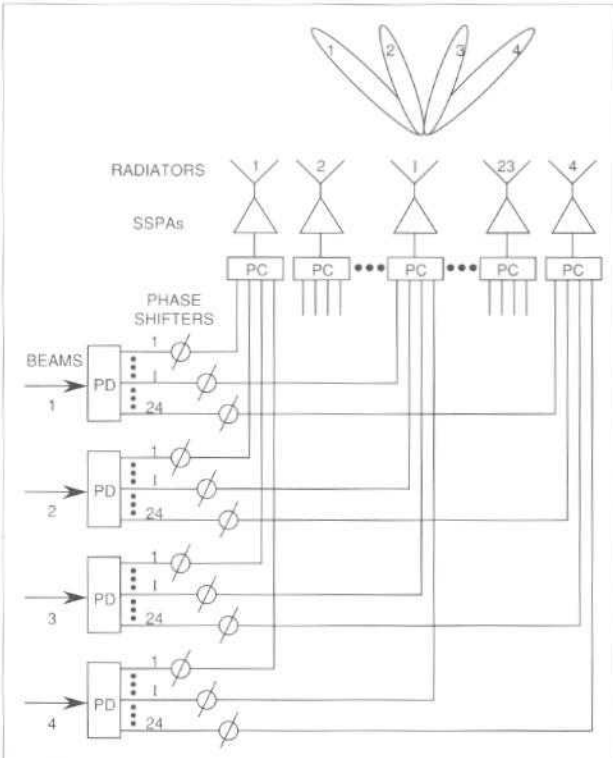


Figure 1. Ku-band, high-power, phased-array antenna concept to provide independent steerability for multiple beams

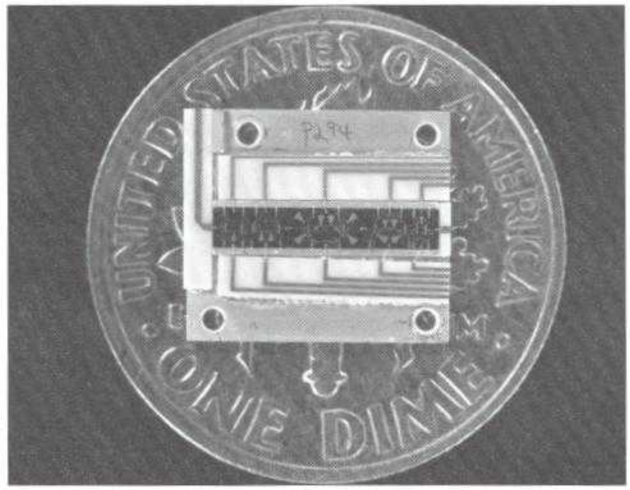


Figure 2. Miniaturized MMIC phase shifter forms a key building block of the beam-forming matrix

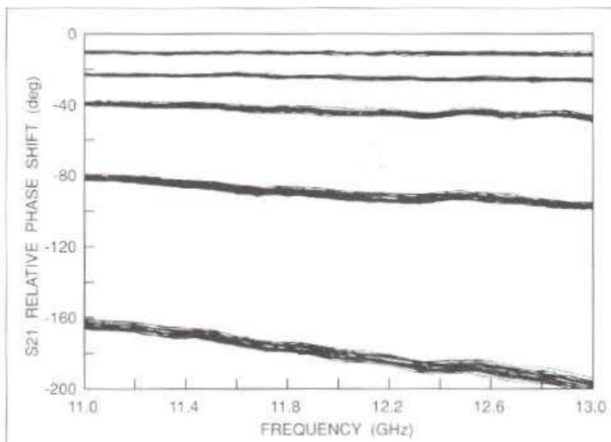


Figure 3. MMIC phase shifters provide uniform and reproducible phase performance of the BFM shelf

The BFM, power amplifier, and controller will be completed and the array will be integrated during 1991. Testing to evaluate the RF and scanning performance under multibeam conditions will then commence. Extensive communications systems tests will also be initiated to evaluate the impact of the array on bit error rate (BER) and signal-to-noise ratio.

C-Band Lightweight High-Efficiency Antenna

A lightweight C-band multibeam active array currently under development incorporates the best features of the Ku-band array development and will implement additional functions necessary for spacecraft application. The array will combine several key technologies to demonstrate an advanced satellite antenna concept, including broadband high-polarization-purity printed elements; high-efficiency, high-linearity distributed solid-state power amplifiers (SSPAs); and BFM technology for generating multiple independent beams. The design will also include the associated thermal, mechanical, and control subsystems.

A system concept and component development were initiated in 1990. The baseline antenna is a flat-panel array comprising printed radiating elements, behind which high-efficiency and high-linearity SSPAs will be integrated. A BFM capable of generating eight simultaneous beams will interface with the active array. Phase shifters and attenuators will be integrated with the BFM to independently steer and shape each of the eight beams. A controller is used to set the respective states of the circuitry within the BFM and the amplifier modules.

Figure 4 depicts a breadboard section of the array under test. The baseline array, using a confocal parabolic system, will generate a number of spot beams over the earth. Tradeoff studies have resulted in an array of 177 patch radiators, each capable of generating dual circular polarization, with integrated 2-W amplifiers located at each input port. An output filter is included in the radiating element to suppress spurious harmonics.

The array concept is shown in Figure 5. Each radiating element will be an integral part of an active circuit module, and individual modules can be replaced as required. Each circuit module (see Figure 6) contains redundant amplifiers and input/output redundancy switches, plus an output detector for monitoring.

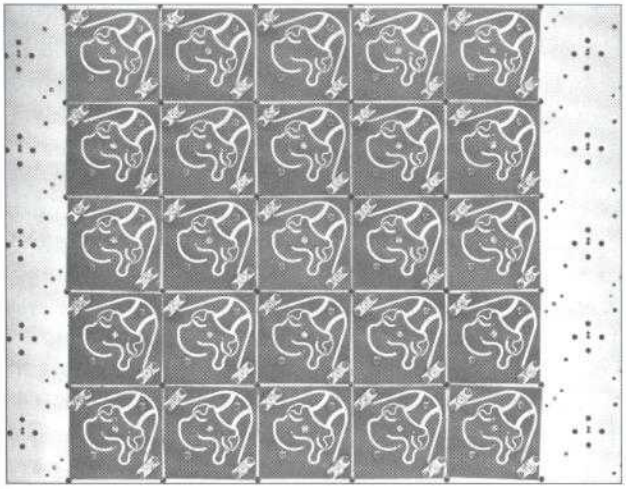


Figure 4. A breadboard 25-element array model used to simulate performance of the full array

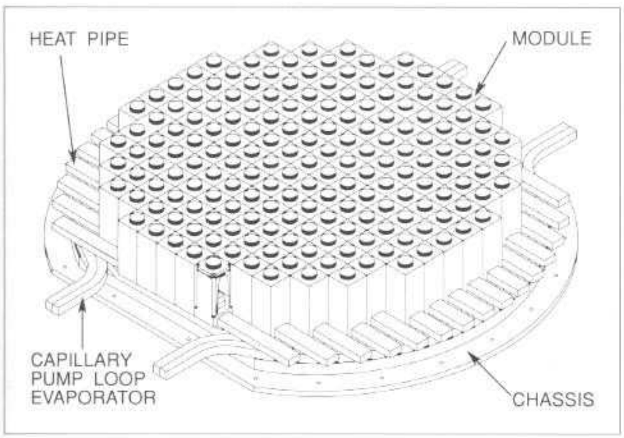


Figure 5. C-band, 177-element active array emphasizing modularity and light weight

A four-element demonstration array currently under development will include all of the components shown in Figure 7. Subsequent work will include building and testing a 64-element subarray, a BFM, and a controller to verify antenna performance.

Compact 4-GHz Diplexer

A compact 4-GHz dual circularly polarized diplexer is being developed for small prime-focus INTELSAT earth station antennas. Under consideration is a design approach that achieves very good transmit (6-GHz) performance but with some compromise in receive (4-GHz) axial ratio and loss in exchange for compactness and low cost. A breadboard diplexer based on this design approach has been built and tested. It demonstrates good transmit band performance and provides receive-band orthogonal linear polarization outputs. A bar-line or stripline polarizing network will be developed in 1991 to form circular polarization for the receive band.

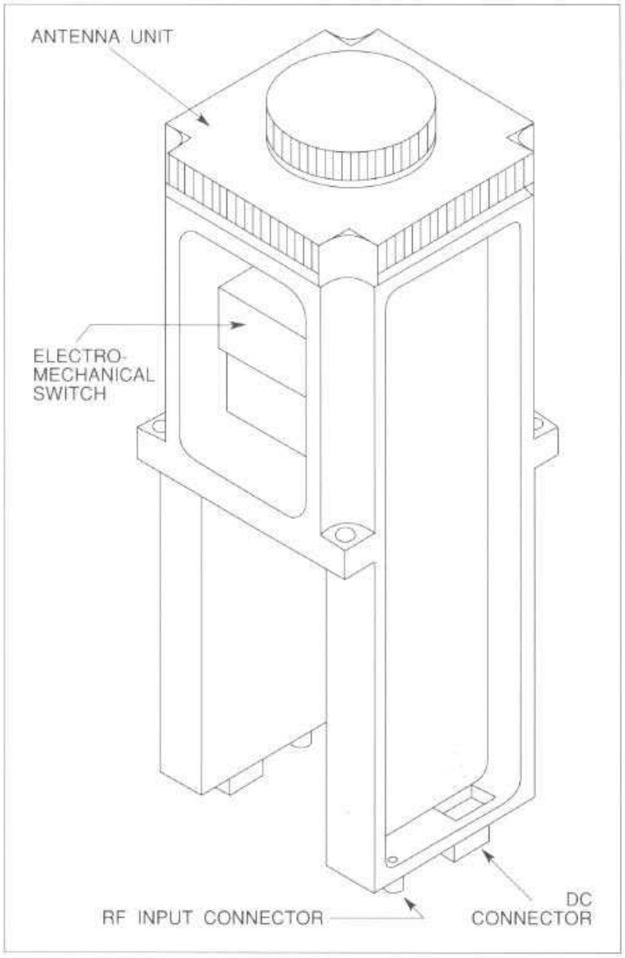


Figure 6. Single module with patch antenna and MMICs forms a basic building block of the C-band array

Automated Antenna Measurement System

A major upgrade of the large antenna test chamber completed in 1990 included the installation of a hydraulic lift platform, the addition of computer-controlled positioner equipment, and software written specifically for antenna measurements. These improvements allow the setup to be optimized for a wide range of test conditions.

The stability of the new hydraulic lift permits more accurate measurement of both the electromagnetic field phase and amplitude. Placing the positioner near the antenna under test at the center of the quiet zone also minimizes parallax errors. The positioner, which was improved by adding tachometer feedback and a new four-axis position controller, can be operated by a computer over an IEEE-488 bus.

The upgrade involved designing, writing, and testing software for automated antenna measurements. With the added feature of phase-stable measurements in the large anechoic chamber, the previously developed Holographic Antenna Measurement System was installed in the chamber. This system measures the amplitude and phase response of the antenna and calculates the field in the antenna aperture using an inverse Fourier transformation. A correcting algorithm was written to modify chamber pointing angles to account for the azimuth-over-elevation geometry of the chamber positioner. In addition, the automated measurement software was enhanced to provide user-defined antenna cut or contour patterns.

Dual-Band 4/6- and 11/14-GHz Antenna Feed System

A dual-band feed has been developed to permit simultaneous access to a satellite at both C- and Ku-bands from a single earth station antenna. The design uses a multi-aperture directional slotted-waveguide array to achieve unity coupling at Ku-band from rectangular waveguide input into the C-band circular (2.125-in.-diameter) waveguide. Fabrication techniques were developed for the feed components to achieve a more favorable cost differential between the single dual-band reflector antenna and a dual-band system consisting of two antennas. The 1990 effort was devoted to optimizing the coupler design and fabricating and testing a complete dual-band feed system.

The complete feed system is pictured in the "Division Highlights." Figure 8 is an outline drawing of the feed, including the diplexing arrangement. An existing COMSAT design is used for the C-band (4/6-GHz) diplexer. Since 4/6-GHz signals travel through the Ku-band couplers without attenuation, the dual-band feed system provides virtually the same 4/6-GHz performance as the C-band diplexer alone. Separate unity couplers for the Ku-band transmit (14.0- to 14.5-GHz) and receive (10.95- to 11.7-GHz) frequency bands provide efficient coupling from the Ku-band rectangular waveguide inputs to the fundamental mode in the 2.125-in.-diameter circular waveguide. A high degree of mode purity in the circular waveguide enables the dual-band feed to meet the 30-dB cross-polarization isolation and sidelobe requirements for an INTELSAT Standard-C antenna. The axial ratio of the feed in the 5.840- to 6.425-GHz band is less than 0.25 dB, thereby providing a substantial margin for meeting the INTELSAT 0.5-dB requirement.

All the dual-band feed components have been fabricated and tested, and tests of the integrated feed are in progress. The objectives for this project are to provide support for the installation and testing of the dual-band feed in a new or existing U.S. earth station antenna, and to develop a dual-polarization coupler to provide access to both polarizations on the planned INTELSAT VII-A series satellites.

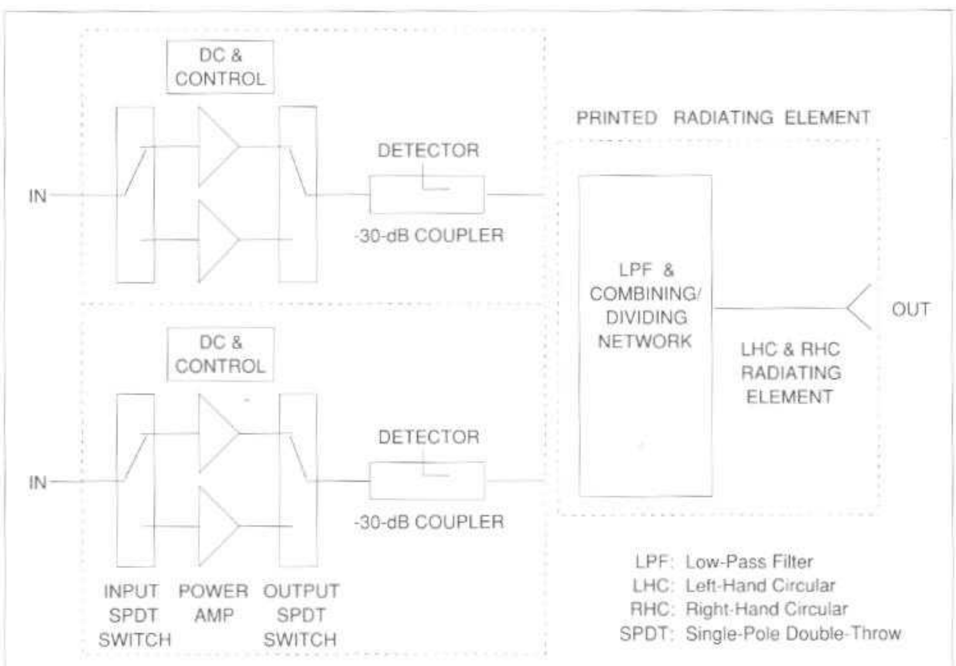


Figure 7. Active circuit module showing MMIC components, redundancy, and monitoring capability

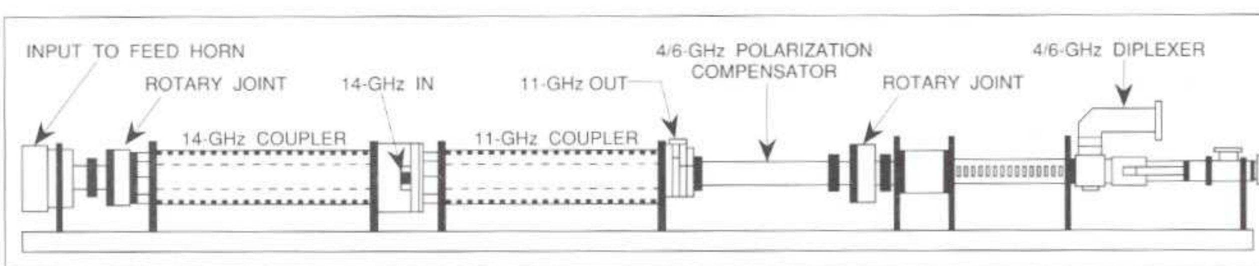


Figure 8. Dual-band earth station antenna feed capable of operation at C- and Ku-band up-links and down-links

Earth Station Antennas for Use With Inclined-Orbit Satellites

COMSAT Laboratories has completed a study of antenna techniques that could reduce the cost of earth station antenna tracking for inclined-orbit satellites. In 1989, a study of antenna pedestals appropriate for single-axis tracking of inclined-orbit satellites was conducted, a design was implemented, and a performance measurement phase was initiated to demonstrate the reliability and accuracy of the technique.

The tracking system consisted of a single-axis pedestal with a low-cost step-tracking drive that utilized the automatic gain control (AGC) output of a standard video receiver. AGC voltage is a linear function of the RF signal level of the video carrier and can be used to maintain the antenna pointing to the satellite. The AGC output was digitized and processed by a microprocessor controller to position the antenna for maximum signal level.

The performance measurement phase continued through June 1990. After March, the Atlantic Ocean Region (AOR) INTELSAT V (F4) was no longer available, and subsequently no INTELSAT satellite having a substantial inclination was visible from COMSAT Laboratories. Therefore, measurements were continued using a domestic satellite having a nominal inclination of 2.5°. Figure 9 shows the pedestal drive positions at the beginning and end of a 92-day time period, illustrating the automatic tracking of the increasing satellite inclination, which is slightly less than 0.3° for this time period. The antenna position is given in "counts" as a function of sidereal time. A count is an impulse from the counter on the encoder shaft of the antenna drive actuator and corresponds to about 0.1° of antenna movement in the plane of the inclined-orbit motion. Data taken on consecutive days show that the antenna position derived from the step-tracking process repeats each day, with a typical pointing error of less than one count (0.1°). This error corresponds to a signal loss of less than 0.2 dB due to antenna mispointing.

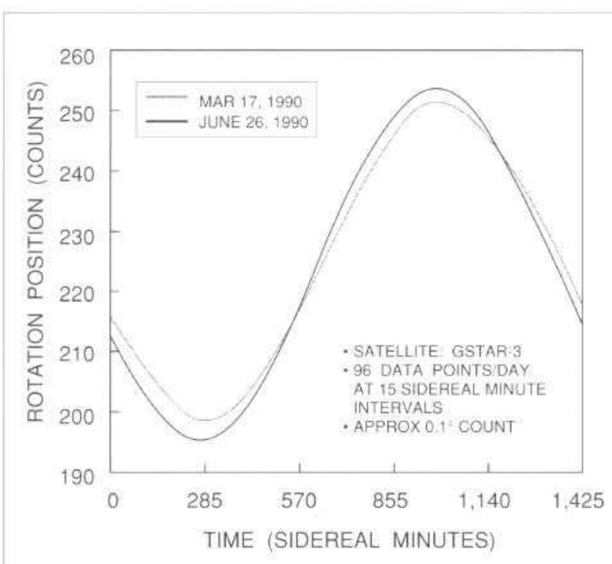


Figure 9. Pedestal drive positions showing tracking of the increasing satellite inclination

COMSAT NONJURISDICTIONAL R&D

Analog Phase Shifter

MTSD has developed a fully monolithic (MMIC) analog phase shifter to achieve electronic steerability in the flat antenna. Based on a microwave integrated circuit (MIC) prototype built in 1989, this design demonstrates low absolute insertion loss and minimal insertion loss variation with phase states. The active devices in the MMIC consist of eight hyperabrupt varactor diodes, fabricated monolithically on a GaAs wafer using a proprietary process developed at COMSAT Laboratories. These diodes, which are reverse-biased, consume negligible DC power and provide a control-voltage-dependent variable capacitance. In Figure 10, the layout of the MMIC chip is superimposed on the MIC hybrid circuit, showing significant size reduction. Furthermore, the analog MMIC phase shifter is approximately 50 percent smaller than an equivalent MMIC digital phase shifter.

Integrated Low-Noise Amplifiers

Miniaturized, high-performance, integrated low-noise amplifiers (LNAs) were developed at COMSAT Laboratories during 1990 so that they could be embedded in the flat-plate antenna structure to significantly improve gain-to-noise temperature ratio (G/T) performance. These LNAs

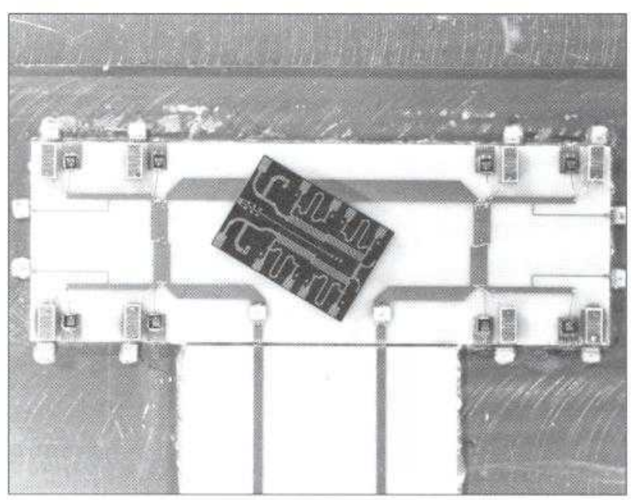


Figure 10. MMIC analog phase shifter shows considerable size reduction compared to its MIC counterpart

incorporate self-biasing with inductive feedback to achieve a simultaneous noise and power match and to operate from a single power supply. Both the single- and dual-stage configurations have demonstrated state-of-the-art performance (0.8-dB and 1.1-dB noise figure [NF], respectively) using ultra-low-noise high electron mobility transistor (HEMT) devices. These NF values are close to the theoretical minimum for the HEMT devices being used. The two-stage LNA circuit (Figure 11) incorporates a vertical mounting scheme developed to enable the amplifier to be inserted in the stripline between the two ground planes of the antenna structure.

Microstrip Patch Array

A software package was developed to evaluate the performance of the microstrip patch radiator by determining the resonant frequency and input impedance of circular and rectangular patches. As part of the project, a number of patch elements were fabricated and their measured performance was compared to program predictions. In most instances, good agreement was obtained.

Flat-Plate Antenna

COMSAT and Matsushita Electric Works have undertaken a joint program to develop and produce low-cost, lightweight, high-efficiency flat-plate array antennas for satellite reception. Efforts during 1990 focused on the development of a dual circularly polarized antenna which will operate between 12.2 and 12.7 GHz.

The antenna, shown in Figure 12, consists of the previously developed dual linearly polarized flat plate fed by an integrated waveguide section. This section contains a 3-dB quadrature hybrid, which converts the two linearly polarized signals at the hybrid inputs to two circularly polarized signals at the hybrid outputs. The 64-element, 0.15-m prototype has realized circular polarization gains of about 25 dBi, corresponding to an aperture efficiency of about 60 percent, and axial ratios of better than 1 dB for both polarizations (see Figure 13). The 256-element, 0.31-m prototype has a similar axial ratio performance and an efficiency of greater than 55 percent.

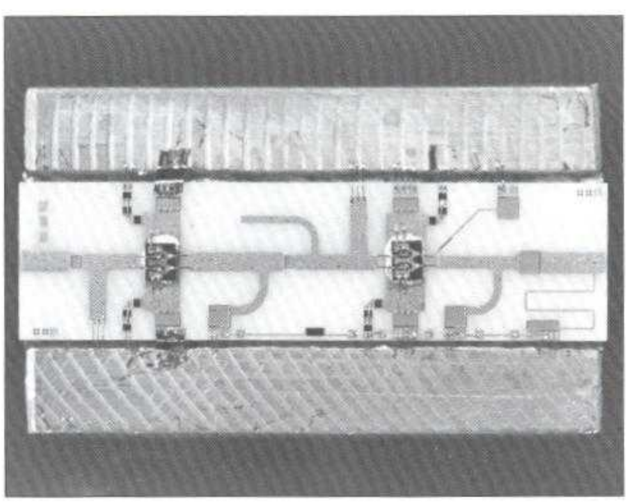


Figure 11. A low-cost, two-stage LNA for integration in the flat-plate antenna

COMSAT SUPPORT

Inmarsat Earth Station Modifications

During 1990, MTSD helped to modify existing antennas at Santa Paula, California, and Southbury, Connecticut, for use with the Inmarsat 2 satellite series and to meet new traffic requirements such as fourth ocean region service. The successful modification of these older

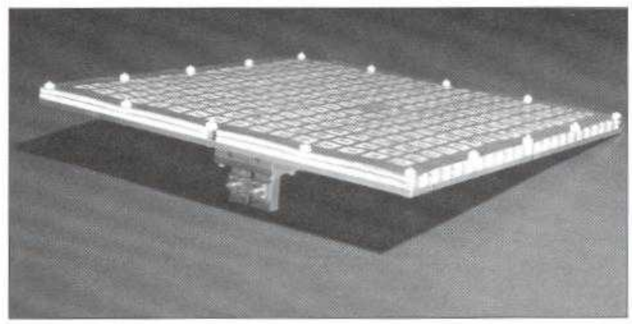
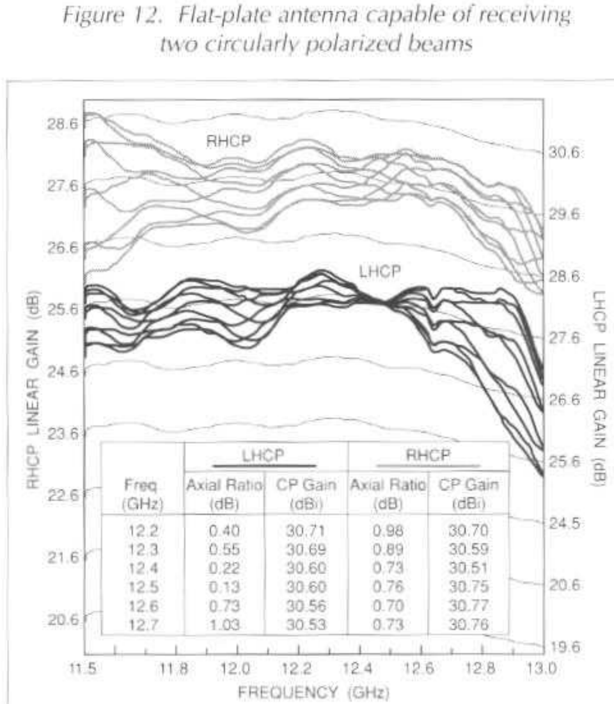


Figure 12. Flat-plate antenna capable of receiving two circularly polarized beams



	LHCP		RHCP	
Freq (GHz)	Axial Ratio (dB)	CP Gain (dBi)	Axial Ratio (dB)	CP Gain (dBi)
12.2	0.40	30.71	0.98	30.70
12.3	0.55	30.69	0.89	30.59
12.4	0.22	30.60	0.73	30.51
12.5	0.13	30.60	0.76	30.75
12.6	0.73	30.56	0.70	30.77
12.7	1.03	30.53	0.73	30.76

Figure 13. Measured axial ratio data showing good discrimination between two circularly polarized beams

stations prolongs the use of existing antennas and is considerably less expensive than buying and erecting new antennas.

The full-performance and MARISAT antennas at the COMSAT General site at Santa Paula were evaluated to determine their suitability to operate in the new Inmarsat 2 frequency bands. As part of this project, the feed systems were modified and tuned, 4-GHz LNAs operating over the new band were installed, and complete antenna G/T, gain, and system temperature were measured. Based on the tests and modifications, it was determined that the existing antennas could be used to access the new Inmarsat 2 satellite series.

An older 11-m antenna at Southbury was converted for operation with the new Atlantic Inmarsat fourth ocean region satellite. A dual-polarized C-band diplexer was added to the existing feed to provide operation from 3,600 to 4,200 MHz and 5,850 to 6,453 MHz, thus meeting all Inmarsat 1, 2, and 3 and INTELSAT requirements. A separate 5-ft reflector located behind the subreflector was added to provide L-band transmit and receive operation. All specifications were met, and the antenna has been accepted for use by Inmarsat.

The 14.2-m Ku-band antenna system at Santa Paula was converted to C- and L-band operation by the addition of a 4/6-GHz prime-focus feed, shown in Figure 14, and a separate 5-ft L-band antenna attached to the quadrupod structure located behind the prime-focus feed. This quick-reaction, low-cost project provided the satellite access that was lost when the full-performance antenna was modified for use as the Pacific Ocean Region (POR) telemetry, tracking, and command (TT&C) antenna.

The full-performance antenna at Santa Paula, originally built in 1975, was modified for use as the Inmarsat POR TT&C antenna. The modification consisted of replacing part of the original Nippon Electric Company feed with a new COMSAT Laboratories dual circularly polarized diplexer. Extensive measurements, including G/T, gain, system temperature, polarization, and patterns at both C-band and L-band, were also taken. This antenna calibration will allow determination of the satellite parameters and will also present a measurement standard for test and calibration of future coast earth station (CES) antennas.

Inmarsat 3 Proposal Evaluation

Evaluation of the third-generation Inmarsat satellite took place in London in February through April 1990. MTSD participated in the evaluation in support of COMSAT General. Communications payload designs, including the multiple-beam antenna, were assessed, and the hybrid matrix amplifier assembly, proposed by two bidders, was analyzed. The assembly, which offers a vehicle to share all L-band power amplifiers among all beams, provides good isolation between the output ports only if the amplifiers and the hybrids perform within tight performance limits. These limits were studied, and the matrices' performances, based on the manufacturer's data, were assessed.

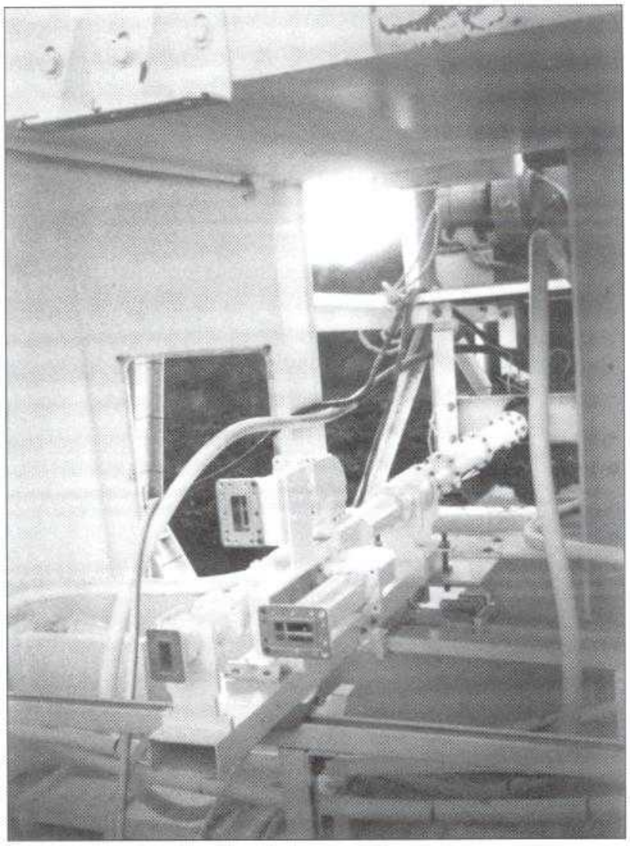


Figure 14. New 4//6-GHz feed for Santa Paula earth station provides low off-axis cross polarization

American Samoa Antenna Retrofit

An INTELSAT Standard-B antenna in American Samoa was retrofitted to facilitate dual-polarized operation. To ensure the necessary low off-axis cross polarization, a new corrugated horn input section was designed as a transition from the circular waveguide's TE_{11} mode in the diplexer to the balanced hybrid HE_{11} mode of the corrugated horn. The transition was accomplished without exciting unwanted higher-order modes while providing an excellent impedance match. The new feed parts were installed and the INTELSAT antenna verification tests, including radio-star gain, antenna temperature profiles, G/T, transmit and receive antenna patterns, and cross-polarized isolation contours, were performed. The antenna met the specifications with margin.

Type Acceptance for the INTELSAT System

COMSAT Intelsat Satellite Services developed and implemented a new procedure which permits antenna models, antenna systems, and earth stations to be tested for compliance to INTELSAT standard specifications. This process reduces cost and speeds service implementation by eliminating the need for individual on-site earth station testing. MTSD provided technical guidance on appropriate antenna measurements required for proof of performance. In support of this effort, design reviews have been performed, and measurement results have been witnessed, analyzed, and documented for presentation to INTELSAT. During 1990, a combination of seven antenna models, antenna systems, and earth stations by U.S. manufacturers have successfully completed the process. Other systems are in the type acceptance stage.

OTHER SUPPORT

Matsushita Electric Works

Under contract with Matsushita Electric Works of Japan, COMSAT is developing a low-noise block downconverter (LNB) for integration with the flat-plate antenna. The LNB will incorporate MMIC technology in a contactless small-sized package to improve performance, size, and cost. A new LNA has also been developed using low-cost manufacturing technology. The LNA provides improved noise performance in a package less than one quarter of the size of existing designs.

Alcatel Espace

This ongoing contract for Alcatel Espace is aimed at achieving a state-of-the-art MMIC power amplifier module capable of delivering 1-W output power over the relatively broad bandwidth of 10.7 to 12.75 GHz. The module is also designed to achieve high efficiency and good linearity, with a small-signal gain of at least 20 dB. COMSAT has been pursuing both an MMIC driver amplifier and an MMIC power amplifier chip for application to this work. These two chips will be connected in cascade to form the complete MMIC power amplifier module.

Torus Antenna C-Band Feed Systems

A new C-band feed (Figure 15) with a low voltage axial ratio over an 800-MHz band was developed for a 7-m torus antenna for Radiation Systems, Inc. The feed operates from 3.4 to 4.2 GHz and achieves an axial ratio of less than 0.3 dB. The dual circularly polarized feed system includes an OMT, a quarter-wave polarizer, and a corrugated horn. The horn was designed to give the optimum gain illumination for the torus antenna while providing excellent off-axis cross-polarization performance. The OMT and polarizer designs enabled the feed system to achieve the axial ratio specification.

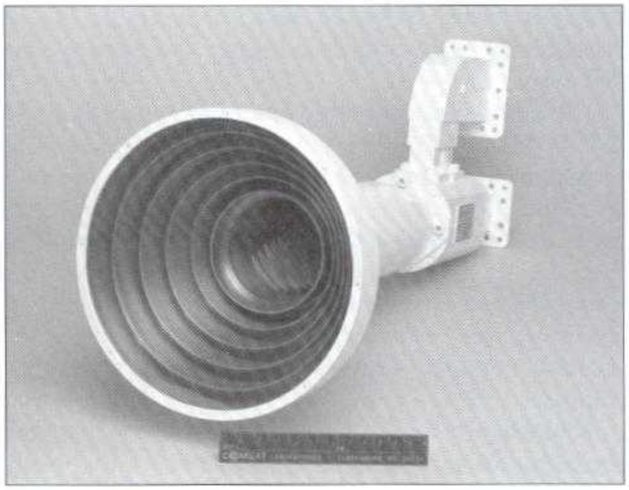


Figure 15. Corrugated horn feed for torus antenna

Superconducting Phased Array

Under a contract with MIT Lincoln Laboratories, COMSAT worked on the development of a superconducting phased array. A number of radiating elements, including the linear tapered slot and the Vivaldi slot, were designed on $LaAlO_3$ and $LaGaO_3$. These substrates have an E_r of 25 and are used for deposition of superconducting thin film. A two-element array of Vivaldi slots was fabricated and tested at room temperature and 70 K.

Selenia Spazio

Under a contract with Selenia Spazio, COMSAT Laboratories designed, fabricated, space-qualified, and delivered an in-orbit test transponder (IOTT) for the ITALSAT satellite. This 12- to 20-GHz transponder bypasses the on-board demodulators, baseband switches, and remodulators on the ITALSAT satellite by routing the signal from the output of the down-converted low-noise receiver sections at 12 GHz to the 20-GHz traveling wave tube amplifiers (TWTAs). Such a bypass allows comprehensive characterization of both the receive and transmit portions of the satellite. The IOTT, shown in Figure 16, features advanced technology developed at COMSAT Laboratories, including high-performance 12-GHz MMIC amplifiers, 12-GHz channel filters, a power supply, and telemetry and command interface circuitry. COMSAT delivered this fully documented space hardware in less than 1 year.

