COMSAT LABORATORIES
1991 Annual Review

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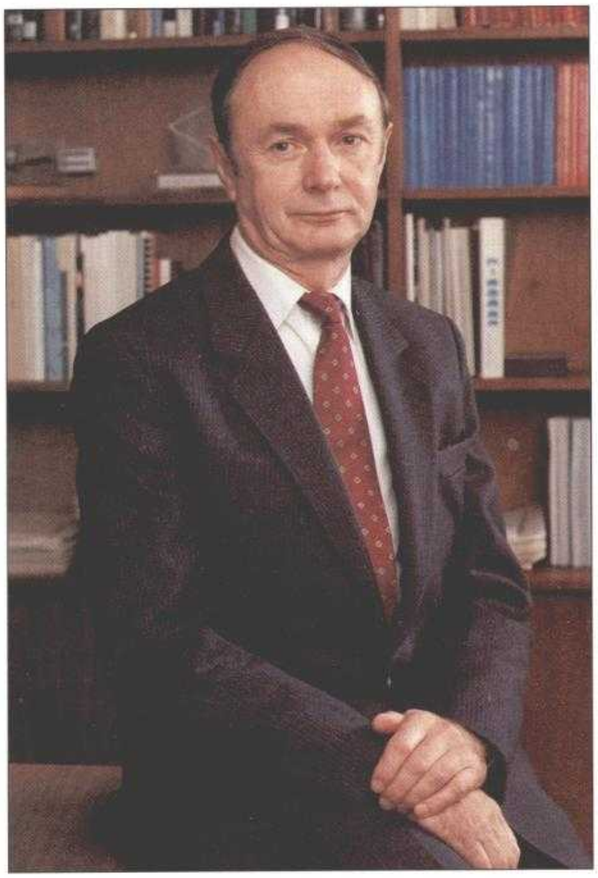
PERSPECTIVE

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.

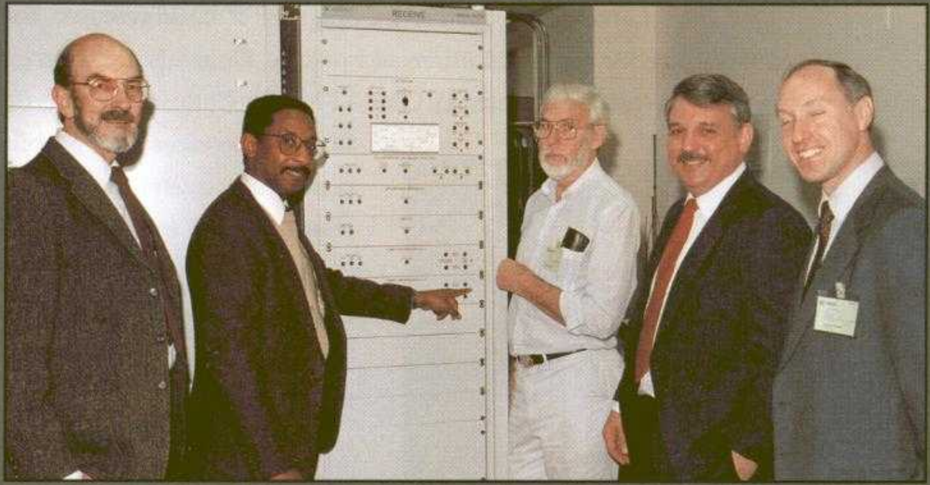


During 1991, the Laboratories had an operating budget of $42 million, of which about 50 percent came from Corporate sources and the balance from outside. Approximately 30 percent of the Corporate funding (15 percent of the total) supported an applied research program with the goal of creating new technology which has the potential of improving communications systems over the long term. A further 50 percent of 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 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 ninth in the series, summarizes all of the R&D efforts undertaken with Corporate support during 1991.

J. V. Evans

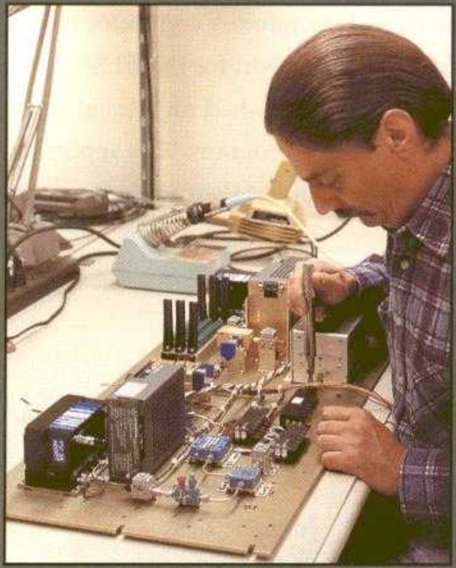
J. V. Evans
June 1991



In 1984, COMSAT Laboratories was selected to culminate its extensive participation in the establishment of ACTS with a major role in developing the ACTS system. Under the direction of the ACTS Program Office, the Laboratories assumed responsibility for the NASA Ground Station (NGS) and Master Control Station (MCS). This effort was subdivided into five specific management areas: systems engineering, RF terminal development, time-division multiple access (TDMA) terminal development, MCS development, and performance assurance.

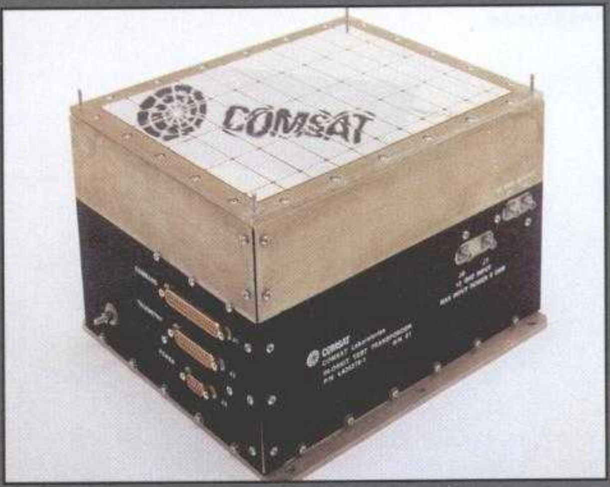
Despite extensive restructuring in 1988 and delays resulting from various Congressional funding issues, a fully compliant system was delivered to General Electric and NASA in 1991, several months before it was needed and several million dollars below budget. ACTS has been the single largest program conducted at COMSAT Laboratories and has involved technical support from virtually every division. It has demonstrated that the Laboratories, by combining outstanding technical resources with a highly effective management team, is capable of assembling and managing a large systems development and integration program. COMSAT will continue to support the program by providing the ACTS operations and maintenance team for NASA until 1995.

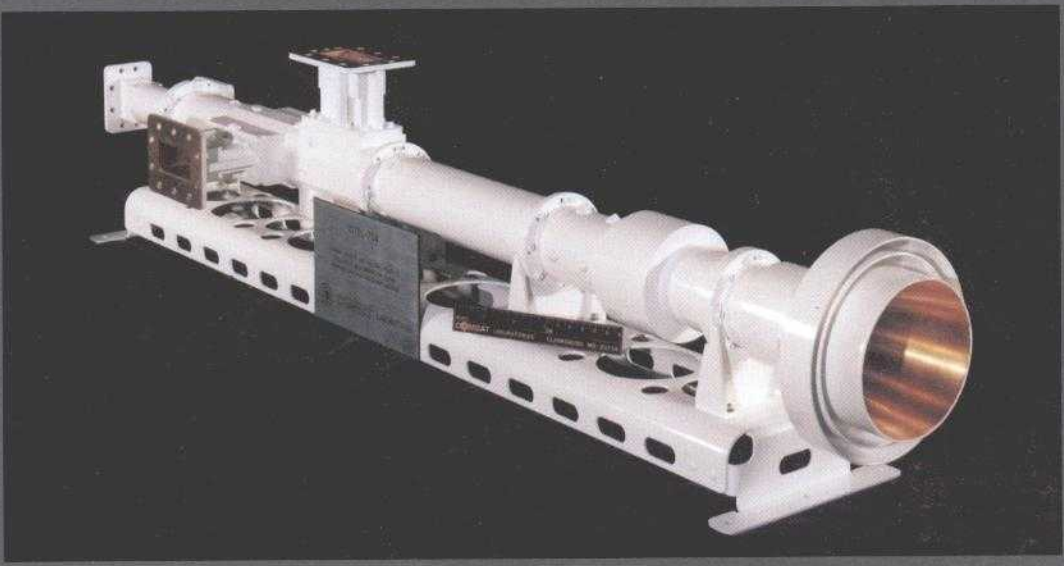
This is the last time the ACTS Program will be included in the *Annual Review*. To mark its final appearance, these two pages offer a retrospective of memorable events from the 8-year program.



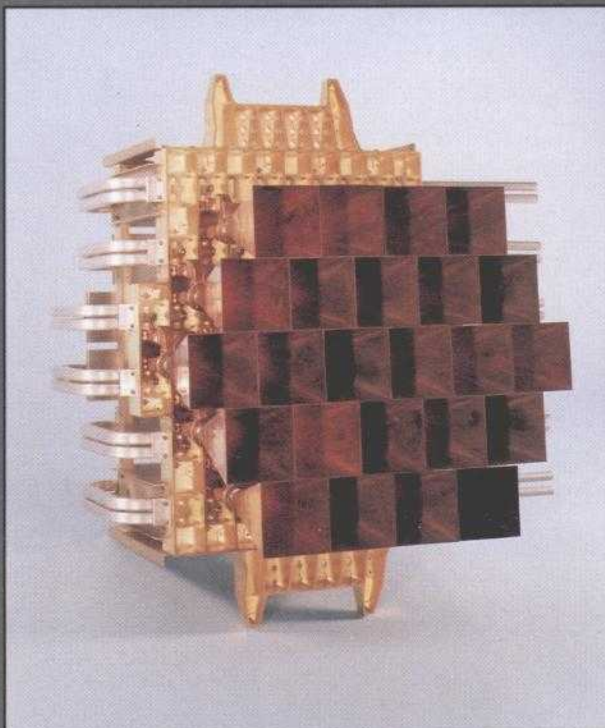
Microwave Technology & Systems

The Microwave Technology and Systems Division (MTSD) conducts research and development on satellite and earth station antennas and associated microwave hardware, space segment analysis and systems engineering, and satellite communications system monitoring. Hardware programs such as communications payload modules, antennas, and associated microwave components may extend from R&D through analysis, design, development, fabrication, flight qualification and, ultimately, flight.

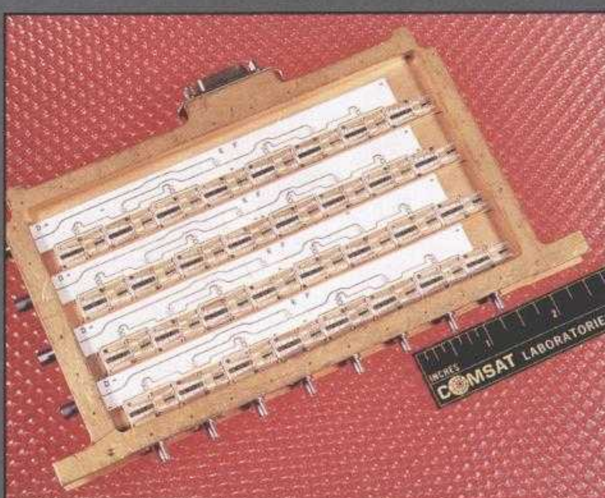


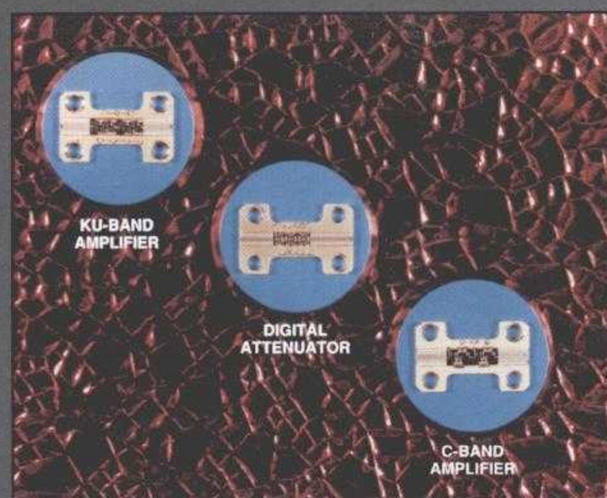


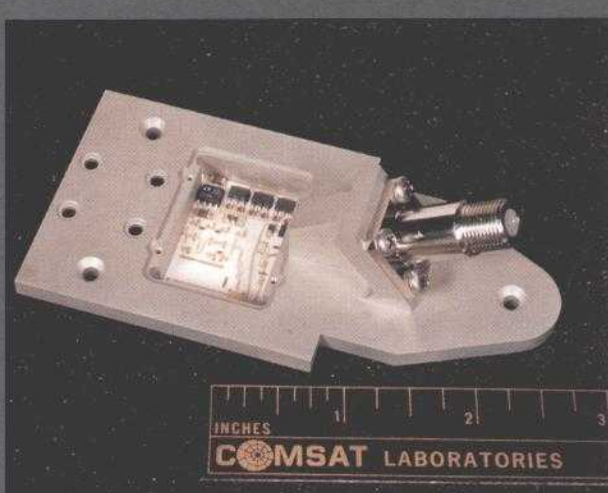
MTSD

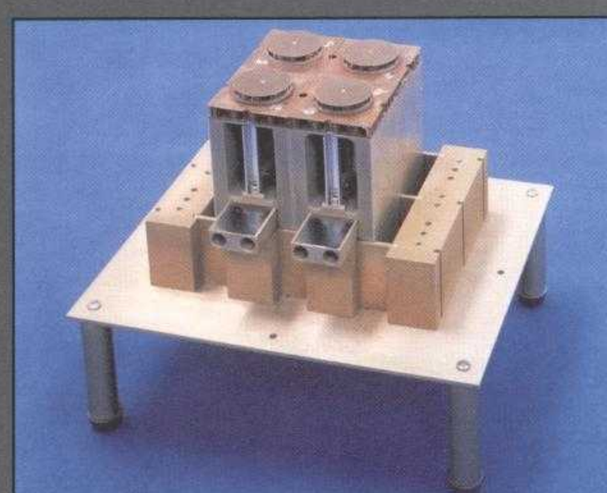


Division R&D contributes to a broad spectrum of state-of-the-art microwave technologies in such areas as transponders, active phased arrays for satellites, planar arrays for customer terminals, feed systems for satellites and earth stations, standard-gain antenna systems, onboard regenerative repeaters at C- and Ku-band, microwave switch matrices, and MMIC-based supercomponents. The work relies heavily on sophisticated computer-aided design and engineering tools, either developed internally or obtained from outside sources. Modeling is used as a basis for analysis, synthesis, and evaluation prior to fabrication and testing. Modern test facilities and anechoic chambers are available for component and system evaluations.





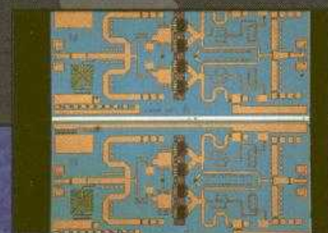




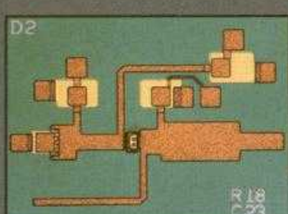
Microwave Electronics

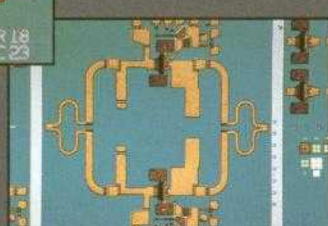
The Microwave Electronics Division (MED) of COMSAT Laboratories designs and fabricates gallium arsenide monolithic microwave integrated circuits (MMICs) and integrates them into modules and components. Covering the 1- to 94-GHz range, these microwave and millimeter-wave components are used in receivers and transmitters for both communications and radar applications.

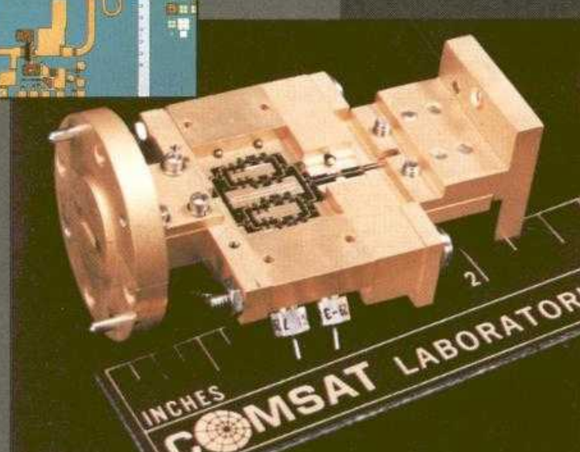
MED's MMICs have been qualified and inserted in satellite payloads requiring components of the highest reliability. This background, with emphasis on producibility, performance, efficiency, and reliability, has made MED and COMSAT Laboratories world leaders in MMIC technology.



Frigate and ATF
10-W X-Band
Power Amplifier

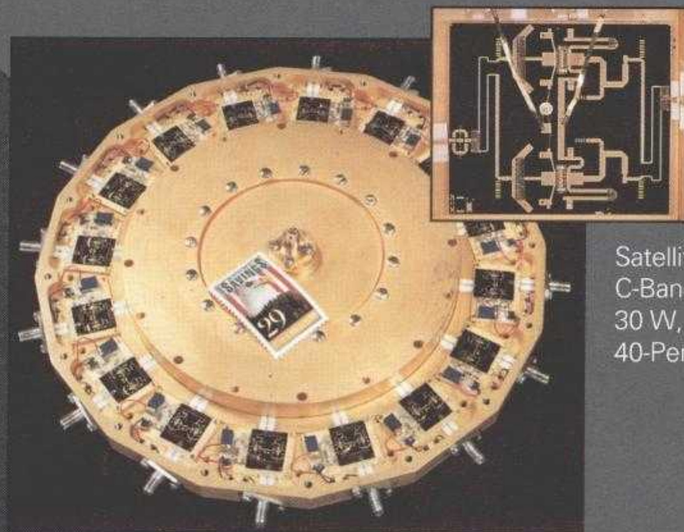




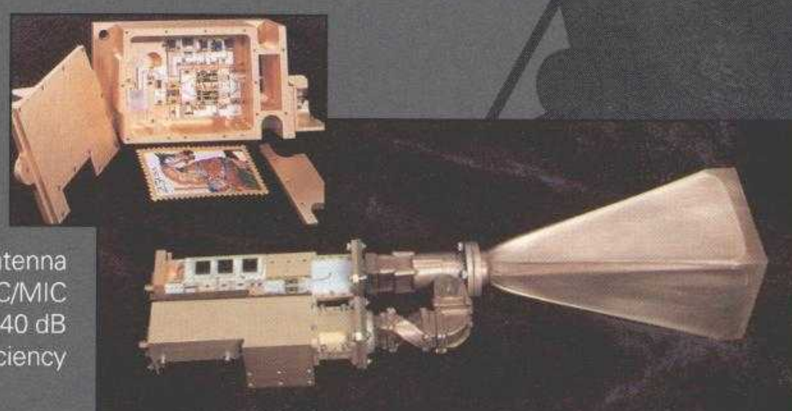


Smart Munitions
94-GHz Integrated
50-mW Power Module

MED



Satellite Amplifier
C-Band MMAC
30 W, 40 dB
40-Percent Efficiency

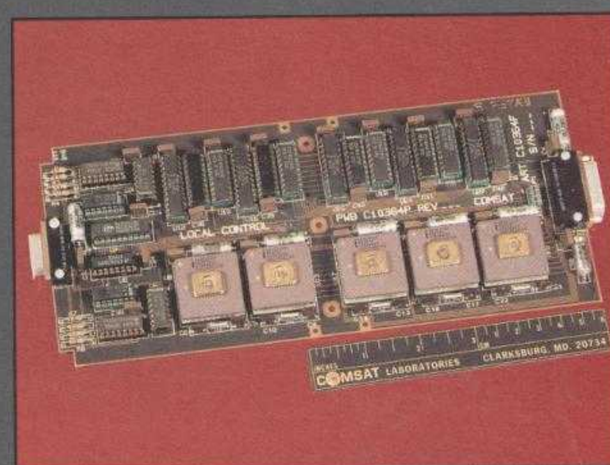


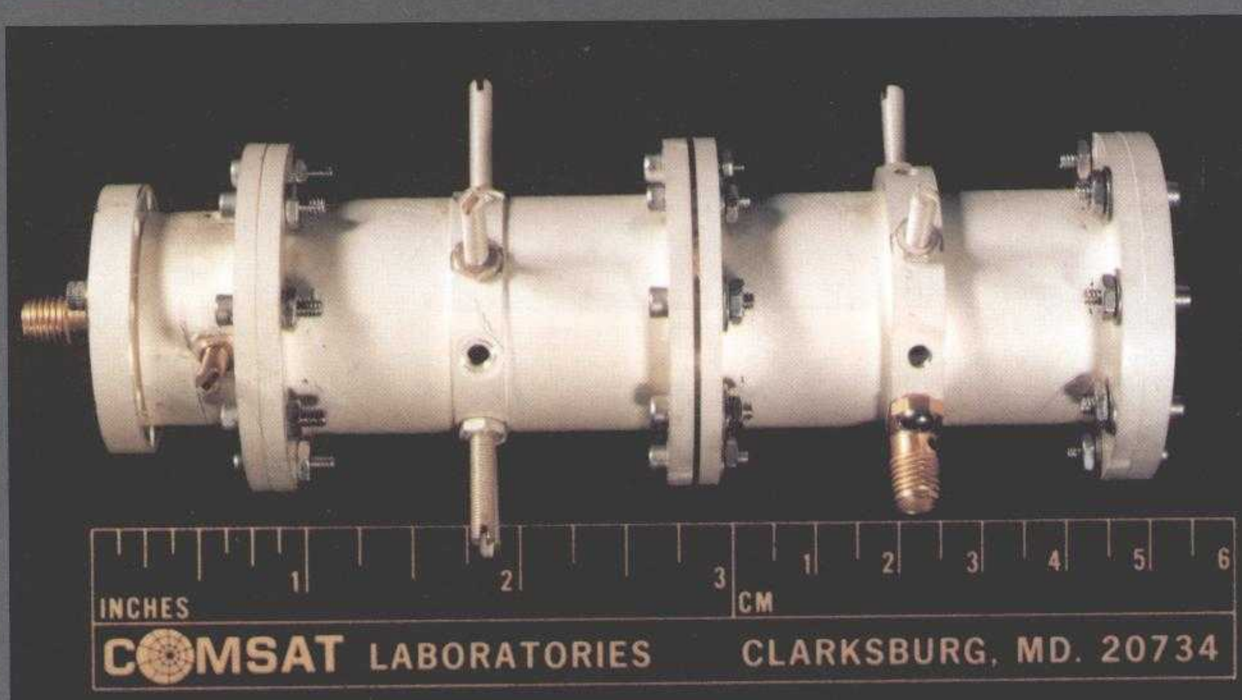
Phased-Array Antenna
Ku-Band MMIC/MIC
2 W, 40 dB
28-Percent Efficiency