An assembled transponder is shown in the "Division Highlights." The IOTT was integrated with ITALSAT

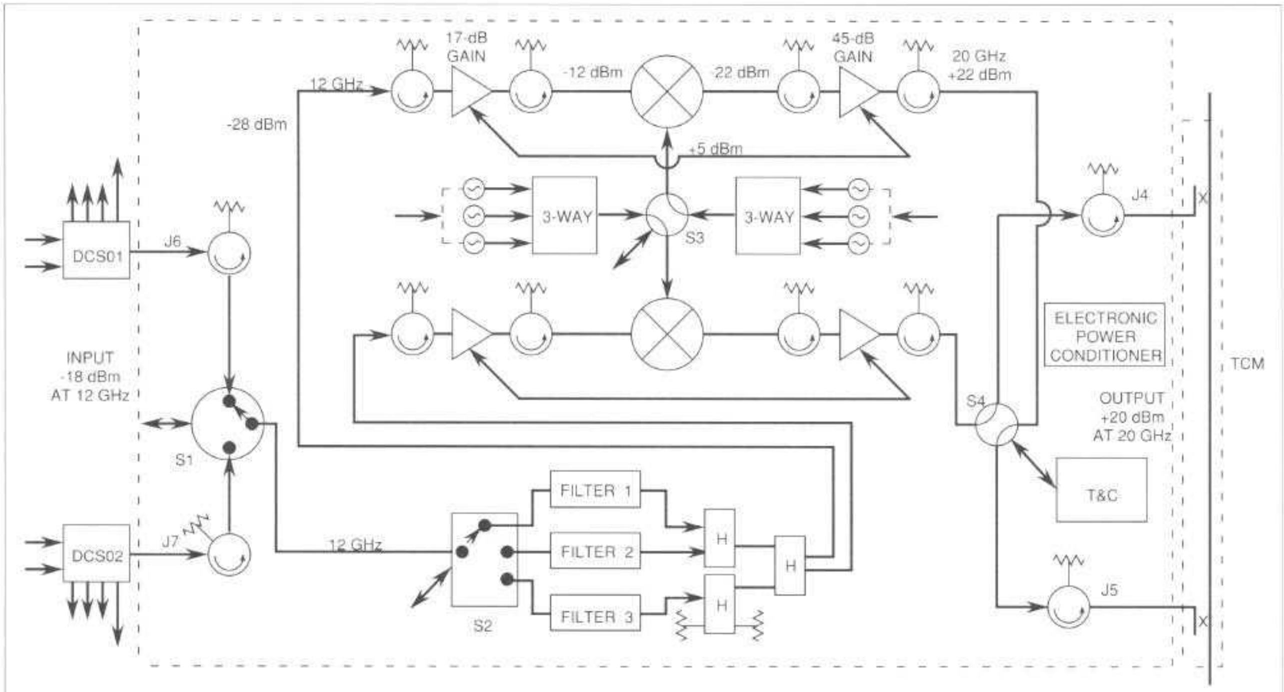


Figure 16. Block diagram of ITALSAT IOTT which provides bypass capability during in-orbit testing

spacecraft in March 1990, and the spacecraft was successfully launched on January 15, 1991.

Communications Performance of the M-SAT Matrix Transponder

A task was initiated in 1990, supported by the American Mobile Satellite Corporation, to analyze the interference and impairment mechanisms in the M-SAT matrix transponder. The hybrid matrix structure of the power amplifiers allows for amplifier power sharing among a number of beams in a multiple-beam system. The isolation between the output ports of the matrix amplifier is dependent on the tracking accuracy of the amplitudes and the phases of the amplifiers and hybrids. The degradation in port-to-port isolation, and the consequent degradation in beam-to-beam isolation, were addressed in parametric studies using the manufacturer's measured data. As a result of the parametric study, performance limits were set for the amplifiers and hybrids in order to satisfy isolation requirements. The study will continue in 1991 and will investigate variations on the original M-SAT design.

The Microelectronics Division (MED) performs research and development of microelectronic components for enhancing the capacity, performance, and reliability of communications satellite systems. MED also evaluates satellite components to determine their reliability and tolerance to environmental effects such as solar radiation.

MED's leading-edge capability in advanced monolithic microwave integrated circuit (MMIC) and subsystem technology covers a broad frequency range from 1 to 94 GHz and encompasses a large family of both small- and large-signal chips. MMIC chips have been successfully incorporated into numerous subsystems.

MMIC chips are developed at COMSAT's in-house, vertically integrated facility. This state-of-the-art facility performs device modeling, MMIC chip design and layout, materials preparation, MMIC chip production, chip and submodule packaging, RF testing, and reliability evaluation. Implementation of new quality assurance procedures has resulted in circuit yields of up to 80 percent at the DC level for millimeter-wave amplifiers with a gate width of 400 μm. MMICs developed by MED have shown a mean time to failure exceeding 10^6 hr and have been qualified to class-S level for space applications.

COMSAT JURISDICTIONAL R&D

MMICs for Phased-Array Antennas

COMSAT has demonstrated the viability of active phased-array antennas for future communications satellites using gallium arsenide (GaAs) MMICs designed and built in MED. The many advantages of phased-array antennas include the flexibility to effectively increase the antenna gain by generating narrow pencil beams and to reconfigure the beam shape and reallocate power resources in each beam on demand.

At the heart of the phased-array antenna is a solid-state power amplifier (SSPA) incorporating many advanced COMSAT techniques. A demonstration model of a Ku-band active antenna has been built, in collaboration with the Microwave Technology and Systems Division, using a mix of microwave circuit technologies, some of which are shown in Figure 1. The MED-fabricated MMIC chips include power, driver, and buffer amplifiers, as well as phase shifters and attenuators. The technologies represented range from microwave integrated circuits to quasi-monolithic circuits and state-of-the-art fully monolithic circuits.

C-Band SSPA on Silicon Motherboard

Major progress was achieved in 1990 in the development of silicon motherboard technology for payload applications at microwave frequencies. Using this approach, microwave subsystems comprising MMICs, discrete field-effect transistors (FETs), and other components can be integrated onto a single silicon substrate, thus eliminating many of the discontinuities and parasitic elements associated with conventional hybrid technology. (Discontinuities and parasitic elements degrade performance and introduce unit-to-unit variation and performance variation with frequency.) In this technique, active elements are incorporated into recessed wells, and all passive elements are fabricated in monolithic form on the silicon motherboard.

The demonstration vehicle for this technology is a three-stage, 2-W power amplifier, shown in Figure 2. The amplifier was designed to operate over the 3.7- to 4.2-GHz band with approximately 30-dB gain. The silicon chip, measuring approximately 1 x 2 cm, is shown in one possible packaging configuration; the other substrate in the package is the bias controller chip. The silicon substrate contains two MMIC chips in the first stage, and discrete power FETs in the second and third stages.

Figure 3 is a plot of the output power and efficiency of the amplifier vs input power. The amplifier delivers 2 W of output power at 43-percent efficiency, with the promise of improved performance when it is optimized.

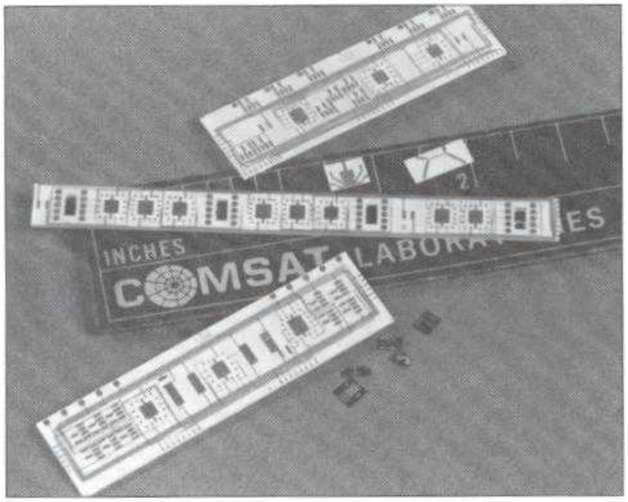


Figure 1. Microwave circuit components for Ku-band antenna

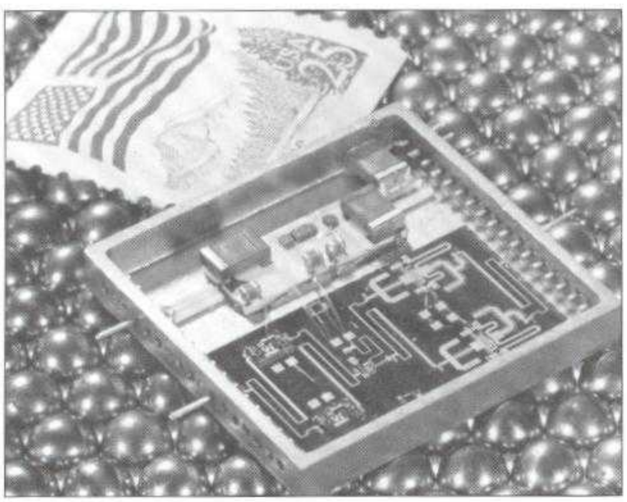


Figure 2. Demonstration amplifier using silicon motherboard technology

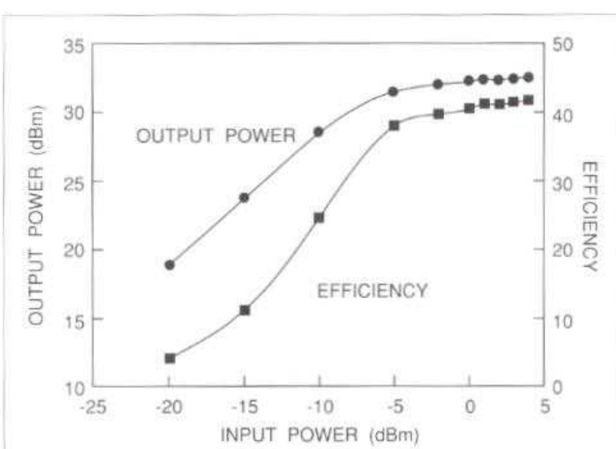


Figure 3. Optimized amplifier offering better than 2-W output power and 43-percent efficiency

Work will continue in 1991 to improve amplifier efficiency and linearity, and to streamline the fabrication process.

High-Voltage FET Amplifier

Existing FET amplifiers are operated at a bias voltage of 6 to 10 V, due to their breakdown voltage limitation. A novel combination of several devices, together with appropriate circuitry, has allowed multiple FETs to be combined in DC-series and RF-parallel (e.g., four devices in series allow bias voltages of 24 to 40 V). This technology has applications in systems where the prime power is available only at a much higher voltage than the separate devices can use. For example, the prime power for satellite systems is supplied at 28 to 40 V. Amplifiers operating at that voltage can improve total system efficiency in two ways: by reducing ohmic loss in the DC power distribution network in systems such as phased arrays; and by improving efficiency in any required DC-to-DC power conditioner, such as that normally used to reduce a satellite bus to the lower voltage needed for SSPAs.

A 2-W MMIC has been developed which is biased at 30 V and incorporates active gate bias circuitry directly in the integrated circuit. The gate bias circuitry includes a resistive dividing network to establish voltage references for the gate of the power FETs, as well as small FETs used as source-follower voltage regulators to maintain steady bias voltage when the power FETs require gate current, as they do during their most efficient mode of operation. The bottom FET requires a negative voltage, which may be supplied off-chip for maximum efficiency or by an on-chip resistor used to self-bias the amplifier (at the expense of some DC power). Figure 4 shows the MMIC circuit implemented to allow efficient, high-voltage operation. The circuit was tested with 30-V drain bias and a small negative bias. Output power of 2.3 W was demonstrated at 11 GHz. At a reduced bias voltage, power-added efficiency of 34 percent was achieved.

Selective Epitaxy for Multifunction Chip Integration

Selective area epitaxy has long held promise for integrating different electronic components on the same substrate. For example, the ability to form the different material structures required for mixer diodes and FETs on the same substrate would permit on-chip integration of a low-noise amplifier (LNA), local oscillator, mixer, and IF amplifier for receiver applications. COMSAT has developed a technique which uses a dielectrically assisted lift-off (DAL) process to deposit single-crystal GaAs layers via molecular beam epitaxy (MBE) on selected areas of a GaAs substrate. The process can be repeated for each desired materials structure.

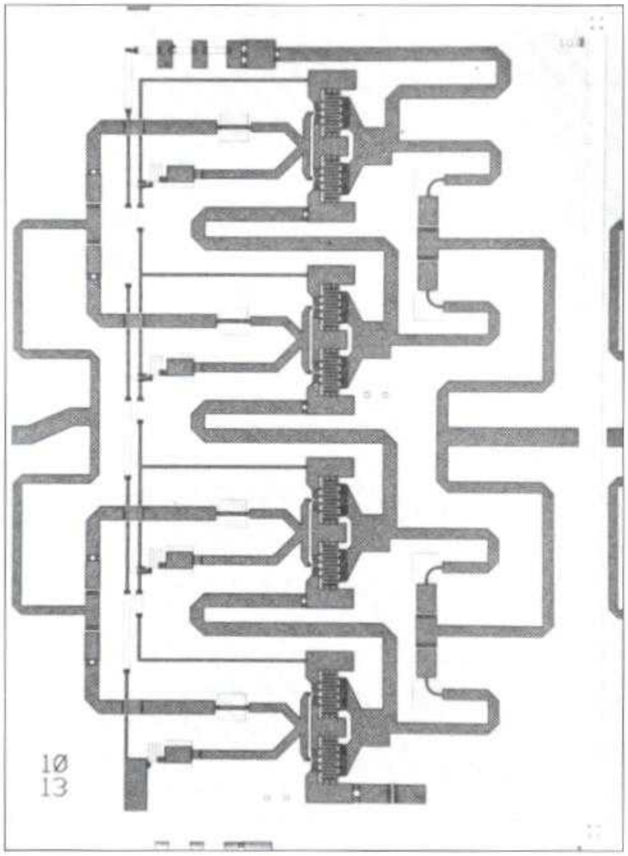


Figure 4. Four-stage MMIC designed to operate at 30-W bias

In the DAL technique, the GaAs substrate is masked by a double dielectric layer consisting of 1,000 Å of Si_3N_4 deposited on top of 9,000 Å of SiO_2. The wafer is patterned, and openings are etched through the dielectric using reactive ion etching and buffered hydrofluoric acid. Due to the etch rate differential between the two dielectric materials, the SiO_2 is undercut. During sample preparation prior to MBE growth, the patterned openings are recessed with an ammonium-hydroxide/hydrogen peroxide solution to a depth equal to the thickness of the layer to be grown. This recessing step undercuts the dielectric, providing a negative edge profile which minimizes sidewall growth. The desired active layer structure is then grown by MBE on the patterned wafer. The growth on the dielectric (amorphous material) is polycrystalline, while the growth on the exposed GaAs is single-crystal. The poly and single-crystal layers are discontinuous at the patterned openings. Figure 5 is a scanning electron micrograph of the patterned dielectric structure with overgrowth. After deposition, the wafer is soaked in a solution of HF to dissolve the SiO_2 and lift off the polycrystalline deposition. The wafer is now ready for subsequent processing, whether it be device fabrication or additional material structure formation via the DAL process.

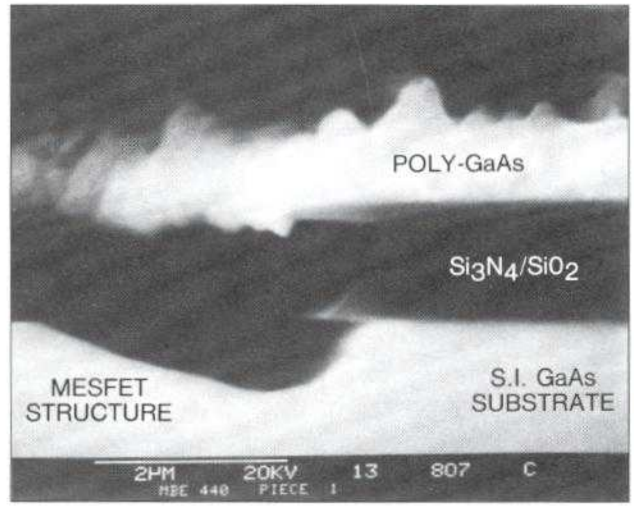


Figure 5. SEM of a T-gate created using COMSAT's improved process

MED has implemented the DAL process to form standard metal-semiconductor FET (MESFET) material structures. Hall mobility and capacitance-voltage measurements performed on the fabricated test structures have indicated that the quality of the selectively grown material is excellent. For an active channel doping of $2.5 \times 10^{17}/cm^3$, MED has measured a room-temperature Hall mobility of 4,000 cm^2/V-s. Furthermore, the surface morphology of the material is optically smooth. Power MESFET devices fabricated from selectively grown material have been DC and RF tested, and the results compare favorably with similarly fabricated devices from a normally grown wafer.

T-Gate Process Development

During 1990, MED developed a novel technique for forming subquarter-micron "T-gate" structures. The T-gate is often employed in millimeter-wave FETs and high electron mobility transistors (HEMTs) to reduce gate resistance and thus improve circuit performance.

Historically, T-gates are usually formed by electron-beam lithography using a double- or triple-layer resist. In this approach, a thin layer of polymethyl-methacrylate (PMMA) is first spun on and baked; then an additional layer of high-sensitivity resist PMMA-methyl acrylic acid (PMMA-MAA) is spun on top of the first layer. Subsequent e-beam exposure produces a T-like profile in the resist (e.g., wider at the top and narrower at the bottom). Inherent in this process are severe limitations on gate uniformity and yield. Furthermore, wide-aspect (i.e., higher ratio of top to bottom dimensions) T-gates are more difficult to achieve on a repeatable basis.

The improved T-gate fabrication process (Figure 6) uses a thin dielectric layer of silicon nitride to define a small footprint by e-beam lithography, and reactive ion etching in combination with a second resist writing step to produce the broad T-top (Figure 7). This results in a very large aspect ratio, low parasitic gate resistance, integrated passivation, and reduced possibility of the gate shorting to the source or drain contacts.

Discrete devices incorporating COMSAT's T-gate process have shown DC yields of approximately 70 percent for a nominal 0.25-μm gate length (across a 3-in. wafer). This yield is considerably better than what would be obtained using the conventional double- or triple-layer resist approach. Finally, S-parameter measurements on a few of COMSAT's 0.25-μm gate length MESFETs have yielded state-of-the-art cutoff frequencies as high as 65 GHz. This improvement is the direct result of the decreased gate resistance of the T-gate structure.

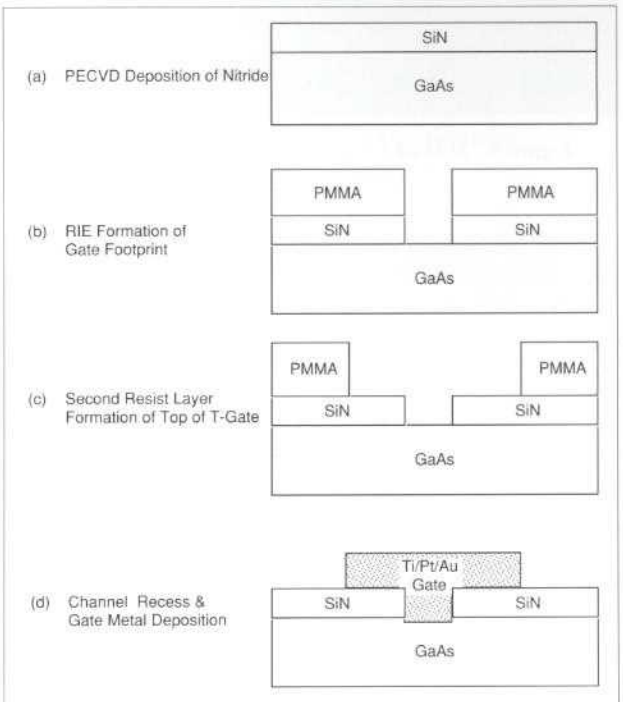


Figure 6. COMSAT's improved T-gate fabrication process

Figure 7. Cross section of the T-Gate

Heterojunction Bipolar Transistor

AlGaAs/GaAs heterojunction bipolar transistors (HBTs) offer many advantages over FETs for microwave applications such as high-speed and high-power amplifier circuits and low phase noise oscillator circuits. HBTs have higher transconductance and current-driving capability, lower demand for fine-line lithography, easier control over breakdown voltage, higher power density, and lower 1/f noise. A recent technological advancement has led to HBTs with f_t and f_{max} above 75 GHz and 210 GHz, respectively.

To obtain power gain at high frequencies with HBTs, the base resistance and the base-collector capacitance, the electron transit times, and the various charging times must be minimized. The extrinsic base-collector capacitance can be reduced by ion-implantation damage to the external n^- layer. The base resistance can be minimized by reducing the separation between the base contact and the intrinsic device using the self-alignment method, which allows scaling of intrinsic device and extrinsic parasitic parameters, thus improving both f_t and f_{max}.

Figure 8 is a schematic of COMSAT's novel HBT fabrication process, designed to produce devices of high uniformity and yield. The emitter, base, and collector contacts are formed by self-alignment involving optical lithography, ion implantation, etching, and alloying. The microwave performance of a 2.5 x 3.0-μm HBT is shown in Figure 9.

MMIC Chip Reliability Meets Space Requirements

DC-biased life tests of generic power MMICs produced by MED were completed in 1990. RF-biased life tests on these power MMICs are continuing, using the life test system shown in Figure 10. Highlights of this system include individual, dynamic temperature control of each heater block up to 180°C and dynamic monitoring of MMIC bias currents, voltages, and operating power.

Extensive temperature-accelerated life testing of COMSAT-fabricated MMICs has consistently shown that the predicted mean time to failure (MTTF) exceeds 10^6 hr at operating channel temperatures of 125°C for pseudomorphic-HEMT MMICs and MESFET power MMICs. COMSAT MMICs have been qualified for space flight in the ITALSAT program. As an example, the life test results for COMSAT's 2.5-W power amplifier MMICs are shown in Figure 11. This MMIC, with a 4.5-mm gate width

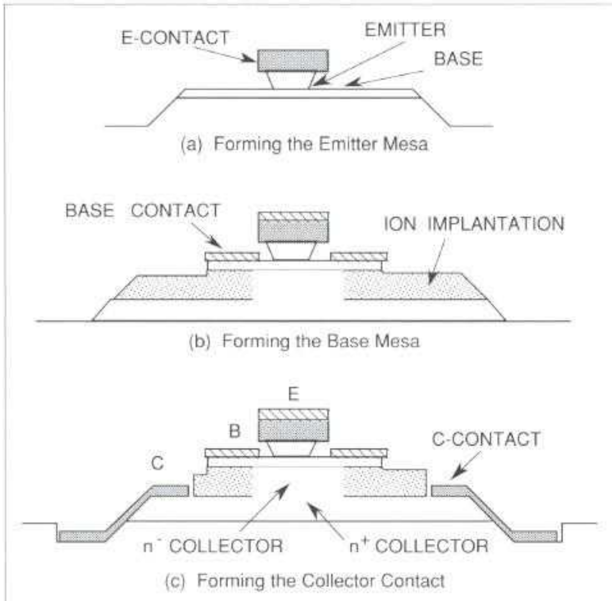


Figure 8. HBT cross sections showing steps in COMSAT's unique fabrication process

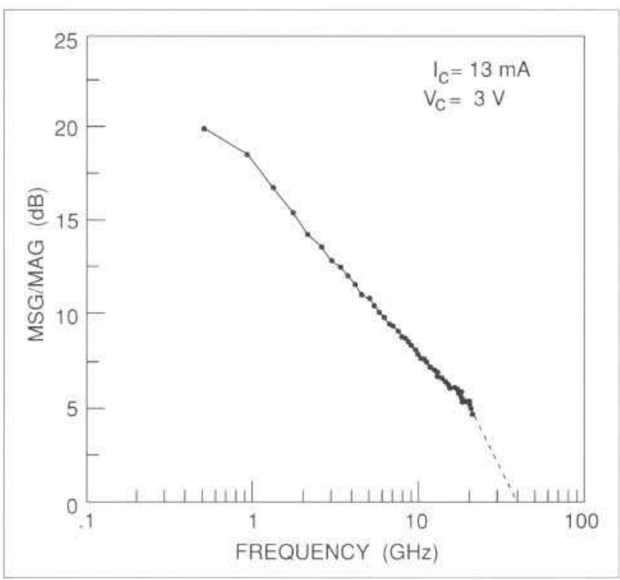


Figure 9. Microwave performance of 2.5 x 30-µm HBT

FET, achieves 35-percent power-added efficiency and has very low thermal resistance (7°C/W). Twenty MMICs have been tested under DC bias at two temperatures; the 50-percent cumulative failure times are 2,200 hr at T_{CH} = 195°C and 504 hr at T_{CH} = 215°C . The measured activation energy is 1.45 eV, and the predicted MTTF is >1 x 10^6 hr at T_{CH} = 125°C (baseplate temperature = 103°C) and >1 x 10^8 hr at T_{CH} = 82°C (baseplate temperature = 50°C). Thus, the predicted lifetime of COMSAT MMICs exceeds the highest reliability requirements for satellite applications.

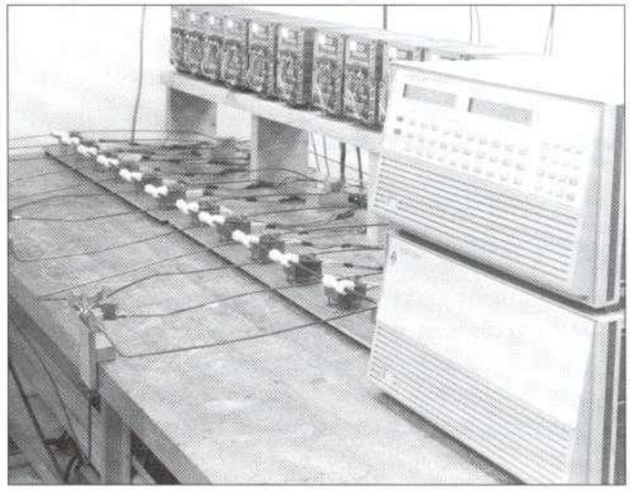


Figure 10. GaAs MMIC RF-biased life test system with individual dynamic temperature control

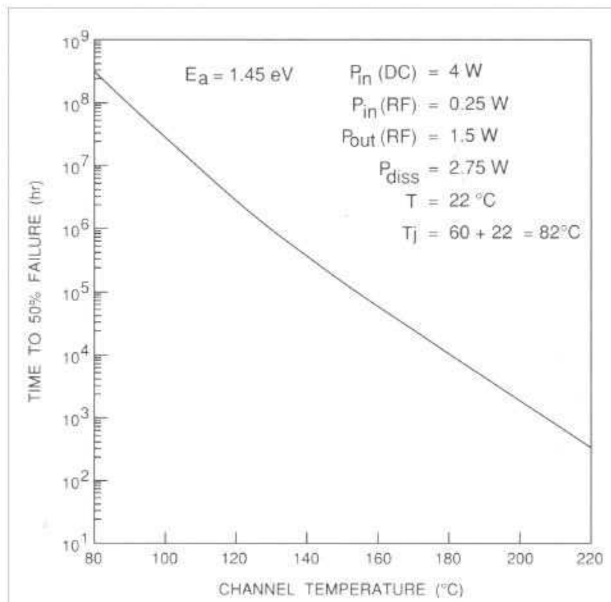


Figure 11. Reliability test results for COMSAT power-MESFET-based MMICs

Life tests of COMSAT C-band LNAs are also in progress. Based on early test results, it appears that lifetimes will be similar to those of MED's power MMIC.

GaAs MMIC Hybrid Dry/Wet Via-Hole Process

GaAs MMICs require low inductance source-to-ground contact for improved circuit performance. Such contact is achieved through via-holes etched from the back of a thinned GaAs wafer to the front-side source contacts, by either wet or dry chemistry. COMSAT Laboratories has implemented a hybrid dry/wet via process into GaAs MMIC production. This process combines the advantages of dry processing, small via-hole size for higher circuit density, wet processing, and smooth via-hole wall profiles for metalization step coverage into one process.

TWT Cathode Reliability

The materials and metallurgical study of oxide-coated traveling wave tube (TWT) cathodes was concluded in 1990. A correlation was identified between near-surface porosity in the cathode nickel and reprocessing history which was associated with occasional peeling of the oxide coating. Recommendations were made for better traceability of materials and improved process control during manufacture to reduce the risk of premature TWT cathode failure.

COMSAT NONJURISDICTIONAL R&D

Ion-Implanted Hyperabrupt Varactor Diode GaAs MMIC Analog Phase Shifter

A GaAs MMIC analog phase shifter was designed and fabricated for 12-GHz operation as part of the flat-plate antenna program. The circuit design used ion-implanted hyperbrupt varactor diodes developed on a previous program. Circuit fabrication experience was obtained through the development of MMIC voltage-controlled oscillators using varactor diodes. The diodes were characterized at RF, and these data were used in the phase shifter circuit design. The circuit consisted of eight varactor diodes, ion-implanted resistors, thin-film capacitors, inductors, and Lange couplers. Figure 12 is a photograph of the completed chip. Target values for capacitance and resistance in the circuit were within 1 percent of the design data obtained from the modeled diodes and resistors. Wafer uniformity for the individual circuits was better than 99 percent. Circuit performance showed 420° of phase shift at 12 GHz with 12.5-V varactor diode bias, exceeding the circuit requirement of 360° phase shift.

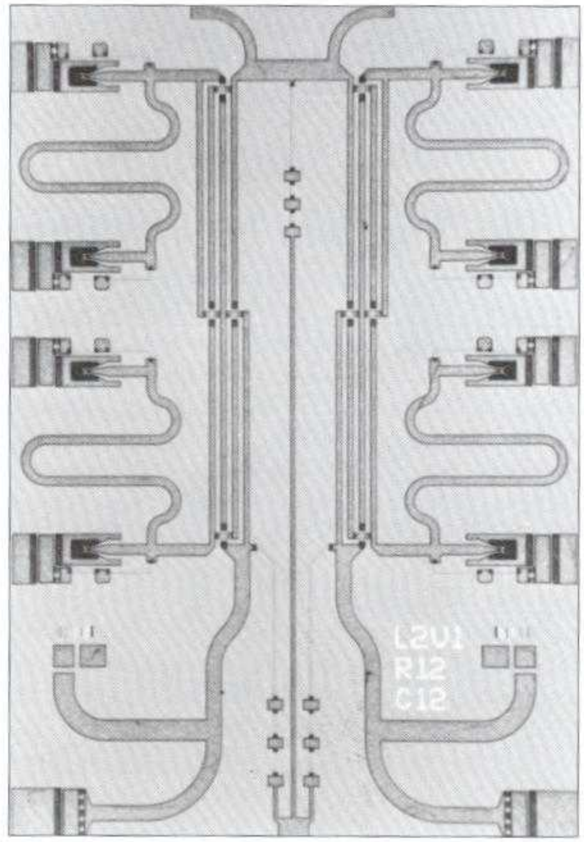


Figure 12. GaAs MMIC analog phase shifter based on ion-implanted varactor diodes

COMSAT SUPPORT

100-W C-Band SSPA

A state-of-the-art prototype 100-W SSPA that covers the C-band communications frequency range of 5.9 to 6.4 GHz was developed. This SSPA can replace the traveling wave tube amplifier (TWTA) currently used in earth station transmitters. It has several advantages over the TWTA, including high reliability, low life-cycle cost, better linearity as a function of input power backoff, lower insertion phase variation as a function of output power level, and smaller size. The amplifier is digitally controlled and is monitored by a built-in controller, either manually using an integrated keypad, or through a computer when switched to remote mode. The overall gain of the amplifier is about 70 dB at the 100-W output power level, and can be backed off by 50 dB in 0.2-dB steps.

Inmarsat 2 and 3 Support

Many electronic devices in the communications and control systems on board satellites are sensitive to electrostatic discharge (ESD) phenomena generated on spacecraft surfaces when the surrounding "plasma" is excited by solar flares. In 1990, in support of the Inmarsat 2 program, MED evaluated conductive coatings (proposed for the dielectric films used as thermal control blankets) and calculated the requirements for the thermal blanket ground tab spacing needed to prevent surface potentials from building up and producing ESD.

MED personnel also participated in evaluating transponder designs—in particular, for the L-band downlink transmit power amplifiers—in all proposals submitted for Inmarsat 3 satellites. Overall SSPA designs, device reliability, and amplifier RF performance related to system requirements were assessed.

Degradation of Materials on INTELSAT VI (F3)

The launch failure of INTELSAT VI (F3) in March 1990 marooned the satellite in a low earth orbit (LEO). Soon after, it was realized that, if rescue were to be contemplated, the health of the satellite had to be assessed to evaluate the effects of long-term exposure of the silver interconnects on the solar cell panels to atomic oxygen, a major constituent of the atmosphere at altitudes between 200 and 600 km.

Under the sponsorship of COMSAT Intelsat Satellite Services (ISS) and with assistance from INTELSAT, an urgent program was undertaken by MED materials scientists to identify the materials at risk on the marooned satellite, to calculate the total exposure of the materials to atomic oxygen, and to determine the oxidation rate of the vulnerable materials. NASA computer programs were used to calculate the density of atomic oxygen in the topside ionosphere and to forecast the concentrations based on projected solar activity; however, no software existed which could calculate the atomic oxygen fluence on the satellite as a function of orbital parameters.

COMSAT's System Development Division was commissioned to revise software previously written for ISS to accommodate elliptical satellite orbits and to calculate the atomic oxygen fluence on the satellite for its current orbit, for all intermediate orbits from launch to date, and for future orbits, pending a planned rescue mission in the second quarter of 1992. The atomic oxygen erosion of the silver solar cell interconnects on the satellite was subsequently assessed for INTELSAT during a Space Shuttle mission in October 1990 (see "INTELSAT Support").

INTELSAT SUPPORT

Space Shuttle Flight Experiment

The possible rescue of the INTELSAT VI (F3) satellite marooned in LEO by the failure of a Titan launch rocket in March 1990 prompted a study of environmental degradation. Because corrosion by atomic oxygen posed a significant risk to the silver solar cell interconnects on the satellite, INTELSAT proposed an experiment to evaluate the extent of corrosion and determine the condition of the solar array at the time of the proposed rescue.

The experiment was constructed by the Satellite Technologies Division at COMSAT Laboratories. Two small panels of interconnected solar cells and three separate plates with silver interconnects attached were mounted on the remote manipulator arm of the Space Shuttle *Discovery* and exposed to atomic oxygen for a total of 45 hr during a flight in October. MED materials scientists then measured the oxide thickness and composition and the thickness of the silver remaining on the interconnects. Figure 13 shows cross-sectional views of a 12.5-µm-thick silver ribbon interconnecting two solar cells that were exposed to atomic oxygen during the Space Shuttle flight. The resulting oxide layers are evident on both the front and back surfaces of the silver loop joining the cells.