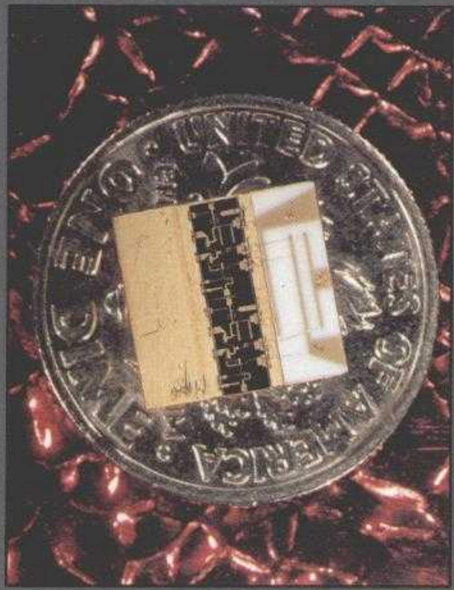
Earth Station Ku-Band 20-W
40-dB MIC Amplifier

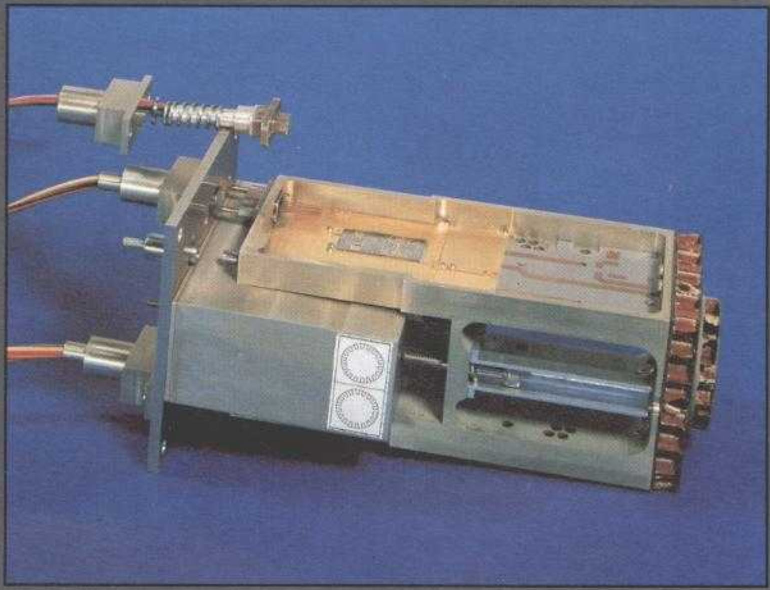
SATELLITE TECHNOLOGIES

The Satellite Technologies Division (STD) of COMSAT Laboratories conducts research, development, and support activities in a number of technical areas, including advanced communications satellite concepts that employ multibeam antennas and onboard processing. STD encompasses a broad range of engineering skills in disciplines related to satellite attitude control and dynamics, telemetry and command, structures, mechanisms, thermal control, electrical power systems, energy conversion and storage, environmental and qualification testing, satellite in-orbit testing, traveling wave tubes, microwave filters, transponders, and radiowave propagation studies.

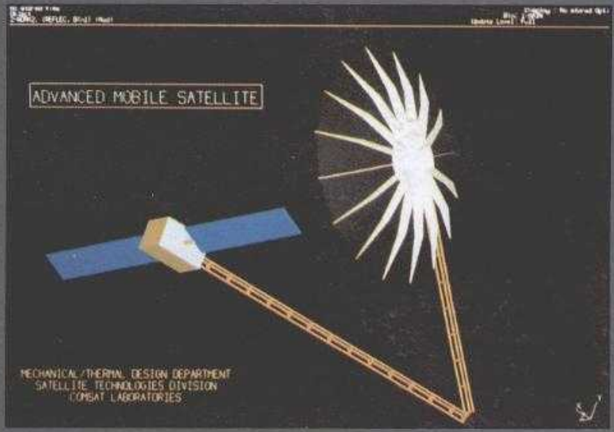


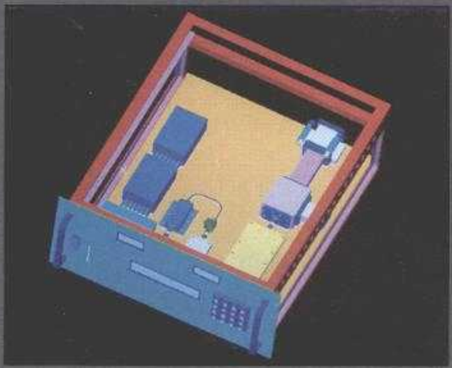


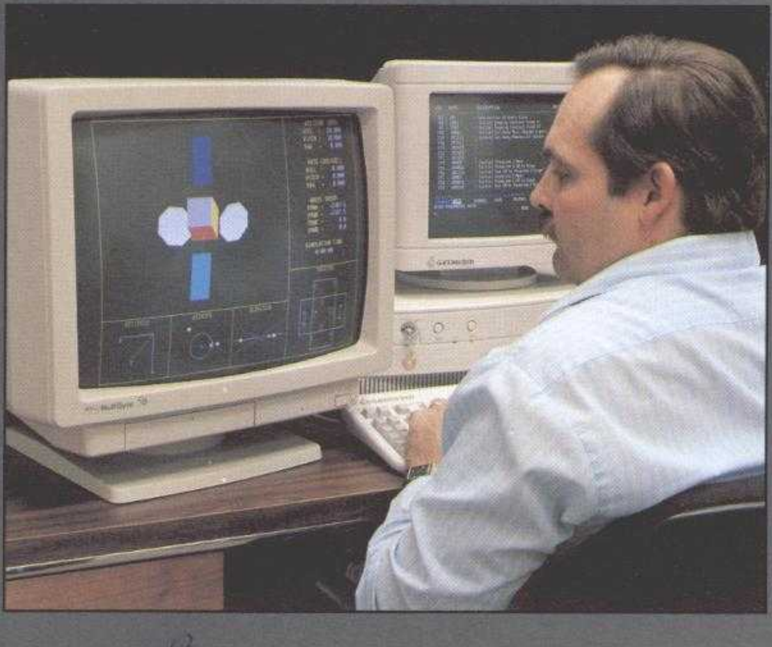




The division furnishes engineering support to INTELSAT and Inmarsat, and also contracts with other organizations to provide consulting services. STD's Design and Fabrication Center, which contains mechanical design and fabrication facilities and a model shop, assembles, integrates, installs, and tests microwave hardware systems.





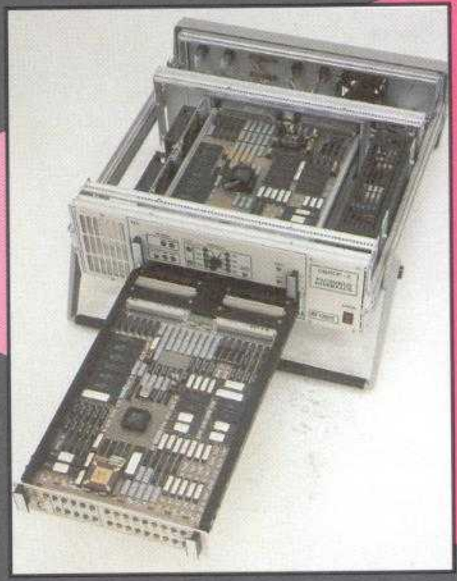


COMMUNICATIONS TECHNOLOGY

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. Our mission is to provide "Technical Excellence in Systems, Services, and Products for Global Communications." 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.

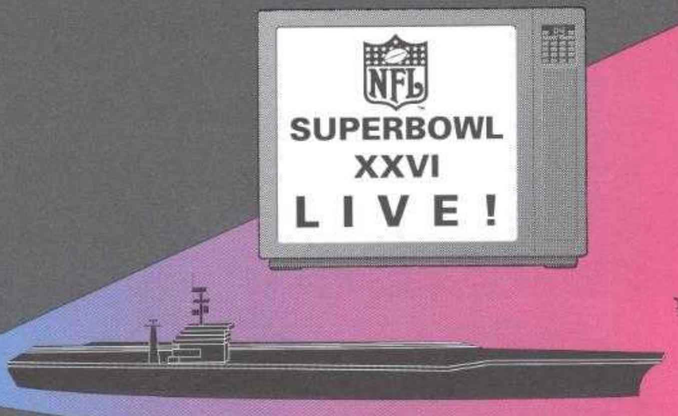
AUDIO

- **FAX Demod/Remod**
- **DCME**
- **Fax Compression**
- **Digital Broadcast Audio**
- **Echo Control**



VIDEO

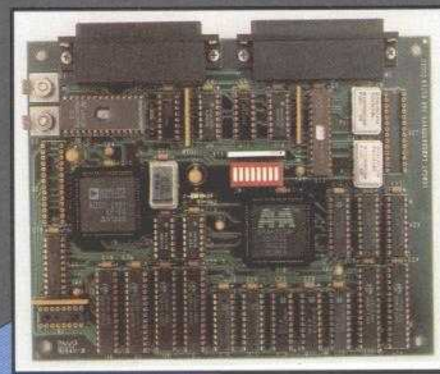
- **HDTV**
- **Time-Compressed TV**
- **N-MAC**
- **Digital TV**
- **Modified NTSC**
- **Shore-to-Ship**

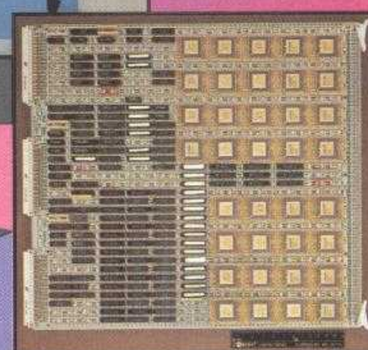


SIGNAL PROCESSING TECHNOLOGY

MOBILE AND PERSONAL

CTD





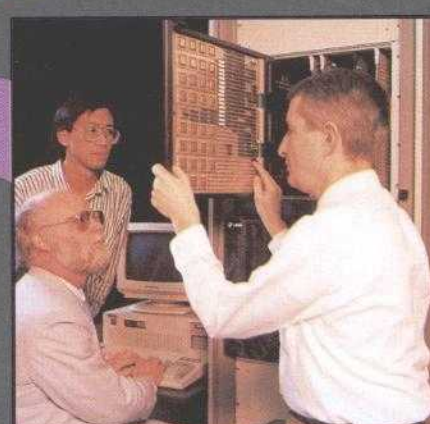
CODECS
- Block
- Viterbi
- Reed-Solomon

MODEMS
- High-Speed Burst
- Trellis-Coded
- μP and DSP-Based
- Digital Programmable
- BISDN

CDMA

ENCRYPTION

ONBOARD PROCESSING
- Demux/Demod

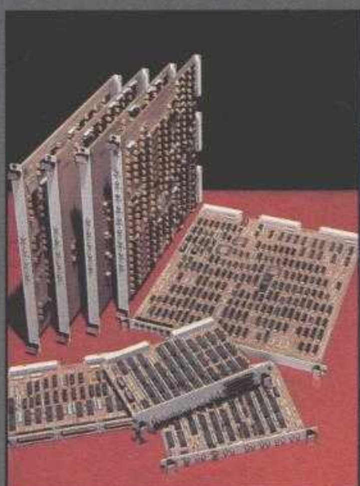


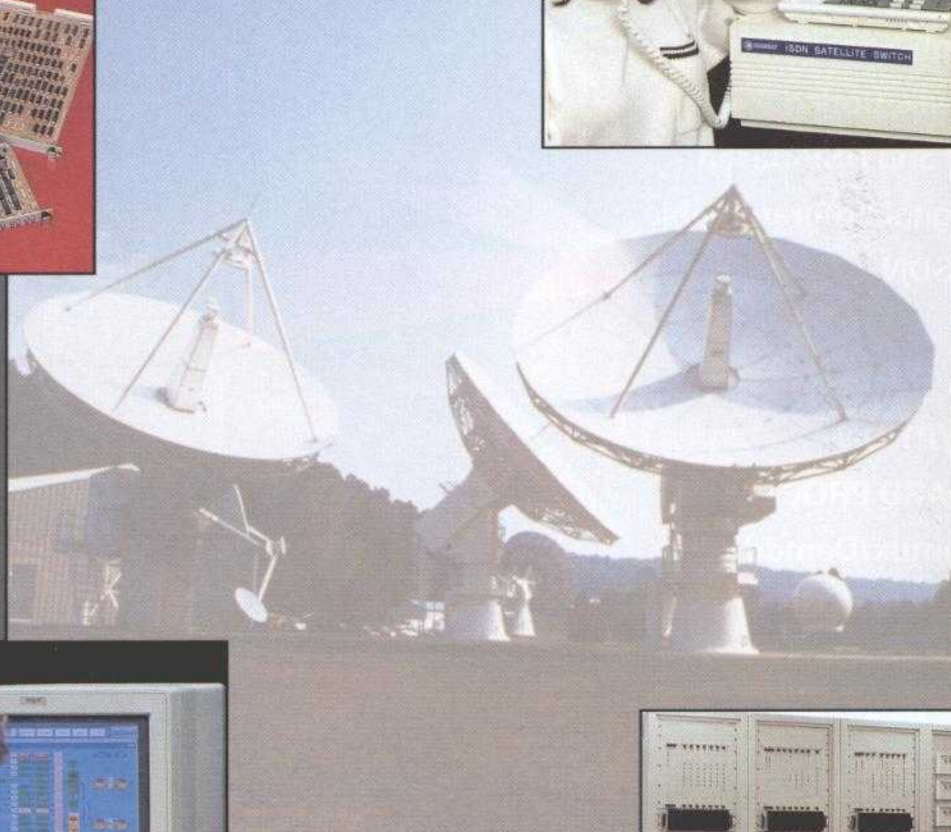
TRANSMISSION AND ONBOARD PROCESSING TECHNOLOGY

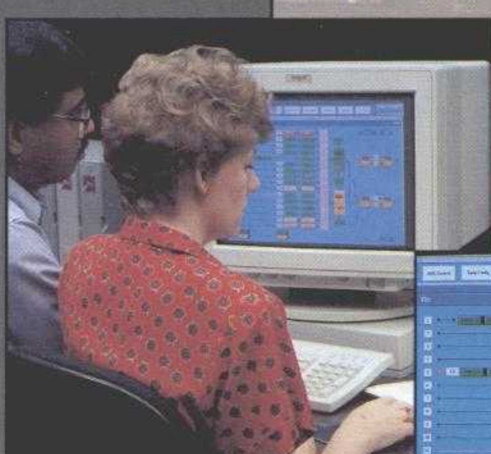
TERMINAL TECHNOLOGY

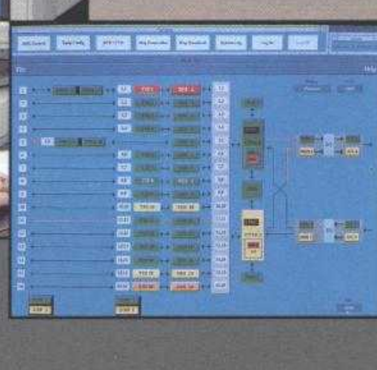
NETWORK TECHNOLOGY

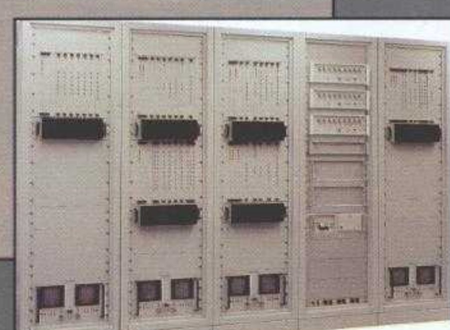
The Network Technology Division (NTD) performs R&D related to the analysis, design, implementation, and testing of advanced satellite and terrestrially based communications systems. Application areas include fixed and mobile satellite networks, onboard baseband switching and processing, integrated services digital networks (ISDNs), data communications and protocols, time-division multiple access (TDMA), intelligent systems, and optical communications and processing. Activities within the division range from conducting studies to implementing hardware- and software-based systems.



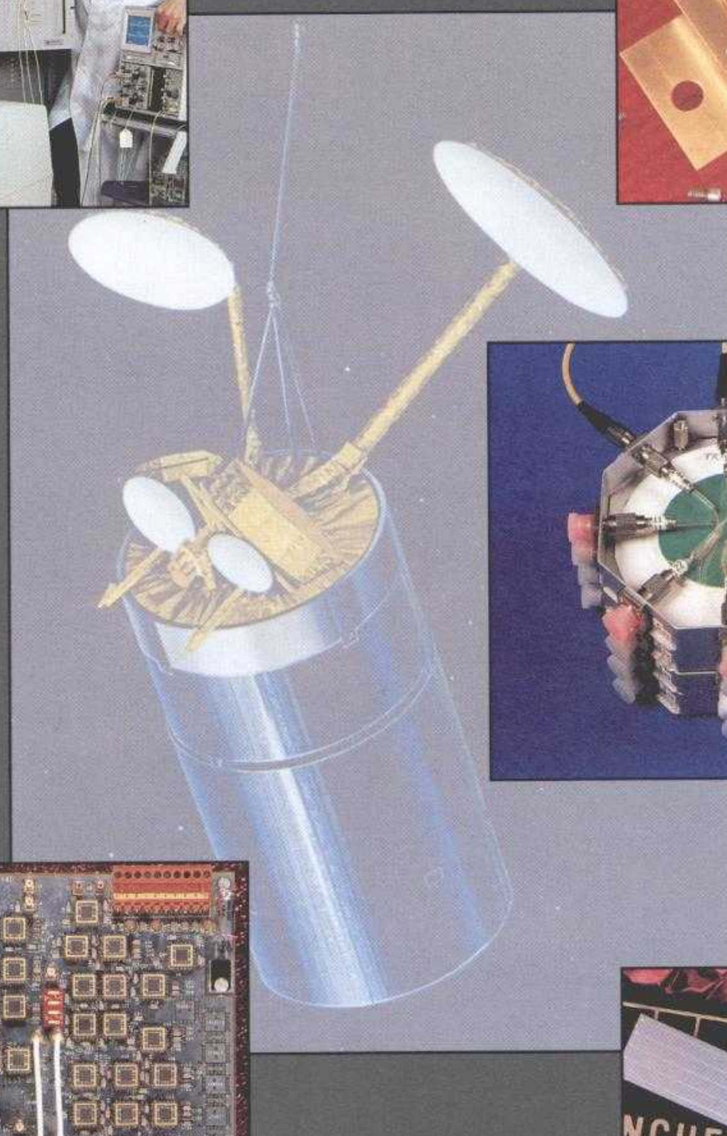


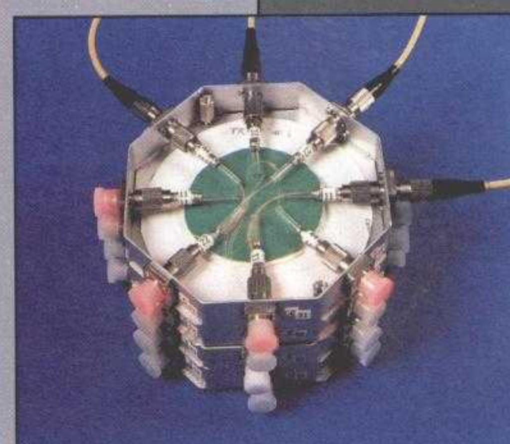


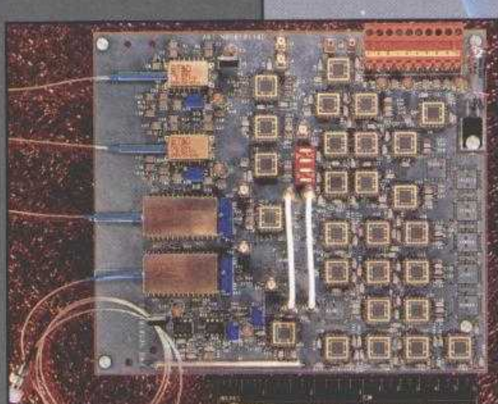




Recent efforts include the development of TDMA equipment and ISDN interface equipment for the NASA ACTS Program, as well as an X.75 satellite gateway interface for INTELSAT. The development of a high-speed optical interconnect for onboard applications and a demand-assignment system for thin-route satellite transmissions are among the division's ongoing programs. Major effort continues to focus on efficient data and ISDN transmission via satellite.

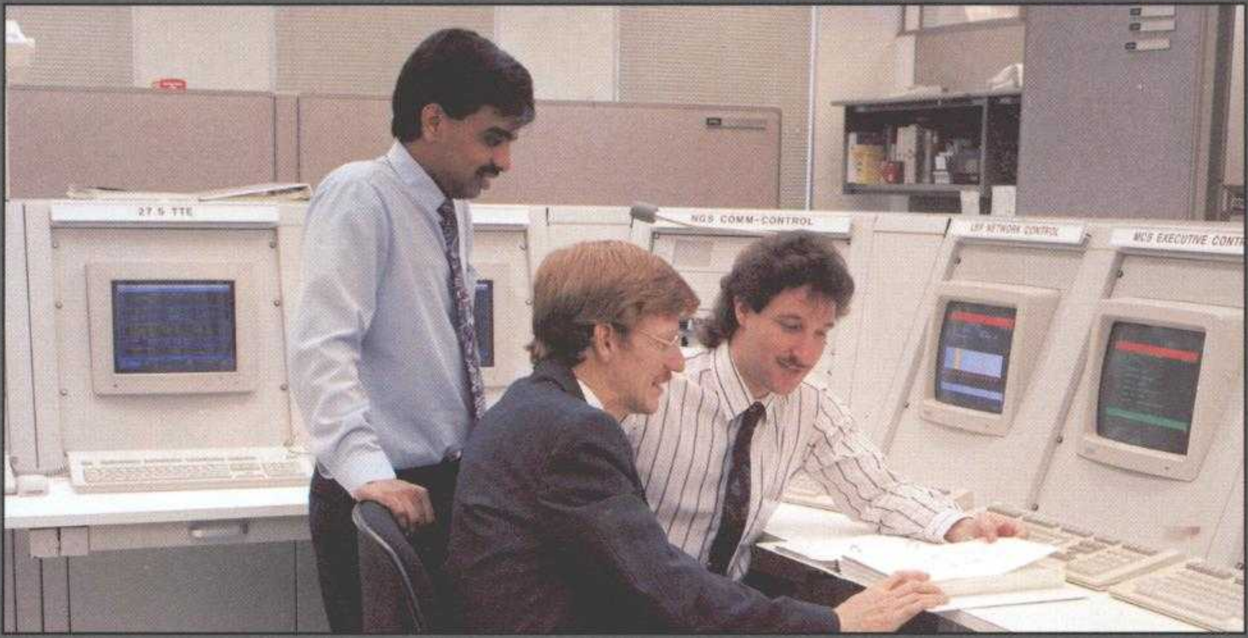


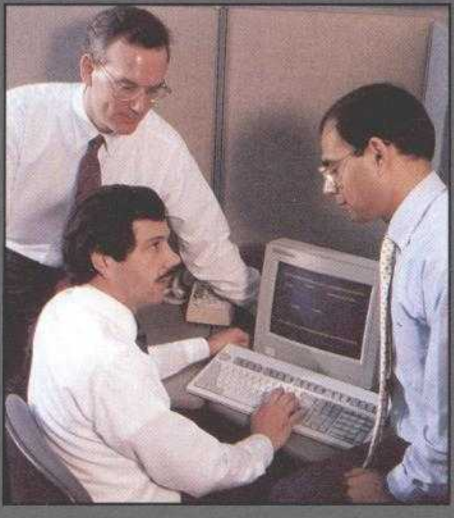




System Development

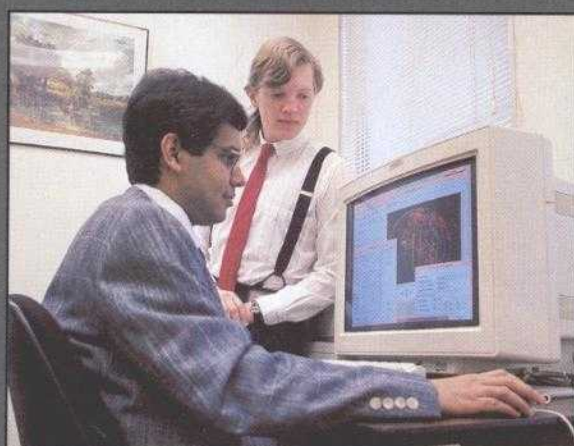
The System Development Division (SDD) of COMSAT Laboratories performs software R&D encompassing the development of computer-based systems. Division activities include the design and implementation of software and the selection, acquisition, integration, and installation of hardware. SDD is responsible for designing and implementing real-time systems, developing modeling and simulation tools, and establishing standards, methodologies, and tools to improve the overall software development process within COMSAT and yield highly reliable, easily maintained software products.



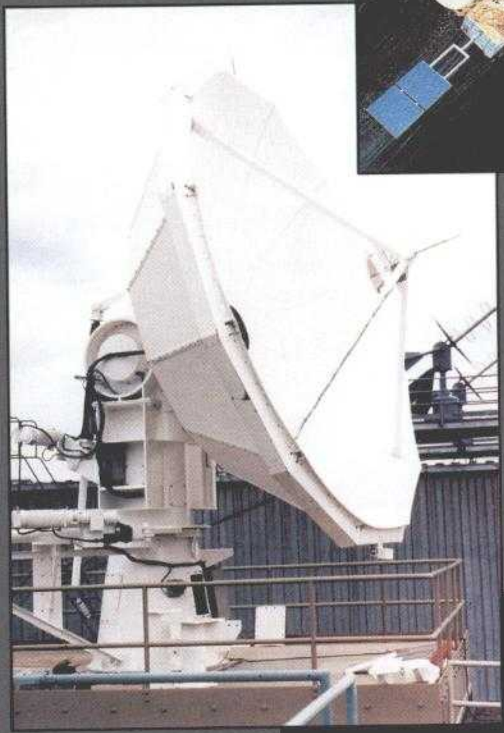


SDD

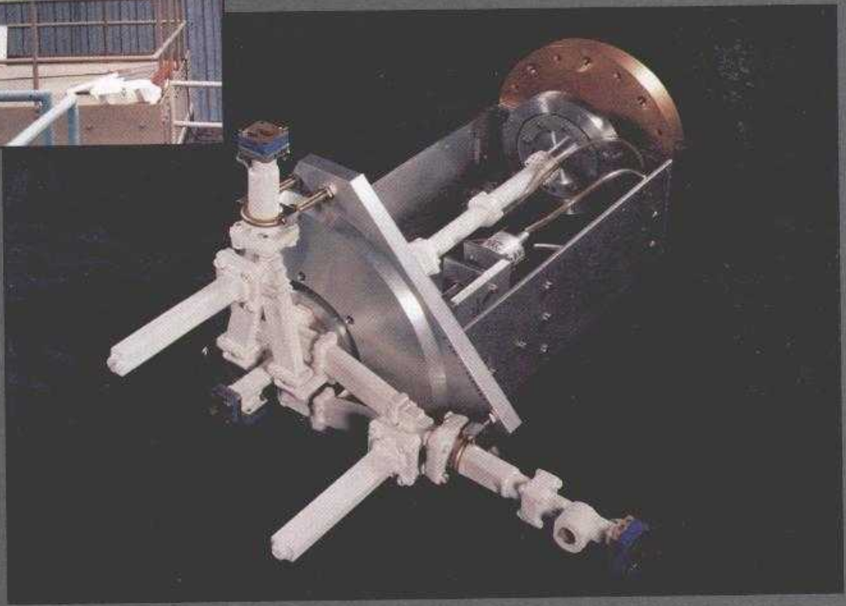
Communications system monitoring and control and measurement are two examples of typical real-time applications for SDD's software products. The modeling and simulation tools used to evaluate and optimize satellite communications systems and subsystems include programs that predict transmission impairments and plan the deployment of satellite resources. The division's 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.

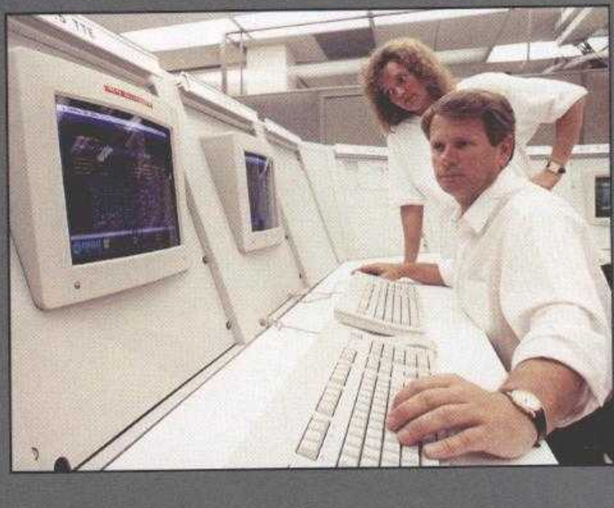


ACTS PROGRAM



In 1978, to ensure the continued availability of the orbital arc spectrum that is so vital to satellite communications technology, the Executive Branch of the U.S. Government directed the National Aeronautics and Space Administration (NASA) to reassume responsibility for advanced satellite communications technology. With Congressional support and in close coordination with U.S. industry, NASA's Lewis Research Center began planning the Advanced Communications Technology Satellite (ACTS) Program to develop and implement a baseline system of advanced technologies and equipment that would affirm the preeminence of U.S. technology in the satellite communications industry beyond 1990.





1991 Organization Chart

COMSAT CORP.

I. Goldstein
Chairman & CEO

B. Crockett
President & COO

- **COMSAT LABORATORIES**
  J. Evans
  President and Director
  - Microwave Technology & Systems Division
    F. Assal, Director
  - Microwave Electronics Division
    H. Huang, Director
  - Satellite Technologies Division
    C. Mahle, Director
  - Communications Technology Division
    R. Fang, Director
  - Network Technology Division
    B. Pontano, Director
  - System Development Division
    B. Williams, Director
  - ACTS - Program Management Office
    W. Schmidt, Director
- **COMSAT WORLD SYSTEMS**
  B. Alewine
  President
- **COMSAT MOBILE COMMUNICATIONS**
  R. Mario
  President
- **COMSAT SYSTEMS DIVISION**
  J. Alper
  President
- **COMSAT VIDEO ENTERPRISES**
  C. Lyons
  President

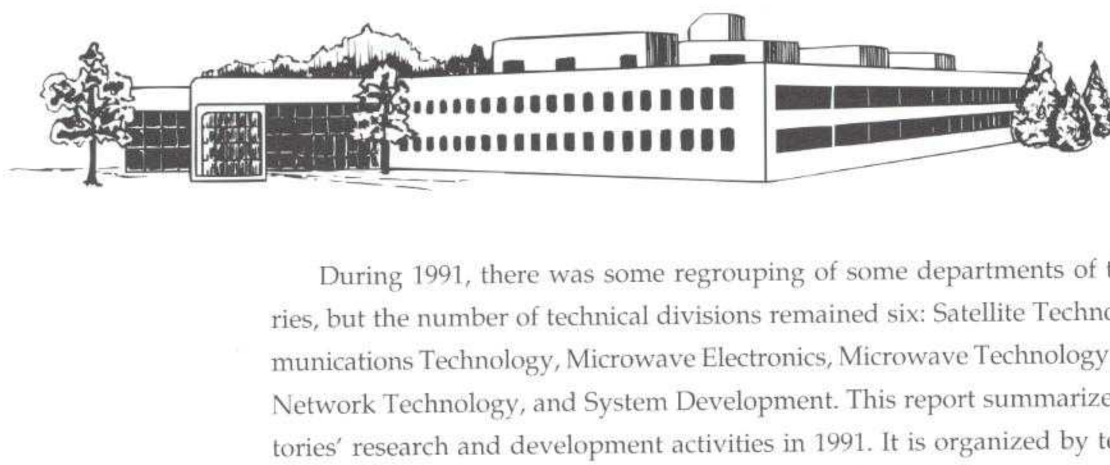
INTRODUCTION

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 number has since grown to 130 member countries, and the organization currently 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 currently 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 1991, four separate operating divisions were established, namely, COMSAT World Systems (CWS), which serves as U.S. Signatory to INTELSAT; COMSAT Mobile Communications, the U.S. Signatory to 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 four divisions and performs work for outside customers. The figure on the preceding page shows the Corporation's organization during 1991.

In 1991, 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 Corporate Shareholders. Efforts funded entirely by sources outside 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 1991, there was some regrouping of some departments of the Laboratories, but the number of technical divisions remained six: Satellite Technologies, Communications Technology, Microwave Electronics, Microwave Technology and Systems, Network Technology, and System Development. This report summarizes the Laboratories' research and development activities in 1991. It is organized by technology, as defined by the six technical areas represented by the divisions.

TABLE OF CONTENTS

MICROWAVE TECHNOLOGY & SYSTEMS

Significant progress was made by the Microwave Technology and Systems Division (MTSD) during 1991 in the areas of satellite antennas, microwave components, earth station antennas, and satellite systems. Hardware feasibility was demonstrated for the key subsystems of the 24-element, high-power, Ku-band, multibeam phased-array antenna, which is capable of generating four independently steerable beams. A key subsystem of the Ku-band array is a beam-forming matrix (BFM) consisting of RF divider/combiner networks, 96 monolithic microwave integrated circuit (MMIC) phase shifters, and associated control electronics. Development continued on a 69-element, lightweight, C-band phased-array antenna consisting of an 8 (beams) x 69 (elements) BFM, patch radiators, and 2-W solid-state power amplifiers. To verify the performance predictability of an array of patch radiators, a 25-element breadboard array was assembled and tested successfully. Development also continued on a lightweight, low-cost, dual circularly polarized flat-plate antenna for direct broadcast satellite receive applications in the 12.2- to 12.7-GHz band. In order to improve the gain-to-noise temperature ratio of the flat-plate antenna, a miniaturized low-noise block converter consisting of a low-noise amplifier (LNA), an image rejection filter, an MMIC mixer/oscillator chip, and an RF amplifier is also being developed for integration into the antenna.

In an ongoing effort to improve earth station operation, MTSD has developed a dual-band feed that permits simultaneous access to a satellite at both C- and Ku-band from a single earth station antenna. The in-orbit test transponder that was designed, fabricated, and tested in 1990 was successfully launched aboard the first ITALSAT 30/20-GHz multibeam spacecraft in January. Clean-room assembly and test facilities were expanded to produce space-qualified components and subsystems.

Other developments in 1991 included a state-of-the-art MMIC power amplifier, an MMIC X-band oscillator, a compact frequency reuse feed system, and microstrip patch radiators. Work also continued on performance verification, life analysis, gain standards, and type acceptance testing of earth station antennas; microwave components such as LNAs, analog attenuators, and mixers; and satellite system studies and design for COMSAT World Systems, COMSAT Mobile Communications, and other programs. ■

L-BAND MATRIX AMPLIFIER PERFORMANCE SIMULATION

The high-quality performance of signals transmitted via a communications satellite that incorporates a high-powered, multi-matrix, multibeam antenna system requires hardware components that maintain uniform performance as environmental conditions change over the design lifetime of the satellite. Any significant dissimilarities among the individual characteristics of high-efficiency amplifier modules can degrade the overall transmission performance of the satellite. To accurately predict and validate potential performance degradations caused by hardware imperfections and environmental variations, a software simulation model and a representative 6 x 6 matrix amplifier are being developed under the sponsorship of COMSAT Mobile Communications (CMC). The software will include both linear and nonlinear models.

The linear model was validated in 1991 by characterizing the individual components, measuring the matrix, and comparing the measured data with the software-generated results. Several tests were performed by introducing known hardware perturbations and comparing the results. Figure 1 shows a sample result of the various test cases. For this case, a signal was injected in the input port of path 1 and the output was measured at the output ports of paths 1 to 6. The figure presents the insertion loss characteristics of the desired paths (approximately -12 dB) and the five path-to-path interferences caused by hardware imperfections. The path-to-path isolation for each of the five possible paths is below -40 dB for this particular case. The data points shown by the solid symbols were computed for three frequencies: band center and the two band edges (1.53 GHz and 1.56 GHz), as allocated for satellite system operation.

Software for the nonlinear model is under development and will be completed in 1992. Characterization and validation of the matrix amplifier in the nonlinear mode are in progress. Under this program, the solid-state amplifiers for the matrix were developed by the Microwave Electronics Division (MED), using feedback techniques to improve linearity.

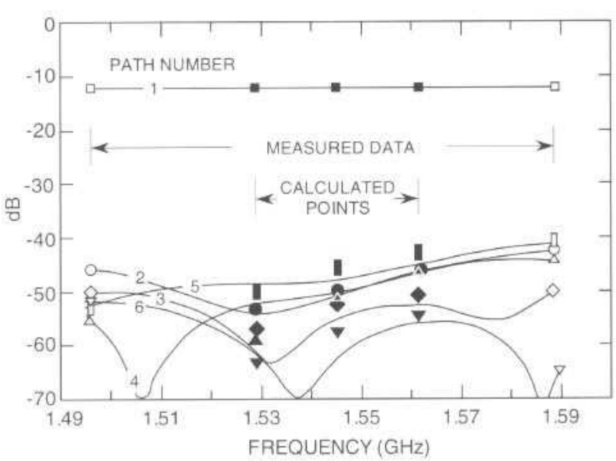


Figure 1. Computed vs *measured performance of 6 x 6 L-band matrix amplifier shows that insertion loss is predicted accurately, while isolation prediction is in good agreement*

SATELLITE ANTENNAS

C-Band Lightweight High-Efficiency Array

Demand for greater traffic volume and sophistication of service, combined with developments in satellite telecommunications technology, gives rise to more complex payloads, while still requiring high reliability, long service life, and low mass and volume. Part of this challenge can be met with new and improved antennas.

A lightweight, active C-band array currently under development for COMSAT World Systems (CWS) emphasizes broadband printed-circuit elements with high-efficiency amplifiers employing silicon motherboard technology. The array is capable of generating multiple beams in each polarization via a BFM.

A number of systems studies completed in 1991 defined the mechanical configuration for an antenna array consisting of individual modules that contain a radiating element and redundant solid-state power amplifiers (SSPAs). A subarray of approximately 64 elements, which is being planned as a proof-of-concept unit, will eventually be integrated with a confocal parabola system to demonstrate performance over a full earth field of view (FOV). With a proposed magnification factor of 3, the array must operate over a 30° FOV with minimal scan loss and depolarization.

Figure 2 shows the module design used for the array. The printed electromagnetically coupled patch (EMCP) element is located on top of the module. In addition to the dual-stacked patch, the sandwich construction includes a four-point feed network and a reject filter for each polarization.

The 25-element breadboard array (Figure 3) was optimized for bandwidth and polarization, taking into account the mutual coupling effects in the array.

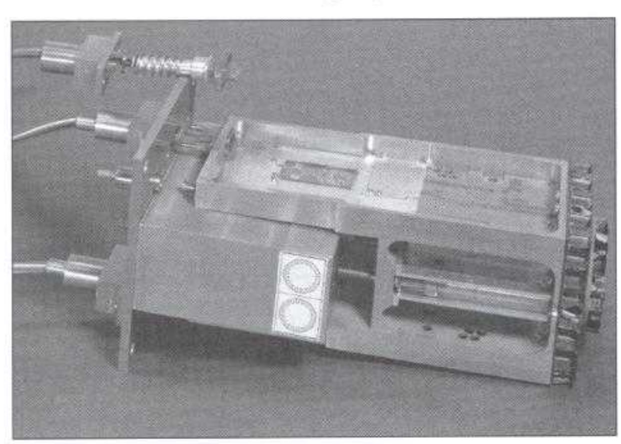


Figure 2. Single module with patch antenna and MMICs—the basic building blocks for the C-band lightweight array

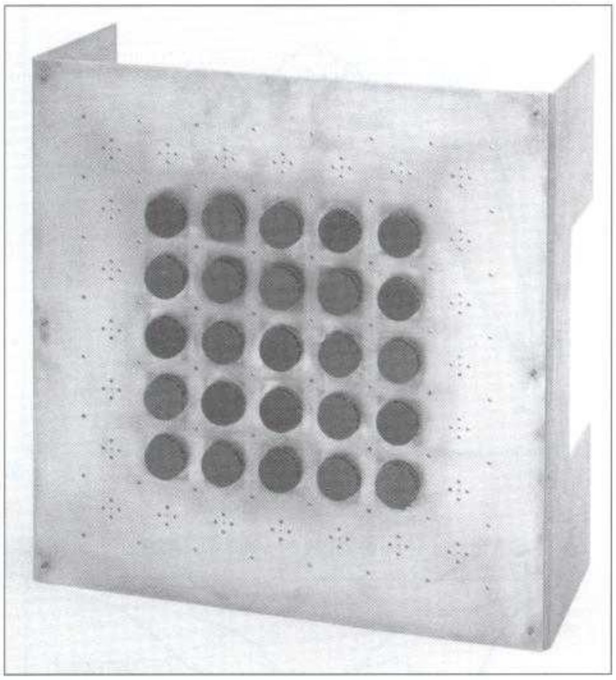


Figure 3. Front view of 25-element breadboard C-band array, optimized for bandwidth and polarization

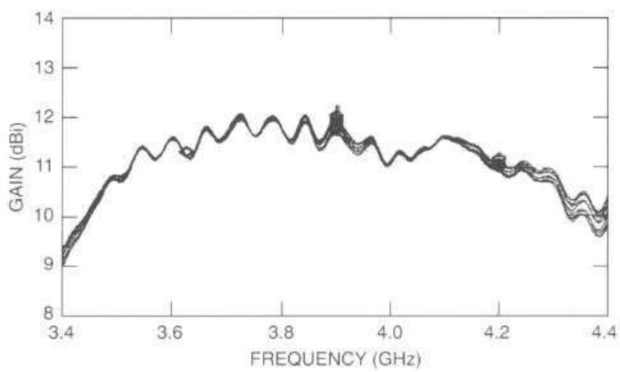


Figure 4. Measured performance of 25-element breadboard array shows an axial ratio of less than 0.3 dB over the 3.6- to 4.2-GHz band

Figure 4 shows the measured performance of this array. The design exhibits broadband performance over the 3.6- to 4.2-GHz band, with an on-axis axial ratio of less than 0.3 dB in each polarization. Off-axis performance shows the axial ratio degrading to 0.8 dB at a 30° scan angle, with a corresponding scan loss of less than 2 dB.