Based on a conservative extrapolation to the predicted total oxygen fluence on the satellite, the loss of silver was estimated as not more than 2.4 µm from launch through December 1990, and 3.4 µm total through March 1992. This would leave a silver thickness of 9.1 µm, which would be more than adequate for the satellite to conduct the solar-generated power and to survive the mechanical

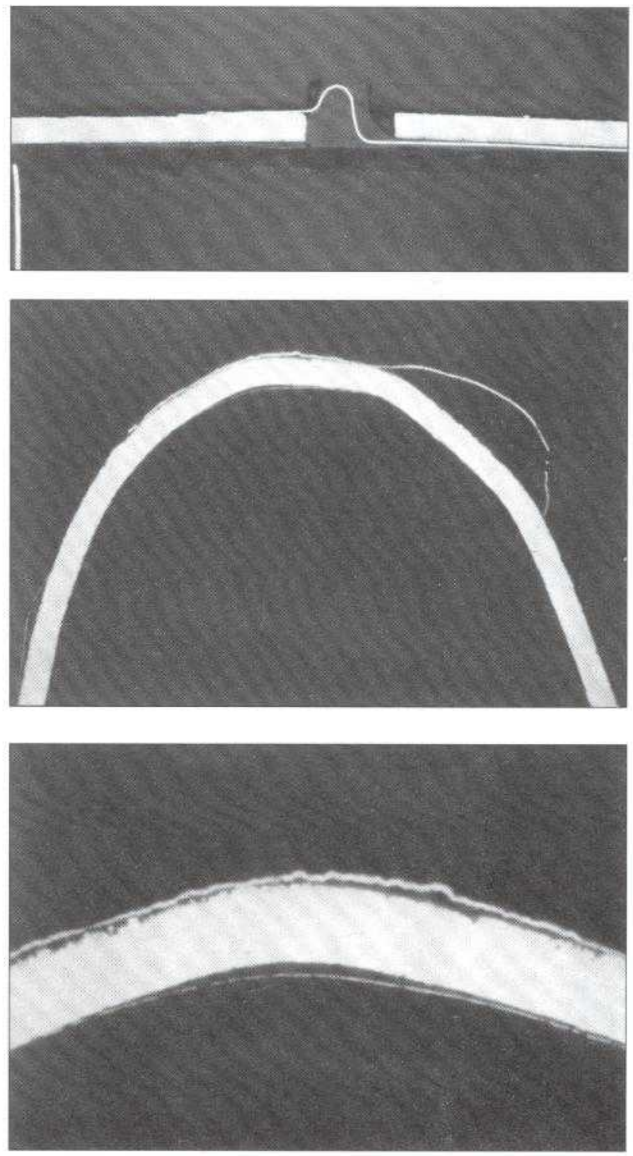


Figure 13. Cross sections of an INTELSAT VII solar cell interconnect exposed to atomic oxygen during a Space Shuttle flight

shock of perigee motor firing. These results weighed heavily in the decision to proceed with the Shuttle rescue mission.

Radiation Effects on Solar Cells and ESD Production

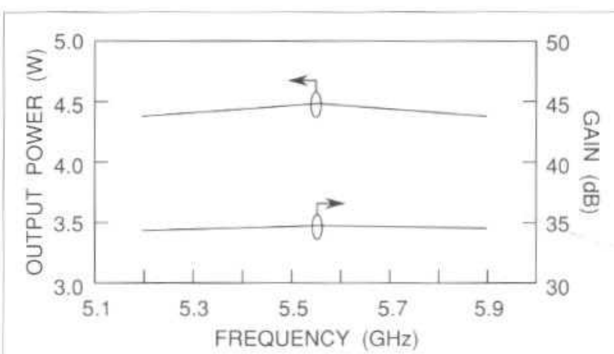
MED has conducted particle radiation tests and provided technical direction and evaluations for INTELSAT VII solar cells and optical solar reflectors (OSRs). These tests are important for the prediction of long-term solar array performance and the selection of OSRs.

Ongoing support of the INTELSAT VII program has included evaluation of the thermal, mechanical, and ESD properties of the proposed antenna sunshields. It was planned to install an on-board ESD and plasma environment monitor; however, weight and other considerations have eliminated this option.

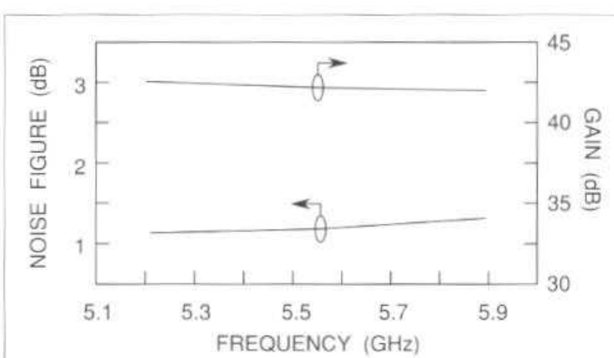
OTHER SUPPORT

T/R Submodule Development and Production

COMSAT has an ongoing program to produce transmit/receive (T/R) submodules for advanced tactical and surveillance radar being developed by Unisys for the U.S. Air Force. The C-band transmit and receive amplifiers for this program were developed at COMSAT using MMIC technology, and integrated with other control MMICs, such as the receive protect switch, transfer switch, and phase shifters, into a hermetically sealed submodule housing. With the delivery of four prototype T/R submodules, the program has progressed into the small-scale production phase. The submodule has exceeded RF performance specifications, with a transmit power of approximately 4 W and a receive noise figure of 2.5 dB. Performance uniformity among the submodules has been within 10 percent. The results of accelerated, DC-biased life tests of the low-noise and power MMICs used in these modules provide a predicted MTTF exceeding 10^6 hours, which meets requirements for high-reliability military and space applications. The RF performance of the receive and transmit amplifiers inside the submodules is shown in Figure 14.



(a) Transmit



(b) Receive

Figure 14. Air Force T/R submodules exhibit good RF performance

94-GHz Doubler/Amplifier Chain

Under contract to Hercules Corporation, an MMIC W-band varactor doubler was developed that delivers 30 mW of output power at 93 GHz with 12-percent conversion efficiency. U-band MMIC MESFET power amplifier chips were also developed that exhibit 0.23 W of output power with 13-dB gain from 45.5 to 46.5 GHz. A doubler/amplifier chain has been integrated to deliver 30 mW of output power at 93 GHz, with an overall gain of 7 dB, as shown in Figure 15. These chains are intended for missile seeker/transceiver applications.

External Customer Base

MED activities are also sponsored by external customers. The Division has successfully completed the design, fabrication, test, and qualification of GaAs MMICs for several outside contracts. For instance, a monolithic single-balanced mixer chip (Figure 16) has been developed which is applicable for 94-GHz seeker/transceiver

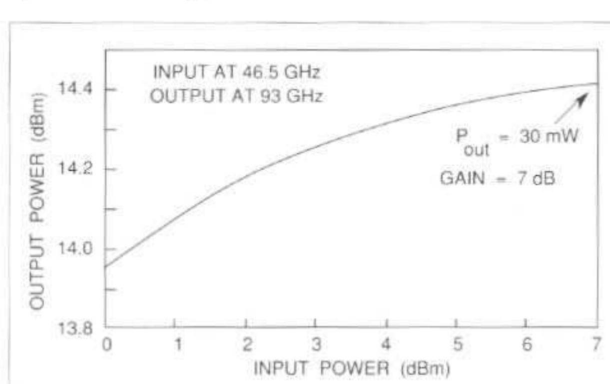


Figure 15. W-band MMIC doubler/amplifier chain delivers high power and gain for missile/transceiver applications

systems at Hercules. Figure 17 shows the performance of the chip, which demonstrates a conversion loss of about 10.5 dB and a double sideband (DSB) noise figure of about 7 dB at 94 GHz.

Other current MED customers include Loral Space Systems (space-qualified MMICs for satellite communications); Unisys (MMIC modules for a communications data link and X-band power modules for phased-array radar); Boeing (MMICs for an extremely high-frequency phased-array antenna and Ka-band power HEMT-MMICs); and Harris (60-GHz HEMT frequency translators). In addition, MED provides fabrication foundry services for General Electric Astro Division, Pacific Monolithic, the Canadian Research Council, Motorola, Northrop, and Loral Space Systems.

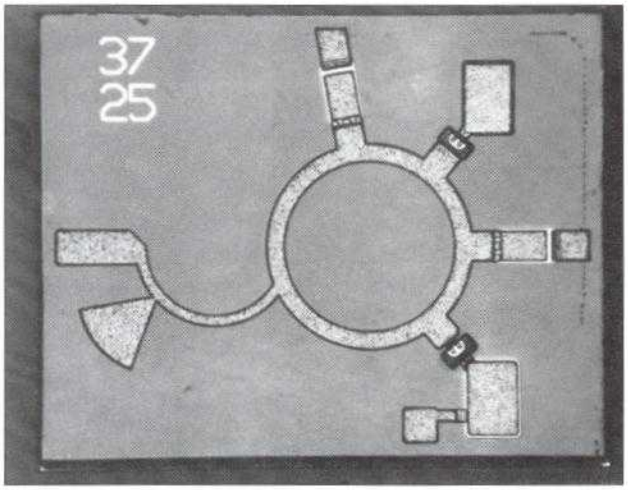


Figure 16. W-band monolithic mixer chip for seeker/transceiver systems

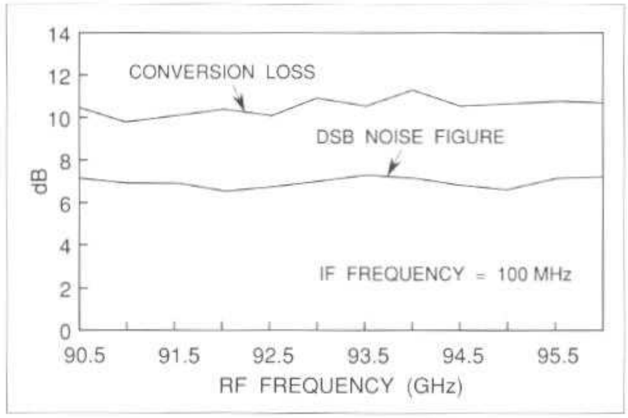


Figure 17. Performance of the MMIC W-band mixer

The Satellite Technologies Division (STD) completed development of a satellite flight simulator in 1990 and continued work on microwave filters, common pressure vessel battery life testing, satellite monitoring and in-orbit testing, and microwave propagation studies. In collaboration with the Lincoln Laboratory, STD developed stripline bandpass filters using high-temperature superconducting filter technology. STD also designed and fabricated test hardware which was flown on the October 1990 Space Shuttle Discovery *flight.*

COMSAT JURISDICTIONAL R&D

Advanced Spacecraft Developments

Three shelves of digital electronics, which control the beam-forming matrix of the high-power antenna array (see Microwave Technology and Systems Division [MTSD], "Ku-Band High-Power Array"), were fabricated and assembled, and software to support the hardware was written and tested. The controller comprises three different circuit designs: a monolithic microwave integrated circuit (MMIC) driver and two level shifter circuits on alumina boards. Each board has complementary metal-oxide semiconductor (CMOS) integrated circuit chips and surface mount resistors and capacitors. More than 200 integrated circuits are required in order to control the 96 phase shifters.

The design of a C-band lightweight antenna (see MTSD, "C-Band Lightweight High-Efficiency Antenna"), which consists of 177 antenna modules each containing a patch antenna and redundant dual-polarized amplifiers, was initiated during 1990. The preliminary mechanical design uses a separate module inserted into a common chassis to form the antenna. Each module makes good thermal contact with a redundant heat pipe assembly to remove a maximum of 17 W of heat, for a total antenna heat dissipation of about 1,500 W. Heat pipes are attached to a two-phase capillary pump loop which transports the heat to a remote radiator for rejection into space.

A thermal model of a geosynchronous communications spacecraft with a multibeam antenna payload was developed to evaluate system mass, volume, and power requirements. An important result of this study was that the area required for heat rejection could be reduced 25 percent by using extensions to the north and south spacecraft radiators. Fixed-conductance heat pipes embedded in the radiator panels increase thermal efficiency and permit the use of both front and rear surfaces.

Automated Satellite Command and Control

Communications satellite systems such as INTELSAT and Inmarsat face increasingly complex requirements for their command, telemetry, and other ground operations, as more satellites of varied designs place a heavier burden on ground operational systems. The purpose of this project is to develop expertise in applying methods such as knowledge based or expert systems and neural networks in order to operate the system safely and cost-effectively through increased automation of satellite command and control functions.

One demonstration expert system, called Anomaly Analysis Assistant, has been developed to aid in detecting and diagnosing anomalies in the attitude control system and telemetry system of a typical satellite. A system structure for semi-independent but cooperating expert systems was selected. The underlying theme of this structure is that, for this complex, real-time, on-line environment, the most appropriate structure is one that models the way human experts are organized to monitor and control satellite systems, and the way they use their expertise to reason about flight anomalies.

The expert system developed uses a commercially available expert system shell designed for real-time applications, and a team of cooperating expert systems (Figure 1). A "telemetry expert" processes telemetry signals to eliminate data corruption such as dropouts or noise spikes; a "monitor" watches the processed outputs of the telemetry

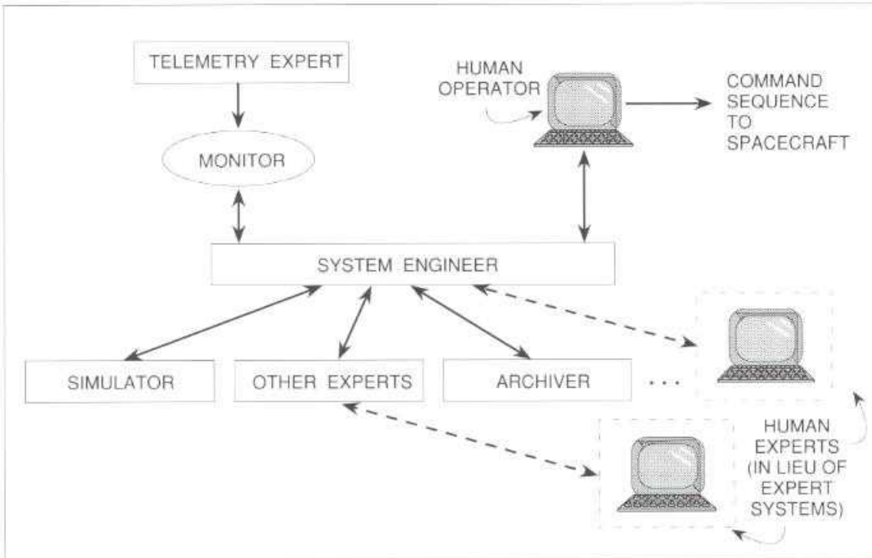


Figure 1. Expert system comprises a team of cooperating "experts"

expert to detect abnormal conditions; and a "system engineer" handles multidisciplinary knowledge, runs a simulator, and anticipates spacecraft behavior in order to supply detection criteria to the monitor. Other experts are on call, but do not use machine resources until activated by the "system engineer." An attitude control simulator (ACS) generates test telemetry and responds to spacecraft commands. This demonstration model is self-contained in a workstation. For on-line application, this system concept can be expanded by using a network of computers.

Multimode Microwave Filter Technology

In past years, this effort has focused on miniaturizing filters by taking advantage of the degeneracy of modes in high-Q waveguide cavities. During 1990, work was concentrated on exploiting filter size reduction possibilities by using stripline or lumped-element components. However, due to the low Q of these components, active or negative resistance elements must be used to develop high resonator Qs. A number of narrowband active filters were designed and are being fabricated.

Superconducting Filter Technology

In a joint effort with the Lincoln Laboratory on the Naval Research Laboratory (NRL) High-Temperature Superconducting Space Experiment (HTSSE-I), STD developed four- and six-pole stripline bandpass filters using YBaCuO superconducting thin films on lanthanum aluminate substrates. These filters were produced at Lincoln's processing facilities using COMSAT designs and AT&T Bell Laboratories superconductor thin film. The transmission response of the four-pole filter at 77 K (see Figure 2) shows a residual dielectric loss of a few tenths of a dB, which corresponds to a resonator Q of approximately 5,000 (compared to Qs of only 300 obtained from standard stripline filters). Figure 3 shows the four-pole superconducting filter compared to a dielectric loaded cavity filter. Note the significant reduction in both size and weight that is possible with high-temperature superconducting filter technology.

Propagation Studies

A number of investigations on propagation impairments in satellite communications and ways of ameliorating them are being pursued. The types of impairments and the means of combating them were studied, particularly with respect to emerging telecommunications design

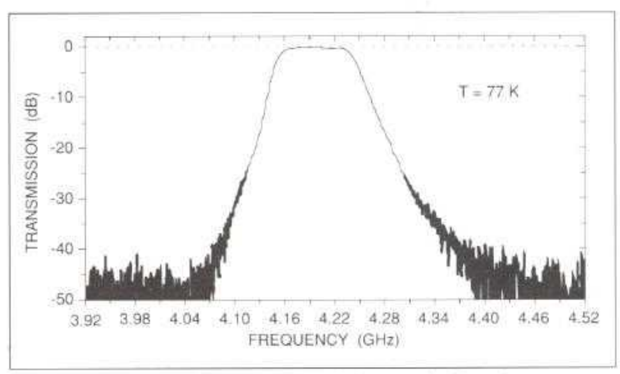


Figure 2. COMSAT-designed four-pole filter features resonator Q of approximately 5,000

Figure 3. High-temperature superconducting filter technology realizes significant size and weight reduction

requirements. Toward this end, several clear-air propagation phenomena were modeled to facilitate the design of low-availability systems. Special emphasis was placed on developing tools for propagation modeling and measurement. During 1990, efforts were focused on modeling tropospheric scintillations, predicting sun outage, and developing low-cost radiometers for estimating path attenuation.

Mechanical/Thermal Design of Common Pressure Vessel Battery Mount

The purpose of this research program was to investigate the feasibility of various mounting configurations for integrating the nickel-hydrogen (Ni/H_2) common pressure vessel (CPV) battery into existing or proposed spacecraft structures. The investigation considered the mechanical requirements imposed by the launch environment, as well as thermal requirements based on the need to transfer heat generated within the battery to the spacecraft radiator. The design goal was to develop a lightweight, rigid support structure that provides good heat transfer.

Five different mechanical/thermal CPV battery spacecraft mounting concepts were investigated. Figure 4 illustrates one of the more promising concepts which uses aluminum brackets for mechanical attachment to the spacecraft structure and a heat pipe sleeve to transfer generated heat to the spacecraft radiator with a minimum temperature gradient.

Figure 5 shows the results of a weight study in which different mounting concepts for a 120-Ah CPV battery were evaluated. Note that a weight savings of 20 to 50 kg

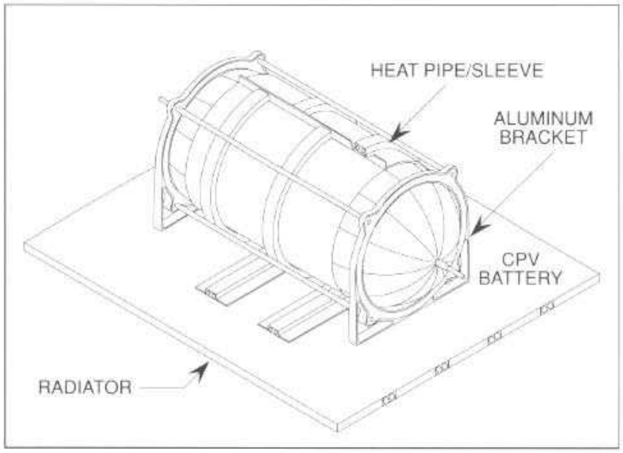


Figure 4. CPV battery mount is a lightweight, rigid support structure that provides good heat transfer

can be realized for a high-power communications satellite. Replacement of this mass with propulsion fuel would increase the useful spacecraft lifetime by more than 1 year.

Bearing Cage Instability Investigation

The ball bearings used in a spacecraft momentum wheel, which is part of the attitude control system, can suffer from an abnormality wherein the ball separator or cage vibrates violently. This can dramatically reduce momentum wheel lifetime and cause spacecraft control problems. As momentum wheel lifetime requirements have increased (16 years for INTELSAT VII), empirical testing has become impractical. Therefore, it

	CONCEPT				
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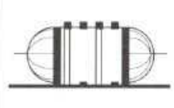
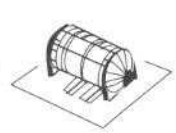
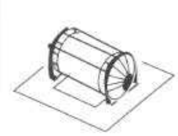
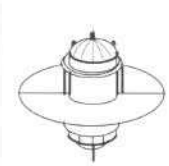
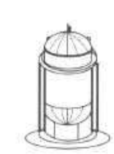
					
WEIGHT OF MOUNTING STRUCTURE (kg)	3.2	3.3	3.5	4.7	5.9
TOTAL WEIGHT OF BATTERY (kg)	45.4	45.5	45.7	46.9	48.1
% OF MOUNTING STRUCTURE IN BATTERY	7	7	8	10	12

Figure 5. CPV battery mount can provide significant weight savings

has become necessary to attempt to analytically model ball bearing performance so that parameters such as temperature, lubricant type and quantity, bearing and cage dimensions, and wear rates can be studied. These studies include projected end-of-life performance, which is of special interest in regard to cage stability margin.

ADORE (Advanced Dynamics of Rolling Elements) is a computer program capable of modeling the dynamics of a ball bearing operating at high speed. This program is particularly refined with respect to cage dynamics, and was modified to model the novel geometrical features of the INTELSAT VII momentum wheel bearing cage. A number of possible bearing operating conditions were analytically evaluated, and it appears that the INTELSAT VII momentum wheel has adequate stability margin.

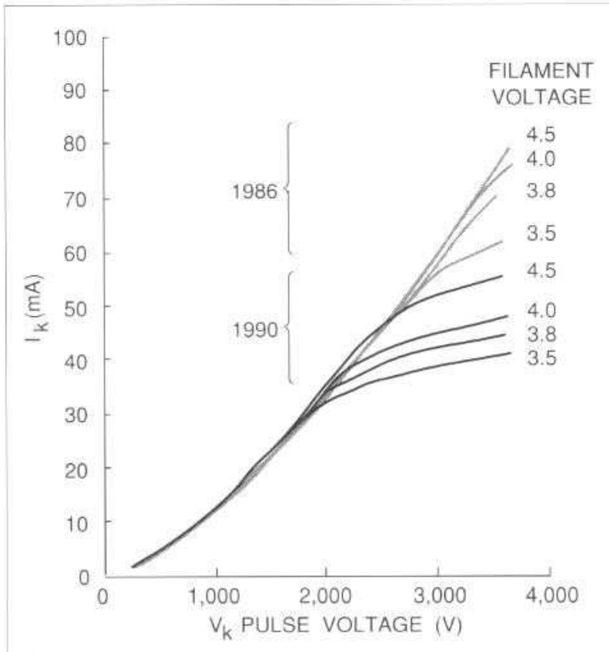
Microwave Tube Studies

Although traveling wave tubes (TWTs) have given excellent service over the years as the power output stage of communications spacecraft transmitters, their tendency to develop problems (which are not apparent even through burn-in) necessitates the provision of generous spares (three for two, and even two for one). This project is devoted to minimizing the incidence of problems and to refining tests which might expose latent defects early in the manufacturing process.

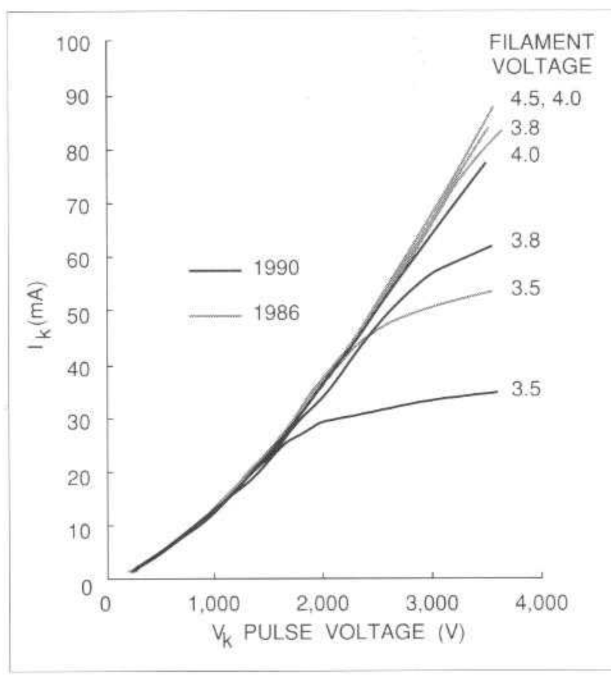
A long-standing problem has been the relatively early (3- to 5-year) failure of the oxide cathode, which affects some portion of the C-band TWT population. This problem occurred in both INTELSAT V and VI, and two TWTs from the INTELSAT V program have been under extended study for 5 years. Efforts have centered around developing tests for evaluating cathode quality (activity), which may be more revealing than the traditional "dip-test." Since two INTELSAT V TWTs were suspected of having intermittent leaks, a test was devised in which the cathode current was measured with short pulses over a range of cathode temperatures. Test results showed variable activity at the time, and the measurements have been repeated over the years.

The difficulty of finding correlations in long-term tests such as these is illustrated by comparison of the signatures recorded in 1986 and 1990, as shown in Figure 6. Tube 1 is still performing nearly to specification but shows significant deterioration, while tube 2 appears new.

During 1990, the method for measuring shot- and flicker-noise in the cathode current was investigated on the grounds that defects in the oxide layer (which perhaps lead to peeling) might result in recognizable signatures in the way that noise levels develop as the cathode is heated up from cold. Typically, the noise increases rapidly with the current, until space-charge limitation occurs and the



(a) Tube 1



(b) Tube 2

Figure 6. Oxide cathode signatures show variable activity

noise is suppressed. Interesting signatures were recorded, but it appears that the monitoring time-scale may be long enough to see the M-cathode replace the oxide cathode.

Another TWT problem—occasional high-voltage breakdown leading to spurious shutoff (SSO) once per week to once per year—has also occurred in recent spacecraft programs. STD plans to analyze several tubes that have shown a tendency for this breakdown in a 1991 program to characterize the more subtle signatures of the pre-breakdown phenomena.

Expert Systems Applications

A key element in satellite communications earth station equipment is the uplink high-power amplifier (HPA), for which a microwave vacuum tube (klystron or TWT) is the output RF stage. While these tubes are generally very reliable, they do give rise to a significant proportion of operating interruptions, particularly during initial operation in a new earth station. Problems that arise are variously related to the tube, the high-voltage power supply, and the control and protection circuitry.

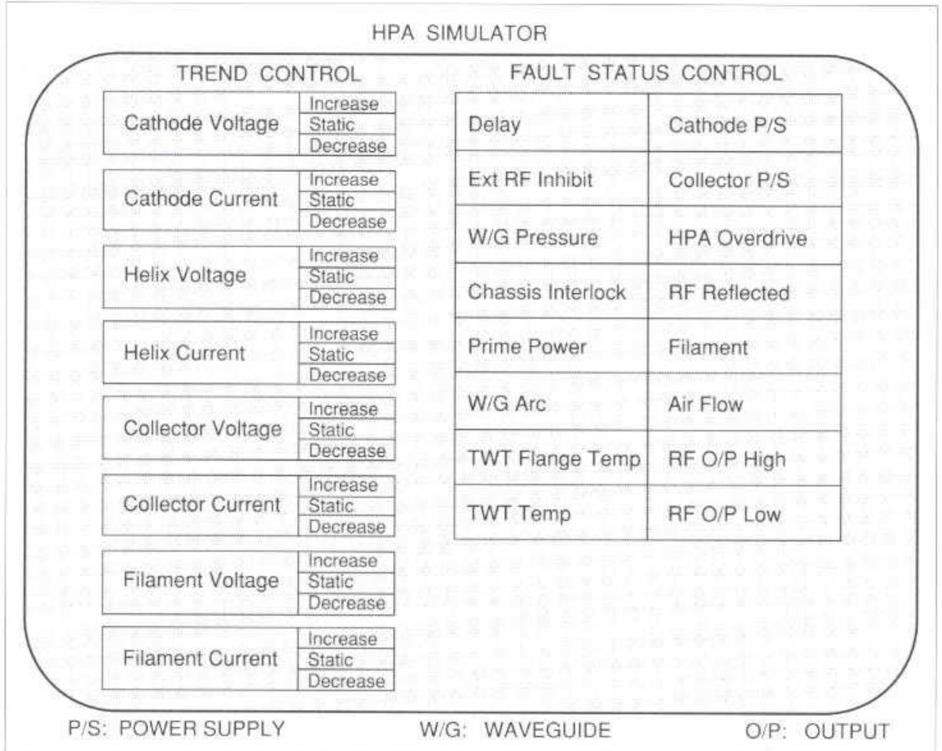


Figure 7. HPA expert system identifies operating problems

Although much prior experience exists in these areas, it is mostly in the minds of a small number of individual experts. An expert system appears to be an ideal way of recording and systematizing such knowledge. Under this project, the experience obtained from the development and commissioning of several generations of earth stations is being assembled into the knowledge base of an HPA expert system. The system runs on a PC with an 8-Mbyte memory and a 150-Mbyte hard drive.

For convenience in practical application, the user interface with the prototype system is based on the display of status and operating parameters provided by the circuit and RF monitoring equipment of a typical HPA, as shown in Figure 7. By "clicking" on the appropriate anomaly indicator with a mouse, an operator connects to a chaining system which leads through further questions and recommendations to the depth of knowledge available from the experts.

In addition to providing archived knowledge, the expert system is structured to receive simulated real-time data from the HPA monitoring instruments and use these data to look for anomalies and provide limited predictions. In the prototype version, the operator can initiate a consultation by setting anomaly conditions in an HPA simulator–a simple ancillary system that sends typical analog or digital signals to the expert, as prompted. The relation between the elements of the complete system is illustrated in Figure 8.

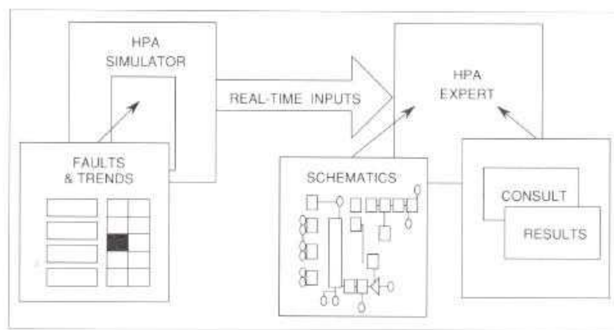


Figure 8. HPA expert system receives simulated real-time data from monitoring instruments

Power System Life Extension Studies

The basis of this study is the possibility of extending the operational life of INTELSAT satellites by the careful selection of battery and solar array components, together with the establishment of precise in-orbit management procedures.

A performance model developed in previous years to predict the life expectancy and voltage behavior of Ni/Cd and Ni/H_2 batteries was extended to include a new coefficient in the regression equation to reflect the effect of KOH content in cells. Parametric temperature studies with flight-model Ni/H_2 cells showed that capacity decrease with increase in temperature is nonlinear, with an inversion in the curve at 45°C. The change in the cell's response to temperature at 45°C is due to slightly increased chargeability of the cell at 40° to 60°C, which can be attributed to a structural transformation that occurs in the positive active material at 42° to 46°C.

Failures of solar strings continue to plague the INTELSAT V satellites, which have experienced a total of 19 failures among the 13 satellites in orbit. Analysis of experimental results obtained through various investigative techniques, including vibration, thermal cycling, electrostatic discharge, and cell reversal, points to open circuit diode failure as the reason for the failures.

Propagation Measurements in Africa

Since 1986, COMSAT has participated in a Ku-band propagation data collection program with three African nations: Cameroon, Kenya, and Nigeria. This effort is driven by the need for reliable propagation data from tropical climates. The measurement and data reduction phase of the program continued in 1990. Measurements at a new site, Kericho, Kenya, were initiated in April 1990, and COMSAT continued to actively participate in INTELSAT's analysis of data collected from the 1987–1989 measurement campaigns.

Ku-Band Up-Link Power Control Development

The viability of open-loop up-link power control (ULPC) as a fade countermeasure has been demonstrated, and efforts toward consolidating the basic concept and implementing it in an operational earth station continued in 1990. A key element of the ULPC system is estimation of the down-link fade by careful measurement of a down-link beacon signal. The up-link fade is estimated by frequency translation from the down-link fade. The measured beacon signal level reflects the combined effects of propagation- and nonpropagation-related phenomena; however, the accuracy of the ULPC system is heavily dependent on its ability to isolate propagation phenomena from nonpropagation or equipment-related effects.

Effects of Scintillation on Satellite Communications

The objective of this project is to evaluate the effects of propagation-induced signal scintillations on the performance of satellite communications systems. During 1990, the specific task was to evaluate such effects on the performance of various satellite antenna-tracking systems, with a goal of establishing techniques and rules for handling the associated operational problems. Categorization of path scintillation phenomena and their impact on different types of tracking and pointing methods was undertaken.

COMSAT NONJURISDICTIONAL R&D

Ni/H_2 Aerospace CPV Battery

During 1988, a project was initiated to develop a prototype test module of the Ni/H_2 CPV aerospace battery to exploit the desirable technological achievements from a previous program in which a terrestrial CPV battery was developed.

Final assembly of a 26-cell, 22-Ah aerospace CPV battery occurred in February 1989. After initial characterization, the battery was placed into an accelerated cycling regime which removed 44 percent of its energy on each discharge before recharging. Seven thousand cycles of very stable voltage performance were achieved before battery performance degraded in mid-1990. Analysis of the failed battery provided valuable input to the design of a second prototype, planned for 1991. This CPV technology offers significant improvement in specific energy (energy per unit weight) and energy density (energy per unit volume).

Efforts to produce a new synthetic separator have paralleled the CPV development. An inorganic/organic synthetic separator was developed to replace the currently used asbestos and zircar separator. The new structure, developed in collaboration with W. R. Grace & Co., is chemically stable, microporous with a porosity higher than that of asbestos, and mechanically stronger than zircar. Samples of the separator are undergoing cycle testing in experimental Ni/H_2 cells.

COMSAT SUPPORT

INTELSAT VI BAPTA Life Test

The life test of the INTELSAT VI engineering model bearing and power transfer assembly (BAPTA) began in January 1989 and was continued in 1990 under COMSAT sponsorship. The primary assemblies in the BAPTA are the bearing assembly and the electrical contact ring assembly (ECRA).

The performance of the bearing assembly and the ECRA is critical in sustaining the life of the satellite because neither system has a redundant backup. The BAPTA is being tested in a thermal vacuum environment to simulate in-orbit conditions, and has shown normal performance since the beginning of the life test. Parameters monitored continuously include temperature at several locations, condition of the bearing lubrication film, spectral analysis of the torque signal, and power brush noise in the ECRA. The friction torque of the BAPTA is computed from the drive motor voltage and the current.

In addition, an accelerated life test was conducted on an ECRA wherein the speed was increased to 300 rpm (normal is 30 rpm) and the current was increased to 36 A (normal is 18 A). After the equivalent of 20 years of operation in a thermal vacuum environment, the ECRA life test was stopped in December of 1990. The brush wear measured at the conclusion of this test was found to be minimal—less than 6.5 percent.

Inmarsat 2 and 3 Support

An independent evaluation of the Inmarsat 3 proposals was completed by COMSAT Laboratories to help formulate the U.S. Signatory's position on the status of the five independent Inmarsat 3 spacecraft proposals.

STD staff also provided support to Inmarsat via a CSD consulting contract which involved monitoring of thermal vacuum tests of Inmarsat 2 in Toulouse, France; participation in the Flight Readiness Review for the F1 spacecraft; evaluation of the momentum wheel lubrication conditions; and a review of spacecraft contingency plans. Plating and conversion coating samples were developed at the Laboratories to support selection of a substitute high-power waveguide and feed, which was subsequently installed on the flight spacecraft at the launch site. Additional activities consisted of assisting Inmarsat related to thermal and mechanical aspects during contract negotiations. In addition, a task was undertaken to develop a thermal model of the Inmarsat 3 spacecraft.

Battery Support

COMSTAR and Satellite Business Systems (SBS) satellite batteries continue to be life tested in a charge and discharge cycling regime which simulates real-time battery operation in orbit. The test results provide a database for projecting in-orbit performance and lifetime expectancy on board COMSTAR and SBS satellites. A computer model is used to calculate the expected end-of-discharge voltage on the longest eclipse day and to forecast overall performance. The COMSTAR-type batteries have completed 29 eclipse seasons (14 years), while the SBS batteries have completed 21 seasons (10 years). The real-time life test and the performance projections should provide a basis for estimating battery capability for operating these satellites up to and beyond their contractual lifetime.

INTELSAT SUPPORT

INTELSAT Atomic Oxygen Shuttle Experiment

When the INTELSAT VI (F3) spacecraft failed to achieve geosynchronous orbit in March 1990, concern was raised regarding possible low earth orbit (LEO) environmental damage to materials, which might limit the spacecraft's life after reboost. Atomic oxygen erosion of the thin silver solar cell interconnects was of particular concern. INTELSAT asked COMSAT Laboratories to develop hardware for the STS-41 (*Discovery*) shuttle flight which would allow the determination of solar cell interconnect erosion as a function of temperature.

To meet INTELSAT's objectives, three thermal plate assemblies were designed and fabricated with different thermal finishes to produce distinct temperature profiles. The design of these assemblies included provisions to thermally isolate the critical front face from the Shuttle environment and for attachment of the solar cell interconnects. Figure 9 shows one of the completed assemblies. The three thermal plate assemblies were attached to a NASA-supplied witness plate, along with two solar array coupons. The witness plate was mounted on the Shuttle's remote manipulator arm and deployed 60 ft from the Shuttle during a flight in October 1990.

Since no temperature telemetry was allowed on the experiment, flight temperatures were predicted using experimentally determined thermal properties and orbital parameters supplied by NASA/Johnson Space Center. Figure 10 is a typical example of the temperature predictions. After the shuttle flight, erosion of the solar cell interconnects was measured and used to predict erosion rates that the INTELSAT VI interconnects are likely to experience based on their expected atomic oxygen dosage.

The mechanical integrity of the INTELSAT VI solar cell interconnect when subject to loads from the perigee kick motor firing and temperature excursions in LEO was investigated. It was concluded that, even with erosion, the interconnect would survive the injection and life at synchronous orbit.

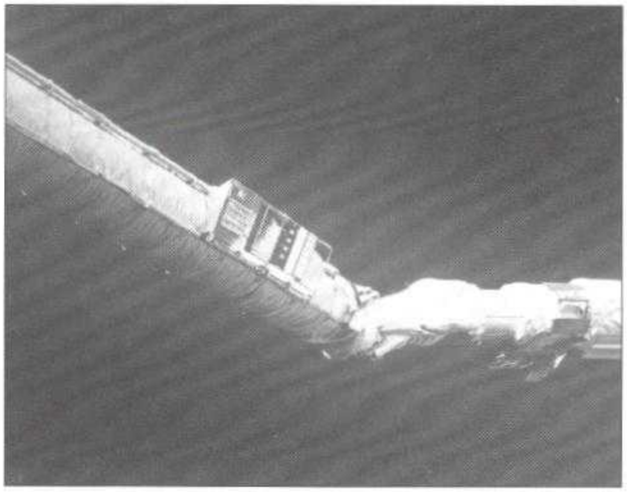


Figure 9. Thermal plate assembly provides thermal isolation from Shuttle environment

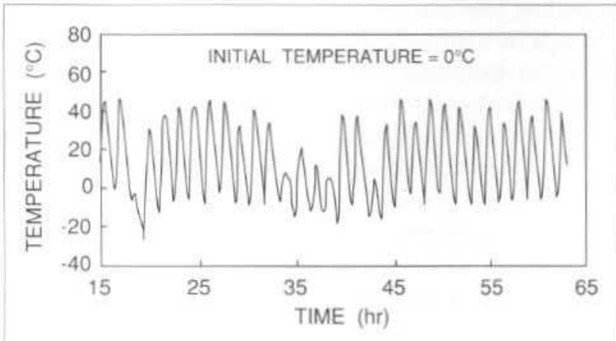


Figure 10. Experimentally determined thermal properties and known orbital parameters were used to predict flight temperatures of Shuttle experiment

INTELSAT V Momentum Wheel Life Test

The antenna-pointing performance of INTELSAT V/V-A satellites is critically dependent on the life of the momentum wheels. The long-term effects of speed and temperature cycling on the momentum wheel motor, electronics, and bearings were not fully known prior to launch of the first INTELSAT V satellites. Work is continuing to evaluate the long-term performance of two engineering model momentum wheels.

The ongoing life test program has accumulated more than 19 wheel-years of running time. One wheel acts as a control case by operating at ambient conditions at a nominal 3,500 rpm, while the other is speed and temperature cycled to simulate worst-case in-orbit conditions. Performance data such as power consumption, spectral analysis of the torque signal, and reaction torque are collected monthly and added to the database. The momentum wheels have shown normal performance since the beginning of the life test. During 1990, one wheel was removed from life test and disassembled to provide engineering data for the INTELSAT VII momentum wheel design.

The continuing wheel tests provide an empirical critique of the current generation of momentum wheels. In addition, they have produced a valuable database for future momentum wheel designs.

INTELSAT VII Momentum Wheel

The INTELSAT VII momentum wheel is similar to that used on INTELSAT V, but has a much higher operating speed. During the wheel Critical Design Review, it was observed that the existing database for the active lubricator used for the bearings could not technically support the lubrication design at 6,600 rpm. The contractor was directed to perform a series of special lubrication tests, which determined that the properties of the grease used were not well understood and that the proposed processes were inadequate considering the variability of the grease. In further support of INTELSAT VII, an INTELSAT V life test wheel was disassembled after running for 10 years. The disassembly revealed that the active lubrication system was ineffective and unlikely to be capable of supporting a 22.5-year momentum wheel life test requirement. Consequently, adjustments were made to the lubricator design and processing and the construction of flight wheels was allowed to proceed.

INTELSAT V and VI Battery Life Tests

In 1990, battery testing included real-time life tests of batteries from the INTELSAT V, VI, and K spacecraft. The ongoing life test for INTELSAT V consists of a Ni/Cd and a Ni/H_2 battery which are tested by simulating the electrical and thermal parameters of the in-orbit power subsystem. The Ni/Cd life-test battery has been tested for 23 eclipse seasons (11 years), and the Ni/H_2 battery for 19 eclipse seasons (9 years). These tests provide a baseline for performance data, an early look at the effects of wear, and an opportunity to develop procedures to correct for anomalous performance in orbit.

The effort to develop new methods which will aid in long-term operation of in-orbit batteries continued in 1990. Tests were initiated to determine the preferred method of Ni/H_2 battery storage, with the main goal of reducing degradation due to water loss.

The INTELSAT VI Ni/H_2 battery life test, simulating real-time battery operation in-orbit, began in 1986 and has continued through 1990. The method of pre-charge was the major variable under investigation. The batteries have completed nine eclipse seasons (4 years) and have shown excellent electrical performance, although with an unexpected high rate of pressure rise.

As part of a continuing effort to evaluate storage-related degradation in flight cells, new production lots of INTELSAT VI cells have been introduced into the INTELSAT VI life-test regime. Previous studies at COMSAT showed loss of performance in stored flight cells which necessitated their eventual rejection for flight. Replacement of these cells, coupled with current testing, will improve the performance and reliability of INTELSAT VI in-orbit battery systems.

Up-Link Power Control Transmission

COMSAT is under contract to INTELSAT to develop an open-loop ULPC system and verify its performance by conducting transmission tests at Ku-band over a period of 1 year. The receive facility for the evaluation of transmissions from the Laboratories will be located in the Netherlands at the University of Eindhoven, a subcontractor on this effort. Substantial development work was completed during 1990, including development and fabrication of the controller hardware, main site and remote site system integration, and conceptual development of the ULPC algorithm.

Low-Elevation-Angle Clear-Air Effects

The extension of satellite coverage down to elevation angles well below the established norms will provide substantial economic benefit to the INTELSAT system. Propagation impairments will be a dominant factor in determining the operational aspects of such low-elevation-angle links. COMSAT was awarded a contract to study low-elevation-angle link availability issues, mainly under clear-air conditions. Tropospheric scintillations and low-angle fading are expected to be the dominant impairments. Modeling of these and other clear-air phenomena was undertaken during 1990.

Propagation Measurement Field Support

A variety of field support and consultation services were provided to INTELSAT in relation to ongoing radiometric measurements and data analysis from several tropical and subtropical sites. Field support was provided to sites in Australia, Kenya, and Papua, New Guinea, and technical consultation was provided for data reduction and analysis of radiometric data collected at three African sites. Such services are an outgrowth of COMSAT's long involvement in the worldwide development and deployment of propagation measurements, and are vital to the successful operation of remote experiments.

In addition, refurbishment of two sets of radiometric equipment was begun in 1990. Originally designed and developed at the Laboratories, this equipment was used in radiometric measurement campaigns in Africa and will be redeployed in Brazil and New Zealand.

INTELSAT Technical and Engineering Support

COMSAT Laboratories was engaged in several activities in support of INTELSAT, including participating in the INTELSAT VI (F3) launch and recovery operations in the propulsion and attitude determination and control system (ADCS) areas, providing inputs to the sequence of launch events, system-readiness testing at the Launch Control Center, and assistance with launch rehearsals. COMSAT was also involved in generating INTELSAT VI ADCS in-orbit test procedures; assumed the ADCS on-call and supervisory duties for 1 week in May; and performed analyses related to INTELSAT V end-of-life operations and electrothermal thrusters. COMSAT took the lead in testing and commissioning the INTELSAT V Autonomous Commanding System on new computer systems at all TT&C ground stations, participated in the expert system development, and trained INTELSAT engineers for on-call duties and emergency spacecraft recovery with the aid of the INTELSAT V ADCS Flight Simulator.

OTHER SUPPORT

ARABSAT Life Extension Project

This project was supported by directing the adaptation and revalidation of an ADCS simulation program for the ARABSAT satellite; directing the simulation runs; analyzing the results; and preparing and giving lectures to ARABSAT personnel on several topics related to spacecraft design, operation, and orbit maintenance.

ITALSAT Attitude Control System Flight Simulator

Under contract to Telespazio, COMSAT Laboratories completed the design, fabrication, integration, delivery, and test of the ITALSAT Attitude Control System Flight Simulator (IAFSIM). The IAFSIM facility (Figure 11), now in operation at Telespazio's ITALSAT Operations Control Center in Fucino, Italy, is being used to aid ground controllers and engineers in operating the ITALSAT spacecraft. The purpose of the facility is to accomplish the following:

- Enable better understanding and evaluation of real-time spacecraft dynamics and attitude control operations and performance.
- Facilitate development of operational sequences for transfer orbit and geostationary orbit.
- Validate the ITALSAT control center software and hardware.
- Train spacecraft ground controllers.
- Support anomaly analysis.

The simulator combines spacecraft hardware (attitude control processing electronics) with software models of the rest of the spacecraft, including sensors, thrusters, momentum wheels, attitude dynamics, disturbance torques, and orbital mechanics. The simulated attitude control system responds to commands and generates a dynamic telemetry response. Static models of other spacecraft telemetry are combined with the dynamic response to form the complete spacecraft telemetry stream. The IAFSIM can be operated either in stand-alone mode or, when connected to the control center packet-switching network, from the actual control center consoles.

This real-time, high-fidelity, operator-interactive simulator covers the entire range of missions phases, including

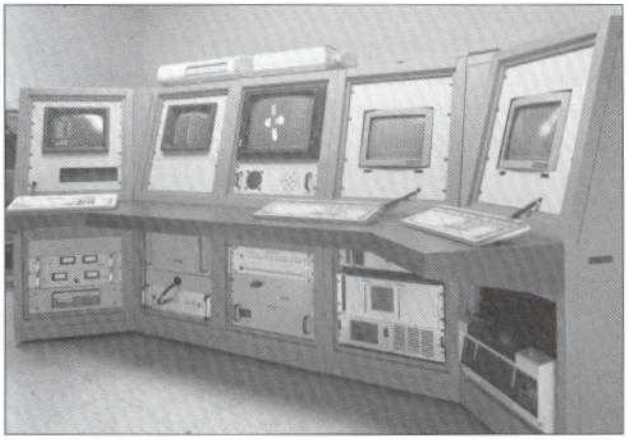


Figure 11. IAFSIM facility assists in operating the ITALSAT spacecraft

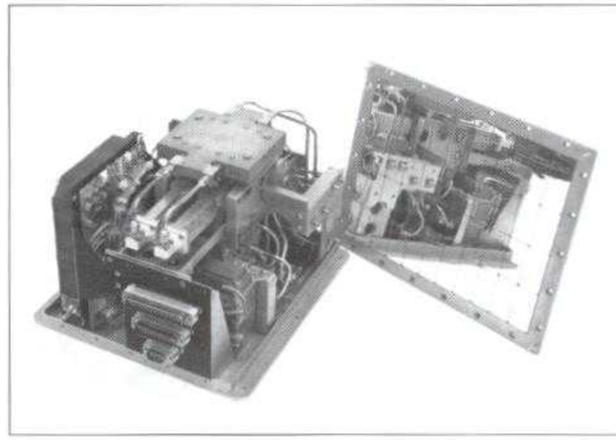


Figure 12. IOTT functions as designed on the ITALSAT spacecraft

three-axis-stabilized transfer orbit operations, liquid apogee engine firing, attitude acquisition and reacquisition, normal mode, and stationkeeping modes.

Various failure modes are simulated and can be triggered during a simulation run. This feature, together with the modeling or inclusion of all redundant equipment in the attitude control system, allows failures and corrective action to be emulated. Thus, failures can be analyzed, and recovery or workaround procedures can be practiced and evaluated.

ITALSAT In-Orbit Test Transponder

The in-orbit test transponder (IOTT), (Figure 12), is a COMSAT Laboratories designed and manufacture package mounted externally on the ITALSAT spacecraft and used for in-orbit RF testing (see MTSD, "Selenia Spazio"). The thermal/mechanical design features a multilevel packaging concept utilizing the top cover (with second-surface mirrors) as a heat rejection surface. Thermostatically controlled heaters are used to maintain the IOTT temperature during inoperative periods. The IOTT was fully qualified by thermal, vibration, and electrical testing at COMSAT Laboratories prior to integration onto the flight spacecraft in mid-1990. The elapsed time between contract initiation and delivery for spacecraft integration was less than 7 months. The IOTT package weighs about 5 kg in flight configuration and dissipates approximately 25 W. The ITALSAT spacecraft was launched in January 1991 and preliminary data indicate that the IOTT is functioning as designed and tested.

Microwave Monolithic Active Filter

The results of the first phase of a contract with the Naval Research Laboratory were reported in the 1989 *Annual Report.* This involved the successful design of a 4- to 8-GHz bandpass active filter having a stopband performance which exceeds 20 dB below 3 GHz and above 9 GHz. Following completion of the filter in late 1989, STD initiated the design and development of the second phase of this work, which calls for construction of an active filter with similar passband characteristics but having a stopband in excess of 60 dB. By the close of 1990, the design and mask drawings of this filter had been completed and fabrication was scheduled for 1991.

IOT/ESVA System

In 1988, EUTELSAT awarded COMSAT Laboratories a contract to develop a fully integrated in-orbit test (IOT) and earth station verification (ESVA) system. This system was installed in the Rambouillet, France, earth station during 1990 and was used by EUTELSAT to test its first EUTELSAT II satellite. The systems software, consisting of approximately 400,000 lines of code, is based on the UNIX operating system and the MPCP II, a proprietary operating system developed at COMSAT Laboratories. The system can perform several different measurements concurrently. Operator interaction with the system is via pull-down menus, dialog boxes, and a mouse; the user interface is based on the X Window and OSF/Motif standards.

The Communications Technology Division (CTD) achieved significant progress during 1990 in on-board digital processing, 155-Mbit/s modem/codec development, high-definition television compression, and development of a simple time-division multiple-access version of time-multiplexed television. Advances were made in understanding the bit error characteristics of INTELSAT intermediate data rate carrier burst error events, and their effect on the operation of digital circuit multiplication equipment. A 4.8-kbit/s code-excited linear prediction design was completed, and techniques used for 16-kbit/s speech encoding were extended for sound program applications. A facsimile quality assessment was conducted, International Telegraphy and Telephony Consultative Committee (CCITT) facsimile standards were changed, and work on a facsimile demodulation/remodulation unit neared completion. Hardware for the distribution of global positioning signals via Inmarsat satellites is under development, and the Inmarsat-C 600- and 1,200-bit/s signaling and message channel burst demodulator development was completed for coast earth station applications. Other 1990 activities included a subjective evaluation of 16-kbit/s speech codecs for INTELSAT, functioning as the host test laboratory for the 16-kbit/s algorithm standardization question in CCITT, echo control studies for EUTELSAT and INTELSAT, spread spectrum software simulation program development, and initial work on a flexible high-speed digitally implemented modem (2 to 300 Mbit/s) for the NASA Lewis Research Center.

COMSAT JURISDICTIONAL R&D

Time-Multiplexed Television

Following the successful completion of prototype time-multiplexed television (TMTV) equipment capable of transmitting three broadcast-quality National Television System Committee (NTSC) television signals in a single 36-MHz transponder from a single up-link, an effort was launched in 1989 to develop a time-division multiple-access (TDMA) version which allows the transmission of three television signals from geographically separate up-links. An innovative TDMA format was designed that permits transmission of television signals in both NTSC and phase alternate line (PAL) standards simultaneously within the same transponder, and a simple TDMA synchronization scheme which does not depend on a reference station or reference burst was developed. Extra memory was provided at the transmit and receive ends to permit operation with inclined-orbit satellites.

A proof-of-concept (POC) prototype consisting of two up-link processors (one capable of transmitting up to two NTSC signals and another capable of transmitting one PAL signal) and one receive processor (capable of receiving any of the three signals) was designed and constructed during 1990. The burst acquisition and tracking algorithms were implemented and integrated with the TMTV signal processing hardware. Preliminary testing with this prototype established the feasibility of TDMA TMTV.

The TMTV technology was demonstrated in a transatlantic field test jointly conducted by British Telecom, COMSAT, and INTELSAT. After TMTV processing, three network television signals originating from London, U.K., were transmitted in one-half of a 72-MHz Ku-to-C transponder on INTELSAT VI in parallel with their normal 36-MHz leases. As depicted in Figure 1, the network television signals were routed to Goonhilly, U.K., via terrestrial microwave, multiplexed by TMTV equipment, and transmitted using a 3.7-m Ku-band up-link. To simulate the loading on the other half of the transponder, another station at Martlesham, U.K., was used to send a 30-MHz NTSC test signal in a two-carrier-per-72-MHz configuration. At Staten Island, N.Y., the TMTV signal was received with a 15-m C-band antenna. For comparison, the three signals were displayed side by side with signals transmitted directly from the London Teleport. Other than a slightly increased noise level, which was expected, no degradation was observed in subjective evaluation of the processed signal compared to the NTSC test signal.

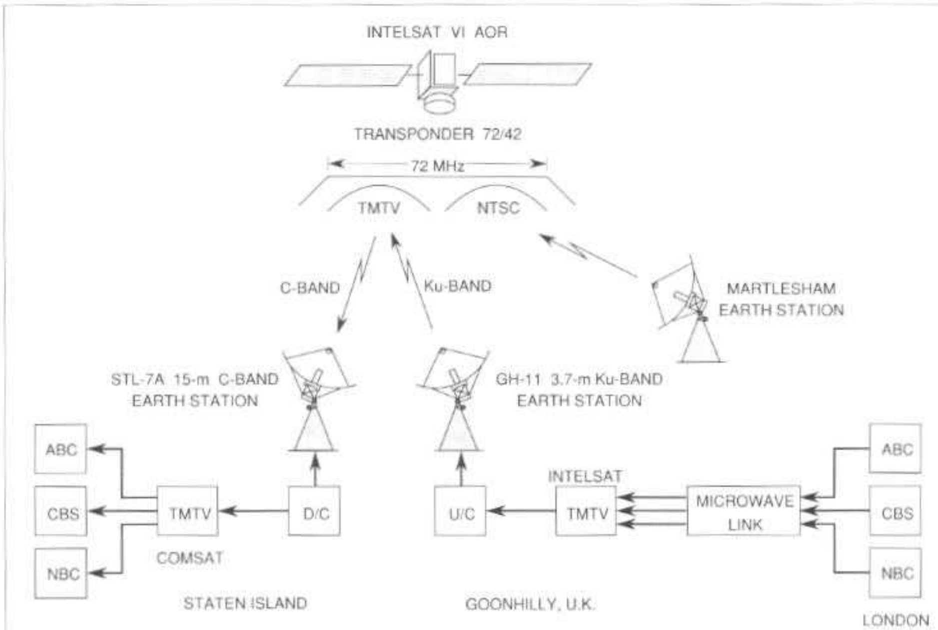


Figure 1. TMTV technology was demonstrated in a transatlantic field test

Digital Coding of Television Signals

Most of the recent advances in digital television have been based on "symmetrical" algorithms related to variations of the discrete cosine transform (DCT) technique in which decoding is an exact inverse of encoding. However, such algorithms may not offer the best approach, in terms of overall system cost, performance, and reliability, for broadcast networks which may involve only a few transmit stations and many receive stations.

Recognizing the significant advantages of "asymmetrical" algorithms for broadcast television applications, CTD developed a video compression algorithm with relatively simple encoders and extremely simple decoders based on a simplified form of vector quantization. In this technique, the television screen is partitioned into a large number of small blocks, each containing 4 x 4 samples, or pixels. The information of user interest in such a small block can be classified into 16 two-dimensional image patterns (Figure 2) and up to two gray-scale values for a monochrome image. A straightforward compression technique involves the selection of the best approximation for the block from among the candidate patterns. Typical television pictures contain a large number of DC blocks, which require an average of only 16 bits (compared to the 128 bits needed for uncompressed blocks). Use of additional coding such as Huffman coding will result in approximately 15:1 compression, and motion compensation and condition replenishment introduce another factor of 2:1 or 3:1, resulting in an overall compression of about 30:1 or 40:1.

A computer simulation of the above technique on a still test picture is shown in Figure 3. Note that this method preserves the high-frequency information on the edges of the picture. The computations for the encoding process are about the same as those required for a two-dimensional DCT for the same sized block. However, the decoding process involves only a table lookup of the pattern and filling the patterns with the appropriate pixel value(s). Thus it offers very good potential for use in broadcast networks.

Advanced On-Board Signal Processing

Satellites that employ on-board signal processing will enable greater connectivity between small, low-cost earth stations. A small earth station can be placed closer to the end user, thus reducing terrestrial transmission costs and overall user costs. On-board demodulation of the signals has the added advantage of improving the link bit error rate (BER) performance. Efforts at COMSAT have focused on implementing a POC demultiplexing/demodulation processor and reducing the size, mass, and power of processors compatible with satellite payload requirements.

Subsystems of the POC model on-board processor were integrated and tested during 1990. The current processor, shown in the block diagram of Figure 4, can demultiplex and demodulate carriers occupying 20 MHz of bandwidth, with carrier sizes ranging from 1.544 to 11 Mbit/s. The concepts demonstrated are applicable to

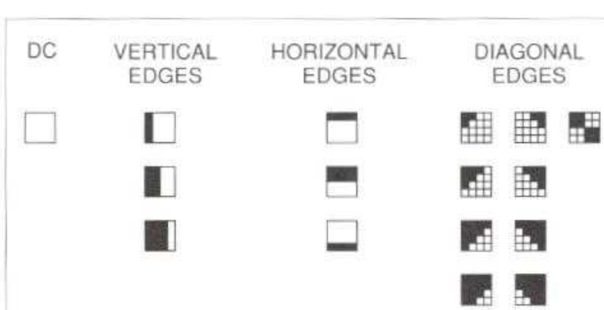
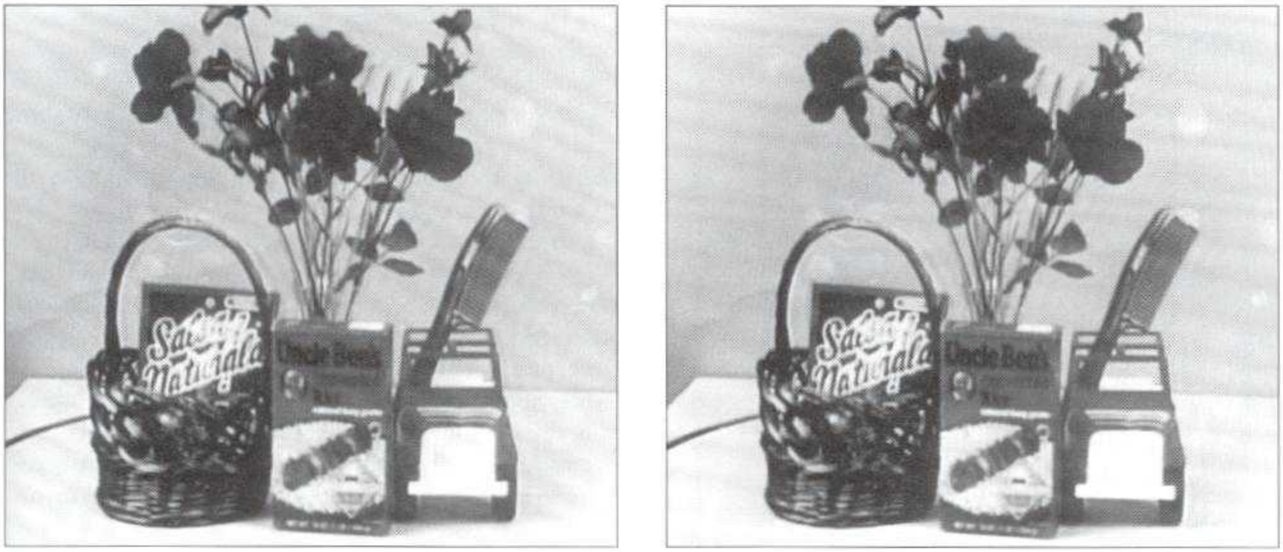


Figure 2. Perceptually important image patterns in a 4 x 4 block



(a) Original *(b) Coded*

Figure 3. Computer simulation of COMSAT's video compression technique shows that high-frequency information on the edge of the screen can be preserved

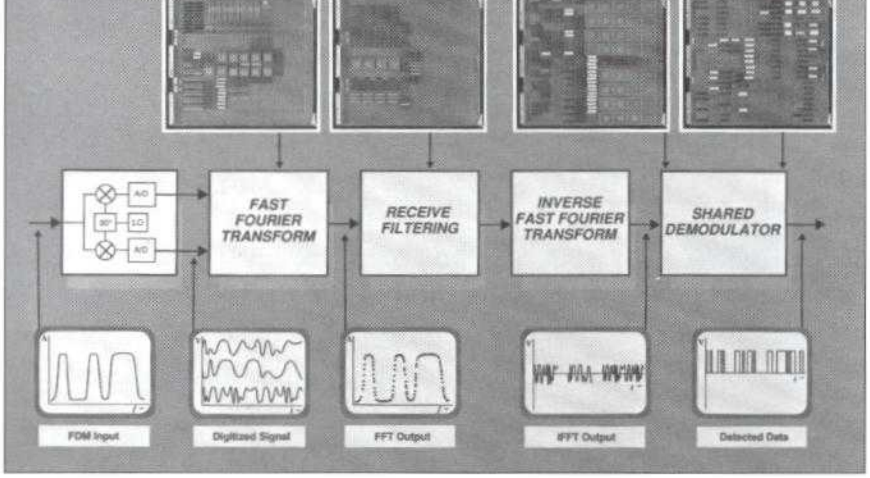


Figure 4. POC on-board multicarrier demultiplexer/demodulator is intended to reduce system mass and power

full-transponder, 72-MHz operation. The BER performance of a 2-Mbit/s carrier after processing through the entire system is shown in Figure 5. The POC processor will be tested in 1991 using a variety of frequency plans and carrier bit rates.

With the POC processor as a baseline, work focused on reducing the power and mass of an on-board digital demultiplexer/demodulator processor. Specifically, means were found to simplify or eliminate many of the large memory buffers that precede and follow the fast Fourier transform (FFT) and inverse FFT (IFFT) processors, which are central to the demux/demod system. In addition, fault tolerant techniques were developed for these processors to permit self-diagnosis and self-healing operation. In the demodulator arena, methods were developed to perform the acquisition and tracking functions using the same synchronization circuitry, thus resulting in further savings in power and mass. Investigation of power and mass reduction will continue in 1991. Estimates based on these changes and the introduction of application-specific integrated circuit (ASIC) chips, where possible, indicate that a sixfold reduction in power and mass is achievable.

Mobile and Portable Terminal Technology

COMSAT Laboratories has successfully developed a 4.8-kbit/s code-excited linear prediction (CELP) speech codec (Figure 6) for digital speech transmission over a 5-kHz multipath fading mobile satellite channel. The encoder, decoder, and analog interface functions are all accommodated on a six-layer, 3U x 220-mm printed circuit board with a standard VME bus P2 connector. Two Texas Instruments TMS320C30 32-bit, third-generation, floating-point digital signal processors (DSPs) are used, one each for the encoder and decoder.

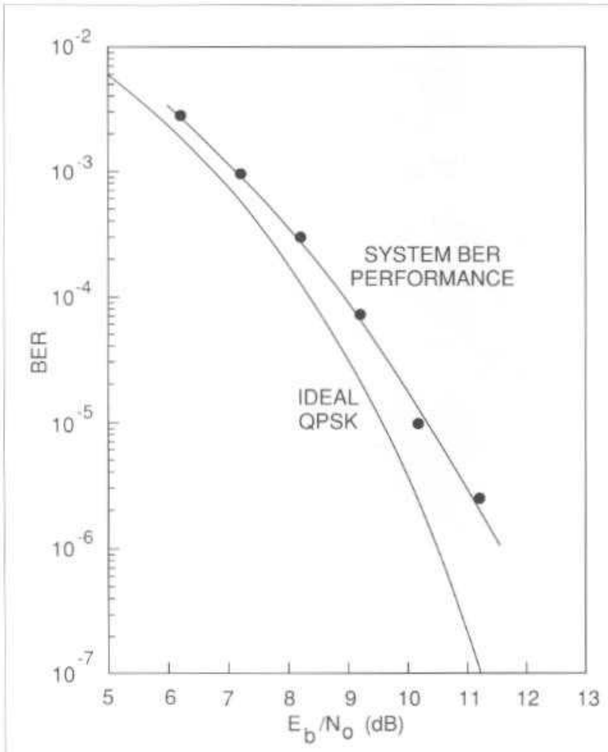


Figure 5. BER performance of 2-Mbit/s carrier after processing

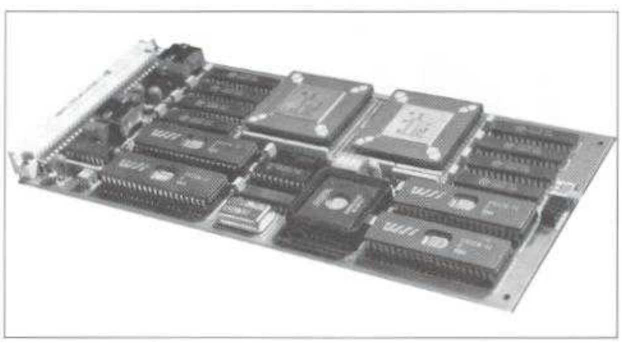


Figure 6. COMSAT's 4.8-kbit/s CELP speech codec

The speech data rate is 4.8 kbit/s. With error protection, the total data rate is 6.4 kbit/s.

The vocal tract filter coefficients, in terms of the line spectrum frequencies, are computed, quantized, and interpolated into four different sets of values in each frame. The excitation signal, including a first-order pitch filter and a stochastic excitation codebook, is computed four times per frame using a perceptually weighted analysis-by-synthesis method. Special features are included to improve high-frequency voice quality and to accommodate the dual-tone multifrequency (DTMF) tones. The reconstructed speech is natural-sounding, highly intelligible, and has excellent speaker recognizability.

For real-time operation, a fast method for transformation from predictor coefficients to line spectrum frequencies was devised. The pitch filter analysis was simplified by employing a recursive filtering approach, and the search through the excitation codebook was greatly simplified by using a Gray-coded multipulse basis vectors structure. The end-to-end codec delay is less than 100 ms, including a 30-ms speech input buffering delay.

The error protection strategies involve selective error correction, detection, and speech parameter smoothing. Effective error protection is achieved with little redundancy by judicious bit placement, appropriate application of error detection by parity check, and the use of a special sum code for forward error correction. A distinguishing mechanism was devised for separate treatment of burst and random errors. Subjective listening test results with a simulated multipath fading channel model and random errors (with BERs up to 4 percent) show that the codec is very robust under combined burst/random error conditions.

155-Mbit/s Modem/Codec Development

To facilitate 155-Mbit/s broadband integrated services digital network (B-ISDN) transmission over satellites, and to enable 140-Mbit/s fiber optic cable restoration, COMSAT has developed a versatile high-speed combined modulation and coding system that uses octal phase shift keying (8-PSK) modulation combined with a multistage variable-rate code. The system will transmit information at rates of 155.52 or 139.264 Mbit/s through a single 72-MHz transponder. The multistage codec implements a rate 13/15 code when transmitting B-ISDN information, and a rate 7/9 code when supporting cable restoration at 139.264 Mbit/s.

The multistage codes were selected for their superior performance from a group of other viable codes after an extensive simulation and study effort which was completed in 1988. The system-level design, including the modem, codec, and special test equipment, was largely completed in 1989. Particular attention was given to providing a manufacturable engineering model and incorporating the features necessary for operational deployment. The system design also includes a Doppler buffer that enables information transmission over satellites with inclined orbits of up to 3°. To support these codes, the 8-PSK modem operates at approximately 60 Msymbol/s, which generates a signal spectrum well within the available bandwidth of the 72-MHz transponder.

Functional hardware testing and laboratory additive white Gaussian noise testing of the 155-Mbit/s operating mode of the system were conducted in 1990, and the results were found to be consistent with theory. The measured vs predicted performance of the system is shown in Figure 7. In 1991, CTD plans to complete the

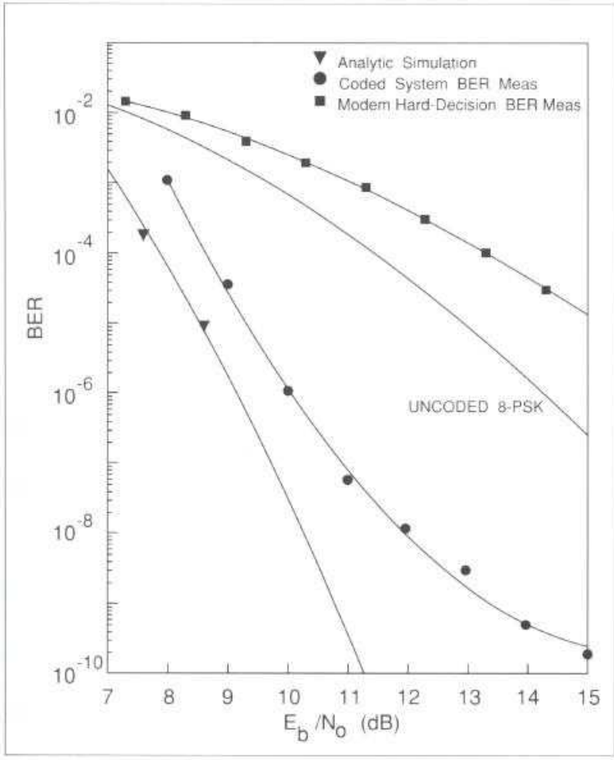
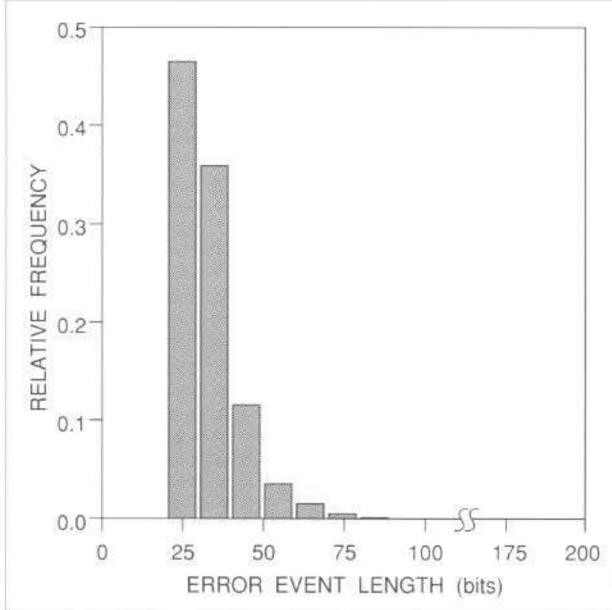


Figure 7. System performance test results

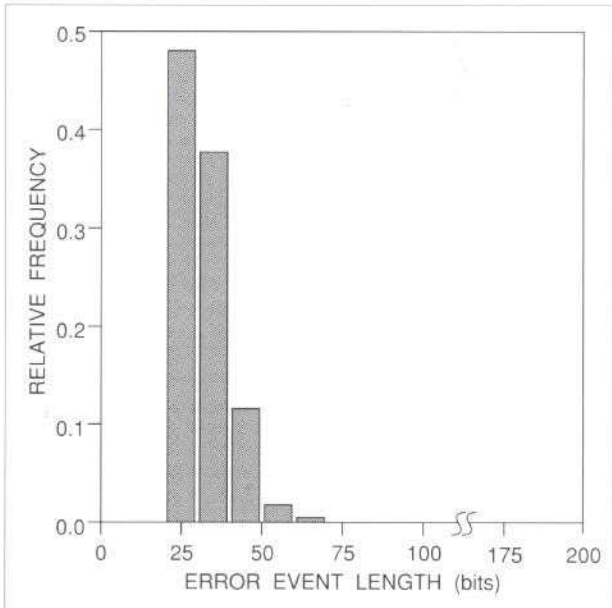
140-Mbit/s operating mode testing and to conduct nonlinear system tests over COMSAT's satellite simulator. In addition, an outer code that will greatly improve the BER performance will be added to the coded 8-PSK system. The BER performance of the concatenated coded system is expected to be comparable with that achieved on a fiber optic link.