Ku-Band High-Power Phased Array

During 1991, all major subsystems of the high-power, Ku-band array were assembled and tested. The components were integrated into the array structure, and calibration testing was initiated.

The BFM (see "Division Highlights," p. v, center left) was fully assembled and tested. The three shelves were individually evaluated, and then assembled and tested in the final configuration. The BFM feeds the 24 elements and can produce four simultaneous, independently steerable beams. Located within the BFM are 96 phase shifters that steer the four independent beams. Figure 5 shows the amplitude and phase tracking at the 24 output ports for a representative beam. The amplitude and phase variations are within 1 dB and 8°, respectively.

The power supply and BFM controller were also completed this year. The power supply, which provides power to all the SSPAs and the controller, consists of a number of power sources and individual protection circuits for each amplifier. The controller, which comprises three circuit boards, serves as an interface between the personal computer (PC) input for the BFM and the driver circuits within the matrix. Controller operation was completely validated with the BFM.

Twenty-six high-power amplifiers were assembled and tested. The units can produce 1.5-W output power, with a typical small-signal gain of 40 dB. At this output power, a maximum efficiency of 23 percent is typical. Under backoff, a two-tone third-order intermodulation level of 20 dB is achieved, with a corresponding efficiency of 15 percent. In 1992, MTSD will complete the assembly and testing of this array. RF antenna tests will be conducted to evaluate pattern performance and scan loss under multibeam conditions. In addition, an extensive set of communications systems tests will be performed to evaluate the impact of nonlinearities in the array on bit error ratio and signal-to-noise ratio.

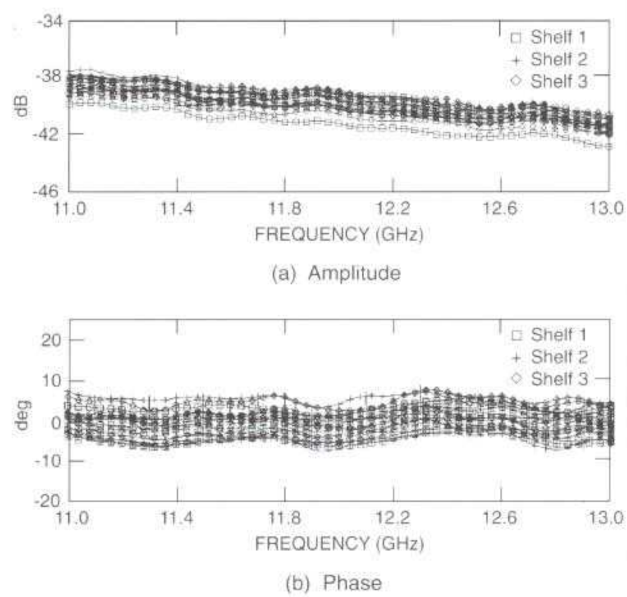


Figure 5. Measurements taken at the 24 output ports of the phased array show good amplitude and phase tracking

Ku-Band Dual-Polarized Array Development

Lightweight array techniques are also being applied to Ku-band antennas. A broadband, dual-polarized, printed-circuit element was developed for potential satellite application. The element incorporates an EMCP and a printed feed network for simultaneous dual linear polarization, and was constructed of individual printed layers consisting of the radiating elements and the feed network. To obtain acceptable cross polarization, the patch was fed at two points in antiphase. Figure 6 illustrates the layout of the element and feed network.

Measured performance of the element showed that, in both polarizations, the gain was flat over the 10.95- to 12.5-GHz band. Additionally, with the two-point feeding technique, cross-polarization isolation was greater than 30 dB. Methods to further increase the bandwidth are under investigation.

Analysis of Microstrip Patch Radiators

Broadbanding techniques for printed microstrip antennas were also examined in 1991. Traditionally, microstrip radiators have been very narrowband, and conventional broadbanding techniques consist of stacked or coupled elements for improved directivity and bandwidth. The approach employed in this project was to synthesize broadband impedance-matching networks to improve power transfer from the transmission line to the radiating element. Three cases were investigated: a probe-fed single patch, a probe-fed multilayer patch, and a slot-fed single patch. In each case, bandwidth was improved by including the matching network.

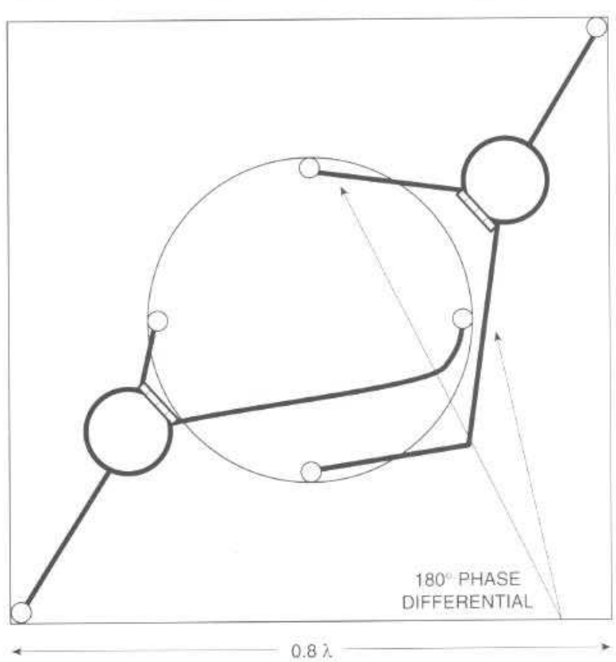


Figure 6. Ku-band dual-polarization array element depicts printed circuit layout and feed network

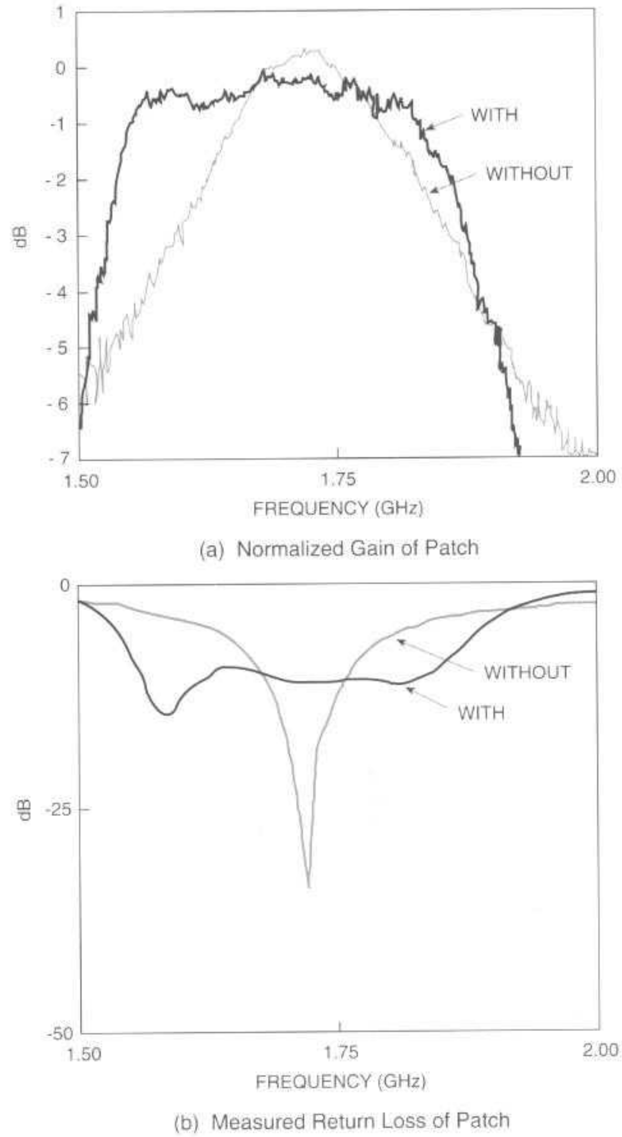


Figure 7. Normalized measured gain and input return loss of a microstrip patch radiator showing 50-percent increase in usable bandwidth

Figure 7 compares the gain and input return loss *vs* swept frequency for a single probe-fed patch radiator with and without matching networks. The usable bandwidth is increased by more than 50 percent. (The slight reduction in gain is attributed to the insertion loss of the matching network.)

Miniaturized LNB for Flat-Plate Antennas

MTSD is also involved in a number of programs to supply antenna designs and hardware to several customers. One such commercial venture is the manufacture of receive-only flat antennas for Ku-band broadcast video. As part of this effort, a miniaturized low-noise block converter (LNB) is being developed for integration into the flat-plate antenna. The LNB amplifies signals in the 11.7- to 12.2-GHz band and down-converts them to the 0.950- to 1.450-GHz band. The design emphasizes a miniaturized, compact converter which can be inserted into the stripline distribution network of the flat-plate antenna for improved gain-to-noise temperature ratio, *G/T*. The performance goals for the unit are 50-dB gain and a maximum noise figure of 0.9 dB.

The LNB (see "Division Highlights," p. v, bottom left) consists of a three-stage microwave integrated circuit LNA, an image reject filter, an MMIC mixer/oscillator chip, and an IF amplifier. The design employs an 0.8 x 1.0-in. alumina motherboard on which all the RF, IF, and DC circuitry is mounted. The RF input to the LNB from the stripline distribution network is located in the LNB housing. The housing is fully integrated into the array structure, with only the F-type connector exposed at the back of the array.

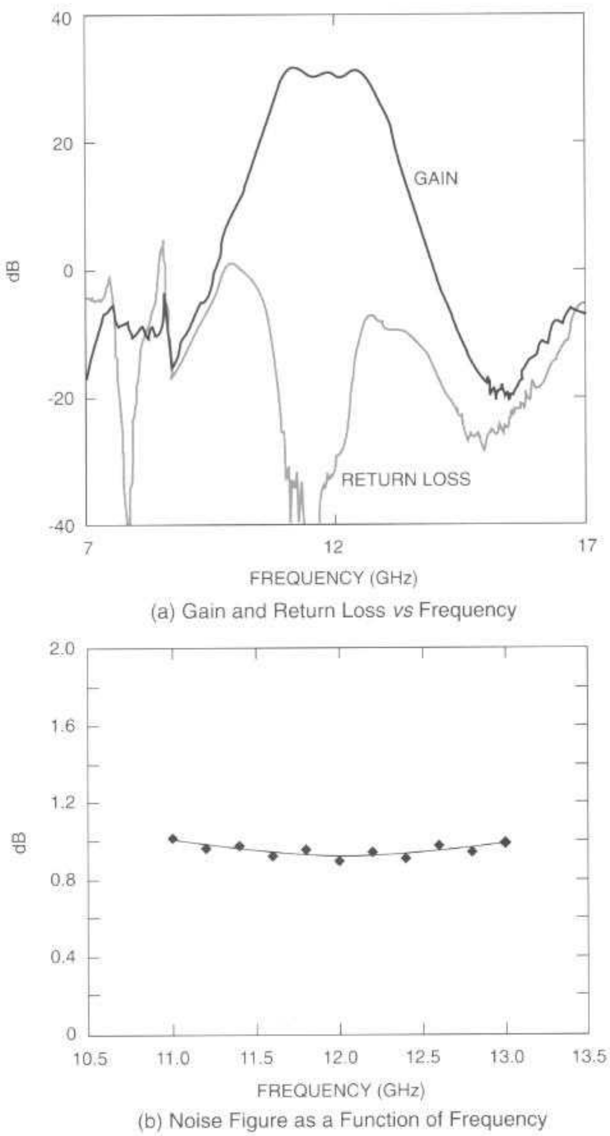


Figure 8. Measured gain, return loss, and noise figure of the LNA—the key component in the LNB

During 1991, all the components of the LNB were designed and layout was completed. The LNA, image reject filter, power conditioning circuitry, and IF amplifier were designed, built, and tested; the MMIC was also designed and is being fabricated. Figure 8 shows the measured gain, input return loss, and noise figure of the LNA, which employs series feedback to achieve simultaneous noise and conjugate match.

EARTH TERMINAL ANTENNAS

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

To further enhance satellite telecommunications system performance, MTSD conducts ongoing research and development, primarily for CWS, on earth station antennas. R&D goals include reducing the cost and improving the quality and reliability of antennas.

MTSD has developed a dual-band feed that permits simultaneous access to a satellite at both C- and Ku-band from a single earth station antenna. The design uses a multi-aperture directional slotted waveguide array to achieve unity coupling at Ku-band from a rectangular waveguide into the C-band circular (2.125-in.-diameter) waveguide. A prototype of the feed system was built in 1990, and integration and testing were completed in 1991. The design was modified to provide the added capability to access both linear polarizations of the planned INTELSAT VII-A series of satellites at Ku-band.

The polarization that can be achieved in an earth station antenna depends primarily on the mode purity of the feed system, which includes the diplexing network and feed horn. To demonstrate the degree of mode purity that can be achieved for the full feed system, the input section of the feed horn was fabricated and tested. This mode transducer transitions from the fundamental TE_{11} mode in the smooth-wall waveguide to the hybrid HE_{11} mode in the corrugated horn, and is a critical part of the horn design. The design employs ring-loaded corrugations to provide a smooth transition in surface reactance between the plain-wall and corrugated waveguides. Figure 9 shows the off-axis co-polarization and cross-polarization frequency of the dual-polarized 14-GHz coupler feeding the corrugated horn adapter. The peak off-axis cross polarization is greater than 27 dB below the co-polarized peak. This is equivalent to the performance of many single-band earth station

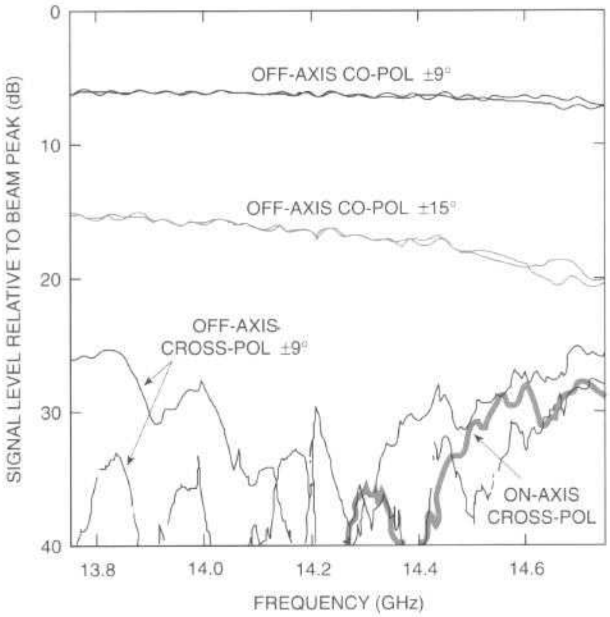


Figure 9. Off-axis co- and cross-polarization isolation achieved with the dual-band feed is equivalent to the performance of a single-band feed

feed horns currently in use. Similar results are achieved in the other frequency bands. The peak cross polarization is greater than 33 dB in the 4-GHz band, greater than 26.5 dB in the 6-GHz band, and greater than 25 dB in the 11-GHz band. This cross polarization will be slightly improved by addition of the aperture section of the feed horn.

Compact Frequency Reuse Feed System

The work described above focused primarily on large antennas. In a related effort, MTSD is designing a compact 4/6-GHz circularly polarized diplexer suitable for frequency reuse on smaller diameter, front-fed reflectors. Design objectives include lighter weight and lower cost. In 1991, the electrical design was completed, and a high-quality breadboard (Figure 10) was fabricated and tested. As expected, measured results show good axial ratio and high return loss. The use of orthogonal coaxial probes to form the 4-GHz orthomode transducer junction results in a significant reduction in size, but increases dissipation by approximately 0.15 dB.

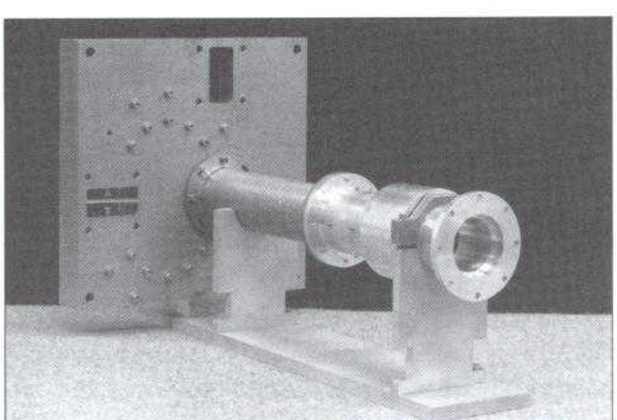


Figure 10. Compact C-band, four-port, circularly polarized diplexer is suitable for frequency reuse on small antennas

Earth Station Antenna Life Analysis

The oldest U.S. antennas in the INTELSAT system have been in service about 25 years. Some encounter mechanical wear and present difficulty in maintaining the control and drive systems. Major changes in servo system technology have occurred since these antennas were built, and replacement parts for some drive system components are no longer readily available. Although modernization and refurbishment of the drive system for a 30-m antenna is quite expensive, many of these antennas worldwide have been refurbished in recent years, including those at Cayey, Puerto Rico, and Andover, Maine.

Under CWS sponsorship, MTSD assessed the mechanical and electrical condition of existing U.S. earth station antennas as well as changes in their performance resulting from aging and environmental conditions. The goal of this assessment was to predict, for planning purposes, the service life and replacement cost of these antennas. Of particular interest were the older 30-m Standard A antennas, which carry a substantial portion of the traffic load. If necessary, they would be replaced by revised Standard A 18-m antennas, which have a reduced *G/T* and thus require additional satellite resources.

RF performance data from several earth stations which have been re-measured after as many as 15 years of service showed no degradation in radiation pattern or gain performance as a function of time. Based on the information gathered during this assessment, it was concluded that, if the antennas are well-maintained, even the oldest antenna in the INTELSAT system should provide satisfactory performance for at least another 20 years.

On-Site Earth Station Antenna Verification

Satellite communications systems require earth station antennas that have established performance levels, in order to use the limited geostationary arc efficiently. On-site performance verification is generally required before the antenna is placed into service. Historically, this testing has been time-consuming, costly, and difficult, often producing erroneous results. However, recent advances in microwave measurement equipment and PCs led to a solution for this problem. For CWS, MTSD has developed a new PC-controlled measurement system designed to completely characterize antennas. The system aids in verification by performing automated measurements using readily available test instruments, and by processing the data for immediate display, thus allowing early detection of problems. The system saves the user valuable data reduction time and facilitates more complete measurement by recording multiple frequencies in an automated configuration.

Complete characterization of the RF performance of an antenna requires four measurements: swept frequency (*e.g.*, return loss or port-to-port isolation), system and antenna temperature, *G/T*, and radiation pattern. The system to accomplish the above measurements was designed using readily available computers, software, and microwave measurement equipment. HTBasic™ was selected as the programming language because it handles instrument communications protocols, thus allowing the straightforward addition of new instruments to the system. It is also an easy language to program. Data are collected and stored in ASCII files, which can be printed, processed, and displayed using commonly available PC software.

Figure 11 shows a sample noise temperature response at three elevation angles for an 8.1-m antenna. The sharp ripple response occurs at points in the band where the return loss is only about 15 dB and subreflector-to-feed interactions are significant. This plot illustrates the value of swept-frequency noise

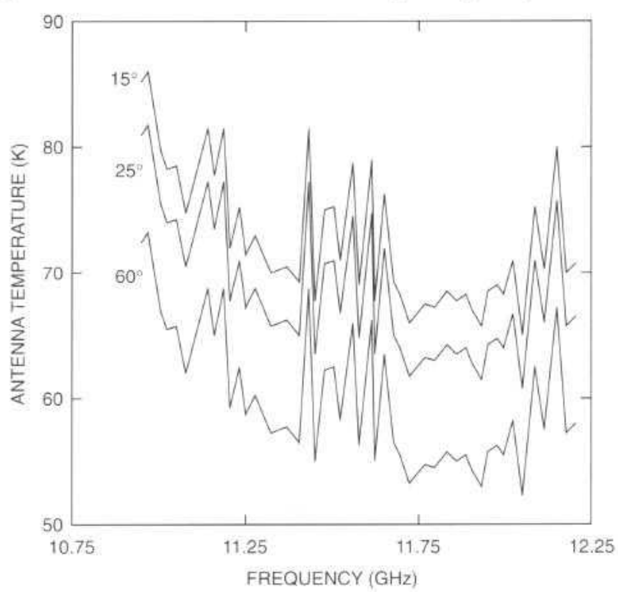


Figure 11. Accurate measurement of antenna noise temperature is key to complete characterization of antenna RF performance

temperature measurements in accurately determining antenna performance.

Antenna Type Acceptance

As U.S. Signatory to INTELSAT, CWS is responsible for verifying earth station antenna compliance with INTELSAT standards before an antenna may be used in the INTELSAT system. The type-acceptance procedure reduces the cost of verification and speeds the process by eliminating the need for individual on-site earth station testing. Quality antennas manufactured in large quantities may be type-accepted through comprehensive testing of randomly selected units. In support of this effort, MTSD has reviewed the antenna measurements required for proof of performance, and has performed, witnessed, and analyzed measurements and documented them for presentation to INTELSAT. During 1991, the following antenna type-acceptance activities were conducted: data gathered on a modified C-band feed were reviewed for type-accepted 1.8- and 2.4-m antennas; a circularly polarized feed was measured and rejected; acceptance tests were monitored for a 3.7-m split reflector; and a 3.7-m segmented antenna was evaluated for F-1 compliance.