Error Analysis and Improvement in IDR

CTD has characterized the distribution of bit errors at the output of an INTELSAT standard intermediate data rate (IDR) modem operating at an information rate of 2.048 Mbit/s. This was done through measurement using an IDR error analyzer (designed and built at COMSAT in 1989) and analysis using a hybrid analytical/simulation software model. Each approach can produce an account of error events as a function of various parameters such as energy-per-bit to noise-power density ratio (E_b/N_o) and carrier-to-intermodulation ratio (C/I). Figure 8 shows histograms based on the measured and the modeled results for a case with E_b/N_o = 6.3 dB, C/I = 12 dB, and a transponder input backed off by 10 dB. The good agreement between the two histograms demonstrates that the hybrid modeling accurately reflects the actual hardware results and that it can be reliably used to test procedures aimed at improving error conditions.



(a) Obtained via hardware measurement



(b) Obtained via hybrid analytical/simulation model

Figure 8. Hybrid modeling accurately reflects hardware results

A concatenated coding scheme was investigated as a simple add-on method to improve the performance of the present IDR system. The scheme consisted of a convolutional inner code of rate 3/4, currently in use in the IDR system, and a 10-error-correcting Reed-Solomon outer code of length 255 and interleaved to a depth of 4. The proposed scheme will substantially improve IDR system performance at both high and low signal-to-noise ratios (S/Ns).

Transmission Software

COMSAT requires a variety of computer programs related to satellite transmission in order to perform systems planning, analysis, and operations functions. In 1990, CTD and the System Development Division (SDD) jointly initiated new software developments and upgraded previously implemented programs. In the area of new software development, techniques for implementing automated carrier frequency assignment programs were investigated. This study included identifying computational techniques for the rapid evaluation of candidate frequency plans, as well as an investigation into algorithms appropriate for the automated synthesis of frequency plans. Synthesis techniques including the use of neural networks, expert systems, and multivariable optimization approaches were considered.

Another new software development was a program that evaluates satellite links statistically. This program uses Monte Carlo analysis to compute the performance of satellite links in terms of cumulative probability distributions and probability density distributions, given user-specified probability density distributions for link parameters whose precise values are either unknown or are known to vary over specified ranges. At the user's option, rain impairments can be included in the analysis.

The third new software development was the definition of a software operating environment that will integrate many different satellite system planning and transmission analysis programs previously developed at COMSAT Laboratories. This integrated operating environment will make these programs easy to use and will include interfaces with the satellite system databases that are required inputs to these programs.

Enhancements to existing transmission software included the addition of output tables to the Communications Intermodulation Analysis (CIAS) program for easier use; increased accuracy of the Sun Outage (SUNOUT) program at high elevation angles; and improvement of the input/output structures of the Rain Analysis (RAIN) program. Evaluation methods applicable to future analysis software were also developed.

Sound Program Low-Rate Encoding

The objective of the sound program low-rate encoding (LRE) project was to develop and implement a high-quality audio codec for 5-, 7.5-, 10-, and 15-kHz sound program channels using LRE techniques. The targeted bit rates ranged between 24 and 64 kbit/s per monaural channel, corresponding to the above range of bandwidths. The 1990 effort focused on development of the LRE technique for audio signals, the real-time hardware implementation of a full-duplex audio codec at the above bandwidths and bit rates, and informal subjective evaluation of the quality of the coded audio signal.

The LRE technique used to develop the audio codec is based on the adaptive predictive coding with transform domain quantization (APC-TQ) method developed at COMSAT Laboratories in 1988. The APC-TQ method was originally developed for toll-quality coding of telephony speech with a 3-kHz bandwidth. Preliminary tests during 1989 indicated that APC-TQ might lead to high-quality audio coding at low rates. However, differences between voice and audio signals require that the coding technique be modified to match the characteristics of the audio signal. To perform this task, a number of spectral parameters were studied for a large and diverse audio signal set. This led to the optimization of a number of design parameters. In addition, a number of signal processing operations based on signal generation models were reevaluated to ensure their applicability to audio signals.

The optimized audio codec has been implemented in real time for two bandwidths: 5 and 7.5 kHz. The corresponding bit rates are 28 and 35 kbit/s per monaural channel. The implementation is based on the Analog Devices ADSP-2100 DSP. Two DSPs are required for the encoder, while one is adequate for the decoder.

Informal expert-subject evaluations were conducted at the 5- and 7.5-kHz bandwidths. In each case, the coded audio signal was compared with the original signal, which was similarly band-limited. For most audio signals, it was difficult to differentiate between the original and coded audio signals. Thus, near-transparent quality was achieved for a large class of audio signals.

The results obtained during this project demonstrated the power of the APC-TQ coding method and its potential for audio coding. Specifically, audio signals of wider bandwidth (up to 20 kHz) can be coded more efficiently. By employing hardware with larger computation and storage capabilities, transparent-quality coding of compact-disk-quality (20-kHz bandwidth) audio should be possible at 64 kbit/s per monaural channel using the APC-TQ method.

Facsimile Transmission

The recent rapid growth in facsimile traffic has raised concerns regarding the quality of such transmissions in the public-switched telephone network (PSTN). These concerns have focused on the quality of service offered to the end-customer with respect to four performance indicators: connection establishment, retention, quality, and billing integrity.

A study focusing on the quantification of two service performance indicators (connection establishment and retention) was undertaken in 1990 by monitoring the completion rates and specific characteristics of incomplete facsimile calls transmitted and received from three Group 3 facsimile stations at COMSAT Laboratories. Three Group 3 facsimile terminals from different manufacturers were employed in this study, and the information analyzed was collected by means of summary reports, typically printed out from each terminal. With regard to call retention, each call that resulted in the receipt of a complete document was considered successful, irrespective of the number of transmission errors manifested during the communication. Connection establishment failures attributed to "paper jamming," "paper empty," "busy" connections, "no-answer" requests, or other network congestion conditions were excluded from the study. More than 5,000 calls were analyzed over a 9-month period during the normal course of business (test calls were not included in the survey). An average of 9 percent of transmit and 15 percent of receive facsimile calls failed to complete.

In 1990, a parallel study addressing the characteristics of Group 3 facsimile transmissions in the PSTN was undertaken, whereby a comprehensive test plan for evaluating facsimile performance characteristics was developed, and a limited analysis of outgoing facsimile calls was conducted. These activities were undertaken to enable an analysis of facsimile protocols in order to assess the level of conformance of commercially available terminals to CCITT Recommendation T.30.

The study revealed that a substantial number of facsimile terminals do not fully adhere to the relevant CCITT Recommendations. Deviations from the standard could account for some call failures; however, additional study is required to quantify this supposition.

Also initiated in 1990 was the design of a facsimile test set that could be inserted in an analog voiceband link (i.e., between two end-user facsimile terminals) to permit the introduction of specific impairments and/or the manipulation of voiceband facsimile protocols in real time under external control. Hence, the response and behavior of facsimile terminal equipment could be studied using a reduced number of distant facsimile terminals, while the validity of the results could be generalized beyond what might be possible if the characterization were performed on the basis of only one distant terminal.

The facsimile test set comprises demodulator and remodulator units connected by a digital interface (see Figure 9). This architecture permits real-time manipulation of facsimile protocols, and also allows preselected impairments or channel BER conditions to be inserted at specific points along a protocol transaction in the baseband domain.

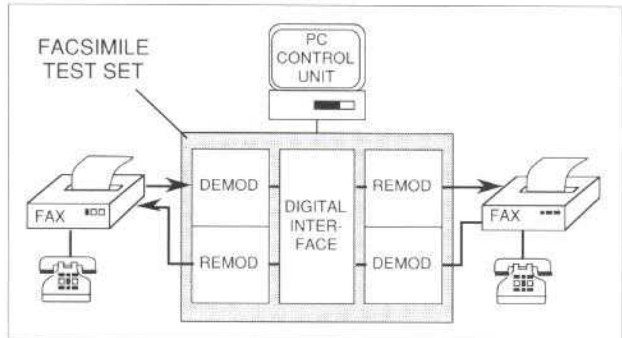


Figure 9. Facsimile test set permits real-time manipulation of facsimile protocols in the presence of various impairments

COMSAT NONJURISDICTIONAL R&D

DGPS Reference Signal Distribution Using Inmarsat Satellites

The NAVSTAR global positioning system (GPS) currently under development by the U.S. Department of Defense will also be accessible to nonmilitary users, but with reduced accuracy. However, a technique known as differential GPS (DGPS) has been devised which will restore to nonmilitary users the accuracy nominally available to the military community. This technique involves the calculation of a position correction factor at a fixed DGPS reference station, and subsequent transmission of this correction to nearby GPS users.

Network-Quality Two-TV Video Multiplexer

Further development of the network-quality, two-TV video multiplexer (see the 1989 *COMSAT Laboratories Annual Report*) continued in 1990. Scrambling and addressability have been incorporated into the video multiplexer, based on several COMSAT-patented inventions. The key functions of the addressable descrambler are implemented on an inexpensive single-chip microcomputer that has security features. The time-multiplexed format of the video multiplexer provides video scrambling that is extremely difficult to break. The flexible scrambler design incorporates most of the features available in commercial video scramblers. Thus, current users of video scramblers can easily phase into TMTV transmission without sacrificing either signal privacy or operational flexibility.

Substantial progress was also made toward development of a new version of the two-TV video multiplexer capable of transmitting two NTSC television signals from two separate locations. The two stations will share a continental United States (CONUS) coverage transponder by bursting their signals alternately. Timing control is achieved by monitoring the down-link based on knowledge of the nominal locations of the satellite and earth stations.

The feasibility of reducing equipment costs by applying ASIC technologies to the video multiplexer was also investigated. Candidate ASIC technologies included full-custom design, array-based design, and cell-based design. A cell-based design approach was selected following evaluation of tradeoffs such as density, cost, flexibility, efficiency, and function partitioning. Using the cell-based design, a single ASIC chip implementation was found to be feasible for the TV multiplexer.

Spread Spectrum Modulation

The development and application of the SPREAD software simulation capability for evaluating spread spectrum systems continued during 1990. In particular, coding for wideband spread spectrum applications was addressed and the simulation software was enhanced to evaluate spectra of Reed-Solomon (RS)-coded minimum shift keying (MSK) using Hadamard sequences with and without additional frequency hopping. The spectra of RS-coded MSK with cyclic code shift keying (CCSK) using a 16-element pseudonoise (PN) sequence were also obtained. A cyclic spectral analysis capability was added to the simulation program to obtain a cyclic spectra and corresponding "signatures" for binary PSK, quaternary phase shift keying (QPSK), staggered QPSK, and 8-PSK signals, each modulated by a 16-element PN sequence. This cyclic spectral analysis capability will allow COMSAT to perform low probability of intercept and low probability of detect signal design in the future.

A hybrid analytical/simulation approach for evaluating the performance of direct sequence pseudonoise spread spectrum systems was also developed during 1990. This approach is computationally efficient and fast compared to the conventional Monte Carlo method. The hybrid approach enhances COMSAT's credibility in the spread spectrum area, facilitating fairly quick system design without large investments in hardware development.

COMSAT SUPPORT

CSD Standard-C CES Support

During 1990, COMSAT Laboratories provided extensive support to COMSAT Systems Division (CSD) for integration and test of the Inmarsat-C 600- and 1,200-bit/s signaling and message channel burst demodulators, successfully developed in 1989. Extensive testing was performed for both demodulators using the Inmarsat-approved Standard-C Automated Terminal Tester (SCATT), which introduces Doppler shifts, multipath fading, frequency offsets, adjacent carrier, blockage, and phase noise impairments on the desired IF carrier in accordance with the Inmarsat-C channel parameters. Results of the IF and SCATT integration show that the desired raw packet acquisition performance under worst-case Inmarsat-C channel conditions was successfully achieved.

During 1990, support was also provided for design of the CSD production channel unit, development of link processor interface specifications, and testing and debugging of the production channel unit hardware. Following successful IF testing with the prototype boards, the DSP software was ported to the CSD-designed production channel unit printed circuit boards. A representative BER curve for the production version of the preambleless signaling channel raw demodulator output (Figure 10) indicates a raw BER performance within 0.6 dB of the ideal BER curve for all energy-per-symbol to noise-power density ratio (E_s/N_o) values between 0 and 6 dB for all IF impairments except multipath fading. The measured BER with multipath fading and other IF impairments was 2.9×10^{-2} over 300 packets, which agrees very well with the theoretical BER of 2.5×10^{-2} for a long-term average.

Advanced Video Processing and INTELSAT-K Transmission Parameter Optimization

Noise-reduction video signal-processing techniques, including digital preemphasis, companding, and an innovative two-dimensional differential pulse-code modulation (DPCM) technique, were investigated in terms of their applicability for multiplexed analog component and TMTV transmission via satellite. Analytical and computer simulation results indicated that as much as 6- to 8-dB improvement in received S/N can be realized with a combination of these techniques. A breadboard circuit implementing this combination is being designed to demonstrate the feasibility on existing TMTV prototype hardware.

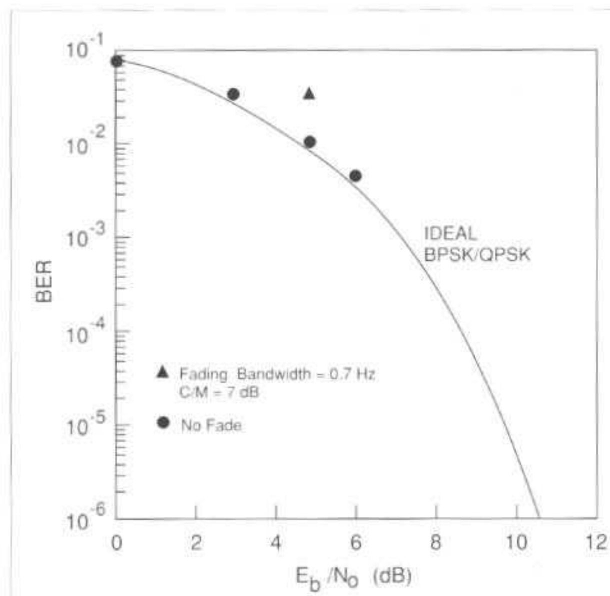


Figure 10. BER performance of the Laboratories' preambleless signaling channel demodulator (production version) (random frequency offsets: ± 1,450 Hz, Doppler period: 48 s, adjacent channel interference: none)

An investigation of optimum link parameters for TV/FM transmission through an INTELSAT-K transponder was completed. The investigation included extensive laboratory tests to characterize TV/FM transmission performance when the signal is overdeviated and modulated by an energy dispersal waveform to spread the FM spectrum. Overdeviation and considerable spectral spreading were found to be necessary to ensure the efficient space- and ground-segment utilization obtainable by operating the transponder close to saturation, without resulting in potential interference into terrestrial microwave links in certain down-link beams. Based on the characterization data, TV/FM transmission parameters were successfully optimized. The results indicated the feasibility of using fairly small receive earth stations without exceeding ITU Radio Regulations limits on the down-link power spectral flux density.

CES Upgrades

Major station renovations are under way to support the increased traffic through COMSAT CESs. These renovations include the installation of new communications and frequency conversion equipment to supplement the existing equipment. To resolve an IF incompatibility problem between new and existing equipment, which resulted from this equipment upgrade, COMSAT Laboratories designed and fabricated IF frequency translators. These units provide the required frequency translation and level adjustment for complete interoperability of new and existing equipment.

The translators were designed as dual-channel units, with both a transmit and receive channel, to operate in a fully redundant mode in conjunction with a redundancy switch unit. This unit will automatically switch to the redundant translator in the event of on-line unit failure. Alarm indication capability is provided with all of the units, along with an interface to the overall station alarm system.

Standards Activities

Standards activities at COMSAT are directed toward the development of national and international standards and recommendations compatible with satellite communications systems operation. CTD activities encompass CCITT and International Radio Consultative Committee (CCIR) in the international arena, and American National Standards Institute (ANSI) in the United States.

A multiyear effort to develop DCME standards culminated in 1990 with the formal adoption of revised CCITT Recommendation G.763, under accelerated approval procedures, and the adoption of an ANSI Standard "DCME Interface, Functional, and Performance Specification." These standards are compatible with DCME as defined in INTELSAT Specification IESS-501 and provide a true international open-network DCME standard containing a common compatible operating mode.

Work in the DCME area is continuing in 1991, with emphasis on processing to intercept, demodulate, transmit, and remodulate facsimile traffic in real time (called facsimile compression), in order to resolve the DCME traffic loading problem caused by the high-activity facsimile signal. Other CTD efforts include developing improved BER performance recommendations, standardizing a 16-kbit/s voice encoding algorithm (including host test laboratory support to the CCITT), improving the CCITT echo canceller Recommendation G.165, modifying facsimile recommendations to solve existing problems and avoid future difficulties, improving DCME test methodology, and working to eliminate clauses in recommendations that discriminate against satellite services.

OTHER SUPPORT

Inmarsat Facsimile Interface Units

In 1989 COMSAT was awarded a contract by Inmarsat to develop system specifications for the transmission of Group 3 facsimile messages using the Inmarsat-B/M, and Aeronautical systems, and to implement one set of interfaces to confirm the validity of the approaches so developed. COMSAT developed an approach whereby analog facsimile signals are intercepted, demodulated, and carried in the baseband over narrowband Inmarsat digital channels after appropriate protocol conversion. Channel-dedicated facsimile interface units (FIUs) located at the fixed and mobile satellite earth stations perform these processes in a real-time transparent mode. The FIUs are capable of interconnection with conventional off-the-shelf facsimile terminal equipment.

The protocols developed included special provisions to minimize distortion of tightly defined timing tolerances, permit conversion of the CCITT Recommendation T.30 point-to-point characteristics to a point-to-multipoint (or broadcast) operation, permit packetization of the facsimile signals, and extend the operating tolerances of Group 3 facsimile to longer propagation delay circuits.

In addition to completing the system specifications for the above three Inmarsat services in 1990, a set of FIUs was designed and the hardware construction was completed. The hardware comprises two sets of two FIU boards: a facsimile processing board (FPU), which performs the demodulation/remodulation and protocol conversion processes; and an elastic buffer/formatting board (EBF), which permits plesiochronous adjustments to be made to user data, as well as the formatting and deformatting of user and control data for each of the three services on a programmable basis. The FIU functionality implemented using the FPU and EBF boards is shown in Figure 11. An access control/signaling equipment and satellite delay simulator, and two local office telephone simulators, were also constructed. The hardware is currently being integrated with applications and multitasking systems software (also written in 1990), and delivery of the FIUs is expected to occur in 1991.

16-kbit/s Evaluation

A number of organizations and standards bodies have recently taken a keen interest in the introduction of low-rate digital encoding in telephone networks. A study was initiated in 1989 under an INTELSAT contract to systematically investigate the status of low-rate voice encoding technology. This study was conducted over a period of 18 months and included the investigation of eight voice coding methods operating around a transmission rate of 16 kbit/s. A test methodology was developed using subjective and objective assessment techniques to assess the performance of these coding methods in a variety of applications. The subjective assessments were conducted in three different languages—English, French, and Mandarin—using eight talkers in each language. The tests were administered using a Replicated Latin Square experimental design and included the assessment of codec performance at different voice input levels and digital channel error conditions. Upon conclusion of the tests, variance techniques were analyzed to assess the effect of various factors (such as talker dependence) on each codec's performance.

The objective measurements included extensive evaluation of the performance of each coding method at several low-speed voiceband data rates (300 to 2,400 bit/s) and with DTMF signaling, CCITT Signaling System (SS) 5, and special facilities control tones (2,100-Hz echo control disabling). A series of measurements was also made to further characterize each coding method's behavior with regard to idle channel noise, nonlinear behavior, quantization noise, amplitude distortion, harmonic distortion, and phase distortion. The subjective and objective measurements were subsequently compared using the modulated noise reference unit (MNRU) as a frame of reference.

The objective and subjective results are summarized in Table 1 and Figure 12, respectively. On the basis of subjective performance, it can be seen that toll quality is indeed achievable at 16 kbit/s. However, on the basis of objective performance, the results were more difficult to interpret because none of the low-rate codecs evaluated was acceptably transparent to voiceband data signaling rates in excess of 2.4 kbit/s. With signaling, on the other hand, most codecs offered satisfactory performance. In addition, the analog performance masks of CCITT Recommendation G.712 applicable to pulse-code modulation (PCM) encoding at 64 kbit/s were met by most codecs operating at 16 kbit/s. In conclusion, the satisfactory performance obtained with voice signals and network

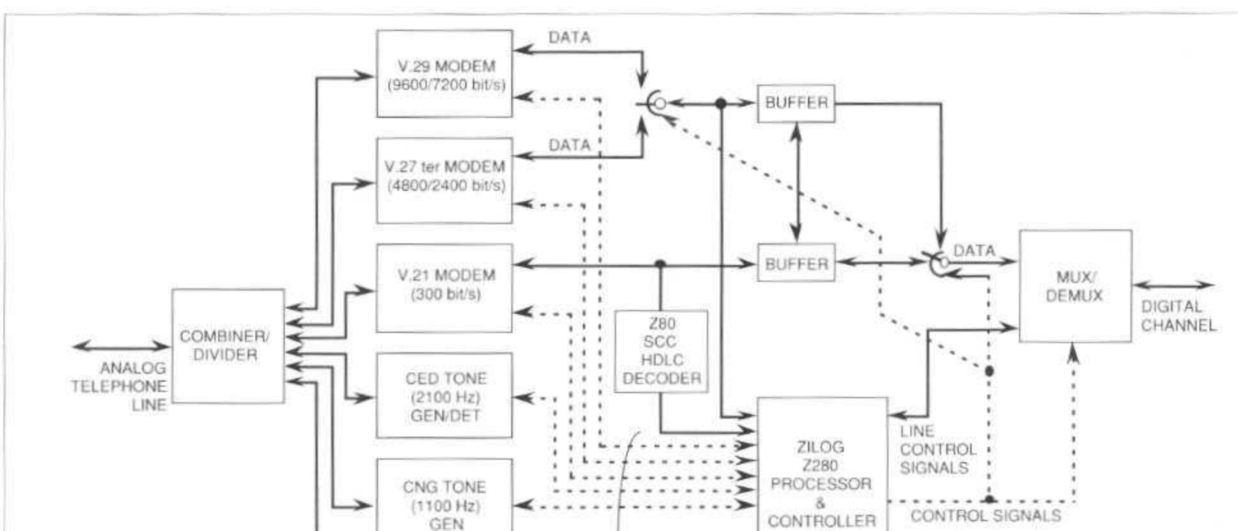


Figure 11. Facsimile interface unit functionality has been implemented in hardware

Table 1. Voiceband Data and Signaling Performance Summary

CODING METHOD	S/N REQUIREMENT V.27ter AT 2,400 bit/s[a] (dB)	CCITT SS5 INTERREGISTER RECOGNITION RATE[b] (%)
Code-Excited Linear Prediction (CELP)	12.7	83
Adaptive Transform Coding (ATC)	11.9	92
Continuously Variable Slope Delta Modulation (CVSD)	20.0	83
Adaptive Predictive Coding With Transform Domain Quantization (APC-TQ)	13.8	94
Vector Adaptive Prediction Coding (V-APC)	–	91
Regular Excited Linear Prediction (RELP)	–	79
G.711 Pulse Code Modulation (PCM)	10.9	85
G.721 Adaptive Differential Pulse Code Modulation (ADPCM)	11.0	78

[a] Includes R-28 impairments. Refers to channel conditions needed for a receive modem block error rate (511 bits/block) of 10^{-2}.

[b] Measured at 22-dB S/N circuit condition.

signaling indicates that 16-kbit/s voice coding technology is suitable for special applications within the PSTN, such as DCME, packet circuit multiplication equipment, and asynchronous transfer mode (ATM).

EUTELSAT/INTELSAT Echo Control

Studies on echo control in satellite systems were carried out for EUTELSAT and INTELSAT. The work for EUTELSAT initially focused on the causes of high signal level, and its impact on echo control, as well as the causes and consequences of phase roll. An echo control troubleshooting procedure was also developed for investigating network echo control problems. A second phase of this work examined various aspects of echo control equipment interaction with other network elements, including tandem echo cancellers, DCME, various signaling systems, and mobile communications applications. In addition to providing a troubleshooting guide, a number of areas for improvement of echo cancellers were identified and rules for the application of echo cancellers were provided.

For INTELSAT, a survey was conducted of the use of echo control devices in the INTELSAT network. A product survey of echo canceller manufacturers, with a tabulation of their product features, was also included. Responses to the survey questionnaire indicated that 80 percent of the echo control in the INTELSAT network, outside the United States, is still provided by echo suppressors. This, coupled with initiatives by COMSAT Intelsat Satellite Services, has led to an increased emphasis on encouraging administrations to convert from analog echo suppressors preferably to echo cancellers.

Programmable Digital Modem

CTD is developing a very flexible, high-speed, digitally implemented modem for the NASA Lewis Research Center. The modem will be capable of operating over a broad range of data rates (2 to 300 Mbit/s), with several different modulation formats, in burst or continuous mode. Operation will be completely programmable in all modes, and no hardware modifications are required. A major design goal is to minimize the size and power needed in the hardware implementation. To satisfy these requirements, a general-purpose GaAs ASIC now being developed will be used in nine separate locations in the demodulator. The chip, using a standard-cell design architecture, primarily contains two reconfigurable multiplier-accumulators. The nine ASICs will satisfy about two-thirds of the functionality requirements in the demodulator. Because of the criticality of the ASIC chip operating speed, a computer emulation of the hardware is being performed to validate the design for various operational modes.

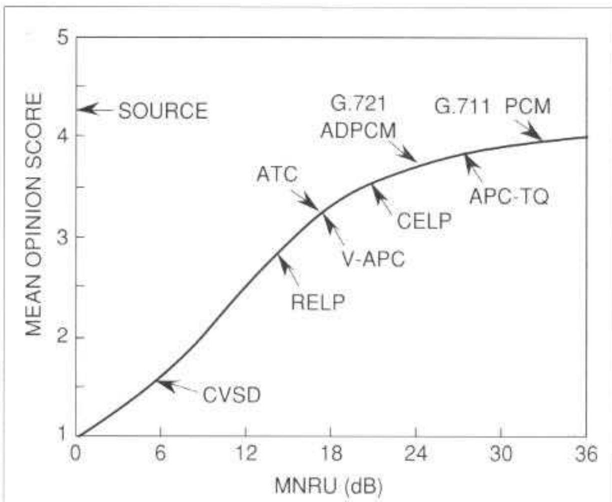


Figure 12. Subjective codec performance shows that toll quality is achievable at 16 kbit/s

Projects carried out by the Network Technology Division (NTD) in 1990 include the development of a breadboard for a 1-Gbit/s on-board baseband switch which employs a high-speed optical ring; time-division multiple access terminal equipment for the NASA Advanced Communications Technology Satellite; an integrated services digital network (ISDN) earth station interface for INTELSAT Business Services (IBS); a low-cost, value-added demand assignment system for IBS; optical integrated waveguide devices; and an integrated local area/wide area network management system. A number of technical studies and field experiments on ISDN and data protocols via satellite and on optical beam-forming architecture for phased-array antennas were completed, as well as a packet-switching quality-of-service field trial. Technical support promoting the interests of satellite transmission was provided for the American National Standards Institute (ANSI), International Telegraphy and Telephony Consultative Committee (CCITT), and International Standards Organization (ISO).

COMSAT JURISDICTIONAL R&D

On-Board Baseband Switch and High-Speed Optical Interconnect Ring

When used in conjunction with other on-board processing functions and multiple spot beams, baseband switching on board a satellite can provide enhanced service and functionality, thereby reducing earth station cost and complexity. Coupled with multiple spot beams, baseband switching can also provide interbeam carrier and channel routing for efficient use of spacecraft mass and power.

NTD has initiated development of both a modular baseband switch and processing support functions. The switch will accept traffic from a number of digital satellite services such as INTELSAT intermediate data rate (IDR), time-division multiple access (TDMA), and IBS; demultiplex it to extract baseband information; and forward it to various output modules/down-beams for transmission to the ground.

Input modules will be connected to output modules over a fiber optic ring operating in TDMA mode, as shown in Figure 1. The switch will support six input and output modules, handling a total throughput of 1 Gbit/s. Access to the ring by a given module for data transmission is based on a time-division multiplexed (TDM) allocation of traffic to a particular block of time slots within a frame. This allocation is controlled by the configuration processor, which serves as the start and end element of all data within a given frame, as well as the communications node between the various modules and a terrestrial network control center (NCC). Data transferred over the ring are formatted into data-directed packets. Each module connected to the ring scans the packet header to determine whether the data are to be locally received. Copies of data destined to a given module are stored within that module's local memory and concurrently rebroadcast to succeeding elements in the ring.

The baseband switch is modular; that is, the various input and output modules can process traffic for a full transponder, and each module can process traffic for one particular satellite service. Where possible, these modules are also being designed for reconfiguration from the ground, via a configuration processor, to handle an alternate satellite service such as IBS-to-IDR. Within the input and output modules, modularity has been further extended by functionally partitioning and designing the hardware elements into blocks specific to a particular satellite service (service-dependent elements) and elements common to all input or output modules (core elements). Future service-dependent functions may be readily integrated into the architecture with little or no impact on the modular switch design or capabilities.

To minimize mass and power requirements, the designs are being targeted for semicustom implementation using standard cell or gate array technologies. Further reductions can be achieved by using the high-speed interconnect fiber optic ring as the module interconnect mechanism within the baseband switch. To minimize potential risks with such an implementation, certain critical functions, including the optic drive

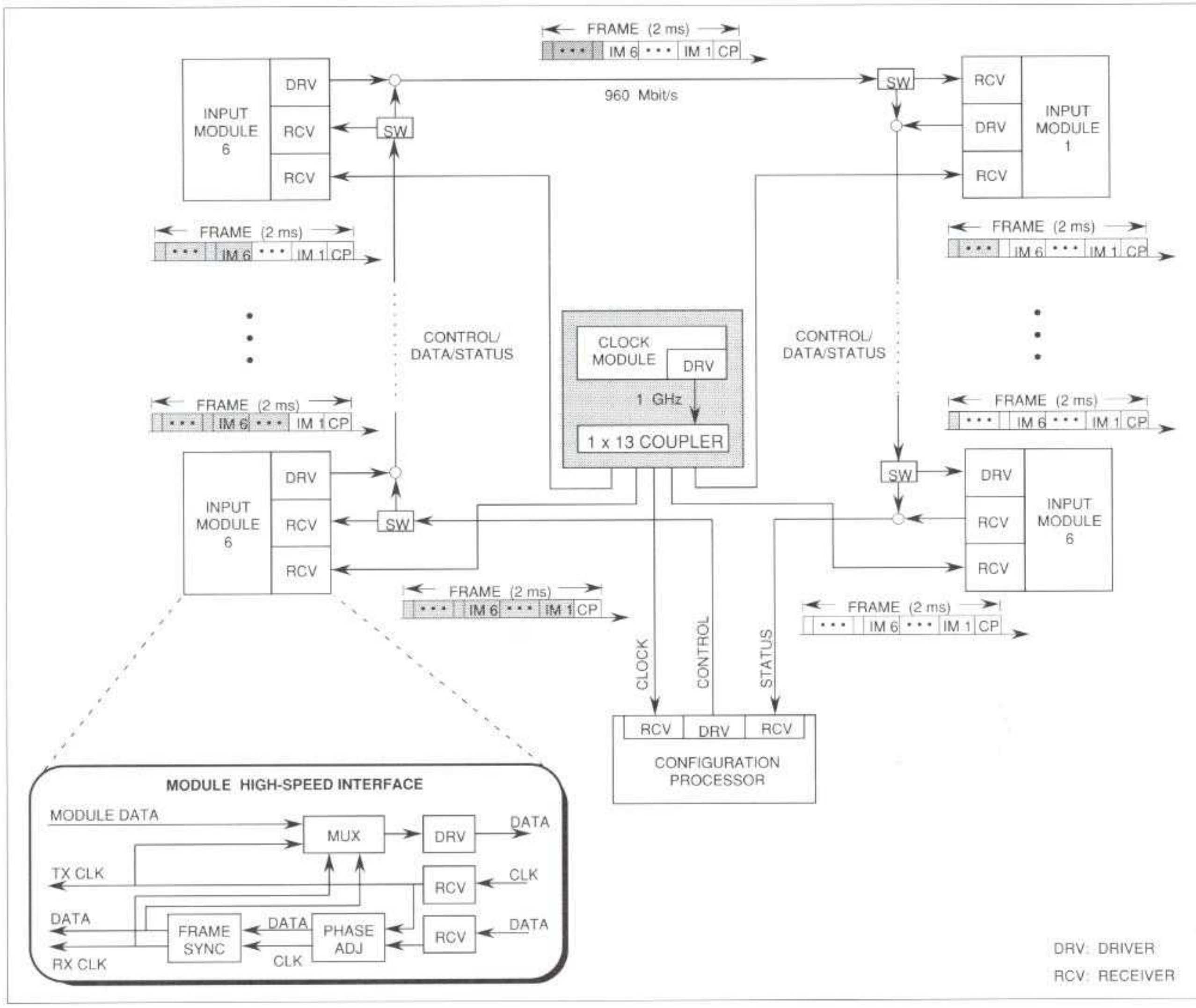


Figure 1. Regenerative ring with star-coupled clock distribution will handle a total throughput of 1 Gbit/s

and receiver logic to the fiber ring and some clock recovery circuitry, have been fabricated with discrete logic for testing. The board, shown in Figure 2, was fabricated with surface-mount technology. The use of optical switches or higher-speed interconnect fiber optic rings also allows very smooth migration of the switch architecture into a multi-gigabit-per-second switching system.

ISDN Protocols

CCITT draft Recommendation Q.922 defines error recovery procedures for frame relay networks. In these networks, error recovery is performed on an end-to-end basis by the user equipment rather than the network nodes. (A network node may detect a damaged frame and subsequently drop it, but does not notify the source end-user. Instead, notification occurs when the destination end-user requests retransmission.) Since a frame relay network may include satellite links, it is important to design the error recovery procedures in Rec. Q.922 for efficient operation over both satellite and terrestrial links.