Gain Standard Antennas

A series of dual-port circularly polarized horn antennas has been designed, fabricated, tested, and delivered to the National Institute of Standards and Technology (NIST). The antennas operate over a 20-percent frequency bandwidth centered about the 65-, 55-, 36.5-, 28-, 24.3-, 7.0-, and 4.9-GHz frequencies. The antennas are packaged and delivered three to a set, with different gain values for each frequency band, allowing calibration by NIST. The 35-GHz horns are shown in Figure 12. For the lower gain

Figure 12. 35-GHz horn gain standard built by MTSD and used by NIST

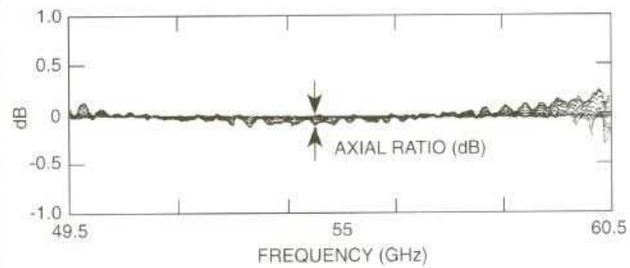


Figure 13. Low axial ratio measurements result from using a scalar ring design

horns, a scalar ring design minimizes off-axis cross polarization so the horns can also be used as field probes or compact range feeds. A very low circularly polarized axial ratio of less than 0.5 dB across the 20-percent band has been measured. Figure 13 shows a typical axial ratio measurement.

C-Band Steerable Spot Beam Feed System

A lightweight, flight prototype circularly polarized diplexer, and a feed horn consisting of a feed system that operates in the 500-MHz transmit and receive bands was designed, fabricated, and fully tested for INTELSAT. The feed system is shown in Figure 14. Standard RF tests were performed, including specialized satellite tests such as those used to evaluate multipaction, passive intermodulation, and the effects of temperature on performance. Extensive primary feed data were collected, as well as secondary data using 0.8-, 1.0-, and 1.2-m offset reflectors. Obtaining high polarization isolation to allow dual-polarized operation in both the transmit and receive frequency bands over a 4° coverage area was a primary requirement of the project.

Typically, satellite antennas that require high-quality circular polarization use separate feeds for the transmit and receive bands. Achieving a polarizing circuit with a low axial ratio (which affects on-axis polarization isolation) and a feed horn with a circularly symmetric radiation pattern (which affects off-axis polarization isolation) that would operate in both the transmit (4-GHz) and receive (6-GHz) frequency bands presented a very difficult design problem. The diplexer/polarizer concept was borrowed from an existing earth station design, but the unit was constructed to be lighter and smaller. The feed horn combined the concepts of a scalar horn and a Potter horn to achieve proper performance in the two bands. The scalar rings located at the aperture of the feed horn optimize the satellite transmit band but do not significantly affect the receive band. The Potter horn step optimizes the receive band by coupling the proper amount of TE_{11} energy into the TM_{11} mode. The waveguide size was selected to preclude launching the TM_{11} mode in the transmit band; thus, the horn can be tuned inside the waveguide in the receive band and outside the waveguide in the transmit band, allowing independent optimization of the two frequency bands.

The diplexer uses two separate coaxially disposed circular waveguides to carry and polarize transmit and receive band energy. The transmit and receive band signals are merged into a common guide and impedance-matched by the action of a corrugated ring matching section.

The aluminum feed weighs 3.18 kg and is 1.07 m long. After successful completion of sinusoidal and random vibration tests, the feed was mounted with offset reflectors and an extensive series of secondary measurements was conducted. All secondary measurements, including cross-polarization levels (both circular and linear polarization), gain, edge-of-coverage gain, scan characteristics, patterns, polarization, and polarization-sensitive beam squint, agreed with predictions and with the existing literature on the radiating characteristics of offset reflectors. Of particular interest was polarization isolation across the frequency bands and coverage areas, which agreed with program specifications. This project is now complete.

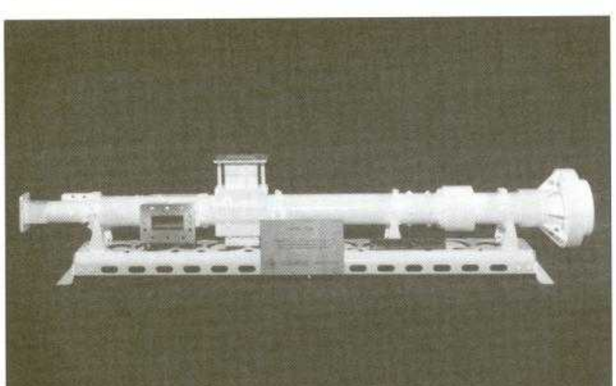


Figure 14. Lightweight, flight prototype, circularly polarized C-band diplexer combines scalar and Potter horn concepts to achieve best performance in the two bands

MICROWAVE COMPONENTS

Using its broad-based expertise in electronic microwave components, MTSD designed and experimentally demonstrated a dielectric resonator MMIC X-band oscillator capable of delivering up to 17-dBm output power at 10.75 GHz. The MMIC oscillator chip (Figure 15) features self-bias operation and an external voltage tuning capability. Measured performance demonstrated excellent second harmonic rejection (40 dB) and low phase noise (-110 dB/Hz at 100-kHz offset). This circuit and similar designs will have wide application for low-noise receivers and down-converters.

Recently, MTSD successfully completed a contract with Alcatel Espace for a state-of-the-art MMIC power amplifier module for space communications applications. The module (Figure 16) operates at Ku-band (10.7 to 12.75 GHz) and delivers 1 W of output power and 20-dB small-signal gain. The amplifier chain consists of a single-stage driver amplifier followed by a two-stage power amplifier. Other key performance features are 30-percent power-added efficiency and greater than 16-dB carrier-to-intermodulation (*C/I*) linearity, which is crucial to successful operation in a multicarrier signal environment.

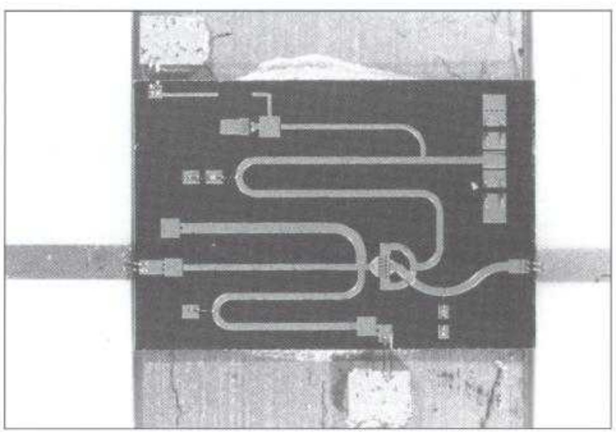


Figure 15. MMIC oscillator chip features self-bias operation and an external voltage tuning capability

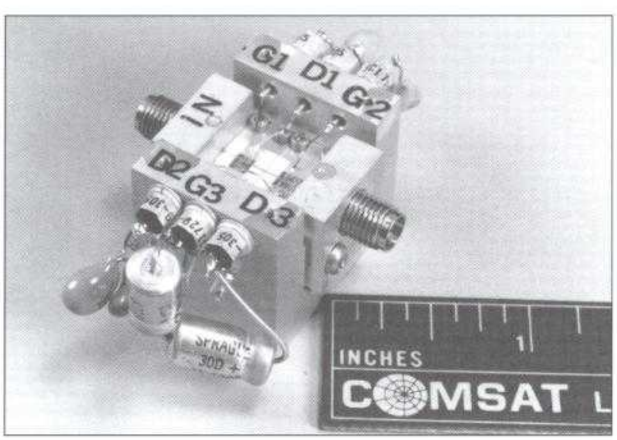


Figure 16. MMIC Ku-band power amplifier module for space communications can deliver 1-W power and 20-dB small-signal gain

Subsequently, Alcatel contracted with MTSD to develop, assemble, and deliver 80 such amplifier modules by the end of 1992. These new modules are being designed with integrated bias supplies since they will be used in the final application.

SPACE-QUALIFIED PRODUCTS

Under an 8-month contract with Selenia Spazio, MTSD designed, fabricated, and delivered an in-orbit test transponder (IOTT), shown without its dust covers attached in Figure 17, which was mounted on board the ITALSAT multibeam spacecraft launched in January 1991. It is believed that the IOTT contains the first MMIC circuitry ever launched on a communications satellite.

The onboard IOTT, which has performed successfully in space, allows typical spacecraft tests to be performed by transmitting a 30-GHz signal from an earth station and detecting the received 20-GHz signal. The tests include flux density, effective isotropically radiated power (e.i.r.p.), traveling wave tube amplifier (TWTA) transfer characteristics, and transponder linear gain.

The IOTT incorporates MMIC Ku-band amplifiers, lightweight waveguide Ku-band filters, and electronic power control and combined IOTT telemetry/control circuitry, all designed and fabricated by COMSAT Laboratories. It bypasses the onboard regenerator and connects the input sections of the transponders to the appropriate input sections of the TWTAs, thereby converting ITALSAT digital transponders into transparent analog transponders. This allows full characterization of the transponders, including the TWTAs, using well-established in-orbit test (IOT) techniques.

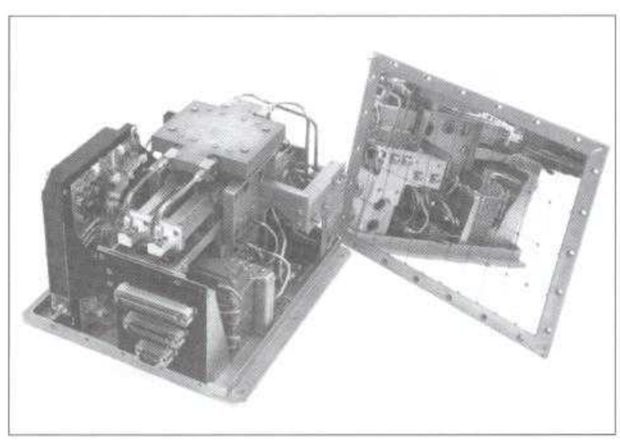


Figure 17. IOTT currently operates on board the ITALSAT multibeam spacecraft

Inserted between a 12-GHz coupler splitter and a 20-GHz test coupler multibeam coupled input, the IOTT does not interfere with the performance of the ITALSAT spacecraft. It accomplishes the RF bypass of the two multibeam chains one channel at a time. Channels are selected using internal switches controlled by external ground command. With the IOTT in use, the transponders can be tested either as part of IOTs or whenever a performance anomaly is suspected.

The IOTT design can be used for both satellite acceptance and operational troubleshooting tests. It allows IOT-type measurements through any one of the six ITALSAT 20-GHz output channels without interference from potential user traffic in the other five channels. The IOTT flight unit weighs 5.9 kg.

The Microwave Electronics Division (MED) has developed and produced gallium arsenide (GaAs) monolithic microwave integrated circuit (MMIC) chips and subsystem components for various commercial and government programs. MED's design and production capabilities are directed toward engineered products such as power amplifiers and receivers for millimeter-wave and microwave communications, radars, and weapon systems. MED's 1991 advances in these areas include a C-band solid-state power amplifier (SSPA) for INTELSAT, a metal semiconductor field-effect transistor (MESFET)-based L-band linearizer for COMSAT Mobile Communications (CMC), a 20-W SSPA for Ku-band earth stations, and a Ku-band receiver for satellites.

MED has assisted customers in developing new products by providing custom-designed MMICs and microwave components such as a 0.5-W, 47-GHz power amplifier; a varactor doubler and single-sideband modulator for 94-GHz transceivers; Ka-band pseudomorphic high-electron-mobility transistor power amplifiers for millimeter-wave radar; and C-band transmit/receive radar modules. In addition, MED has space-qualified its MMIC production processes, and is supplying the spacecraft industry with highly reliable MMICs for transmitters and receivers. Other key products under development are 20/44-GHz MILSTAR components and high-power field-effect transistors (FETs) for spacecraft.

This year, division research focused on applying coplanar waveguide concepts to millimeter-wave component packaging on a silicon motherboard; providing better protection for spacecraft components against solar radiation and other enviromental effects in space, and extending satellite lifetimes with improved batteries and traveling wave tubes. MED's research has proven that a major advantage of GaAs devices over silicon devices is their greater tolerance for gamma, proton, and electron irradiation. Anticipating an increasing number of applications for GaAs MMICs in satellite communications, MED plans to play a major role in supplying this demand.

MED's work in 1991 provided a wealth of experience and a strong basis for further development of product lines aimed at supporting both the communications industry and defense systems. Major government contractors continue to seek MED's custom product capabilities in order to increase their competitive edge in the industry. ■

SOLID-STATE COMPONENTS

Power Amplifiers

One of MED's goals for 1991 was to develop 3.7- to 4.2-GHz power amplifiers for corporate and INTELSAT applications. For corporate applications, two methods for improving linearity and power-added efficiency (PAE) were investigated. The first approach was to design a linearizer or device which predistorts the input signal of a power amplifier to cancel the amplitude and phase nonlinearities inherent in high-efficiency power amplifiers. Two FETs exhibiting nonlinearities opposite those of an SSPA are used in a balanced circuit. When the linearizer and an SSPA are placed in series, the nonlinearities cancel and a more linear response is obtained. The initial design was simulated using computer models. A brassboard design was then fabricated and shown to decrease third-order intermodulation distortion under two-tone testing.

The second approach was to build a Doherty amplifier using GaAs power FETs. This method connects in parallel two power amplifiers in a configuration that allows one of the power FETs to reach saturation prior to signal compression. Conventional power amplifiers achieve maximum efficiency only when the signal is compressed by several decibels; however, the Doherty amplifier is capable of achieving peak PAE at more than one drive level. It should reach maximum efficiency once at an uncompressed input drive level, and again at a drive level that compresses the signal by several decibels. A brassboard version of the design was fabricated and is expected to be tested early in 1992.

MED also began fabricating 2-W SSPAs in quantity. Each SSPA is designed to fit on a single carrier in an active array antenna assembly, while each carrier has a silicon motherboard for the microwave circuitry and several alumina bias boards to supply DC voltages. The bias boards were completely assembled, and six of the microwave assemblies were mounted on carriers and initially tested without bias circuitry. Each assembly will be tuned individually to meet the requirements of the antenna system. All carriers are expected to be completed by March 1992.

For INTELSAT, MED's 1991 objective was to develop, test, and deliver a 3.7- to 4.2-GHz SSPA capable of providing 30 W, with a PAE of over 40 percent, while meeting the other general requirements of the INTELSAT VII satellite series. The approach was to build an SSPA using the combined power of sixteen 2-W amplifiers. Since the design includes a driver amplifier consisting of two 2-W amplifiers, the SSPA is a two-stage device requiring the output power of the first stage (the driver) to be divided by 16. The output of the 2-W devices is combined to provide a minimum of 30 W at a single port. To meet the efficiency goal, a single-ridged, 16-way radial power combiner/divider was developed. This combiner has an average insertion loss of 0.1 dB across the band, ±0.2-dB amplitude tracking, and ±2.5° phase tracking.

Eighteen 2-W SSPA modules were built on silicon motherboards. Each module contains a balanced pair of 1-W GaAs FETs (biased class AB) that must be tuned for stability, power output, and efficiency. The complete 30-W SSPA was tested and produced a peak PAE of 39 percent.

Increasing demand for maritime, aeronautical, and land-based mobile communications has resulted in the need for higher capacity mobile satellite systems. More traffic signals are expected to pass through satellite transponders in future systems. The limited signal-handling capacity on board a satellite is partially attributable to nonlinearities in transmitter power amplifiers. These nonlinearities result in signal degradation in the form of intermodulation distortion products, crosstalk, and reduced signal-to-noise ratio, S/N, in the presence of multicarrier signals.

For CMC, a linearization technique, using the power feedback design concept for the SSPA, was developed for the 1.5-GHz communications band. This technique is especially suited to mobile satellite applications because of the narrow bandwidth requirements and sufficiently high gain obtained from MESFET power devices at operating frequencies and rated output power. The result is improved linearity with minimal effect on the PAE of the SSPA.

The power feedback scheme was evaluated by large-signal analysis of MESFET power devices and circuits using a nonlinear computer-aided design (CAD) program. The design scheme was demonstrated through prototype implementation by evaluating the amplifiers with and without feedback circuitry. A complete feedback amplifier is shown in Figure 1. Performance characteristics for a multicarrier input signal include output power of 5 W, third-order carrier-to-intermodulation ratio, C/I_3,

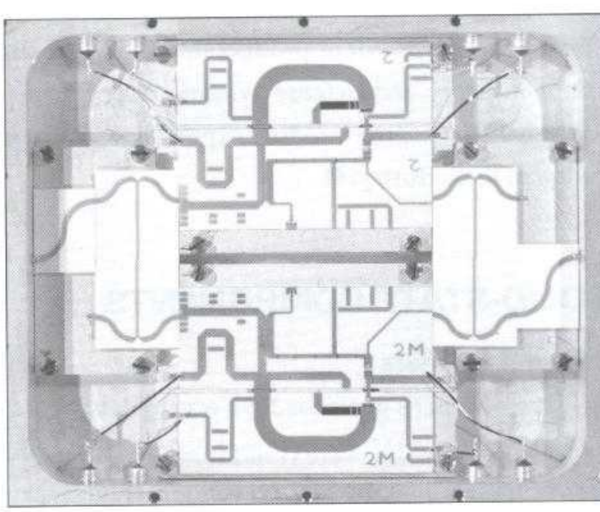


Figure 1. L-band amplifier for CMC demonstrates the power feedback scheme

better than 20 dB, and PAE of 35 percent. RF testing of a number of production feedback amplifiers has demonstrated an improvement in intermodulation products and noise-power ratio (NPR) without sacrificing efficiency. A higher power amplifier (20 W) can be readily obtained by combining four of these amplifiers.

Under the sponsorship of COMSAT Systems Division (CSD), MED developed a 20-W SSPA (Figure 2) for Ku-band earth station applications. The design, testing, and integration of the SSPA was a joint effort between MED and the Satellite Technologies Division (STD). The amplifier is air-cooled, and the power FETs operate below 125°C to provide a lifetime far exceeding that of a traveling wave tube amplifier (TWTA). As shown in Figure 3, the amplifier provides 55-dB gain and 20-W output power from 14.0 to 14.5 GHz. The menu-driven liquid crystal display allows for control of amplifier gain and monitoring of input/output power and internal module temperatures.

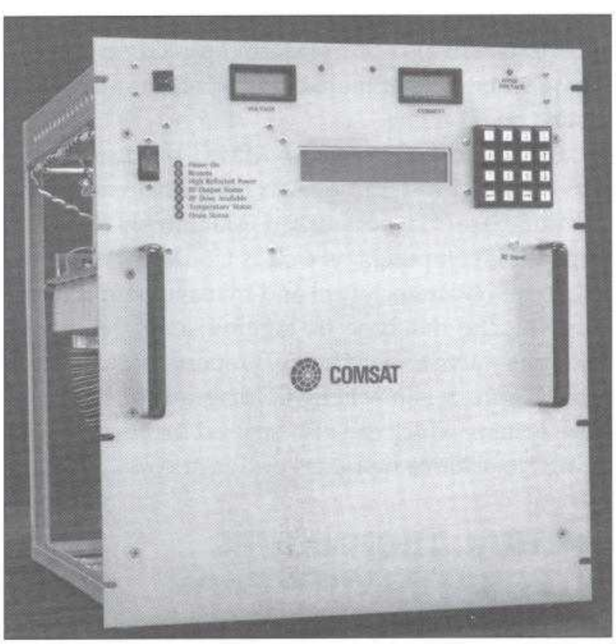


Figure 2. 20-W Ku-band SSPA achieves long life for earth station applications

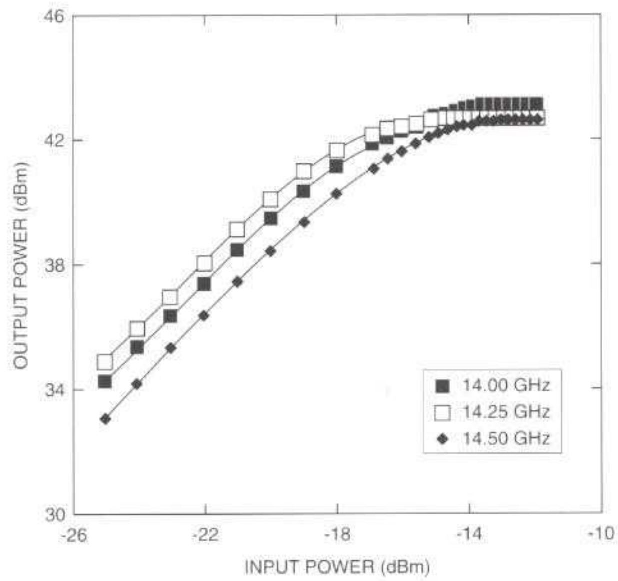


Figure 3. Ku-band SSPA provides 20 W of output power from 14.0 to 14.5 GHz

Ku/C-Band Integrated Receiver

Under the sponsorship of COMSAT World Systems (CWS), a Ku/C-band integrated receiver was developed for future satellite multibeam/multicarrier and/or phased-array antenna applications. The use of space-qualified MMIC technology for the receiver offers better performance uniformity, as well as reduced mass and volume on board the satellite. As a result, communications capacity and redundancy can be increased without additional mass.