The current error control procedure defined in draft Rec. Q.922 is based on the go-back-N (GBN) automatic repeat request (ARQ) procedure. In this procedure, when a data frame is negatively acknowledged, the transmitter backs up and resends that frame plus all subsequent frames, even though some of these frames may have been received correctly. This method results in inefficient use of network resources—throughput efficiency drops rapidly as channel error rate increases or congestion develops. GBN ARQ is inappropriate for networks that have relatively high bit rates, long delays (such as in satellite networks), high error rates, or operating points close to congestion levels. Efficiency can be improved by using a selective retransmission scheme wherein only negatively acknowledged frames are retransmitted.

As described in the 1989 *COMSAT Laboratories Annual Report*, a software model that simulates a frame relay

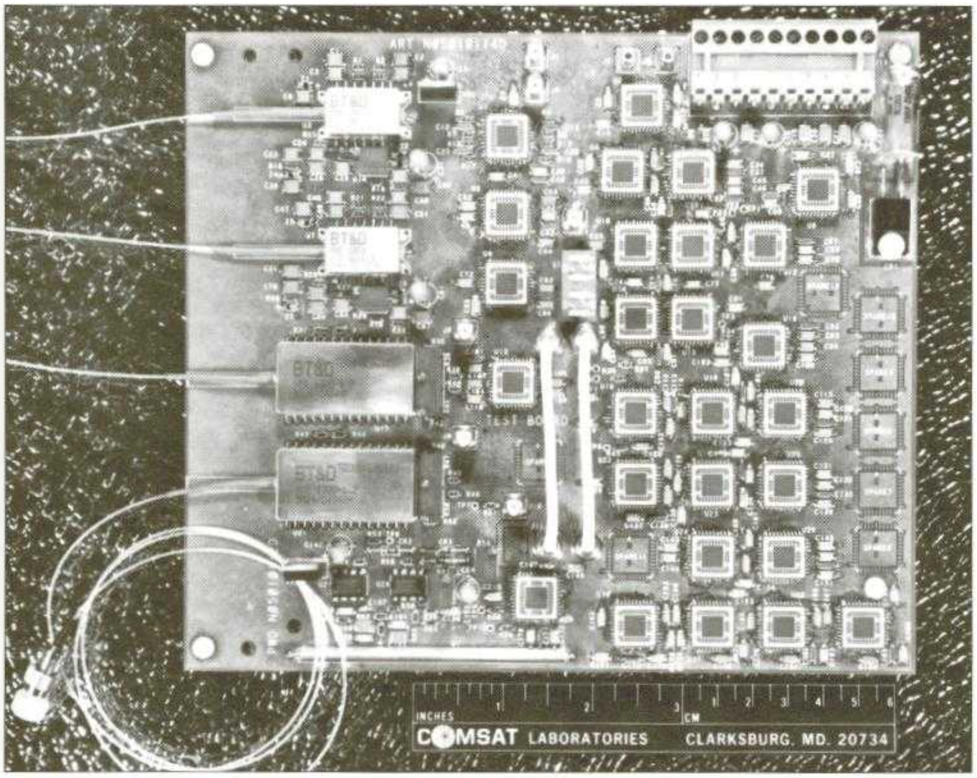


Figure 2. Modular baseband switch reduces earth station cost and complexity

Broadband ISDN Protocols

Widespread deployment of a broadband ISDN (B-ISDN) is expected to occur in the near future. It is extremely important for COMSAT to ensure that B-ISDN protocols and services can be effectively provided over satellite links. In contrast to narrowband ISDN which uses a synchronous transfer mode, B-ISDN uses a fast cell-switching technique called the asynchronous transfer mode (ATM). All services (voice, video, and data) will be provided using the ATM adaptation layer (AAL) and ATM protocol layers. NTD has identified several areas within the specifications of these protocols that may result in degraded performance over satellite links, and has developed potential solutions via analysis.

To demonstrate the feasibility and effectiveness of these solutions, NTD has begun developing two hardware boards. The first is an ATM/satellite gateway board which compensates for burst errors that can be encountered over coded satellite links. The second is an AAL/ATM line card

network has been developed to test the relative performance of various error recovery schemes employed by end-users. This model is built on discrete event simulation using the Simscript simulation language, and a shell based on a message-passing paradigm developed by NTD. It includes network nodes that perform the frame relaying function, and terminal nodes that implement the Rec. Q.922 protocol with different error recovery schemes.

In addition to implementing GBN procedures, two selective retransmission methods have been investigated and simulated. The first, a hybrid of GBN and selective retransmission procedures, attempts to recover new missing data frames using selective negative acknowledgment procedures, but reverts to GBN procedures if retransmitted data frames are found to be missing. The second scheme is a pure selective retransmission scheme which uses selective acknowledgments to acknowledge correctly received data frames, and selective negative acknowledgments to recover missing (new or retransmitted) data frames. It does not use GBN procedures.

Figure 3 shows the throughput efficiency of the different schemes based on simulation results and analytical calculations for a satellite data link with a 2.048-Mbit/s data rate and 1,024-byte frames at various bit error rates (BERs). The results demonstrate that the pure selective retransmission scheme outperforms both the hybrid and GBN schemes for this range of BERs.

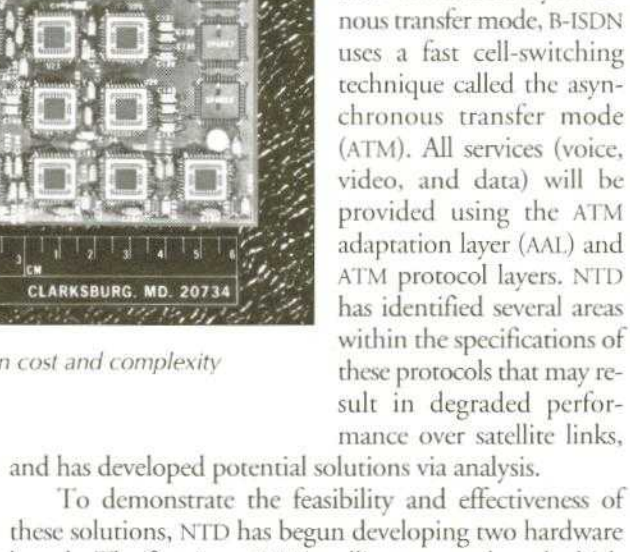


Figure 3. Throughput efficiency can be improved by using a selective retransmission scheme

that implements appropriate extensions to the AAL protocols to compensate for satellite propagation delay. By the end of 1990, a detailed design of the ATM/satellite gateway had been completed. Both boards will be designed, fabricated, and tested in 1991.

ISDN Earth Station Interfaces

NTD has investigated the integration of an ISDN into satellite systems, and the use of an ISDN switching interface at IBS earth stations. A switching interface provides direct user access to international private networks that offer ISDN services, and allows more efficient use of satellite and terrestrial access circuits.

As shown in Figure 4, the architecture of a satellite system employing the ISDN interface is based on a digital cross-connect that switches 64-kbit/s ISDN connections. The key element is a network interface processor (NIP) which extracts the signaling channels from the incoming terrestrial links, commands the appropriate switching of the cross-connect switch, and formats the appropriate outgoing signaling message. In addition, the NIP implements procedures to control the establishment and release of incoming and outgoing calls, allocate satellite link capacity, dynamically switch the digital cross-connect, and perform management functions.

Work begun in 1989 has continued through 1990. Software development includes the implementation of ISDN user network interface protocols, the design and implementation of call control procedures, and the implementation of a proprietary protocol over satellite links for signaling between earth stations. Software and hardware integration has been completed, and an ISDN test bed, consisting of two prototype switches and ISDN user equipment, has been set up. Each switch includes a digital cross-connect that supports up to 16 T1 carriers, a D3/D4 channel bank, and a NIP. The switches are connected through delay and noise generators to simulate a satellite link. The user equipment includes an ISDN private branch exchange (PBX) equipped with primary rate interface (PRI) modules, digital telephones, and SUN workstations and terminals. The test bed demonstrates the ability to establish switched end-to-end ISDN connections, integrate voice and data services, and verify compliance with CCITT Rec. I.352 specifications for call setup and release delays.

During 1991, additional services such as a facsimile group 4 and videophone will be integrated into the test bed; call control procedures will be enhanced to provide multidestinational capability; management functions will be added; and the satellite signaling protocol will be enhanced for basic compatibility with Signaling System 7.

Data Transmission Protocols

Since 1983, COMSAT and the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) have conducted a joint program to examine, implement, and test the performance of high-level data communications protocols over satellite links, and to study different aspects of open systems interconnection (OSI) networks. Experiments jointly completed from 1985 through 1989 by NTD and NIST concerned the Transport Protocol Class 4 (TP-4); connectionless network protocol; session protocol; message handling system (X.400); file transfer, access and management (FTAM); and OSI network management protocols.

Within ISO/International Electrochemical Commission (IEC) Subcommittee JTC1/SC6/WG4, all relevant modifications to TP-4 have been incorporated into an enhancement document, which passed its proposed draft amendment (PDAM) stage in 1990. It is expected to be published as an international standard in 1992.

As noted in the 1989 *COMSAT Laboratories Annual Report*, specific enhancements to FTAM protocols have been presented to standards committees. In view of the propagation delay imposed by satellites, the major goal is to reduce the number of confirmation steps required for file transfer. When the file size is relatively small, each step saved will significantly improve

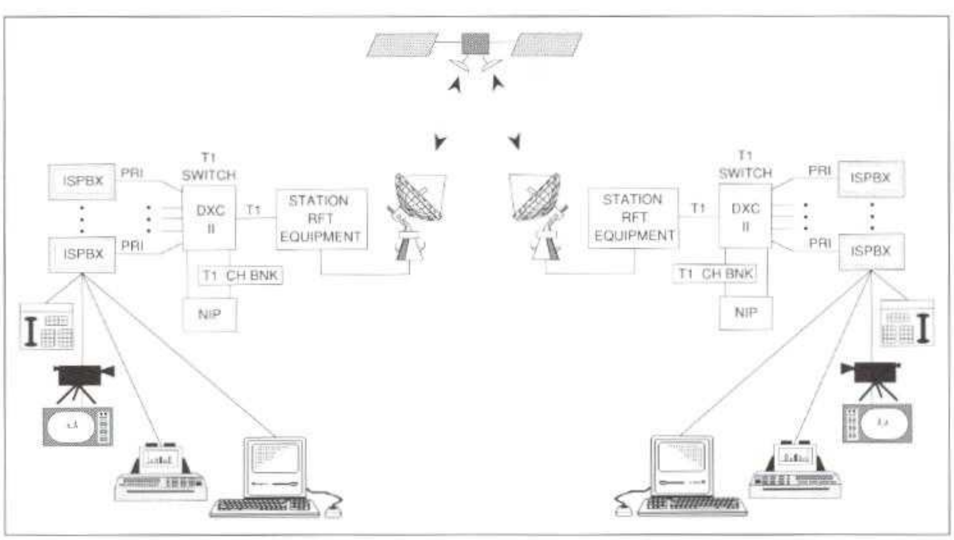


Figure 4. Pilot system for a satellite-based private ISDN uses a NIP for management functions

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the overall throughput. In 1990, ISO/IEC Subcommittee JTC1 established a project to incorporate FTAM enhancements into a revised standard. As project editor, COMSAT has been a key participant in this standards development work.

During 1990, several fundamental issues that promote satellite communications were examined: OSI architecture, quality-of-service (QOS) architecture, and multipeer data transmission. An examination of underlying protocols, as well as International Radio Consultative Committee (CCIR) and session protocols, revealed that the requirements of session synchronization agree with COMSAT's 1987 experimental results. The technical contribution, accepted by ANSI X3T5.5, resulted in enhancement of the session protocol, which will be fully compatible with satellite communications.

Data Network Quality of Service

Since 1987, NTD has been conducting a series of experiments to determine the QOS parameters for satellite-based international packet-switching links. The parameters under consideration, as defined by CCITT Rec. X.134, are call setup and call clearing delay, data packet transfer delay, and throughput capacity. The primary objective of these experiments has been to ensure that the minimum delay requirement specified in CCITT Rec. X.135 is reasonable and attainable, and that the minimum throughput capacity requirement over satellite-based links is identical to that over terrestrial/transoceanic links.

During 1990, software was developed for a high-speed packet-switched interconnection experiment to be conducted in 1991. In contrast to prior experiments which used 9.6-kbit/s links, this experiment will be conducted over 64-kbit/s links. Its timing is extremely appropriate, since the performance objectives for QOS parameters over higher-speed links are now being specified, and national packet networks are being upgraded to 64-kbit/s internetworking links. Other participants in the experiment include INTELSAT, STR Sweden, and OTC Australia.

Figure 5 shows the experimental configuration. Software was developed for a protocol analyzer (Interview 7700) which will simulate the source and destination networks. The software was tested in this simulated environment. Clock synchronization is required in order to measure call clearing and data packet transfer delays, which are specified as one-way delays. Accurate clock synchronization between the source and destination network simulators was established using software on a Macintosh personal computer and via dial-up modems. During 1990, a contribution to standardize the clock synchronization technique was submitted to CCITT Study Group VII. Additionally, a contribution to extend the scope of access section QOS objectives to satellite-based networks was submitted to Committee T1 Working Group T1Q1.3.

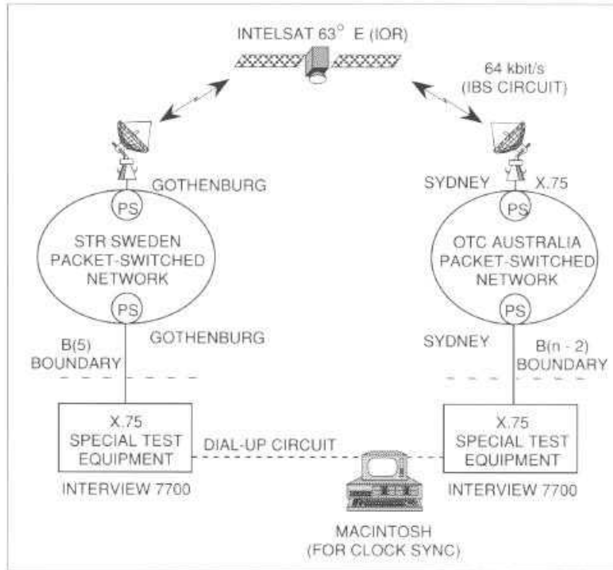

Figure 5. High-speed packet-switched QOS experiment configuration will test QOS parameters over 64-kbit/s links

Optical Space-Fed Beam-Forming Network

Future satellite systems will feature multiple spot beams which will increase transmission capacity by frequency reuse of the scarce satellite bandwidth; provide service flexibility, especially in conjunction with on-board processing; and conserve energy by illuminating each spot only when demand is sufficiently high. Multibeam systems require a beam-forming network (BFN) to distribute RF power to various phased-array antenna feed elements. The use of optical technology in BFNs can result in reduced size and weight, as well as less interference. COMSAT Laboratories is currently designing novel optical space-fed BFNs that employ free-space time delays to create the required phase shifts at the feed array.

Figure 6 shows an optical space-fed BFN, including a possible deployment scheme on board a satellite. A number of communications signals electro-optically modulate laser diode transmitters, and the resulting signals are optically switched to the desired input ports of the space-fed BFN. The BFN uses true time delays (resulting from the geometric arrangement of the input and output ports) to create the required phase shifts at its output ports. The output ports can be properly positioned fiber bundles that collect and transport the optical signals before they are reconverted to electrical signals at the phased-array antenna elements. The light weight and small size of the BFN, optical switch, and fiber bundle compared to their microwave equivalents make the optical space-fed BFN an attractive alternative to conventional BFNs. Optical BFNs are also less susceptible to interference problems, and the low loss of the optical fibers allows remote positioning of the antenna elements from the satellite main body.

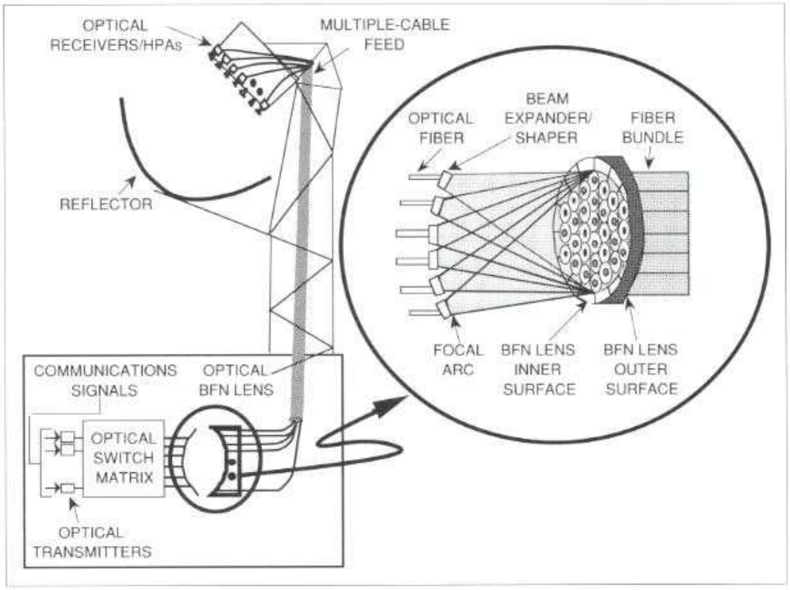

Figure 6. Possible deployment architecture for optical space-fed BFN on board satellites features light weight and small size

In 1990, two optical space-fed BFN architectures were investigated: one using optical fibers as delay lines to simulate the required microwave phase shifts at the feed array elements, and the other formed by reducing the microwave BFN to optical dimensions and then converting, in a 1:1 correspondence, the optical phase shifts to the microwave equivalent. For both approaches, optical space-fed BFNs were designed for switching six signals to 128 different beam positions using a 169-element phased-array antenna. An equivalent microwave BFN would have approximately 1-m spacing between input and output ports and approximately 1-m height, whereas an optical BFN would have dimensions in centimeters. Preliminary estimates of mass and prime power requirements for the 128 x 169-element optical space-fed BFN are between 2 and 3 kg and between 10 and 20 W, respectively.

In 1991, NTD plans to design, fabricate, and assemble a proof-of-concept optical space-fed BFN consisting of a 16-element antenna array with a 27° scanning ability.

Integrated Organic Optical Waveguide Devices

Future communications satellites will exploit on-board processing techniques to improve system performance and flexibility and to reduce the complexity of earth station terminals. However, the implementation of on-board processors (OBPs) using conventional technology will constrain the size, weight, and prime power of the payload. The emerging field of integrated photonics has the potential for realizing lightweight, low-power, compact OBP subsystems. Organic, nonlinear, material-based integrated optical devices are being investigated for applications in systems such as phased-array antennas and on-board baseband processors. Development of three-layer planar organic optical waveguides on a silicon wafer was presented in the 1989 *COMSAT Laboratories Annual Report*. This year, R&D efforts included design, fabrication, and performance testing of optical channel waveguide devices.

Specifically, the devices were designed for single-mode operation, with consideration for reduced loss around curves and efficient input/output coupling. Prototypes were fabricated of an optical channel waveguide power splitter and combiner and an electro-optic channel waveguide phase shifter (Figure 7). Electron-beam writing of the pattern and reactive-ion etching (RIE) proved to be the most successful means of fabricating the waveguide channels. Processes have been developed to fabricate channel waveguides in either the core or buffer layer (see Figure 8). The dielectric properties of the organic layers were measured at microwave frequencies (4 GHz) to estimate the loss tangent and modulation bandwidth-distance figure of merit of electro-optic waveguide devices. Typical data for a device with a microstrip configuration include a loss tangent of approximately 0.02, dielectric loss of approximately 0.01 dB/cm, and a bandwidth-distance figure of merit in excess of 6 GHz/cm.

An integrated organic optical waveguide development effort planned for 1991 will include two tasks: completing performance tests of a prototype channel waveguide phase shifter fabricated in 1990, with iteration for device optimization; and designing, fabricating, and testing a 2 x 2 directional coupler-type optical switch element.

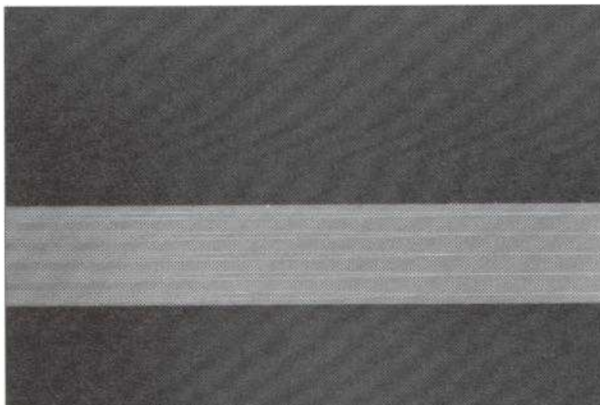

Figure 7. Prototypes of an optical channel waveguide power splitter and combiner and an electro-optic channel waveguide phase shifter

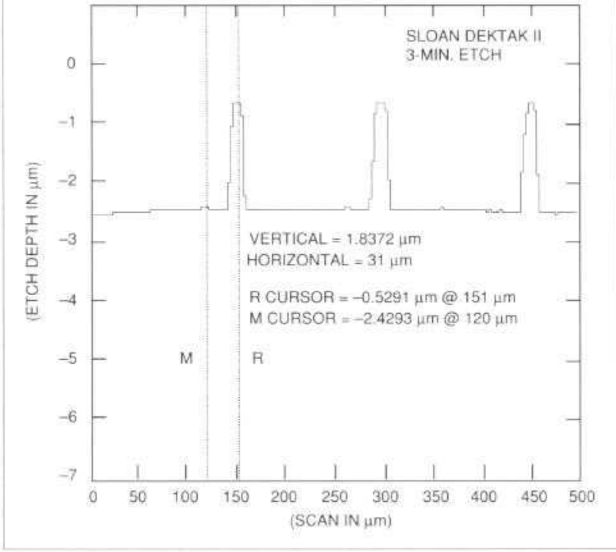

Figure 8. DEKTAK profile of RIE channels etched in the core layer of two-layer polymer films spun on silicon wafer; photoresist optically exposed using image mask; channel filling by buffer completes waveguide fabrication

Neural Network Technology

The B-ISDN is designed to support a large variety of services for voice, data, and video communications. A fundamental means of achieving the B-ISDN network is to use the ATM—a high-speed, short packet (cell) switching network that requires extreme flexibility. In traditional circuit and packet-switching networks, thorough analyses are conducted to establish the relationship between network service quality and the characteristics of incoming traffic. However, because of the dynamic nature of an ATM B-ISDN, analytical solutions for determining traffic patterns and the resulting grades of service are not feasible. An adaptive control scheme that learns from the dynamic environment (i.e., from the traffic patterns to which it is exposed) is desirable. A neural network appears to be suitable for this purpose, as it can map a complex, nonlinear function with a number of inputs without explicitly defining the function. The goal of this effort is to achieve good flow control in the satellite ATM B-ISDN.

The satellite ATM B-ISDN consists of a number of earth stations covered by beams on multiple transponders carrying voice, data, and video calls with different QOS requirements. The network control function needs to allocate resources to new calls/paths so that the service requirements are met for both new and existing calls.

In a simulated environment, a call admission control function that successfully allocates network resources was identified. Five types of traffic generators were multiplexed and fed into a node, and a large number of call configurations were simulated. From each simulation run, network parameters such as link utilization, buffer occupancy, and number of calls lost were measured. Using a three-layer back-propagation neural network program, the number of calls of each class, and the class of the new call, were fed into the input neurons. The neural network (Figure 9) was trained through many iterations and learned to detect the conditions under which new calls should be accepted or rejected.

For on-board-switching satellites, several problems regarding the use of neural networks were identified. Since virtual calls/paths from various up-links are destined for a down-link, the call/path acceptance control function must maximize down-link bandwidth. This function must also constrain the cell loss ratio to an acceptable value on board the satellite by using existing finite buffers. A similar neural network formalism can be applied to resolve these problems. Various other factors such as current switch configuration, buffer lengths for each beam on board the satellite, and traffic destined to each down-link beam also need to be considered.

The down-link capacity increment for increased offered load must be determined to maintain the cell loss ratio at a predetermined value for a given on-board buffer size for that down-link beam. For increasingly complex satellites with shared memory for different down-link beams, the allocation of down-link capacity to a particular down-beam must be balanced with the reallocation of buffers to the down-link beams. This is a complex problem with numerous constraints such as differing QOS parameters for the down-beams and different loading, capacity increments, and a pooled resource of memory. Resolution of these problems will be attempted in 1991.

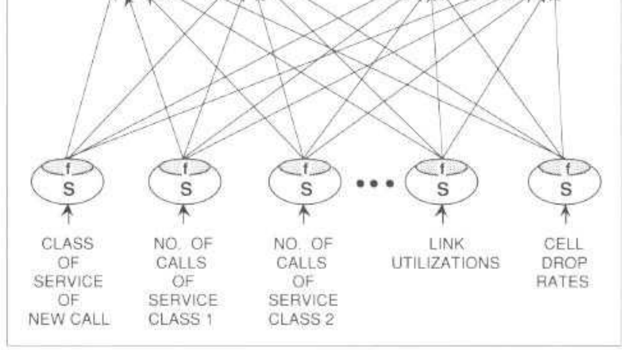

Figure 9. Architecture for neural networks that learn from their environment

COMSAT NONJURISDICTIONAL R&D

Neural Network Processing

Existing methods of managing large networks have proven inadequate. Engineers must extract knowledge from network experts and use it to design and build an expert system. With neural networks, however, the engineer provides examples of the network's operation, thus eliminating the need to assimilate rules, which may not be possible. A system that can detect patterns in network parameters, provide early warning of oncoming congestion, and determine the causes of such congestion will be extremely useful in coping with congestion and will help automate the fault management process. Neural networks can easily be trained to detect patterns. The goal of this project is to develop telecommunications network diagnostics that can recognize incoming congestion and identify possible causes (e.g., traffic surges and link/switch degradations).

In the first stage of training, a simulation environment for a small hexagonal network was built using Simscript on the SUN workstation (see Figure 10). All nodes were sources and destinations. Simulations were conducted with "normal" traffic, traffic surges (four times the normal link traffic) between pairs of nodes, and link/node faults in the network. Network parameters such as utilizations on each link and buffer occupancies at each node were measured. In the second stage, a neural network model was developed which used the information collected from the simulation environment to train the neural network to identify faults and traffic surge conditions. These two stages were repeated for each experiment conducted for different configurations.

The neural system was implemented by using the ANZA Plus/VME Neurocomputing Coprocessor from Hecht-Nielsen Neurocomputers on the SUN workstation, primarily with the multilayer back-propagation network, since it outperformed the counter-propagation neural network model. For each configuration, the inputs, outputs, number of middle layers, and size of each layer needed to be determined in terms of neurodes. If the middle layer was too large, it encouraged the network to memorize the input patterns rather than to generalize the input into features. This would reduce the network's ability to handle unfamiliar inputs after training was complete. Conversely, a middle layer that was too small drastically extended the number of iterations required to train the network and also reduced recall accuracy. Figure 11 shows the output of the neural network during the process training.

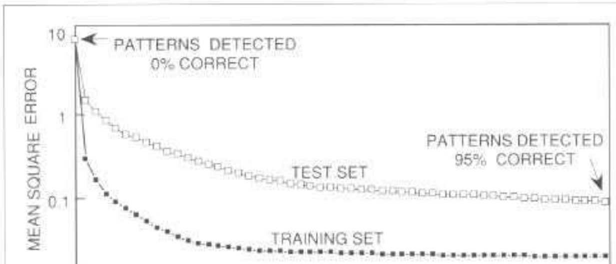

Figure 10. Neural networks can easily be trained to detect patterns

This effort enabled the identification of all single traffic surges that occurred in the network. It was also desired that the neural network be able to recognize and identify multiple traffic surges occurring simultaneously in the telecommunications network. Even in small networks, the total number of combinations of source-destination traffic surges is very large; for large networks, it is prohibitive. Thus, one objective of the neural network implementation was to measure its performance or identification capability using combinations of traffic surges, although it had been trained on only single surges and a few selected combinations of surges. Two common conditions in a real telecommunications network are a single-source flooding of the network and a focused overload, wherein a destination is overwhelmed by traffic from multiple sources. Both of these conditions were successfully detected by the neural network. All combinations of multiple traffic overload can be identified by a combination of two neural networks. Because the time necessary for the neural network to arrive at a conclusion once an input is presented is extremely small (on the order of microseconds), the cause of congestion can be detected in real time.

High-Performance LAN/WAN Interface Processor

The rapid growth of communications technology is dramatically changing the networking environment. Local area networks (LANs) such as Ethernet (10 Mbit/s) are expected to be replaced by much higher speed networks such as the fiber-distributed data interface (FDDI), which operates at 100 Mbit/s. Wide area networks (WANs) are also evolving rapidly from medium-speed T-1 (1.544-Mbit/s) links to T-3 (45-Mbit/s) links. Similarly, with the advent of microprocessors such as the 80486 and MC68040, user workstations can take advantage of the large available bandwidth. As a result of these trends, coupled with bandwidth-intensive applications, internetworking devices such as routers and bridges will require switching speeds in excess of 30,000 packet/s. Accordingly, NTD has been pursuing the development of a high-performance bridge/router.

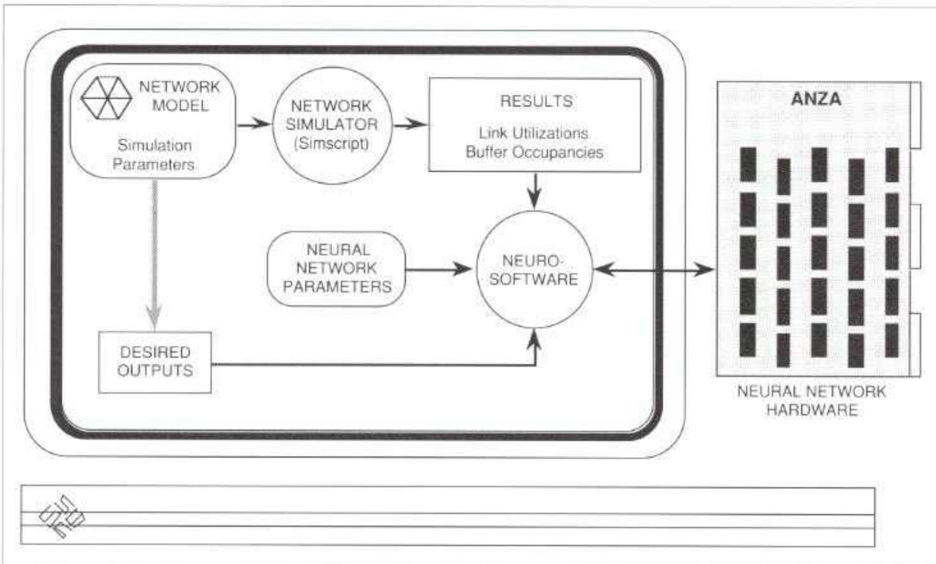

Figure 11. Simulated environment for network training was implemented on a SUN workstation

NTD has an ongoing program to investigate networking technologies, apply them toward building multivendor networks, and provide network management solutions. To this end, an architecture has been developed that facilitates the economical creation of large networks with full connectivity between devices that use the same or different protocols. A test bed has been established which consists of a large number of LANs and devices interconnected over a common WAN backbone. The test bed contains user devices such as PCs, PS/2's, Macintoshes, SUN workstations, IBM mainframes, IBM terminals, and asynchronous terminals; network interconnection devices such as LAN bridges, multiprotocol routers, X.25 packet switches, X.25 packet assemblers/disassemblers (PADs) and gateways; and LANs such as Ethernet, token ring, Appletalk, and FDDI.

During 1990, a high-performance Ethernet-to-Ethernet bridge was developed. The packet-switching function for filtering and forwarding packets between the two interfaces is performed on a RISC processor (MC88000), which processes 20 million instructions per second. Preliminary benchmarks have demonstrated that this system can sustain between 20,000 and 30,000 packet/s. Software was also developed for internet protocol routing as well as for an FDDI interface. Off-the-shelf VME boards were used as the hardware platform for the LAN/WAN interface processor. Since the use of single shared-bus (VME) boards results in less than optimal performance, a design for a dual-bus system was developed. Future versions of the LAN/WAN processor system will incorporate this hardware architecture to achieve an even higher level of performance.

Integrated LAN/WAN System and Network Management

The last few years have seen an explosive growth in private networks due to the availability of inexpensive LAN technology, high-performance workstations, and personal computers. Because these networks comprise equipment from multiple vendors and use multiple protocols and LAN/WAN media, there is an ever-growing need for centralized, automated network management. Two network management protocols, Simple Network Management Protocol (SNMP) and the OSI-based management protocol CMIS/CMIP, are being standardized; however, many vendors still use proprietary protocols. The number and quality of commercially available multivendor network management systems are still low.

A multiprotocol network management system, NetMCC, has been developed to manage the test bed, as well as any other network composed of industry-standard devices. Currently, it can manage X.25 packet switches, X.25 PADs, PCs with Novell Netware software, and any SNMP-compliant device, including UNIX workstations, routers, bridges, and gateways. Based on a SUN workstation, NetMCC uses industry-standard software tools such as UNIX, X Window, Motif, and the Ingres relational database management system to address all major management areas, including fault, performance, configuration, and accounting management.

With NetMCC, a manager can observe the network in graphic form using multiple, hierarchical screens (see Figure 12). The system automatically collects status and alarm information from network devices and displays it in color-coded form to alert the operator when network faults occur. Performance statistics can be collected and displayed in the form of text or graphs and can be saved in the database for later analysis and reporting.

As new devices come on the market or as vendors add new management information to their devices, this information can easily be added to the NetMCC database. NetMCC automatically generates new screens for newly added performance statistics. A number of generators are built into NetMCC for generating reports on alarms, performance statistics, and accounting information. A detailed parameter configuration of network devices can be

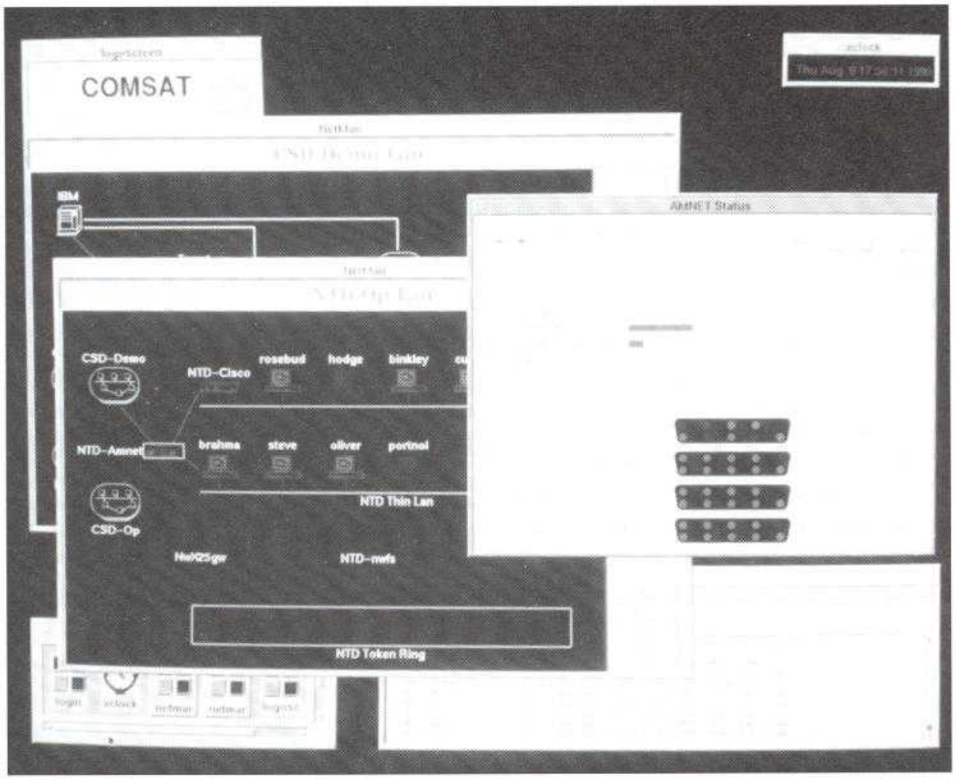

Figure 12. Multiprotocol network management system can manage any network comprising industry-standard devices

defined, saved, observed, and sent to the devices, all using interactive, user-friendly screens.

Since NetMCC is highly modular, it can easily be enhanced to support additional custom management protocols and devices. Its architecture allows it to exchange information with other network management systems and to create hierarchies of NetMCCs for managing very large networks. It is a foundation on which to base specific network management solutions for COMSAT customers.

Expert Systems in Network Management

NTD has been investigating the applicability of expert systems technology to the management of large communications networks, specifically multiprotocol, multivendor networks. Of special interest is the diagnosis of conditions with relatively obscure warning signs which, if unattended, could lead to a catastrophic loss of network facilities.

Among the most widely used network communications protocols are those that comprise the transmission control protocol/internet protocol (TCP/IP) suite originally developed for the U.S. Department of Defense. Information on the status of (and statistics from) network entities for TCP/IP networks is accessible through facilities provided by SNMP.

A knowledge-based system is now under development for use in conjunction with an existing network management system to aid in the diagnosis of faults and performance degradation of networks. In general, the system hypothesizes that a problem exists by observing changes in the values of certain key parameters. Based on the changes the system observes in certain other parameters, it strengthens or confirms the hypothesis and generates an appropriate warning message.

A set of problems and diagnostic tests pertinent to TCP/IP networks has been identified. The knowledge base was designed using the knowledge engineering environment and ported to a SUN SPARC workstation and to a network interface between the expert system and the topology database on the management system. This work will be extended to testing the interface with the management system and developing rules for other protocol domains.

COMSAT SUPPORT

ANSI/CCITT/ISO Standards Activities

COMSAT participates in national and international standards activities in ISDN and data communications to aid in the ongoing development of satellite-compatible standards and to modify existing terrestrial-based standards.

During 1990, NTD continued its activities in Committee T1, Technical Subcommittee T1S1, covering services, architecture, and signaling, including the ISDN and Signaling System 7. COMSAT's major area of interest was the development of protocols for frame relay and B-ISDN.

COMSAT developed a detailed selective reject ARQ protocol for CCITT Rec. Q.922 and submitted a series of contributions to T1S1. A U.S. contribution based on COMSAT's protocol is likely to be submitted to Study Group XI in 1991.

COMSAT representatives were instrumental in developing a B-ISDN baseline document that is transmission method insensitive. In addition, the stringent specification of an ATM cell loss ratio of 1×10^{-10} would have put an undue burden on satellites to provide a BER on the order of 1×10^{-11}. COMSAT succeeded in forestalling such a specification, and subsequently developed a detailed ATM/AAL convergence protocol designed to work efficiently over satellite links at high speeds. A series of contributions on this protocol was submitted to T1S1, and a U.S. contribution based on COMSAT's protocol will be submitted to Study Group XVIII in 1991.

A selective acknowledgment enhancement to TP-4 was presented to ISO/IEC Subcommittee JTC1/SC6/WG4 in May 1987, in conjunction with other enhancements. The COMSAT proposal has been approved as a PDAM and the changes are expected to be published as an international standard in 1992.

The extended grouping sequence enhancement to the FTAM was presented to ANSI X3T5.5 in January 1989. A few cycles of technical refinement were accomplished in meetings of ANSI X3T5.5 in April 1989, and the ISO/IEC JTC1/SC21/WG5 FTAM group in May 1989. Finally, the group agreed to propose a New Work Item for this enhancement with a broad view that includes other possible enhancements. In 1990, ISO/IEC JTC1 approved the project to enhance the FTAM standard. COMSAT will undertake the project editorship.

Efforts are under way to propose enhancements to the Session Protocol and to introduce multipoint features in X.25 protocol.

Value-Added Services

The IBS system is widely used for international private networking. In its present form, it is offered as an extended-period, fixed-bandwidth, leased line connecting pairs of customer sites. Market research has revealed that a majority of IBS customers experience significant fluctuations in bandwidth requirements, even over a period of 1 day. In addition, emerging technologies such as ISDN require a bandwidth-on-demand capability. Accordingly, NTD has designed and developed a prototype demand-assigned IBS system.

A centralized NCC is used to control multirate modems at IBS earth stations via burst modems and custom-developed capacity control units (CCUs). The burst modems are used to implement a very small aperture terminal (VSAT)-like signaling system, with a single continuous outbound channel from a hub CCU to all remote sites, and a shared inbound channel that is accessed by remote CCUs in a TDM/ALOHA (contention) mode. Figure 13 shows the system architecture of the demand-assigned IBS system, which was successfully demonstrated in a field trial at Clarksburg, Maryland. A transponder on INTELSAT 341 provided the satellite bandwidth. Applications such as videoconferencing were used to demonstrate the demand-assignment and variable-bandwidth capabilities of the system.

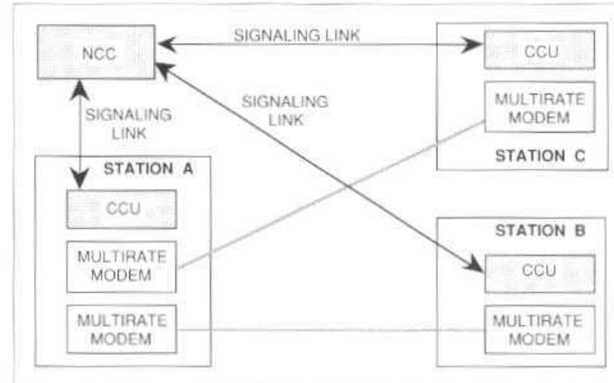

Figure 13. Architecture for a demand-assigned IBS system demonstrated at a field trial in Clarksburg, Maryland

INTELSAT SUPPORT

Study on Satellite Communications System Architectures for ISDN and B-ISDN

The objectives of this INTELSAT contract were to identify ISDN-compatible satellite communications system architectures; to select a few architectures and develop system migration scenarios; and to develop, in detail, the system design for the selected architectures. A detailed review was undertaken of all the CCITT ISDN and B-ISDN Recommendations to investigate their compatibility with the INTELSAT system. Based on this review, and considering the current INTELSAT system architectures, a series of ISDN-compatible architectures for future INTELSAT systems was developed.

Three generic architecture models were considered for support of narrowband ISDN. In the first model, the INTELSAT system provides only a transit connection element; no call routing or switching is performed at the earth station. However, with the availability of certain signaling information (specifically, the lower layer compatibility information element), appropriate satellite delay compensation functions for certain data protocols operating over ISDN channels can be identified and invoked. In the second architecture, the INTELSAT system forms part of an ISDN by providing switched, point-to-point transmission for international transit links. The third architecture incorporates switched multipoint connection configurations.

For B-ISDN, a series of four architectures was considered. These architectures, when viewed as a set, will provide a migration path for the integration of B-ISDN into the INTELSAT system. The first architecture supports B-ISDN services through the transmission of synchronous digital hierarchy carriers. The second examines the addition of a virtual path cross-connect capability at the earth station. The cross-connect allows the earth station to combine traffic from several switches in the terrestrial network. The earth station routes ATM cells based on the virtual path interconnect section of the cell address. Because the mappings used to perform this routing do not change dynamically, the earth station switching functions do not require access to signaling information. This enhancement allows more efficient utilization of both the satellite resources and the terrestrial access connections. The third architecture addresses the inclusion of on-board processing in the form of a virtual path cross-connect on board the satellite. This greatly simplifies the earth station hardware by allowing all up-link traffic to be carried on the same link. Separate up-links for each destination are not required. Finally, in the fourth architecture, signaling capability is included at the earth stations.

The System Development Divison's (SDD's) major accomplishments for 1990 included implementation of a new version of the General Antenna Program, completion of a study of the feasibility of an on-board very small aperture terminal hub, completion of a major portion of the user interface management system, development of an operator interface for the Inmarsat-M/B Network Coordination Station, and completion of the time-division multiple access (TDMA) burst generation and scheduling software for the INTELSAT satellite-switched TDMA (SS-TDMA) system.

COMSAT JURISDICTIONAL R&D

Software Testing Techniques

A significant amount of the budget for every software project is used to correct defects, which can be introduced into software during any development phase (i.e., requirements, design, implementation, testing, or documentation). The objective of this task was to investigate techniques for reducing the defect rate for software developed at COMSAT Laboratories.

A literature search was conducted to investigate industry-wide techniques and tools for improving software quality, and a plan was then developed to reduce the defect rate in SDD-developed software. This plan included making improvements to the existing software development methodology, using utility programs to evaluate complexity metrics for code, and establishing a quality metrics database.

Utility programs were written to evaluate source code using the McCabe complexity analysis criteria. McCabe analysis produces a value for each subroutine or subprogram which is a measure of the complexity of understanding and maintaining the subroutine based on the looping structure, the number of conditional statements, and the size of the subroutine. Programs were developed to evaluate both FORTRAN and PASCAL source code. The source code for each program in the Systems Analysis Software Library was evaluated and the results were stored in a simple metrics database. Each time modifications are made to any of the analysis programs, the McCabe analysis will be rerun to ensure that the complexity measures have not increased.

Quality checklists were also developed and evaluated for each analysis program in the software library. In addition to complexity metrics, the checklists are used to summarize aspects of the analysis programs that relate to quality, such as the availability of documentation, the use of source code prologues and comments, and test results.

Based on the new techniques and tools adopted as a result of this task, SDD anticipates a 15-percent improvement in the quality of software developed by the division in 1991.

General Antenna Program

The General Antenna Program (GAP) is a general-purpose tool for analyzing the performance of reflecting antenna systems. It predicts the near-field and far-field radiation patterns produced by a reflecting antenna system by performing a ray trace of the electromagnetic radiation through the system according to the laws of geometrical optics, followed by a point-by-point integration over the field on the aperture plane or over the currents on the main reflecting surface. Figure 1 is an example of a far-field radiation pattern generated by GAP.

The first version of GAP, developed in 1973, consisted of a single program that performed the basic functions outlined above, as well as modeling a phase correcting subreflector and a finite element method for modeling a reflecting surface of arbitrary geometry. From 1973 to 1988, numerous modifications and extensions were incorporated into GAP to ensure that it remained a useful antenna design and engineering tool.

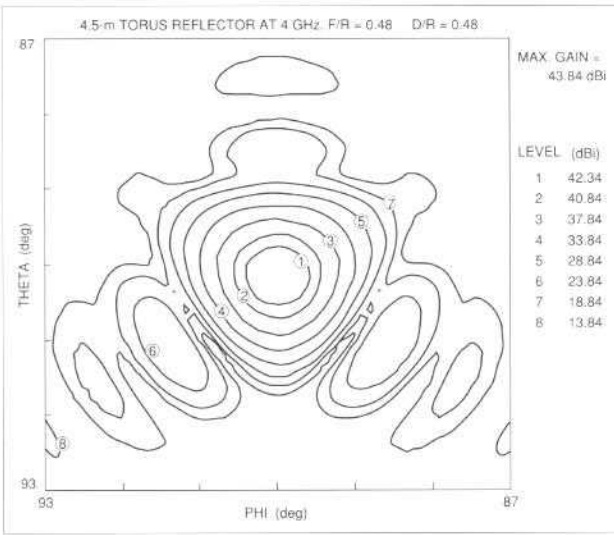

Figure 1. GAP predicts far-field radiation patterns

In 1989 an effort was initiated to restructure GAP to meet the requirements of current software engineering standards. The analysis routines of the 1988 version were extracted for use in the new version, and development was begun on new input processing code. The goal of the 1990 effort was to develop a concise, coherent version of GAP that included the basic functions and some extensions of past versions of the program and that also improved program maintainability and efficiency. The effort concentrated on developing well-structured, efficient, and well-documented software in order to reduce maintenance costs, facilitate the incorporation of new program features, and increase user effectiveness and confidence in the program. All of the code for the new version is highly modular and well-documented, and is contained in a single executable program. A version was developed for the IBM mainframe in 1990, and GAP will be ported to Hewlett-Packard (HP)9000 series machines in 1991.

The 1990 draft documentation produced for GAP includes a user's manual, a programmer's manual, and a theoretical manual. A draft test plan has been produced which contains a comprehensive set of test cases against which future versions of GAP may be tested to ensure that the basic functionality remains intact following enhancement and modification. The complete set of documentation, geared toward a version of GAP running on HP9000 series machines, will be completed in 1991.

COMSAT NONJURISDICTIONAL R&D

User Interface Management System

The development of a user interface management system, initiated in 1989, continued throughout 1990. The purpose of the task was to implement a development system that will be used by programmers to create sophisticated, interactive user interfaces for software applications. The system, referred to as AXIS, is based on the X Window System and OSF/Motif and provides software libraries, productivity tools, and application templates for improving user interface consistency, programmer productivity, and software quality.

During 1990, a software library known as the AXIS toolkit was designed, implemented, and tested. The toolkit provides software developers with a large set of reusable software that simplifies the implementation of Motif applications. Functions performed by the toolkit include:

- application initialization and management
- resource management
- dialog management
- menu management
- table and manager handling
- modal dialog handling
- text manipulation.

In early 1990, SDD completed the implementation of an AXIS-based text editor that provides an intuitive and powerful user interface. A revised version of a Motif Clip Art Library for the Macintosh MacDraw II program was also completed.

The most significant productivity tool completed was the X Widget and Resource Editor (XWARE), which is an interactive screen and resource editor for Motif-based applications. With this tool, software developers can interactively design and modify screens for their specific applications (see Figure 2). XWARE automatically generates the user interface code needed to implement these screens, and reads the code back in so that the screens can be modified.

A complete documentation set was developed for the AXIS system. This set describes in detail the information software developers need to effectively use the available software libraries and productivity tools. SDD will enhance the AXIS system during 1991 with additional functional and productivity tools.

COMSAT SUPPORT

On-Board VSAT Hub

Under the sponsorship of COMSAT's Intelsat Satellite Services (ISS) Business Development, SDD continued for a second year to study the concept of adding limited baseband processing and control functions (an on-board hub) to one transponder on a later INTELSAT spacecraft. Such an on-board hub would allow INTELSAT to offer innovative, affordable thin-route telephone and data services using low-cost, mass-produced very small aperture terminal (VSAT) earth stations with apertures of 1.8 or 2.4 m. Thin-route service is defined as one or a few

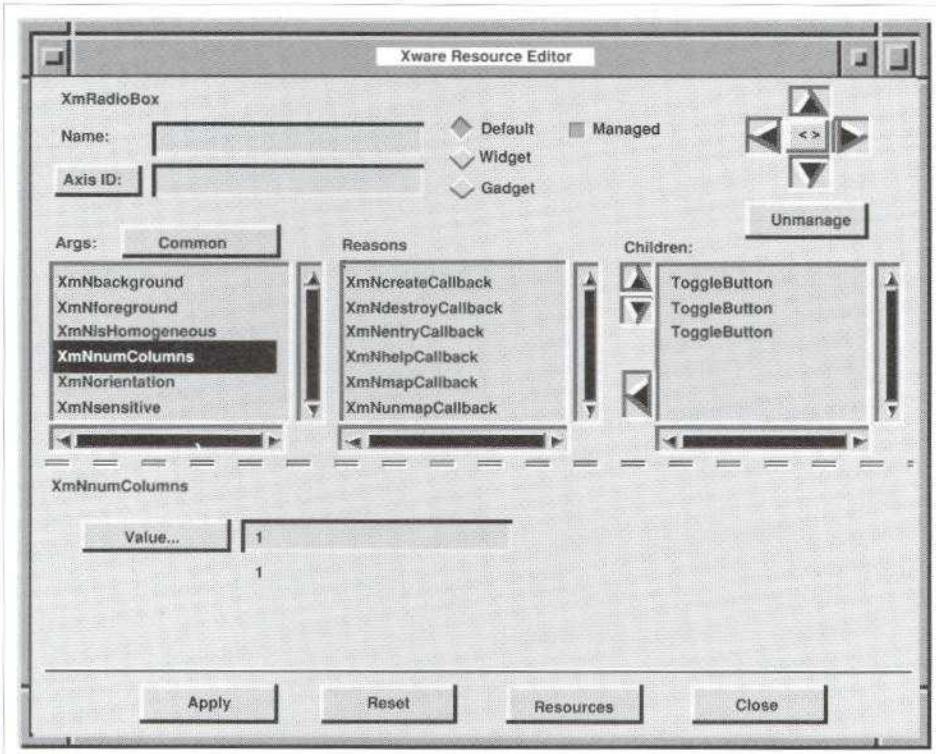

Figure 2. XWARE resource editor screen allows users to design and modify screens for their specific applications

telephone circuits provided to areas currently without international cable or satellite service.

As reported last year, the 1989 work indicated that the on-board hub concept could be technically feasible, and that capacities of hundreds of half-circuits per transponder should be realizable. In 1990, the work was extended in three major areas: estimates of potential demand for thin-route service in the Pacific islands; key issues in choosing C-band or Ku-band operation for the service; and the technological characteristics and requirements of key on-board hub subsystems.

The data used in the preliminary demand estimates made in 1989 were taken from several standard library reference sources available at that time, most dating from 1983 to 1986. More recent data which became available in 1990 produced an estimate of 1.35 million people and 49,000 telephones on 255 islands with significant populations but neither cable nor satellite service. Assuming an average satellite traffic demand of 8 call minutes per telephone per month, the on-board hub would carry 400,000 call minutes per month. For a concentration factor of 1/200, the traffic level is 33.3 Erlangs, which could be carried by 45 circuits (90 half-circuits) with a 0.01 grade of service.

Either C-band or Ku-band could be used for thin-route service with VSATs and an on-board hub. Each approach raises certain issues. At Ku-band, abundant mass-produced VSATs are available, but rain attenuation is an issue. At C-band, rain attenuation is essentially negligible, but until recently few, if any, C-band VSATs suitable for use in the INTELSAT system were being mass-produced, although theoretical analyses showed that 1.8-m C-band antennas could meet the necessary requirements.

A production C-band VSAT that could be used for thin-route service via an on-board hub was identified during 1990. COMSAT worked with INTELSAT and the manufacturer to establish type approval under INTELSAT Standard-G, including extensive tests of off-axis sidelobe levels, and the antenna met all necessary requirements for such approval. Although intended for use in conventional (ground-hub) VSAT networks, the unit would be suitable—with minor modifications—for use with the on-board hub.

Data are scarce on the Ku-band link margins required for good service in rainy tropical areas such as the Pacific islands. The Global Model, which is standard for such predictions, works well in the temperate zone, but has limitations in the equatorial region primarily because there are insufficient measured rain-rate distribution data. Figure 3 shows the Global Model climate regions in the Pacific area; a dashed line encloses the populated Pacific islands.

Despite these limitations, the Global Model is the only practical method for making rain-attenuation predictions where site-specific data are not available. Thus, this model was used to calculate the Ku-band margins required for thin-route service with the on-board hub. The results showed that service can be provided 98 percent of the time with 4-dB down-link and 6-dB up-link margins. The margins required for 99.8-percent service availability are significantly higher (typically 10 to 15 dB); however, link budget calculations showed that the efficiency of on-board demodulation, combined with the antenna directivity achievable on the satellite at Ku-band, could provide them.

A key issue is the mass and power of a flyable on-board hub. A rough order-of-magnitude estimate, based on scaling from the few signal processing payloads that have flown, is 20 to 40 W and 10 to 15 kg. These

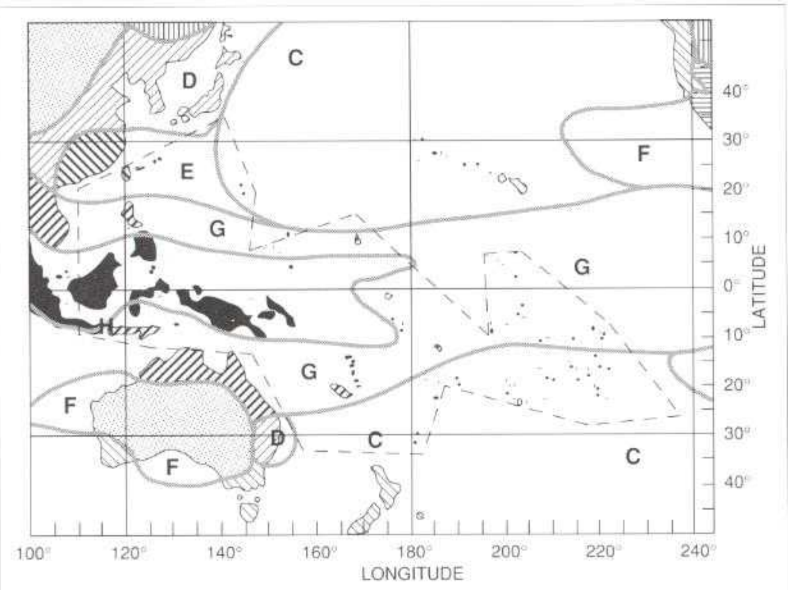

Figure 3. The Global Model predicts rain attenuation in the Pacific area (letters designate various rainfall regions)

estimates include the demodulation/remodulation unit and the controller; it is assumed that a switch-selectable RF receiver and transmitter already on the satellite would be used. The estimates could decrease with the use of technology more advanced than that in the systems already flown, or increase because of overlooked details.

The multicarrier demodulator is at the heart of the on-board hub. The demodulator could be implemented digitally; however, a surface acoustic wave (SAW) chirp Fourier transform implementation would require less power and weight. SAW technology for on-board applications is well established, based upon the volume of articles appearing on this subject in the open literature. A design study of a SAW demodulator for the on-board hub application was thus identified as an excellent candidate for an R&D project exploring the feasibility of an on-board hub.

The other major on-board hub subsystem is the demand-assignment multiple access controller. In 1989, memory requirements for this processor were estimated for 100 to 400 working channels, assuming daily downloading of recorded data. The estimates totaled 158 to 171 kbytes of random-access memory plus 380 to 1,000 kbytes of nonvolatile storage. In 1990, the CPU processing requirements were estimated, assuming an Ada implementation and a fairly detailed software architecture. The result was an estimated processor load of less than 100,000 lines of Ada code per minute, which requires less than 0.05 mips of processor capability.

Frequency Planning Support

Frequency planning is the process of assigning carriers (including carrier center frequencies and power levels) to a set of satellite transponders such that the required standard of performance is obtained for all carriers. Each assigned carrier can be affected by interference from the other carriers assigned in the transponder bank, as well as from thermal noise and intermodulation noise generated by a transponder amplifier when more than one carrier is assigned to it. With the advent of transponder leases in the INTELSAT system, the ISS Operations Department asked SDD for assistance in developing capabilities for frequency planning in leased transponders and for viewing the planned or actual carrier loading of all satellite transponders.

SDD had already developed the Interactive Satellite Transmission Impairments Program (ISTRIP), an interactive version of an impairments analysis program used initially by COMSAT operations personnel and subsequently by INTELSAT. ISTRIP resides on the IBM VM/CMS operating system and can model all or part of a satellite transmission plan, and compute and display signal impairments due to thermal noise, intermodulation noise, and interference from other carriers. ISTRIP also can optimize the transmitted carrier power levels to minimize impairments in the worst carrier in the plan. The frequency plan is displayed as a sawtooth plot which the user can modify interactively.

During 1990, SDD explored the availability of the INTELSAT data required to view actual or planned carrier loadings on INTELSAT satellites. Data required for noise analyses for the 1990 Satellite System Operations Plans were obtained from INTELSAT and converted for use with ISTRIP. Data describing the actual carrier loading of all the transponders of interest to COMSAT were obtained from INTELSAT on a weekly basis and provided to the ISS Operations staff. Work was begun on a frequency planning manual that will provide descriptions of the required data for frequency planning, rules and criteria currently used by INTELSAT to determine the acceptability of a frequency plan, and guidelines for using ISTRIP. ISS Operations staff members were given initial training on the use of ISTRIP to view the planned carrier assignments for a transponder bank, to obtain associated data, and to modify the frequency plan and analyze the performance of all of the carriers. This effort will continue through 1991.

IDR Link Error Analysis Program

The Intermediate Data Rate (IDR) Link Error Analysis Program (LEAP) was initiated in 1989 to analyze the statistics regarding burst errors collected from data on the INTELSAT IDR system and other digital transmission lines. LEAP interprets the encoded error data stream and

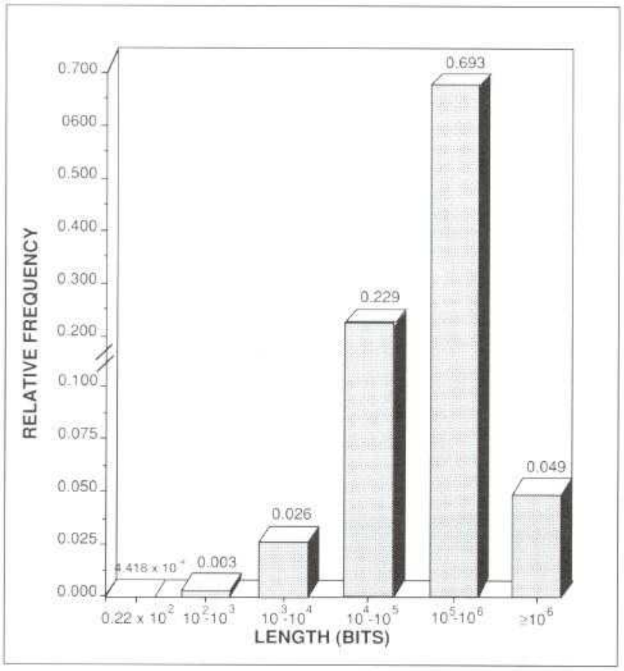

Figure 4. LEAP output is used to predict the effect of errors on link quality

evaluates the bits, and the order of the bits, contained therein. The program then identifies bit errors on the data link and generates statistics used to predict the impact of the errors on perceived link quality (see Figure 4).

In 1989, analyses were implemented to determine the bit error rate over the entire file and over averaging intervals, the relative frequency of the length of error events and error-free intervals, and the average number of errors within the range of error event lengths. In 1990, a user's manual and a programmer's/theoretical manual were completed based on the original analyses. LEAP was also enhanced to include additional analyses, along with refined versions of the original analyses. The enhancements included the ability to calculate probability of burst error; the minimum, maximum, and average lengths of the burst and error-free intervals; the percentage of burst length occurrence; and the cumulative relative frequency concerning error-free intervals.

LEAP was developed and is maintained on an IBM PC using C language for the analysis and Harvard Graphics for the histograms. The work was performed jointly with the Communications Technology Division (CTD), which was responsible for data capture and encoding as well as for interpreting the error statistics.

Inmarsat-M/B Network Coordination Station

In 1990, SDD continued its support for COMSAT Systems Division on the Inmarsat-M/B Network Coordination Station (NCS) project. Inmarsat-B (formerly called Standard-B) is the digital ship-to-shore satellite communications system that Inmarsat is developing to replace its analog Inmarsat-A system. Inmarsat-B supports both voice and data calls, while Inmarsat-M (a subset of Inmarsat-B) supports voice calls only. An overview of the Inmarsat-B system is shown in Figure 5.

The Inmarsat-M/B system comprises the central computer and channel unit equipment that monitors and controls both the B and M networks in its ocean region. The most important function of the NCS is to assign the channels used for voice calls in this single channel per carrier system. Each of the four NCSs also communicates with Inmarsat's network control center (NCC) in London. This allows Inmarsat to remotely monitor operations in all ocean regions from its headquarters, and also allows the NCC to centrally perform functions that affect all ocean regions, such as commissioning new ships.

SDD's principal responsibility on this project is the operator interface software for the NCS and the NCC. This interface includes approximately 200 screens and has the following innovative features.

The operator may enter commands using any of three methods: selecting from menus, typing in a command language, or running a file of prerecorded commands. Menu selection is best for new or infrequent users who need to be guided to correct choices, while the command language is best for experienced users who want to enter commands quickly. The command file is best for repetitive execution of a series of related commands.

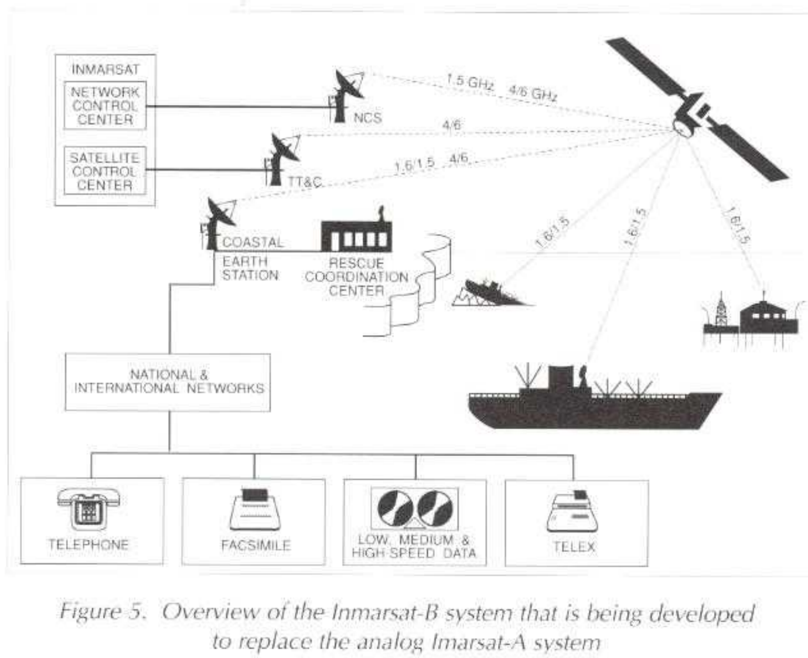

Figure 5. Overview of the Inmarsat-B system that is being developed to replace the analog Imarsat-A system

When the operator selects a command from the menu, the operator interface automatically copies the mnemonic to the command line at the bottom of the screen and displays the next menu. The operator can switch back and forth between the menu selection or typing methods with a single command.

Command files can be created using a conventional full-screen file editor or by putting the terminal into "learn" mode. In this mode, every command the operator enters (by menu selection or typing) is recorded, but not executed, until the operator says to stop.

To provide further help for new or infrequent users, each window lists the mnemonics that are legal in that position. The selected mnemonic appears in reverse video. Next to each is a help text that summarizes the function of that command or subcommand. To save screen space, the help text is covered by the next window.

To speed entry of similar commands, the operator interface also remembers the most recent selections from each type of command. To enter a command similar to a recently entered one, the operator need only start the command and then press the space bar to have each previous choice copied onto the command line. The operator then can accept each choice as is, change it, or back up to follow a different path.

The operator interface includes diagnostic and test features that are normally isolated in separate test support software. These features allow the operator to turn on a variety of diagnostic recording capabilities, collect data for a time, turn off the recording, and examine the results, all without disturbing the operational software. Conventional designs would require the operator to stop the operational software (interrupt service), configure the system to run with the test support software, and then restart the computer. Figure 6 is a sample NCS menu selection screen.

In 1990, SDD completed the NCS software design, presented it to Inmarsat at the Preliminary and Final Design Reviews, coded 16,000 lines of C code (representing 80 percent of the NCS operator interface), and demonstrated the software to Inmarsat. SDD also assembled the NCC and made plans for its installation. In 1991, SDD will complete the coding, testing, and integration of the NCS and NCC operator interfaces, install the NCC, and train the Inmarsat operators.

On-Call Engineering Support

SDD provides support to the ISS engineering staff by developing, modifying, or making production runs of the programs in the Systems Analysis Software Library. This work usually results from an unplanned event such as a problem with a launch or a customer report of carrier performance problems.

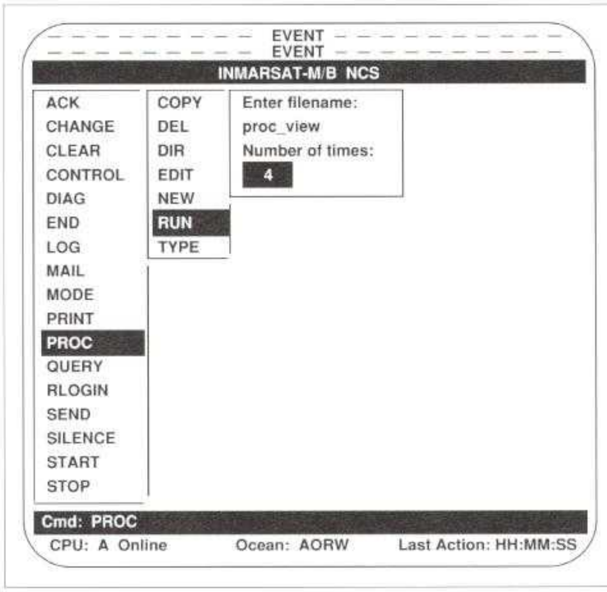

Figure 6. Inmarsat-M/B NCS menu selection screen facilitates the entry of operator commands

During 1990, SDD supported the Microelectronics Division in analyzing the effects of atomic oxygen on the solar panel silver interconnects used on the stranded INTELSAT VI spacecraft. Due to failure of the the INTELSAT VI (F3) (S/C 603) satellite to reach geosynchronous orbit in March 1990, an effort was begun to develop software that would predict the level of exposure to atomic oxygen that the satellite would experience at low earth orbit. Using the atmospheric model, MSIS, developed by Hedin, the software computes the atomic oxygen "ram fluence" (i.e., the total integrated flux, in atoms/cm^2, encountered by a satellite) for a given period by modeling the satellite orbit using the laws of Keplerian dynamics. To extend the Keplerian model to handle perturbation effects, the real nonideal orbit is modeled as an ideal mean orbit using the six Keplerian parameters and their rates of change. The software was used to calculate the amount of atomic oxygen ram fluence encountered by the satellite from March 14, 1990, through December 1990, as well as through the first quarter of 1992. The effort also included development of a method for estimating the effect of the satellite's shape, rotation, and orientation on ram fluence.

SDD also significantly enhanced the personal computer version of the Sun Outage Program (SUNOUT) for ISS. SUNOUT predicts outage times and durations at earth stations due to sun interference. It also generates tabular listings and graphical plots of the increase in antenna noise temperature, system temperature, and gain to noise temperature ratio of the receiving earth station as a function of time (see Figure 7). Enhancements included replacing the program interface with a simple, user-friendly

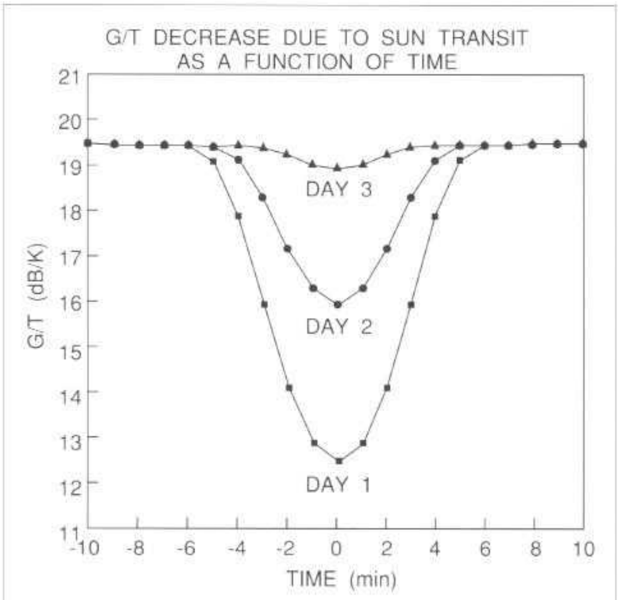

Figure 7. SUNOUT generates plots of G/T decrease during the fall equinox

interface, adding a graphical plotting capability, and refining the analysis algorithms.

ISS Software Support

Every year the SDD staff provides extensive support to the ISS Planning, Marketing, and Operations staff, including antenna coverage plots generated daily so that ISS can evaluate coverages for various customers or plans. During 1990 an Antenna Coverage Notebook was prepared which provides detailed coverage maps for each beam on each INTELSAT satellite for the current and planned orbital station assignments. To support new analysis, modifications were made to the Antenna Coverage Program, including refinement of an algorithm to compute earth station beta factors to determine an earth station's geographic advantage in a specific INTELSAT beam coverage area. Antenna coverage files containing gain data based on prelaunch measurements, along with current beam-pointing parameters, were acquired from INTELSAT, processed, and maintained under this task for ISS.