MESFET-based MMIC components developed for the 14/4-GHz receiver include a low-noise amplifier (LNA), a mixer, and a local oscillator. The mixer employs a pair of MESFETs operating in passive mode and balanced configuration to achieve low spurious performance and high linearity. The X-band local oscillator consists of a MESFET voltage-controlled oscillator (VCO) stabilized by a dielectric resonator and a phase-locked loop. The VCO, which also includes a buffer amplifier, yields phase noise of 115 dBc/Hz at 100 kHz from the carrier. Through experimentation, the down-converter (Figure 4) has been phase-locked using GaAs/Si divider circuits, comparators, filters, operational amplifiers, and a synthesizer in

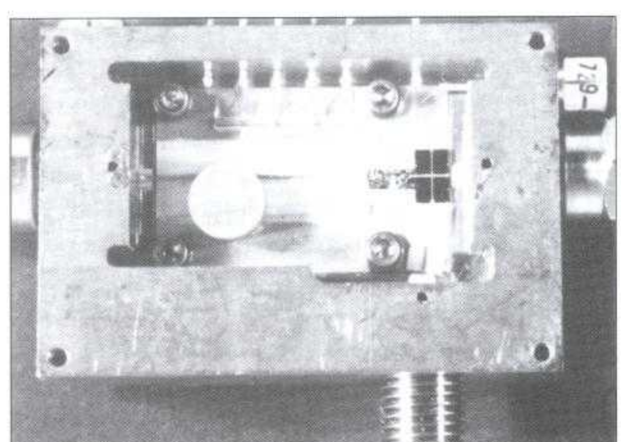


Figure 4. Ku/C-band MMIC down-converter is phase-locked using GaAs/Si divider circuits, comparators, filters, operational amplifiers, and a synthesizer

place of the crystal oscillator. The unique MMIC oscillator design employs a pair of "clipping" diodes to limit FET operation to the linear region. Measurements indicate that phase noise close to the carrier (1 to 20 kHz) has been reduced by the clipping diodes.

SPACE-QUALIFIED GaAs MMICs

For satellite applications, GaAs MMICs offer advantages such as low mass, small volume, and high reliability. COMSAT is a leader among GaAs MMIC suppliers, with experience in manufacturing and qualifying MMICs for space missions. MED has fabricated and successfully space-qualified several GaAs MMICs for satellite applications, including medium-power and low-noise amplifiers, digital attenuators, and digital phase shifters. Space-qualified MMICs are now being delivered to customers such as Space Systems/Loral for commercial satellite applications.

COMSAT has also developed qualification and test procedures to ensure the reliability of these microelectronic devices for 15-yr missions. Key components of the qualification procedure are short-term (168-hr/200°C) and long-term (1,000-hr/125°C) DC-biased thermal stress tests on sample MMICs from each wafer and fabrication lot. Fabrication and test methods comply with military specifications for class S devices. Long-term, high-temperature DC-biased and RF drive life tests of COMSAT 2-W power MMICs predict a median lifetime exceeding 10^6 hr (114 yr) at a channel temperature of 125°C—the highest limit specified for any space or military application.

In an effort to establish uniform industry standards for manufacturing, test, and qualification, MED recently volunteered to participate with eight other GaAs MMIC manufacturers in a beta site study coordinated by Rome Laboratory, Griffiss Air Force Base, New York. The purpose of the study is to address early fallout and risk mitigation issues specific to GaAs MMICs and to implement reliability verification criteria into general specification MIL-I-38535A for manufacturing integrated circuits. Unlike other military and NASA parts specifications, MIL-I-38535A allows for certification of specific process technologies from a fabrication line by enforcing the use of "total quality" programs, instead of using rigorous screening and qualification programs for each part type, regardless of the technology employed. The goal is to expedite introduction of advanced technology microcircuits and modules into high-reliability military and space applications.

SPC FOR MMIC MANUFACTURING & TEST

During the fabrication of GaAs MMICs, close tolerances and controls are maintained by in-process measurement of critical parameters via process control monitors and standard evaluation circuits incorporated in the layout of each maskset design. MED now has approximately 60 different MMIC masksets for low-noise and power amplifiers, driver amplifiers, attenuators, phase shifters, mixers, automatic gain control amplifiers, and VCOs at 1 to 90 GHz.

MED has instituted a fully integrated system for statistical process control (SPC) and MMIC wafer status reporting (wafer tracking). The system will both enhance yield through SPC of COMSAT's MMIC production line, and reduce cost through more effective management of the MMIC production facility via wafer tracking.

The system is based on the Oracle relational database management system and resides on a Macintosh FX database server. This configuration, together with Macintosh terminals available in the clean-room to log wafer fabrication steps and in-process test data, forms a paperless processing system. All wafer processing instructions are brought up on the screen when the technician logs onto the next process step. Currently, on-wafer DC test data are dumped to the database by transferring the data disk to a personal computer (PC) outside the clean-room. With the fully integrated system, this function will be performed through direct network connection. Materials evaluation data will also be transferred directly to the database when an automated Hall effect measurement system goes on line.

Outside the clean-room, MMIC production supervisors and test and design personnel can access the database via networked Macintosh and PC-compatible computers, as well as UNIX workstations. Users can obtain technical and management data by querying the database or logging onto the wafer-tracking system to obtain status reports or create new runs. Figure 5 is a schematic diagram of the complete system, which can also be used for "design centering" to achieve first-pass design success.

OPTICAL TECHNIQUES INTEGRATED WITH GaAs

The conventional MMIC on-wafer characterization technique using mechanical coplanar waveguide (CPW) probes has a number of limitations. Under a

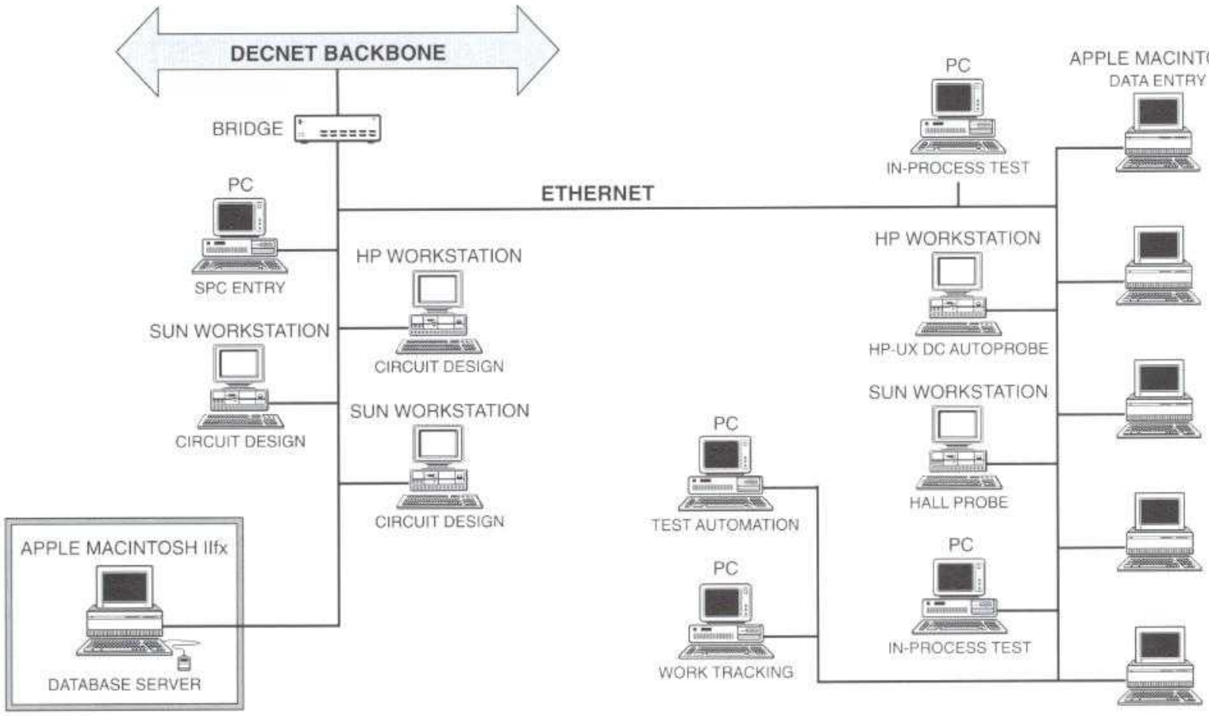


Figure 5. Computer architecture for a paperless MMIC manufacturing flow and SPC system used in all areas of MMIC development, fabrication, assembly, and test

MIMIC program sponsored by the Defense Advanced Research Projects Agency (DARPA)/Tri-Services, and in conjunction with TRW and the University of Maryland, MED has developed an optical technique for on-wafer characterization of MMICs. This method offers a noncontacting approach and provides a very wide bandwidth (approximately DC to over 100 GHz) MMIC characterization in a single measurement run, and the same characterization system. When implemented in MMIC manufacturing, it can provide cost and yield advantages over existing approaches. RF swept responses for a Ku-band MMIC amplifier with integrated optical test structures compared favorably with those obtained from CPW probes. The optical technique was also extended to the measurement of 60-GHz, pseudomorphic high-electron-mobility transistor (P-HEMT) LNAs, where results showed good agreement with those obtained from conventional narrowband waveguide measurement (Figure 6).

During 1991, MED completed the first phase of the Maryland Industrial Partnerships (MIPS) program through a cooperative research project with the University of Maryland which was partially funded by the State of Maryland. The research consists of a fundamental study of optical techniques and their application to the generation of microwave/millimeter waves and the characterization of MMICs. Optically controlled generation of microwave/millimeter-wave signals was achieved by using picosecond switches on GaAs microstrip lines. In addition, phase locking of MMIC VCOs using the optical intermixing effect in GaAs substrates was demonstrated (Figure 7). This technique has potential application to phased-array antenna systems. In October 1991, MED began a second-phase MIPS program on research and applications of optical/microwave techniques to systems such as the phased-array antenna.

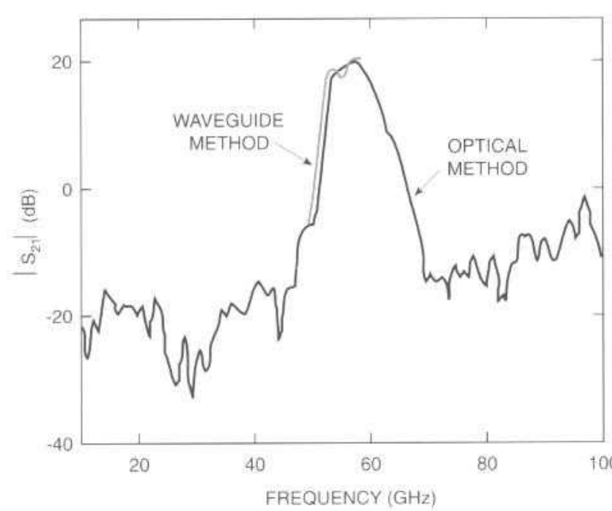


Figure 6. Optical measurements of a 60-GHz amplifier show good agreement with measurements taken using the waveguide method

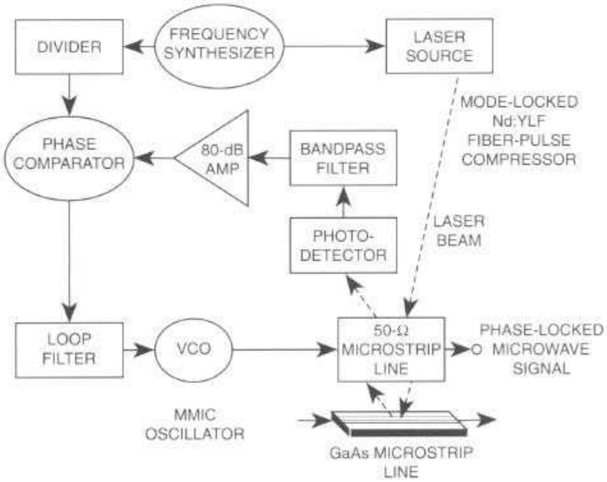


Figure 7. MMIC VCO is phase-locked using the optical intermixing effect in GaAs substrates

SEMICONDUCTOR MATERIALS & DEVICES

Heterojunction Bipolar Transistor Development

Heterojunction bipolar transistors (HBTs) have many applications in microwave circuits, particularly because of their high power density and low phase noise. Since the minimum dimension in HBTs is greater than 1 µm, standard optical lithography can be used for fabrication, resulting in a higher yield, higher throughput process compared to that for MESFETs.

Since many parasitic elements must be minimized to achieve high gain in HBTs, an advanced, self-aligned fabrication process was implemented. Improving the fabrication steps and HBT material structure resulted in better DC and microwave performance. Microwave measurement on the 1.5 x 10-µm HBT (Figure 8) resulted in F_t of 70 GHz and F_{max} of more than 100 GHz (Figure 9).

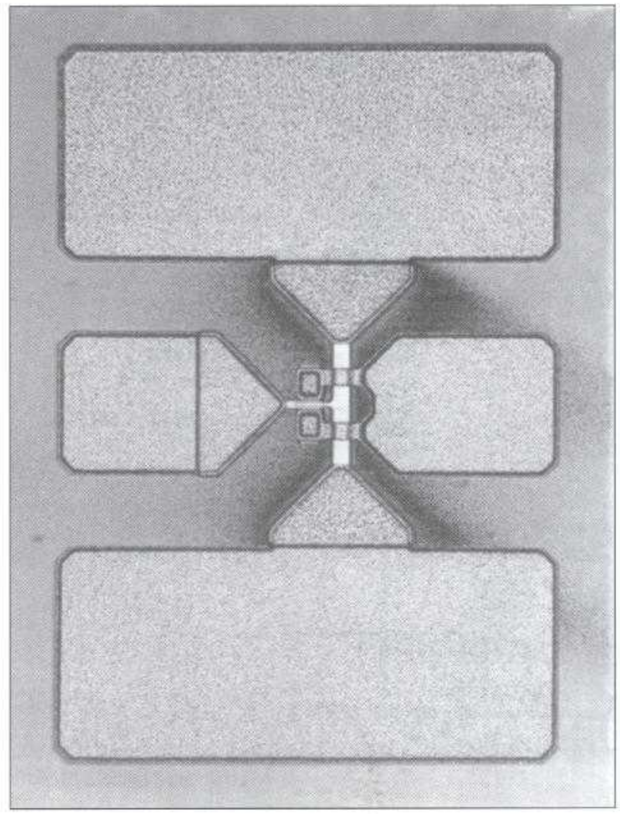


Figure 8. 1.5 x 10-µm HBT

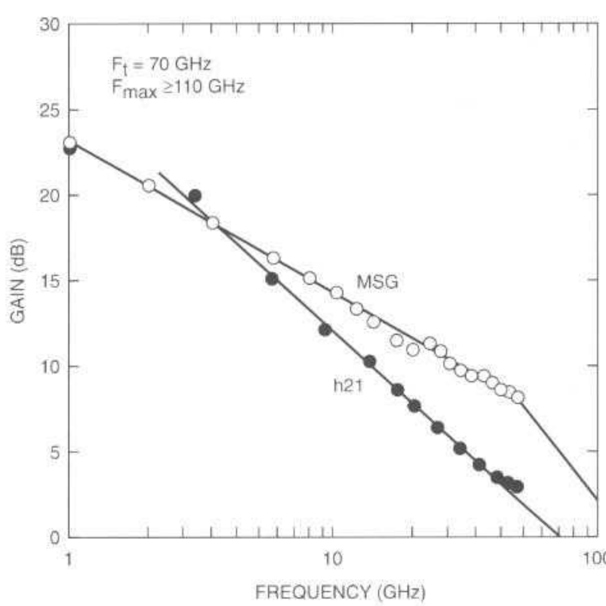


Figure 9. 1.5 x 10-µm HBT achieves improved microwave performance

Refractory Gate Process for MESFETs

A unique process was developed for fabricating ion-implanted power FETs with tungsten silicide gates. As illustrated in Figure 10, electron-beam (e-beam) lithography is used to locate the gate relative to the n^+ implant with an accuracy and precision (3σ) of 0.1 µm, thus enabling n^+-to-gate spacings as small as those achieved by self-aligned gate technologies without the additional processing steps that those technologies require. During 850°C activation of the ion implants, co-sputtered tungsten and silicon gate metalization is annealed to form a low-stress, low-resistivity film of tungsten-silicon intermetallic compound with excellent Schottky characteristics. E-beam lithography and COMSAT's standard MESFET gate processes produce a Ti/Pt/Au "gate" atop the tungsten silicide at the edge that defines the source n^+ implant. The Ti/Pt/Au serves as an etch mask for replicating the gate pattern in the underlying tungsten silicide, and also forms a T-gate structure for lower gate resistance. RF test results for a tungsten-silicide-

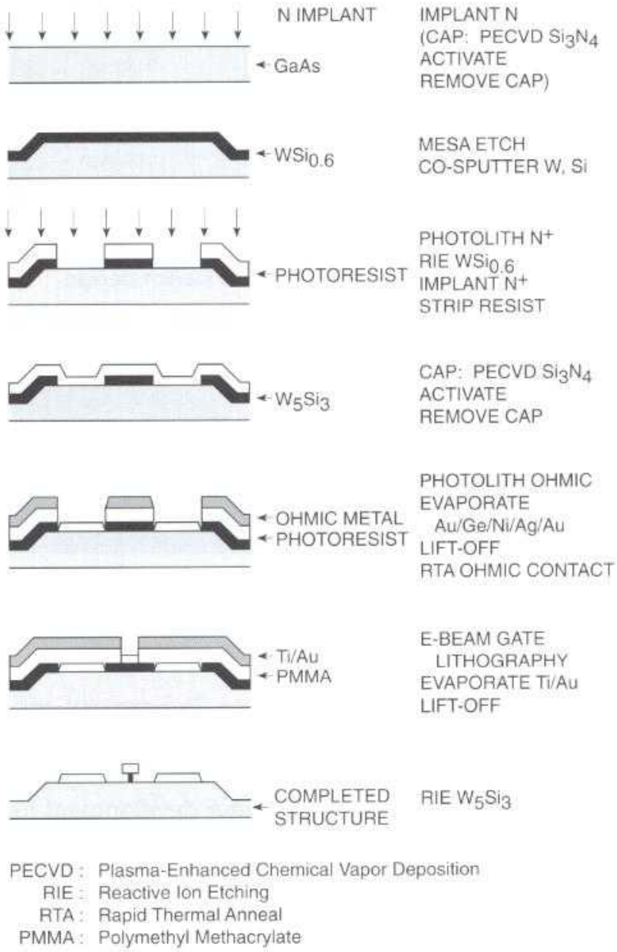


Figure 10. MED has developed a unique refractory gate process

gate power FET produced using this process showed power output exceeding 0.4 mW/mm and PAE approaching 50 percent (class AB operation).

CUSTOM MMIC COMPONENTS & FOUNDRY SERVICES

During 1991, MED designed and developed a W-band MMIC varactor doubler that delivers 50 mW of output power at 94 GHz with 12-percent conversion efficiency, for missile seeker applications. Chips for the 47-GHz power MMIC amplifier that drives the doubler circuit also were developed using MESFETs. The four-way combined power amplifier exhibits output power of 0.4 W, with associated gain of 15 dB, and its saturated output power exceeds 0.5 W. The integrated power amplifier and doubler module assembly is shown in Figure 11.

A W-band single sideband modulator (SSBM), shown in Figure 12, was developed for 94-GHz missile seeker application. A conversion loss of 10 dB was achieved at 94 GHz.

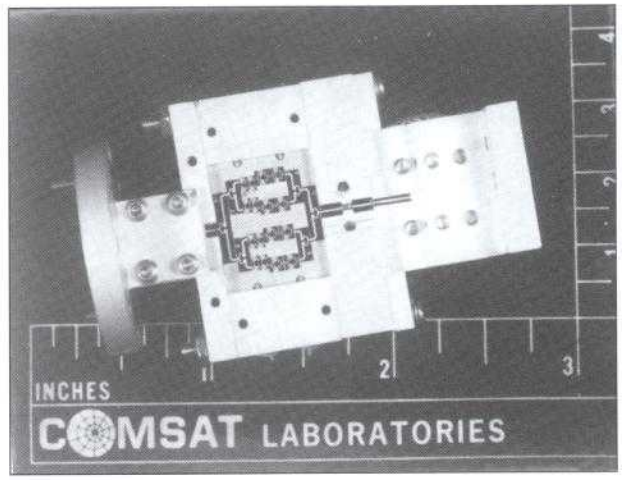


Figure 11. 94-GHz doubler/amplifier integrated module assembly incorporates 47-MHz power MMIC amplifier chips developed using molecular beam epitaxy MESFET technology

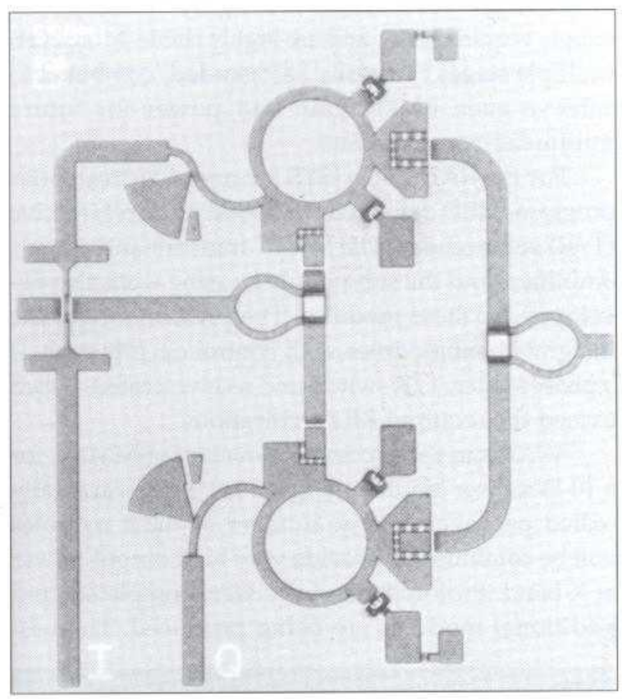


Figure 12. 94-GHz SSBM chip

Also in 1991, MED developed a Ka-band monolithic power amplifier, based on 0.25-µm gate length, single-quantum-well, AlGaAs/InGaAs P-HEMT technology, for millimeter-wave system applications. These amplifiers include combined single-ended and on-chip configurations and have an on-chip DC block, RF bypass, and bias networks. A cascaded, four-stage power amplifier exhibits state-of-the-art results: 210-mW output power with an associated gain of 21.3 dB at 34.5 GHz (Figure 13). Its saturated output power exceeds 230 mW. These power modules need

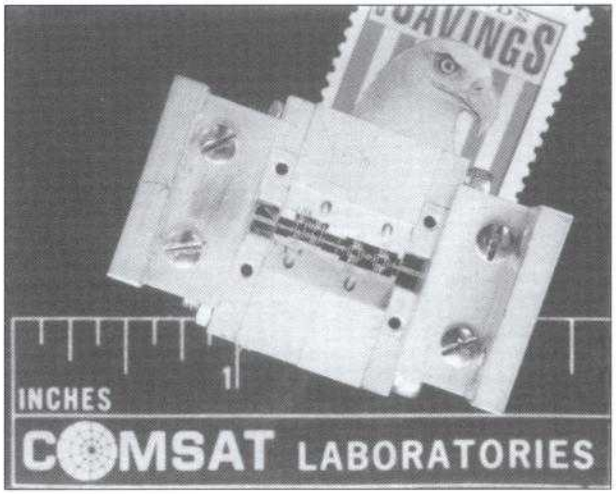


Figure 13. Four-stage 35-GHz P-HEMT power amplifier assembly with waveguide-to-microstrip transitions achieves state-of-the-art results

only a single positive bias to simplify system power supply requirements, and are highly stable. Moreover, multiple stages can easily be cascaded/combined to achieve even higher gain and power for future millimeter-wave systems.

For the RADC/UNISYS advanced tactical radar program, MED delivered 80 C-band transmit/receive (T/R) submodules. The MMIC transmit and receive amplifiers and the submodule housing were also developed for these modules. The performance of the integrated submodules with control circuits such as a phase shifter, T/R switch, and receive protect switch exceed the required RF specifications.

MED is in the process of developing MMICs for a 10-W power amplifier (Figure 14) in a hermetically sealed package. A large number of these modules will be combined to provide very high output power at X-band. Prototype modules were completed, and additional modules are being produced. The best prototype modules demonstrate 26.5-percent efficiency at a 10-W output power level.

A 44-GHz phase shifter (Figure 15) and amplifier (Figure 16) are currently under development for use in a MILSTAR phased-array antenna. The phase shifter employs a unique switch design that requires a single -5 V supply and a single 0/-5 V control line. Previous designs required both a positive and a negative control line, necessitating additional control circuitry either on- or off-chip. The 4-bit phase shifter uses these switches for three of the bits, and a "loaded line" design for the fourth bit. Performance data for the 44-GHz phase shifter are given in Figure 17.

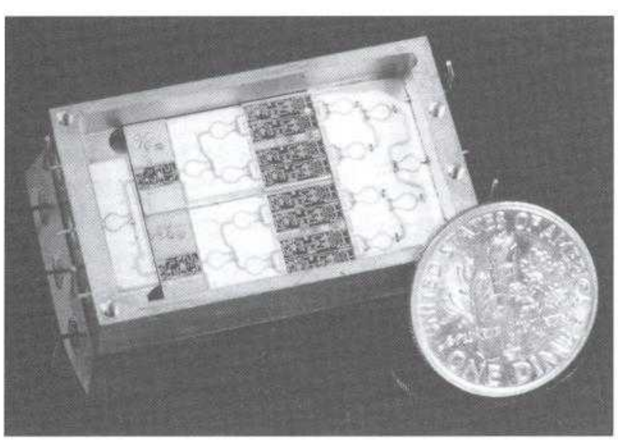


Figure 14. 10-W MMIC-based power amplifier for X-band

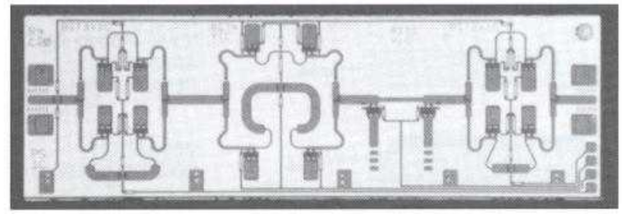


Figure 15. 44-GHz MMIC 4-bit phase shifter (4.1 x 1.27 mm) uses a unique switch design

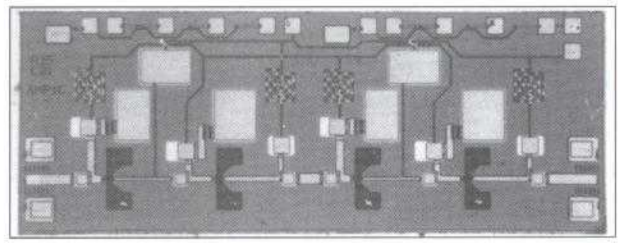


Figure 16. 44-GHz extremely low frequency amplifier achieves high on-wafer RF yield due to careful design and well-conrtrolled processing

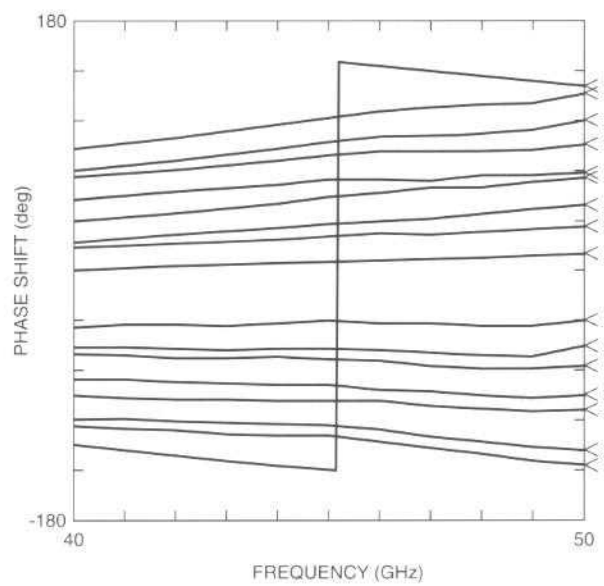


Figure 17. Performance data for the 44-GHz phase shifters

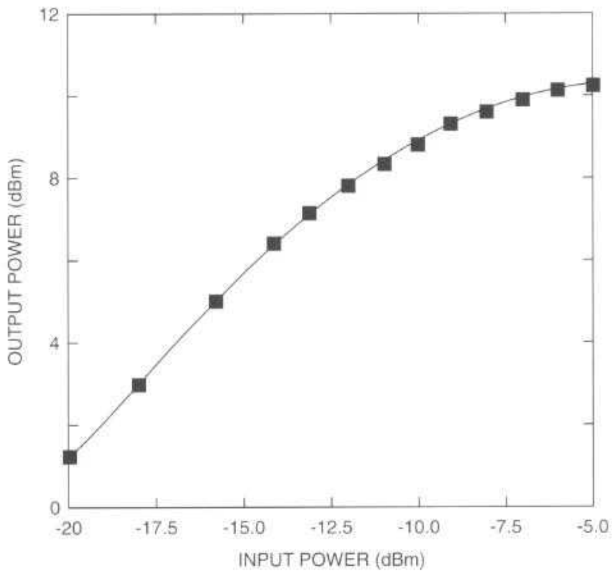


Figure 18. Measured performance of the 44-GHz power amplifier

The MMIC amplifier has shown very high yield, owing to careful design and well-controlled processing. An RF functional yield of greater than 80 percent has been obtained. Selecting amplifiers that exhibit 10-mW output power and more than 20-dB gain provides an on-wafer RF yield of 60 percent. Figure 18 is a plot of the small-signal performance; the design bandwidth exceeds the requirement by more than a factor of 2.

SPACECRAFT COMPONENTS & ENVIRONMENTAL EFFECTS

Radiation Tolerance of Geosynchronous Satellites

A major in-house study was initiated to address the increase in solar flare activity over the last few years. The effects of these flares on in-orbit spacecraft (particularly INTELSAT spacecraft) were studied, and an attempt was made to correlate the effects with specific flare characteristics and to determine the feasibility of various "early warning" systems. Three major effects are solar array degradation, single event upsets (SEUs), and electrostatic discharge (ESD). Anomalously large solar (ALS) flares occur only a few times during each solar flare cycle, but account for most of the solar-flare-related effects observed on satellites. ALS flares can vary in intensity and "hardness." A hard flare has a greater number of higher energy protons than a "soft" flare and will result in more SEUs in digital memory. A soft flare will induce fewer SEUs, but is likely to create ESDs that can cause logic upsets and device failures. An ALS flare with intermediate-energy protons above a certain level (10 to 50 MeV) will cause measurable degradation in spacecraft solar arrays. Much of this degradation is permanent and must be allowed for in the array size specification.

The study also considered reliability and failure mechanisms of MMICs destined for satellite applications. Experimental work included testing MMICs under thermal and RF stress, and MMIC capacitors under voltage stress. Analysis of irradiated GaAs solar cells provided a basis for comparing radiation damage in low electric field regions in solar cells with that in high-field regions of devices such as MESFET channels. Based on this study, MED determined that the reboosted INTELSAT VI (F3) mission was not at risk from the radiation environment while marooned at low earth orbit, that the INTELSAT VII-A MMIC LNAs do not require radiation testing, and that the INTELSAT K spacecraft needed further protection from ESD-related phenomena.

Inmarsat 3 and INTELSAT VII and VII-A will all utilize double antireflection-coated solar cells to improve array output power density. While these coatings do improve beginning-of-life performance, degradation from both particulate and ultraviolet (UV) radiation is greater than for single-layer coated cells. On behalf of INTELSAT and Mitsubishi, INTELSAT VII preflight cells were subjected to electron and UV radiation. UV irradiation of production cells has been carried out, under the sponsorship of CWS, to confirm the unexpectedly high degradation observed earlier in a 2,500-hr test.

MED supported the Inmarsat 3, INTELSAT VII, INTELSAT VII-A, and INTELSAT K programs (at both GE Astro and COMSAT Laboratories) during 1991. Areas of support included specification of the environment, radiation effects, solar array degradation, measurement of thermal-optical properties, and ESD effects and control. These efforts are interrelated and generally interdependent for spacecraft surface components. In particular, a degradation mechanism observed in optical solar reflectors (OSRs), initially attributed to ESD, was shown to be caused by contamination burned off by ESD. Recently improved techniques for measuring the solar absorbance of OSRs were used to study the acceptability of indium-tin-oxide (ITO) OSRs for use on Inmarsat 3, and to accurately determine the optical properties of other thermal control materials for this program.

INTELSAT VII production solar cells and VII-A pre-production cells were characterized, and then irradiated by 1-MeV electrons and exposed to humidity and high temperatures to provide the degradation information necessary for predicting their performance prior to and during extended missions.

A measurement technique was developed to accurately determine the solar absorbance of highly reflecting mirrors at different angles of incident light. This technique permitted more accurate measurement of OSRs in an integrating sphere than hitherto possible. It was also used to confirm the need to replace OSR panels on INTELSAT VII spacecraft; to select and characterize UV-reflecting (UVR) OSRs for the INTELSAT VII-A program; and to fulfill similar needs in the Inmarsat 3 program for ITO-coated, ceria-doped microsheet (CMX) OSRs and other thermal control materials.

The use of UVR/CMX OSRs for improved thermal control is being investigated for the INTELSAT VII-A program. The original UVR OSRs measured were not optimized for the oblique sun angles that thermal control panels experience on board the satellite. When improved samples became available, MED used its newly developed measurement technique to accurately determine the extent of improvement possible with the new UVR coatings at sun angles greater than 60° from a perpendicular to the surface. The results indicated that the use of these OSRs on INTELSAT VII-A is appropriate.

Aging Phenomena in Aerospace Batteries

MED and STD collaborated on a satellite battery life improvement program for CWS. Through long-term, real-life testing of nickel-hydrogen (Ni/H_2) aerospace batteries through an accelerated eclipse season, the gradual change due to aging of these batteries was identified as the redistribution and chemical reformation of active material in the positive electrode. This assessment was facilitated by the development of a new quantitative microanalytical technique based on backscattered electron imaging of cross-sectioned positive electrodes in the scanning electron microscope (SEM).

Aerospace-quality Ni/H_2 cells were aged for 3, 7, and 30 simulated geosynchronous eclipse seasons and up to 8,000 accelerated charge/discharge cycles simulating a 90-min. low earth orbit. The composition and distribution of active material $Ni(OH)_2$ in the positive plates were measured for each cell and compared to the starting conditions in an uncycled plate. Backscattered electron image analysis of plate cross sections in a SEM has identified at least two forms of $Ni(OH)_2$ in cycled positive plates. Capacity loss in the cycled plates is attributed to the formation of a dehydrated, less electrochemically active form of β-$Ni(OH)_2$. The analysis also identified a correlation between aging and reduction in pore volume in the plates.

The conclusion most consistent with these results is that cyclic aging of the Ni/H_2 positive plate results in dehydration of active material in the interior of the plates and regrowth of hydrated $Ni(OH)_2$ at the electrochemically active surface of the plate. In a previous study of the cause of a secondary voltage plateau in Ni/H_2 cells, a β form of $Ni(OH)_2$ was identified with isolated, resistive behavior of the discharged active material. Separation of the conductive α-$Ni(OH)_2$ at the surface of the plate and the resistive β-$Ni(OH)_2$ in the bulk of the plate would tend to restrict the electrochemical availability of all active material in the bulk of the plate and result in reduced charge capacity. The key to avoiding excess formation of β-$Ni(OH)_2$ may be to ensure adequate availability of water to the positive plate to prevent dehydration. Further work with differential scanning calorimetry is expected to elucidate the nature of this chemical charge and point to means of retarding the onset of the change and thus extending battery life.

Long-Lived Traveling Wave Tubes

Ku-band TWTAs for INTELSAT VII and INTELSAT K employ tungsten-osmium dispenser cathodes. These materials provide higher current density than single-component dispensers, but have not been used in other commercial satellites; therefore, proof of their reliability is a concern. Prior experience with TWTA reliability has shown that premature failures in other styles of cathodes have resulted from material or construction problems. In this case, two sets of materials represent potential problems: the tungsten-osmium powder used to form the sinter, and the impregnant—a three-component mixture of barium, calcium, and aluminum hydroxides. Both materials are known to be thermodynamically unstable, and proper manufacturing procedure must be followed to ensure their correct function. A series of life tests performed by the manufacturer and supported by INTELSAT indicated that the life expectancy of these cathodes can exceed 200,000 hr when they are correctly manufactured and operated. The manufacturing procedure, materials specifications and testing, and operating parameters were compared with prior knowledge regarding premature failures. From this activity, a set of recommendations was prepared to allow the application of evaluation criteria to materials, manufacturing procedures, and operating conditions in order to ensure the long-term reliability of this type of cathode.

During 1991, the Satellite Technologies Division (STD) performed research and development for a wide range of projects that had a direct impact on the design of communications satellites. Advances were made in several ongoing activities, notably a fourth-generation attitude control simulator that combines Transputer® and personal computer technology in one package.

Other work focused on improving the common pressure vessel battery and investigating thermal phenomena within the battery. To improve the accuracy of thermal prediction, STD designed and fabricated a calorimeter for measuring instantaneous heat dissipation from nickel/hydrogen cells under various conditions. This "radiative-mode" calorimeter, believed to be the only one of its kind, permits thermal characterization with much higher precision than conductive-type calorimeters.

In advanced filter technology, a new concept for realizing a narrowband filter with a wide spurious-free response was successfully tested. A Ku-band filter employing a combination of modes and iris geometry to yield a spurious-free response from 12 to 26 GHz was designed, tuned, and measured. ■

CONTROL & POWER SYSTEMS

STD's control and power system efforts encompass numerous tasks—including analysis, design and development, simulation, integration, test, launch support, satellite operation, and training—performed at the component, subsystem, and system levels. For more than 12 years, COMSAT Laboratories has advocated the use of real-time, interactive simulators to train satellite operators and to support engineering studies. COMSAT designed, built, and delivered the INTELSAT V and VI and ITALSAT attitude determination and control system (ADCS) simulators. The INTELSAT V ADCS flight simulator, originally built in 1980 and upgraded in 1987, was again upgraded in 1991 to increase its reliability and expand its capabilities. Hardware for the command and telemetry processor was replaced with new personal computer (PC)-based hardware and software, an associated interface electronics unit was built, and several simulation software functions were added or modified. Following successful integration with the INTELSAT Satellite Control Center (ISCC) and testing, this simulator resumed operation at INTELSAT, where it will be used for the lifetime of the INTELSAT V series of satellites, or approximately until the year 2000.

The INTELSAT V ADCS flight simulator is a valuable training tool for both routine and emergency satellite operations. STD personnel experienced in satellite operations used the simulator to train INTELSAT engineers for on-call and emergency spacecraft recovery, and ISCC controllers and technicians for routine duties such as stationkeeping maneuvers, which are critical because of the potential for attitude loss and fuel wastage.

Similarly, based on in-house experience with expert systems and satellite behavior for a large set of anomalies, COMSAT Laboratories engineers contributed to the implementation of an expert system for INTELSAT that will be used to detect and isolate satellite anomalies. STD advocated the functional modeling approach that was selected, recommended the expert system rules, and defined and conducted tests. COMSAT also developed real-time PC-based software for calculating attributes, such as attitude rate, from noisy telemetry.

During 1991, under contract to the U.S. Naval Postgraduate School (NPS), STD began developing an attitude control simulator for use in the school's instructional and research programs. The NPS simulator (see "Division Highlights," p. ix, bottom right) represents a fourth-generation concept. The primary improvement involves the combination of PC and Transputer® technology to replace the high-performance minicomputer used in earlier simulators. The Transputer® satisfies the high numerical processing requirements and fast task switching necessary for real-time simulation of attitude dynamics, sensors, and actuators, while the PC provides the powerful, well-supported capabilities required for the man-machine interface. For example, this approach yields higher-resolution color graphics with a faster update rate than was possible with previous systems.

STD is actively investigating automation techniques and technologies for more effective command and control of spacecraft. The division has developed a demonstration expert system that can aid in diagnosing anomalies in the ADCS of a representative spacecraft. However, certain functions necessary for performing automated diagnosis are not readily solvable by expert systems. This year, STD investigated neural network approaches and found them to be promising for determining whether a stream of real-time telemetry data is anomalous. Two neural networks—the multilayer back-propagation network and the adaptive resonance theory—were evaluated by means of a programmable neural network board that plugs into a PC. Using actual telemetry data, the networks' performance in terms of accuracy and training time were compared critically. The preliminary conclusion from this research, which will continue in 1992, is that the adaptive resonance theory is a better neural network for analyzing telemetry data streams.

Microwave tubes function as the power output stage of all fixed and many mobile satellite communications ground stations, and also in spacecraft downlink transponders. Many space-qualified traveling wave tube amplifiers (TWTAs) are currently being procured for 50 to 200 W at Ku-band, and power traveling wave tubes (TWTs) are available to beyond 90 GHz for ground and 60 GHz for space applications.

For the past 25 years, the Laboratories has actively participated in microwave tube development, fostering contacts with the worldwide tube industry and contributing via special tests and investigations to the steady improvement in TWTA performance and the resolution of TWTA problems. Recent activities have included research in TWT linearity, cathode reliability, quality control stress testing, and high-voltage microdischarges; troubleshooting in ground and space applications; and support to spacecraft procurement programs and to COMSAT World Systems (CWS) as the U.S. Signatory to INTELSAT.

A 3-year research project for INTELSAT on the use of multiple stress testing of TWTAs as a quality control tool in manufacturing was completed in 1991. After 14 of 20 Ku-band space TWTAs were subjected to a variety of rigorous thermal and cycling tests, a computer-controlled life test facility (Figure 1) housing the 20 TWTAs was constructed and delivered to INTELSAT to allow continued observation of the evolution of the TWTAs.

Also on behalf of CWS, STD developed a PC-based expert system (Figure 2) to assist in diagnosing problems in earth station high-power microwave amplifiers. Knowledge accumulated during the development

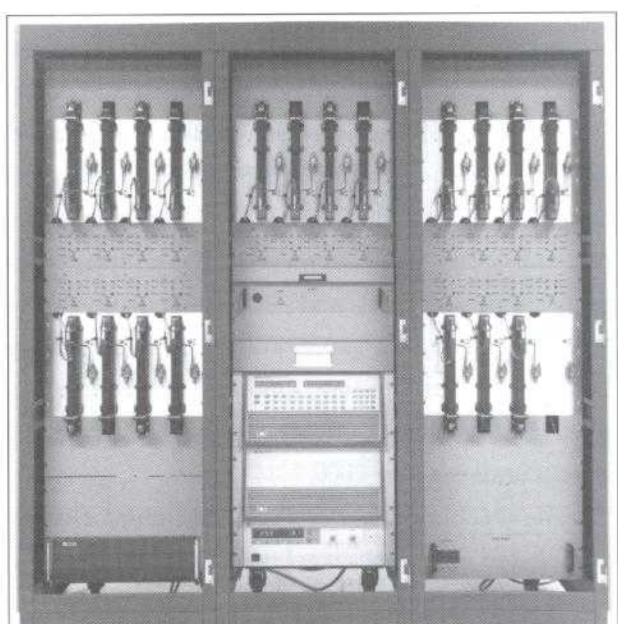


Figure 1. Life test rack for 20 Ku-band space TWTAs was built and delivered to INTELSAT

Figure 2. PC-based expert system is used in diagnosing HPA problems

of this system was applied to problems that arose during commissioning of the 3-kW high-power amplifiers for a new telemetry, tracking, command, and monitoring (TTC&M) earth station that was built by COMSAT for the INTELSAT spacecraft system.

An occasional but long-standing problem with tubes has been high-voltage discharges, which can cause brief interruptions of the RF, and hence affect the quality of communications service. In a world that is moving toward digital signaling techniques, this is a legitimate concern. Certain space programs have encountered this problem, and work on its detection and diagnosis is continuing under support for CWS.