INTELSAT SUPPORT

Fixed TDMA Burst Time Plan Software

INTELSAT operates one TDMA network on a satellite in the Atlantic Ocean Region (AOR) and one on a satellite in the Indian Ocean Region (IOR). The earth stations in these networks transmit traffic within preassigned time intervals in the form of one or more high-rate streams of bits referred to as "bursts," using the entire bandwidth of a satellite transponder.

From 1981 to 1985, SDD designed and implemented the fixed TDMA burst time plan generation (BTPGEN) software system to provide timing and control information via master time plans (MTPs) and condensed time plans (CTPs) for all equipment in each INTELSAT TDMA network. This software system, which resides on the IBM MVS/TSO operating system, takes an input traffic matrix for a TDMA network and generates a coordinated set of time plans for the equipment. The MTPs are used for the planning and setup of the earth stations, and the CTPs are used for the actual timing and control of the equipment.

During 1990, SDD continued to maintain the BTPGEN software system and revise the software in response to INTELSAT's changing requirements. In addition to support provided for users, a minor modification was made to the software to make its tape output compatible with SS-TDMA software tape output, as both outputs are processed by the same INTELSAT software.

Satellite-Switched BTP Software

INTELSAT operates an SS-TDMA network on one satellite in the AOR, and plans to convert the fixed TDMA network in the IOR to SS-TDMA in 1991. Such a system, which can be used on the INTELSAT VI satellite, can expand the coverage areas available to each earth station without requiring additional station equipment. It also allows for much greater flexibility in traffic assignments through the satellite, since beam connections can be dynamically reconfigured to respond to customer requests for transmission paths.

In each INTELSAT SS-TDMA network, a community of transponders is synchronized to a common time period called the TDMA frame. During the frame, each accessing station transmits traffic within preassigned time intervals as one or more bursts, using the entire bandwidth of a satellite transponder. On INTELSAT VI, the beams on transmission channels 1-2 and 3-4 are dynamically switched.

In the SS-TDMA system, a TDMA frame is divided into a number of switch states. During each switch state, the on-board microwave switch matrix (MSM) establishes switch connections to allow interconnections between the up-beams and down-beams of a multibeam satellite. A particular earth station with a single up-beam coverage can then communicate cyclically (according to a controllable sequence over a TDMA frame period) with all of its destinations in various down-beams by placing its transmit bursts in time slots when the required beam connections are made by the MSM.

For operation of the SS-TDMA network, a detailed satellite switched BTP must be developed which provides the burst schedule as well as the switching sequence so that transmission among stations within the various coverages can be maintained without conflict. Requirements for control of the system must also be met. The BTP information is transferred to the reference or traffic stations in the SS-TDMA network as a set of coordinated individual time plans.

In 1989, SDD completed and delivered the SSMTP/SSCTP software system, which generates a set of coordinated time plans for the physical elements of an SS-TDMA network from a BTP database of burst schedule and control assignments.

During 1990, SDD continued work on the software in response to INTELSAT requests for modification as the system became operational and several software requirements were respecified. In addition, SDD provided final documentation for the software system.

Satellite Transmission Impairments Software

INTELSAT planners and operations staff use the Satellite Transmission Impairments Program (STRIP6) and the Outage Margin and Time Program (OUTMAT6) to evaluate satellite frequency plans and optimize transmitted carrier power levels. (A frequency plan consists of all the carrier assignments in a frequency reuse transponder bank on an INTELSAT satellite.) Both programs are command-driven and reside on the IBM MVS/TSO operating system at INTELSAT. The STRIP6 program accepts input data for the components of a frequency plan and computes clear-sky signal impairments due to thermal noise, intermodulation, interference from carriers assigned to other transponders in the transponder bank, and adjacent carrier interference, for all of the carriers in the plan. STRIP6 can also be used to optimize carrier power by using an algorithm that iteratively changes the operating points of each transponder and balances the power of the carriers in it until the performance of every carrier is satisfactory. The OUTMAT6 program accesses a database provided by the STRIP6 analysis and utilizes rain data available for all earth stations to evaluate the additional effects of rain impairments on the carriers assigned in the frequency plan.

Released in 1973, the original version of STRIP6, which modeled FM carriers, was used initially by COMSAT operations personnel, and subsequently by INTELSAT. Since that time, the program has been gradually enhanced by modifications such as the addition of models for new types of carriers. In 1986, as large numbers of small digital carriers increasingly replaced large FM carriers, the OUTMAT6 program was developed for INTELSAT by CTD and SDD in response to the increased importance of obtaining rain impairments and rain outage times, particularly in the higher frequency bands.

As INTELSAT began loading its transponders with increasing numbers of carriers, the STRIP6 and OUTMAT6 programs began to require considerable computer time for calculations, and the number of intermodulation products produced in these transponders became excessive. SDD and CTD worked together in 1990 to modify these two programs to accommodate frequency plans with very large numbers of carriers. Algorithms in the programs were modified to accelerate the calculations without significantly affecting the results. In STRIP6, the algorithm to calculate the impairments caused by intermodulation noise was altered to simulate an intermodulation spectrum in transponders where more than 30 carriers were assigned. OUTMAT6 was modified to import computed intermodulation impairments from STRIP6 and then scale these impairments to reflect the effects of rain. The capacity for storing frequency plan data was modified in both programs to meet current INTELSAT requirements. Both revised programs were delivered to INTELSAT, along with supporting documentation.

OTHER SUPPORT

MITRE Analysis Library

SDD assisted the MITRE Corporation in 1990 in establishing a library of satellite systems analysis programs to enable MITRE to enhance its NASA technical support capabilities. SDD assistance included porting the Interactive Antenna Coverage Program (IACP) and the Interactive Channel Modeling Program (ICHAMP) to a VAXstation 3500 (operating under VMS) from the IBM mainframe on which they were initially developed. IACP was also ported to the DECstation 3100 operating in the UNIX environment. No significant changes were made to the analysis portions of these programs, although minor enhancements were made to the graphical interfaces. By operating these programs on an engineering workstation, the performance of both IACP and ICHAMP has been greatly improved compared with operation on the IBM mainframe.

Many significant milestones were achieved in the Advanced Communications Technology Satellite (ACTS) Program during 1990. In particular, development of all three of the NASA Ground Station (NGS)/Master Control Station (MCS) subsystems was substantially completed, and these subsystems were integrated to form a fully functioning system. Perhaps the most significant milestones were achieved in October, when the NGS, under control of the MCS, successfully acquired the ACTS baseband processor for the first time, and the first end-to-end communications circuits were established. This resulted in substantial reduction of the remaining program risk, and bodes well for the ACTS Program in general.

There were a number of other important accomplishments for the ACTS Program in 1990. COMSAT supported NASA in presenting the ACTS System Critical Design Review in January. The Master Control Facility console subsystem was designed, procured, and installed. Four of seven acceptance tests were completed for the NGS RF terminal (RFT); these tests proved that all of the NGS down-link subsystems and the beacon measurement subsystem complied fully with all specifications. Additionally, the telemetry, tracking and command (TT&C) operations acceptance tests were completed for the MCS, demonstrating that the MCS could monitor and control the ACTS Flight System via the TT&C links. Modem characterization tests proved that the NGS modems built by Motorola and delivered to COMSAT as government-furnished equipment were fully compatible with the interfaces to the NGS.

The NGS RFT and time-division multiple access equipment were integrated with the MCS and engineering model of the ACTS communications-electronics payload. Informal checkout tests demonstrated interface compatibility between the subsystems, as well as functionality of the essential system features. Extensive, detailed testing using formal test procedures will be the primary activity for 1991.

Staffing was completed for the core operations and maintenance team that COMSAT will provide to operate the NGS/MCS equipment at NASA Lewis Research Center in Cleveland, Ohio.

Finally, COMSAT performed two studies for NASA to determine the feasibility of several ACTS system enhancements that would expand experimental opportunities. One of these studies developed a basic design approach to adding Integrated Services Digital Network (ISDN) capability to the ACTS low burst rate network. This would enable ISDN users/experimenters to interface directly to ACTS LBR earth stations. The second study established the basic design of a transportable earth station for use in providing high-definition television (HDTV) demonstrations via ACTS. Given the wide bandwidth of the ACTS microwave switch matrix channel, HDTV and other high-data-rate experiments are deemed particularly appropriate for ACTS.

ACTS PROGRAM MANAGEMENT OFFICE

The overall management responsibility for each technical element of the ACTS Program, as well as for the cost and schedule control and other business/planning activities, resides in the ACTS Program Management Office (PMO). In order to accomplish the various technical goals of the program, the PMO "contracts" with various departments throughout the Laboratories to accomplish specific portions of the program related to their particular areas of technical expertise. Acting as a general contractor, the PMO blends all of these separate elements into a cohesive product combining technical and programmatic considerations to meet the requirements of the contract and the objectives of the customer.

All of the current cost, schedule, and performance measurement information related to each segment of the program plan flows into the PMO for management analysis, review, and evaluation. The output of this process is the technical and programmatic direction necessary to maintain the program on schedule and within the expected cost.

SYSTEMS ENGINEERING AND INTEGRATION AND TEST

During 1990, the focus of the ACTS Program at COMSAT shifted from individual subsystem development efforts to the integration of these subsystems into the fully operational system for final testing. The objective is to complete this integration and test activity by mid-1991, and to deliver the system to NASA in August 1991. Given the success of the informal integration tests, the outlook for meeting these program objectives is very positive.

In January, COMSAT supported NASA in conducting the ACTS System Critical Design Review. COMSAT Systems Engineering and PMO personnel participated in the 2-day design review at NASA Lewis Research Center (LeRC), in Cleveland, Ohio. Prior to the design review, the ACTS system-level interface specifications and test plans were completed. At the design review, COMSAT presented an overview of its equipment designs, its test and operations and maintenance (O&M) plans, and the development status of all major equipment items.

Design, procurement, and installation of the Master Control Facility (MCF) console subsystem were completed in 1990. This subsystem comprises the computer terminals used to operate the time-division multiple-access (TDMA), MCS, and RFT equipment, as well as intercoms and other station support equipment.

Systems Engineering is responsible for execution of the final acceptance tests, which are performed using formal procedures with NASA representatives as witnesses. Acceptance of the equipment by NASA is contingent upon successful conduct of the acceptance tests. During 1990, eight of the planned total of 24 acceptance tests were performed. Four tests, applicable to the NGS RFT, proved that all of the NGS down-link subsystems and the beacon measurement subsystem (BMS) were fully compliant with all specifications. The TT&C operations acceptance tests were completed for the MCS, demonstrating that the MCS could monitor and control the ACTS Flight System via the TT&C links. Acceptance tests were also performed successfully on the forward error correction decoder unit.

Bit-error rate (BER) characterization tests of the modems built by Motorola were conducted using special test equipment (STE) provided along with the modems. These tests proved that the NGS modems delivered to COMSAT as government-furnished equipment (GFE) were fully compatible with the interfaces to the NGS.

Integration of the NGS RFT and TDMA equipment with the MCS and engineering model/communications electronics package (EM/CEP) was completed. With the EM/CEP serving as an emulator for the spacecraft, all network operations functions performed by the MCS and TDMA equipment can be tested, with the exception of the propagation delay inherent in satellite systems. Tests of the control functions include special software features which mimic the propagation delay that would normally be seen in the control data links. This ensures that any timing-related problems will be found prior to operation with the on-orbit spacecraft.

Informal checkout tests of the full NGS/MCS/EM/CEP system demonstrated interface compatibility between the subsystems, as well as functionality of essential system features. Work began in 1990 on the development of formal test procedures required for the extensive and detailed testing to be conducted in 1991.

COMSAT performed two studies for NASA to determine the feasibility of several ACTS system enhancements that would expand experimental opportunities. One of these studies developed a basic design approach to adding ISDN capability to the ACTS low burst rate (LBR) network. This would enable ISDN users/experimenters to interface directly to ACTS LBR earth stations. As of year-end, it appeared that NASA was planning to pursue the ISDN upgrade for the LBR earth stations, based on the results of the COMSAT study.

The second study established the basic design of a transportable earth station for use in providing HDTV demonstrations via ACTS. Given the wide bandwidth of the ACTS microwave switch matrix (MSM) channel, HDTV and other high-data-rate experiments are deemed particularly appropriate for ACTS. The study was well received but, due to budget limitations, the HDTV earth station is not likely to be built in the immediate future. However, at year-end, NASA commissioned COMSAT to perform a follow-on study, which is intended to develop a concept for a high-data-rate earth station, capable of transmission in the 400-Mbit/s region. The primary application would be interconnection of supercomputers and other high-speed networking schemes. Many of the basic concepts developed in the HDTV study will be reused in this follow-on study.

Staffing was completed for the core O&M team that COMSAT will provide to operate the NGS/MCS equipment at NASA LeRC. This staff includes a station manager, station engineer, and three technical specialists, one each assigned to the RFT, TDMA, and MCS subsystems in the NGS/MCS complex. This core group of five highly trained technicians and engineers will be augmented by two system operators, who will be hired from the Cleveland area. A training program for the O&M team was developed during 1990 for implementation in the first half of 1991.

RF TERMINAL DEVELOPMENT

During 1990, substantial progress was made toward completion of the RFT segment of the NGS. The Satellite Technologies Division (STD) undertook the major portion of this task, except the modems, which were the responsibility of the Communications Technology Division (CTD).

The RFT comprises that part of the station from, and including, the 5-m antenna to the digital interface with the TDMA equipment. Its major function is to receive and transmit the LBR mode communications signals. The RFT will also include the TT&C links, as well as equipment to measure the signal strength of up to three beacons down-linked from the satellite. These measurements will provide real-time input for the adaptive rain fade compensation scheme, which is one of the technical innovations of the program.

The major product of in-house activity in 1990 was the integration and test of virtually all of the RFT hardware that is to be delivered by COMSAT. Eight equipment racks containing the multiple subsystems of the RFT were tested together. Test procedures were generated and tests conducted, as witnessed by NASA, to demonstrate the performance compliance of the RFT.

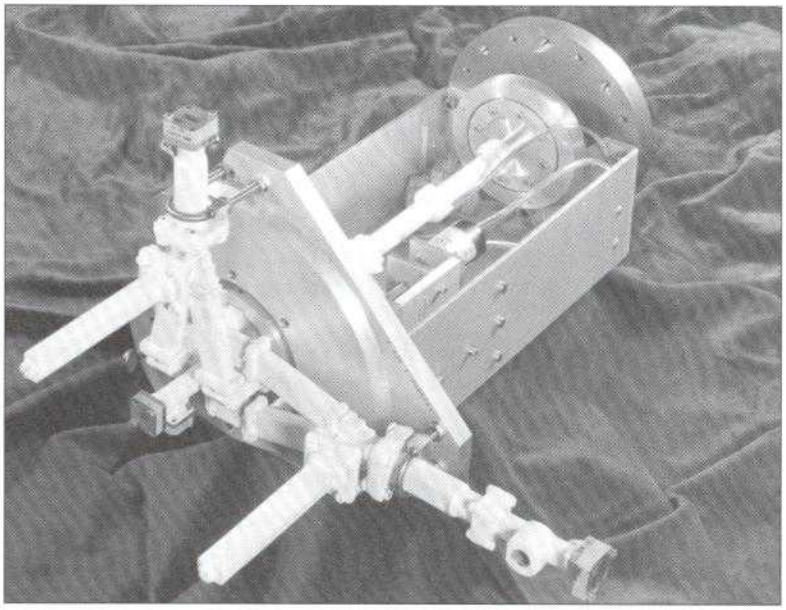

Figure 1. ACTS antenna diplexer

An important part of this testing included measurement of the BER performance of the RFT. Tests were performed with the Motorola-built modems and STE to determine the extent of any BER degradation associated with the RFT. Measurements were made with the modems operating in "back to back" loopback mode, and then through paths specially designed into the RFT, which permit the signal to be looped back, at appropriate frequencies and power levels, to the demodulators. This testing proved very important as it permitted quantitative measurements of the effects of the traveling wave tube transmitters on the TDMA signal.

As a part of the required testing of the RFT, interfaces to other parts of the NGS/MCS, i.e., the TDMA equipment and the MCS, have been established and exercised. The RFT contains the BMS, which measures rain fade data from the down-link beacon signals. This subsystem generates digitized fade data which are transmitted in real time to the TDMA equipment, and then to the MCS for permanent recording for propagation studies. Timing signals required for experimental measurements are received from the TDMA equipment to permit RF measurements within the TDMA frame. Finally, data reporting all status changes in the RFT are transmitted to and stored in the MCS.

Other RFT activity included the design and fabrication of the diplexer, which will ultimately become part of the ACTS antenna. This diplexer, shown in Figure 1, will enable transmit signals on two polarizations at 30 GHz and receive signals on two polarizations at 20 GHz to be coupled to and from the antenna itself. This development represents a significant enhancement of the state of the art. While the design is based on previous COMSAT designs in the 4/6- and 11/14-GHz bands, the extension to 20/30 GHz required attention to many critical mechanical design, fabrication, and RF test details.

In parallel with this in-house diplexer development, the antenna subsystem is being developed under subcontract by TIW Systems. Preliminary and critical design reviews have been completed at TIW. Careful planning and measurement ensured mechanical compatibility between the antenna in its intended rooftop location at LeRC and the RF equipment to be located within the building immediately below.

The RFT will perform many of its functions and be monitored by the RFT supervisor (RFTS)—an HP9000/350C computer—equipped with three operator workstations located in the RFTS area, in the MCF, and at the Satellite Control Center at General Electric (GE) in East Windsor, NJ. This third station will be linked to the RFT by land lines. Hardware and software were integrated into the RFT in 1990. The RFTS provides a user interface whereby the station can be configured to any desired operating mode using "point and click" mouse techniques. Comprehensive capability exists for the user to set, measure, and monitor multiple station operating parameters simultaneously.

Also in 1990, the government-supplied EM/CEP, which provides a subset of the ACTS spacecraft communications capability, arrived at COMSAT and was connected to the RFT, through special interfacing equipment. The RFT will perform measurements of the up-link and down-link LBR burst signals. With the availability of up-link burst signals from the TDMA equipment, the down-link burst signal from the EM/CEP, and the RFTS software substantially completed, actual minimum shift keyed (MSK) signals (the modulation format used through the baseband processor [BBP]) were used to prove the measurement capability. Previously, all the measurement techniques and equipment were developed with non-MSK continuous wave (CW) signals.

Progress on the RFT during 1990 permitted it to be integrated, as planned, with the TDMA equipment, the MCS, and the EM/CEP. With this level of integration completed, the RFT is now being used successfully in the testing of the higher-level communications functions of the ACTS System.

TDMA TERMINAL DEVELOPMENT

During 1990, the ACTS NGS TDMA terminals were completed, tested as a subsystem, and transferred to NGS system integration and test. Early test results proved that the ACTS NGS TDMA terminals are fully capable of communication with the engineering model of the ACTS communications payload, including its BBP, an on-board TDMA system. This success was facilitated through a systematic design and documentation methodology structured in a top-down hierarchy. The system was assembled from more than 75,000 electronic and mechanical components and contains over 44,000 lines of code.

The reference terminal acquires and synchronizes to the BBP-generated TDMA frame to transfer the MCS control and status orderwire channels to the BBP and to the LBR terminals. The reference terminal preprocesses these orderwire channels, which have a combined maximum rate of 1.476 Mbit/s. The reference terminal also continuously compares the BBP on-board clock drift to a local frequency standard, and periodically reports deviations to the MCS. The MCS then up-links frequency corrections to the BBP to maintain network clock stability.

The traffic terminals acquire and synchronize to the BBP TDMA frame to interconnect experimenter terrestrial circuits to the LBR network. The 110-Mbit/s terminal provides service for eight T1 interfaces (1.544 Mbit/s) and six interfaces operating at 6.312 Mbit/s. The 27.5-Mbit/s terminal provides service for four T1 interfaces and two 6.312-Mbit/s interfaces. Together, the terminals can interface 1,072 64-kbit/s equivalent voice channels to the LBR network. Call processing functions within the terminals provide for both single-channel dynamic routing using dial digits and multichannel trunk routing in either point-to-point or broadcast connections.

Figure 2 is a functional block diagram of the 110-Mbit/s TDMA terminal design. The 27.5-Mbit/s design is identical except for deletion of the transmit and receive MCS interfaces. The terminals are partitioned into two major subsystems: the terrestrial interface equipment (TIE), and a TDMA burst controller. The major functional elements for each are given below.

Terrestrial Interface Equipment

- *T1 and 6.312-Mbit/s Interfaces.* Provide a terrestrial line interface, plesiochronous buffering of channel data, and T1 supervisory signaling processing.
- *Transmit and Receive Bus Controllers.* Provide digital switching of channel data to/from the burst controller or the signaling extraction-signaling generation (SXU/SGU) hardware under call processor control.
- *SXU/SGU.* Provides dual-tone multifrequency selective signaling reception/transmission to or from experimenter channels for dynamic single-channel routing in the LBR network.
- *Receive and Transmit Traffic Buffer Interfaces.* Buffer channel data for high-speed transfer to/from the TDMA burst controller.
- *Demand-Assigned Multiple-Access (DAMA) Call Processor.* Processes supervisory and address signaling to/from experimenter channels, sends and receives orderwire messages to/from the MCS to acquire and release satellite capacity, dynamically routes channel data to/from the burst controller, and maintains call records for operator status display.

TDMA Burst Controllers

- *Receive and Transmit MCS Interfaces.* Provide high-speed transfer and preprocessing of orderwire channels to/from the MCS, as well as the BBP and traffic terminal network.
- *Receive and Transmit Traffic Interfaces.* Buffer channel data to/from the TIE, and route channels into MCS-assigned satellite slots.
- *DAMA (Receive and Transmit Frame Management).* Dynamically alters TDMA frame structure and traffic slot assignments in response to MCS orderwire commands, and performs synchronous burst time plan changes.
- *Receive and Transmit Timing and Control.* Acquires and maintains synchronization to the BBP TDMA frame.
- *Receive and Transmit Space Segment Interfaces.* Multiplex/demultiplex channel data to/from the TDMA bursts at either the 110- or 27.5-Mbit/s serial rates, and provide FEC encoding/decoding at rate 1/2 and constraint length 5.
- *System Executive.* Provides overall terminal monitoring and control, processes MCS monitor/control and LBR fade data links, and interfaces to the terminal operator for commands and status displays.

The terminal design presented in Figure 2 represents a carefully balanced selection of digital hardware and microprocessor firmware components. Figure 3 shows

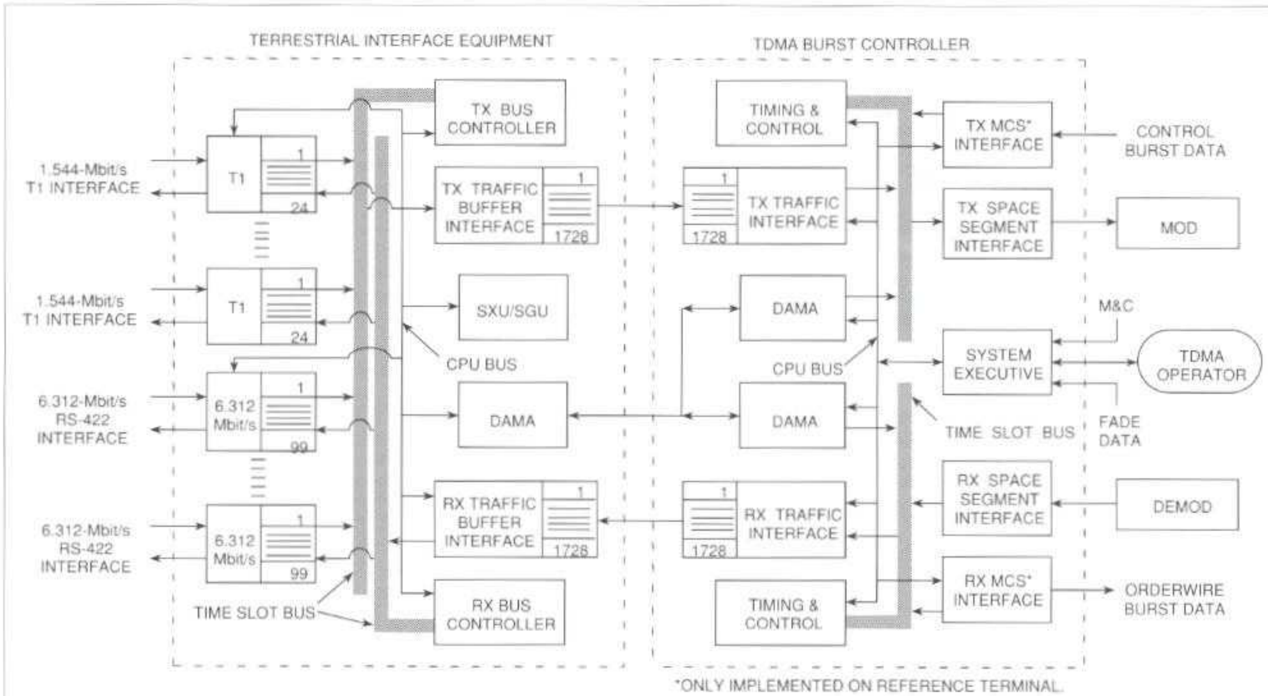

Figure 2. TDMA terminal functional architecture

the 110 Mbit/s-TDMA terminal which provides both reference terminal and traffic terminal functions along with the STE. High-speed digital logic and carefully engineered backplanes ensure error-free performance. Extensive use of programmed array logic hardware and microprocessor firmware results in a design which can be easily adapted to the needs of NASA's experimental program, as well as to the operational requirements of future commercial terminals in the ACTS system. The addition of ISDN capabilities to NGS TDMA terminals, which will begin in 1991, is an excellent example of how this flexible design approach can facilitate system growth as ACTS experimenter requirements evolve.

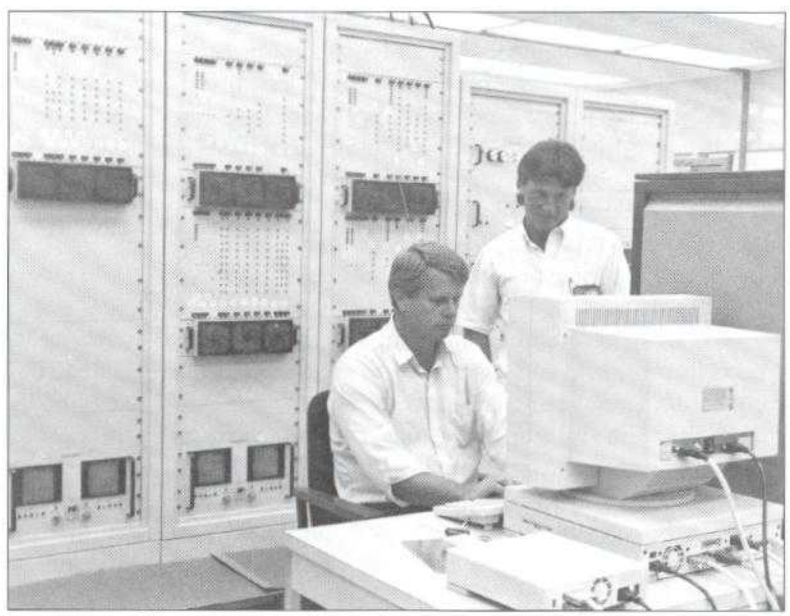

Figure 3. 110-Mbit/s TDMA equipment under test

MCS DEVELOPMENT

The MCS provides real-time control and monitoring of the ACTS LBR communications network, as well as associated control of the ACTS payload, including the BBP. It also supports ACTS experiments by controlling system configuration parameters and managing the recorded data. The MCS is implemented entirely in software hosted on a VAX 8600 super-minicomputer.

By third quarter 1990, 90 percent of the code for the MCS had been integrated into a working system and delivered to the NGS/MCS system integration and test team for integration with the EM/CEP, TDMA equipment, and RFTs. The design, code, and test of the experiment data processing subsystem was nearly complete by year's end.

NASA witnessed demonstrations of the MCS software, both in a test environment and with the other NGS equipment, during 1990. These demonstrations included all of the real-time MCS software, the experiment configuration software, and a major portion of the test support software. Nominal size networks were simulated with the test software. Demonstrations including the EM/CEP and TDMA equipment were also conducted, showing monitor and control of the EM/CEP's multibeam communications package (MCP) and the processing of "live" traffic.

During operation, the MCS will be connected to GE-supplied TT&C equipment and to the LBR TDMA reference terminal. The TT&C equipment will provide command and telemetry links between the MCP and the MCS. The MCS will use these links for sending commands to set the initial configuration of the MCP at the beginning of an experiment and to continually monitor the telemetry from the MCP for anomalies. Once the MCP/BBP has been initialized and the LBR reference terminal has acquired, the MCS will use the high-data-rate control circuits through the LBR reference terminal to communicate with the BBP and the LBR traffic terminals via inbound and outbound orderwires. This functional testing architecture of the MCS is illustrated in Figure 4.

Design, coding, and unit test of the MCS-NGS interface software were completed during 1990. This software processes the measurement data and status information from the RFT equipment and BER test set. Design, coding, and unit test of the experiment data processing software began during 1990 and was nearly complete at year's end. This software processes the data recorded by the real-time software during an experiment and inserts it into a relational database, provides for certain predefined reports, and supports *ad hoc* queries utilizing a high-level query language.

Work begun in late 1989 to implement the revised spacecraft command and telemetry lists was completed in early 1990. Several minor changes to the BBP programming rules were also implemented. As a result of initial network operational tests, it was determined that performance improvements were required in the high-data-rate interfaces between the MCS and TDMA equipment. The input interface software was revised and work began on the output side in late 1990. COMSAT also began a NASA-directed study to analyze the impact of failures in the BBP control and data memories. A small probability exists that cosmic radiation may cause a single bit in one of these memories to fail permanently. The major objective of the study is to propose technical solutions, which can be implemented in the MCS software, that would keep the ACTS LBR network operating in the event of such a failure. At year-end, NASA directed a change in its experiment database to add recording of individual call records; this work will be performed in 1991.

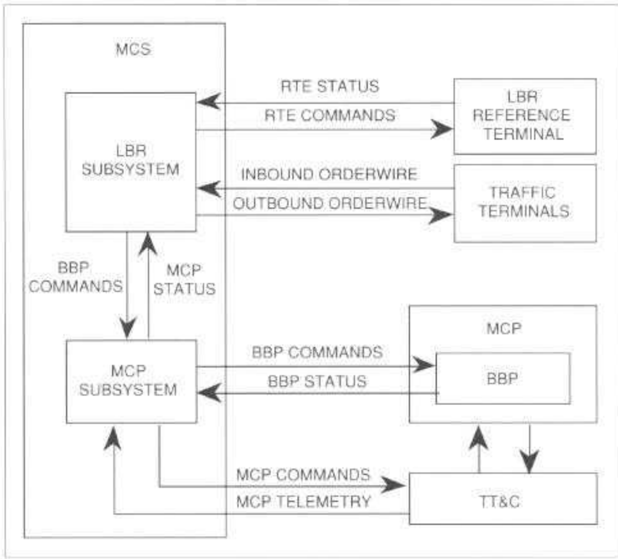

Figure 4. MCS functional testing architecture

Subsystem integration and test ("build" tests) of the MCS software continued during 1990. The final LBR network control build tests were completed, fully exercising the DAMA processing software, in addition to the LBR functions tested in earlier builds. The experiment configuration build tests were also completed and the other experiment data processing build tests began. Except for the experiment data processing software, all of this software is currently in use in formal testing with the EM/CEP and other NGS equipment.

PERFORMANCE ASSURANCE

During 1990, the COMSAT Performance Assurance (PA) team continued to support the ACTS Program in the areas of design reviews, component and subsystem procurement reviews, inspections, manufacturing engineering, production planning, configuration management, product assurance, and product safety.

In manufacturing and fabrication, the PA team supported the preparation of subassemblies, assemblies, and subsystem hardware (both in- and out-of-house). This support included management procedures implemented across the entire hardware development cycle from design, procurement of parts and components, inventory control, kit assembly, and fabrication, through final test and checkout. Formal PA reviews were held for both in-house manufacturing and out-of-house procurements. These reviews will continue through the entire development cycle and through system-level integration and test of the ground system. Hazard and safety analysis procedures were implemented to support parts procurement, assembly, and test. The controls exercised over the ACTS stockrooms resulted in an inventory of products that is accurate and quickly accessed for accountability and preparation of complete kits. In-house fabrication inspections of both the RFT and TDMA units resulted in assemblies that complied with required quality standards. The quality assurance methods, quality engineering, and inspections used on procured and in-house items have proven to be effective for the ACTS hardware development program.

COMSAT's PA program encompasses software as well as hardware. Software PA personnel continued to maintain the configuration control database for all released software for the MCS, TDMA, and RFT equipment. They also established and maintained a reference library of specifications, drawings, analysis documents, and test data for ACTS Systems Engineering.

Many of the PA-related control activities are performed through several engineering/management boards, including the Configuration Control Board, the Software Review Board, and the Material Review Board. The change control procedures for both in-house and out-of-house activities were implemented via these boards, which are composed of representatives of the various project teams and chaired by PA personnel.

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The following is a list of 1990 publications and patents by authors at COMSAT Laboratories. Copies of the publications may be obtained by contacting the COMSAT authors at: COMSAT Laboratories, 22300 Comsat Drive, Clarksburg, MD 20871-9475.

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PATENTS

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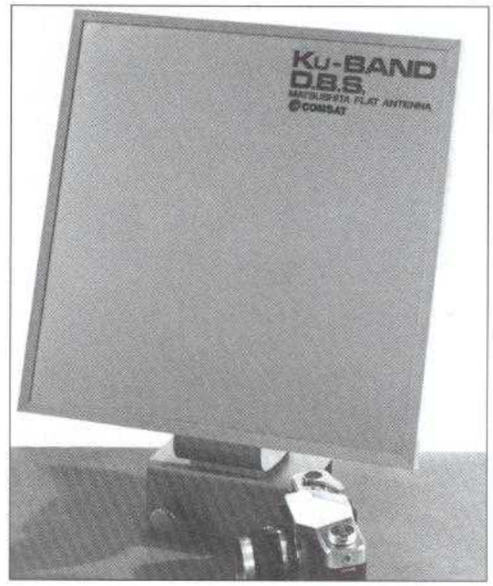
COMSAT Laboratories is pleased to achnowledge those of its scientists who were recognized in 1990 for their significant contributions to the field of satellite technology.

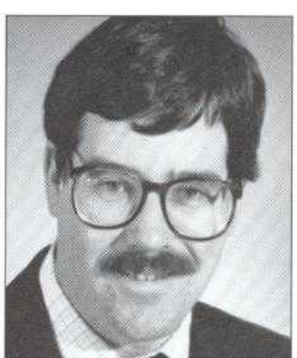
EXCEPTIONAL INVENTION AWARD

COMSAT recognizes inventions developed by the Laboratories that are put into commercial use by the Corporation or by its customers. In 1990, this Exceptional Invention Award was granted to Dr. Robert Sorbello (L) and Dr. Amir Zaghloul (R) for their work on the flat antenna. This antenna, which is manufactured by Matsushita Electric Works, is presently for sale in Japan and parts of Europe. Shown with the recipients is Mr. Irving Goldstein, CEO of COMSAT.

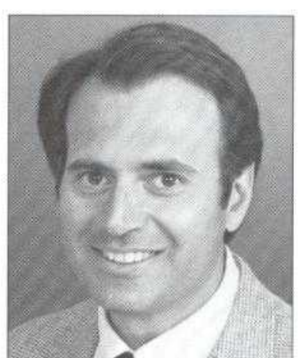


SENIOR IEEE MEMBERS

Also in 1990, Dr. George Metze of the Microelectronics Division, Dr. Ben Pontano of the Network Technology Division, and Dr. Lin-Nan Lee of the Communications Technology Division were elected to the grade of Senior Member in IEEE.



Dr. George Metze



Dr. Ben Pontano

Dr. Lin-Nan Lee