In 1991, STD completed the digital controller subsystem for the beam-forming matrix (BFM) being developed for CWS by the Microwave Technology and Systems Division (MTSD). This subsystem is a hierarchical controller which cyclically switches the values of the phase shifters in the BFM, and also meets requirements for ground command and monitoring. It consists of three distinct units: the executive controller, which emulates ground and spacecraft telemetry and command functions; the data distribution and timing unit; and the local control module (LCM). In addition, low-level controller boards are placed next to the microwave circuits in the BFM.

Most of the work during 1991 focused on completing the LCM (see "Division Highlights," p. viii, center right). After the prototype LCM board was tested, the design was finalized and three deliverable boards were fabricated, assembled, tested, and integrated into the LCM. Firmware changes were made to the executive controller and the LCM to accommodate updated system requirements. Finally, the controller subsystem was integrated, tested, and delivered to the BFM subproject.

STD personnel consult on TWTs, attitude control, simulators, satellite operations, and operational planning for various companies. In 1991, services were provided to Tele Diffusion France (TDF), Space Systems/Loral, Agenzia Spatiale Italiana (ASI), and Mexico Telecomm in connection with the TDF, SUPERBIRD, ITALSAT, and SOLIDARIDAD spacecraft, respectively.

ENERGY CONVERSION & STORAGE

The division's capabilities in energy conversion and storage are primarily directed toward R&D in aerospace batteries. In 1991, STD focused on improving the common pressure vessel (CPV) battery and investigating failure mechanisms and thermal phenomena. Having demonstrated the performance advantages of the CPV design for a high-voltage nickel/hydrogen (Ni/H_2) battery, STD sought to analyze its failure modes. Failure analysis of the 26-cell, 22-Ah aerospace CPV battery revealed that electrolyte had leaked from individual cells through the terminal feedthrough, cell container, and hydrogen diffusion membrane. To enhance the reliability and increase the cycle life of the battery, the design of the cell container (which includes the hydrogen-diffusion membrane and terminal feedthroughs) was revamped. A chemically resistant polymer with well-defined properties was selected for the cell container, and a hydrogen-diffusion membrane with a layer-type structure was designed and fabricated. The terminal feedthrough was redesigned by replacing the compression-sealed terminal with a polymer-encapsulated conductor. CPV Ni/H_2 cells of 10 to 60 Ah can be fabricated using the newly designed container (see "Division Highlights," p. viii, center left).

To improve the accuracy of thermal predictions, STD designed and fabricated a calorimeter to measure instantaneous heat dissipation from Ni/H_2 cells under various conditions. Most measurements of electrochemical cells reported in the literature are conducted under isothermal conditions using a conductive-type calorimeter. COMSAT adopted an alternate approach in which radiation is the major mode of heat transfer. The calorimeter, shown schematically in Figure 3, consists of a liquid-nitrogen-cooled copper chamber arranged inside a vacuum chamber. The Ni/H_2 cells are prepared for the calorimeter by wrapping the 4-in.-wide cylindrical portion with heater tape and insulating the dome ends with 10 layers of aluminized Mylar (see "Division

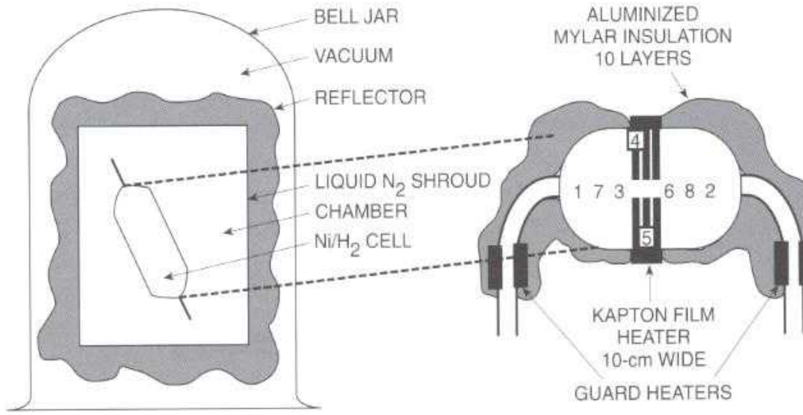


Figure 3. Radiation calorimeter responds to instantaneous changes in cell temperature much faster and provides more accurate data than a conductive-type calorimeter

Highlights," p. viii, top left), thus limiting the radiating surface to the cylindrical portion of the cell. The experiment is conducted in a vacuum of 10^{-6} torr. Experimental heat rate data indicate that the magnitude of endothermic cooling during charge is insignificant and that the endothermic-to-exothermic transition occurs at about 1.46 V, which is a function of rate of charge.

Flight configuration multicell assemblies representing INTELSAT V, VI, K, and VII satellites are being tested in a cycling regime that mimics geosynchronous operation, in order to determine baseline performance. The goal is to develop procedures to correct for anomalous performance in orbit, to obtain an early look at the thermal characteristics of the assemblies, and to assess the effects of wear.

The division also provided consulting services such as monitoring of activities during battery fabrication, laboratory experimentation to verify conformance, and data analysis to explain anomalies. Clients included INTELSAT, Matra Espace, Aerospatiale, British Aerospace, Inmarsat, and U.S. Government agencies.

MECHANICAL & THERMAL DESIGN, ANALYSIS & TEST

STD has conducted conceptual configuration studies of advanced communications spacecraft to demonstrate their feasibility. Figure 4 depicts a high-power, multibeam, phased-array, Ku-band spacecraft with a direct radiating antenna. The C-band spacecraft shown in Figure 5 is a dual-reflector configuration that includes a lightweight, multibeam C-band antenna. Both spacecraft designs utilize advanced thermal control systems with capillary-pumped-loop heat transport and fixed-conductance heat pipe radiator panels. An advanced mobile spacecraft with an unfurlable 15-m antenna and a deployable structure was developed (see "Division Highlights," p. ix, center right).

The lightweight C-band antenna has 177 antenna modules, each containing a patch antenna and redundant dual-polarized amplifiers. The modules are inserted into a common chassis, with a beam-forming network and controller located on the reverse side of the chassis. 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 1,500 W. During 1991, in a cooperative effort with MTSD for CWS, STD continued the mechanical and thermal design of this antenna. Several modules were fabricated to demonstrate the feasibility of the concept. (A photograph of a module about to be attached to a mock-up of the chassis is shown in "Division Highlights," p. ix, top right) A special technique wherein Nomex honeycomb is bonded to the patch antenna was developed to improve efficiency.

STD engineers were involved in the INTELSAT VI bearing and power transfer assembly (BAPTA) investigation. The BAPTA consists of two primary assemblies: the bearing assembly and the electrical contact ring assembly (ECRA). The performance of these assemblies is critical in sustaining the life of the satellite, because neither system has a redundant backup. Since January 1989, STD has conducted life testing of the INTELSAT VI engineering model BAPTA for INTELSAT. In a thermal vacuum environment

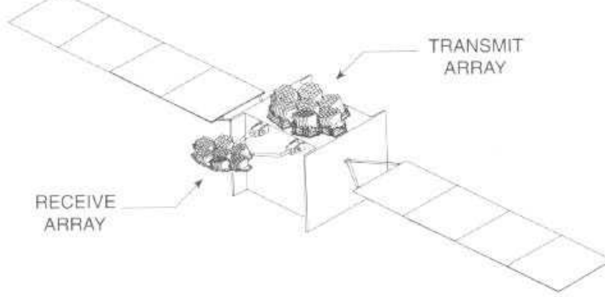


Figure 4. Conceptual configuration of a high-power, multibeam Ku-band spacecraft with direct radiating antenna

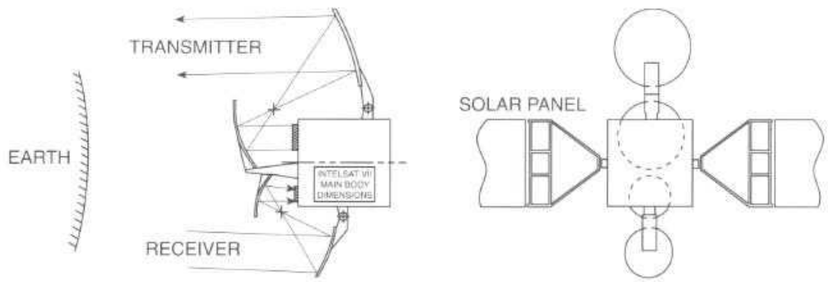


Figure 5. C-band phased-array spacecraft on-orbit deployed configuration

that simulates in-orbit conditions, the engineering model has shown normal performance since the beginning of the 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.

Experience gained from the INTELSAT VI life test was applied directly to investigating the anomalous behavior of the despun antenna drive and BAPTA observed on the INTELSAT VI (F2) spacecraft. This anomaly took the form of higher-than-expected in-orbit temperatures on the aft inner bearing raceway. To investigate various hypotheses as to the cause of the higher temperatures and to provide engineering data on BAPTA performance under simulated orbit conditions, STD reconfigured an engineering model BAPTA that had been undergoing life test at COMSAT Laboratories. The test configuration permitted bulk temperature, ECRA current, and speed to be varied in a vacuum. The bearing lubricant film thickness, ECRA electrical resistances, and accelerometer spectra were recorded. These data made it possible to establish a relationship between lubricant film thickness *vs* temperature and speed—information that is particularly important for managing in-orbit spacecraft. Figure 6 shows the test setup and instrumentation used during the test. In parallel, analytical thermal models of the INTELSAT VI spacecraft and BAPTA were modified to predict BAPTA thermal performance under actual in-orbit conditions. The models were correlated with all in-orbit spacecraft

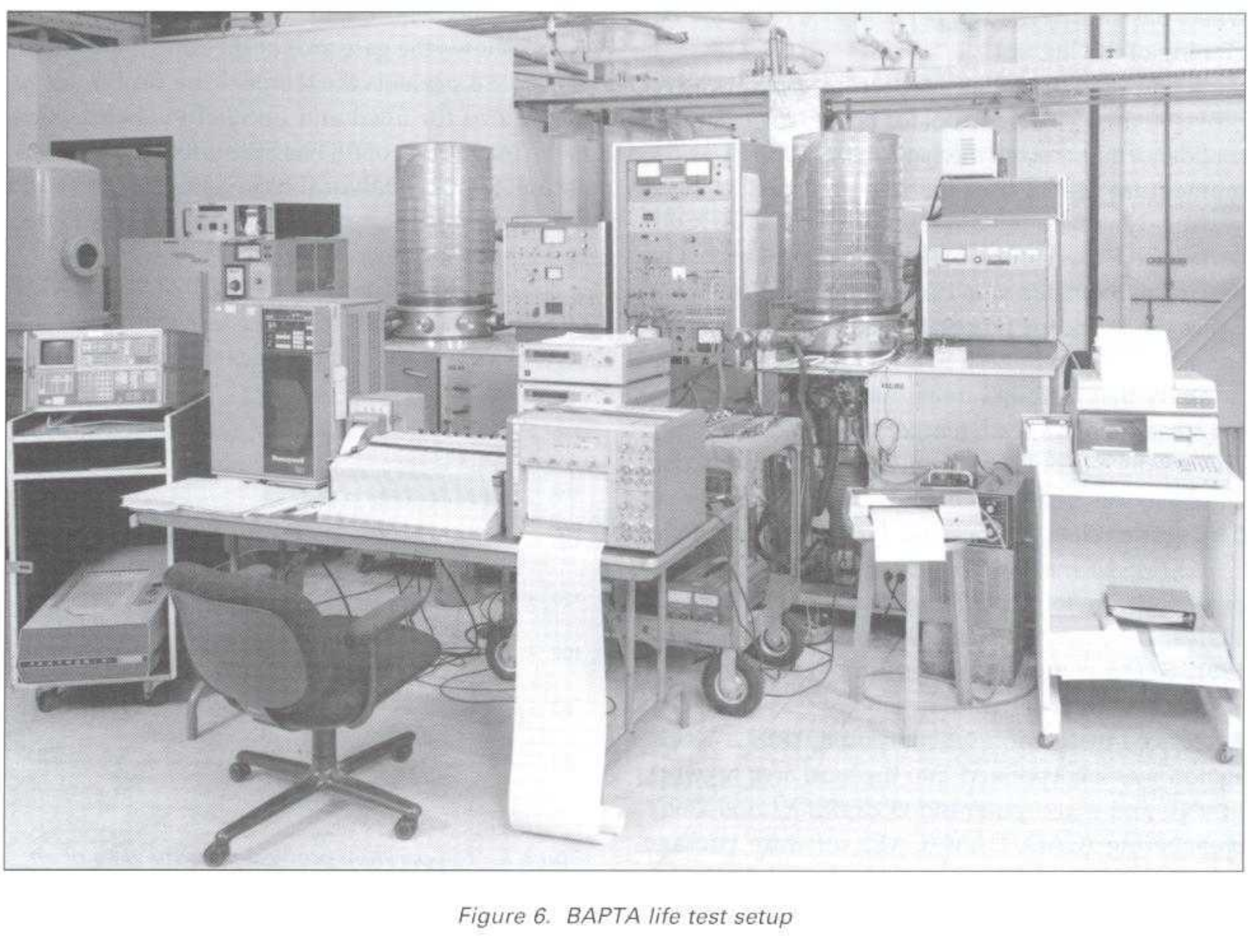


Figure 6. BAPTA life test setup

for every season since launch, in an effort to understand the anomaly and predict future BAPTA operating temperature.

Another spacecraft component that involves mechanical rotation is the momentum wheel. The antenna pointing performance of INTELSAT V/V-A satellites is critically dependent on the life of their 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. STD's ongoing life test program for evaluating the long-term performance of an engineering model momentum wheel has accumulated more than 11 wheel-years of running time. The wheel 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 wheel has shown normal performance since the beginning of the life test.

Computer modeling of bearing dynamics has proven to be a powerful tool for improving customer confidence in spacecraft mechanisms. The INTELSAT K momentum wheel bearing was analyzed using a bearing dynamic simulation program called ADORE (Advanced Dynamics of Rolling Elements). The bearing's geometry was defined by the contractor, while the lubricant properties required for analysis were determined by test. STD conducted a parametric study that included more than 20 cases, combining variations in speed, temperature, and geometry. The model output was evaluated, with particular emphasis on cage stability. Even with worst-case parametric values, the bearing dynamics were stable.

COMSAT maintains an extensive library of computer software for performing structural and thermal analyses of many different types of projects. During 1991, STD's computer system underwent a major upgrade and the software capability was enhanced. A reduced-instruction-set-computing (RISC) workstation was incorporated into the local area network (LAN), and a computer-aided drafting/modeling/engineering (CAD/CAM/CAE) software package known as SDRC I-DEAS was purchased. With this computer configuration, mechanical/thermal design specialists can accomplish the preliminary design of a component, perform the required analyses, and transfer the file to STD's Design and Fabrication Center for detailed layout and assembly.

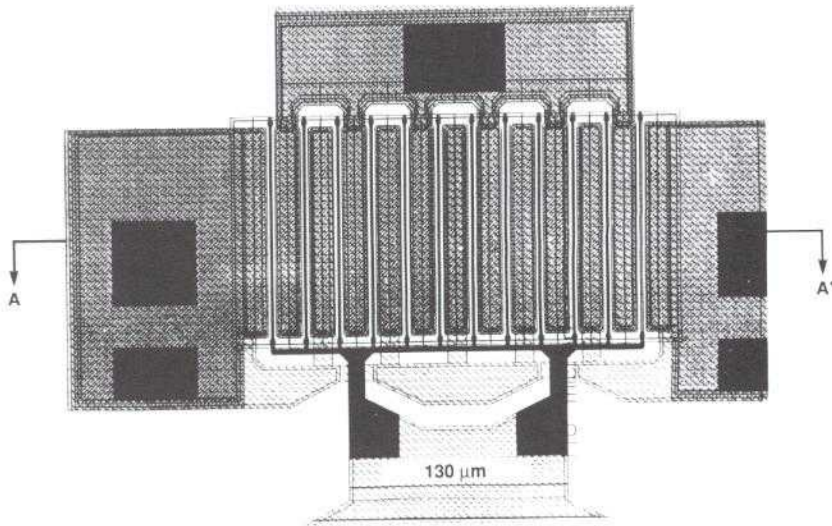


Figure 7. MMIC amplifier gate area

In the area of thermal analysis, a 1,500-node analytical thermal model of the chip gate region was developed to analyze the effect of solder-filled via-holes on the gate temperature of a monolithic microwave integrated circuit (MMIC) amplifier chip. Figure 7 shows the gate area of the MMIC amplifier, and Figure 8 presents the temperature profile across the gate area for filled and unfilled via-holes. Note that the magnitude of fill has little effect on gate temperature. Similar analytical techniques were used to predict the temperatures within a COMSAT-designed amplifier box supplied to Unisys.

The solid model capability of STD's CAD/CAM/CAE software was exploited in the mechanical package design of a 25-W C-band solid-state power amplifier

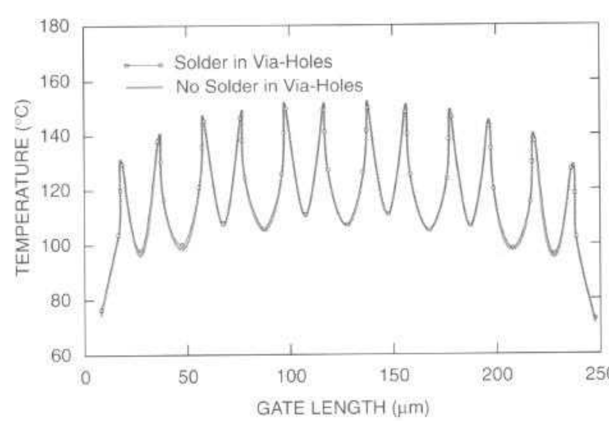


Figure 8. Temperature profile across the gate of an MMIC amplifier chip shows that the amount of fill does not significantly affect gate temperature

(SSPA) for use in a ground station. The design included provisions for forced-air cooling of the amplifier. The CAD solid model of the SSPA package was employed to produce detailed shop drawings for use in manufacturing. Figure 9 shows the disassembled solid model of the SSPA. The model and final assembled SSPA packages are shown in "Division Highlights" (p. ix, bottom left).

STD is actively involved in consulting with both INTELSAT and Inmarsat on spacecraft thermal and structural design and mechanisms. STD's expertise in embedded fixed-conductance heat pipe radiator panels was utilized in spacecraft thermal design for the INTELSAT VII and Inmarsat 3 programs. This work included the development of specifications, evaluation of manufacturer processes, thermal analyses of heat pipe performance, and suggestions for improved designs.

For Inmarsat 3, STD developed an independent analytical thermal model of the spacecraft which highlighted several problem areas in the contractor's design early in the program. To supplement the contractor's data, the thermal properties of several of the spacecraft materials were measured and integrated over solar, xenon, and infrared spectra. A solar beam test was conducted on a representative mock-up of the spacecraft, which was subsequently retested at the contractor's infrared test facility in a flight-like configuration to validate the proposed analysis/test program. COMSAT suggested this test/analytical modeling verification approach and helped to monitor the tests for the customer.

STD operates a comprehensive environmental test laboratory for verifying the integrity of COMSAT products that are to be subjected to specific environmental conditions. During the past year, vibration, shock, temperature/humidity, and thermal vacuum test services were provided to customers within COMSAT, as well as to others such as Lucas-Weinschel, Inc., GEO-COM, and Loral.

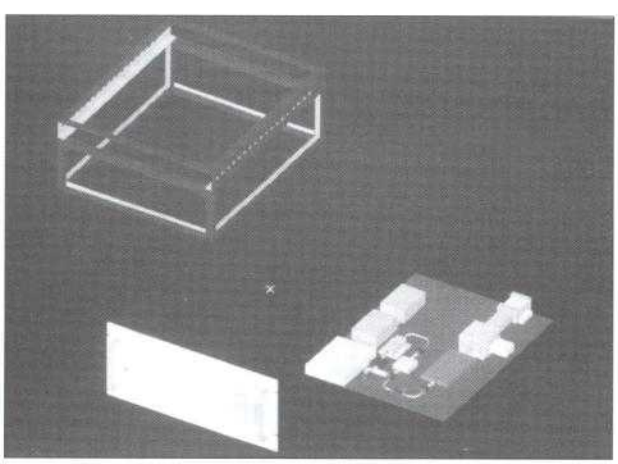


Figure 9. Disassembled solid model of the SSPA shows spatial and mechanical relationships before the unit is built

MICROWAVE MEASUREMENTS, FILTERS & SYSTEMS

During 1991, STD continued to develop and refine its in-orbit test (IOT) measurement techniques, microwave filters, and system capabilities. Fastsweep, a measurement technique for performing a fast frequency response, was improved by adding the capability to measure the earth station's response for calibration. The earth station antenna is pointed away from the spacecraft, and the Fastsweep measurement is performed. The resulting noise-only measurement data contain the frequency response of the earth station's receive chain, and are saved in a calibration file. The earth station's response is subtracted from the Fastsweep measurement of the frequency response of a satellite transponder, to compensate for the earth station contribution. Post-processing fast Fourier transform (FFT) techniques are used to correlate the measured Fastsweep data with the transponder frequency response. With some reduction in dynamic range, Fastsweep can measure the frequency response of a 40-MHz-bandwidth spacecraft transponder in approximately 10 s, compared to several minutes required for a point-by-point frequency response measurement. The highly accurate point-by-point measurement can achieve an 80-dB dynamic range, while the Fastsweep measurement achieves 50 dB.

Another advance in the area of measurement data analysis was the development of a computer program for interactively editing and manipulating measurement data files for the preparation of report-quality output plots. The Interactive Data Editor, written in C++ language using object-oriented programming, is implemented with Open Software Foundation's OSF/Motif graphical user interface (GUI) toolkit and the X Window system, and runs on a Hewlett-Packard UNIX workstation. It enables the user to merge data points from different files into a single plot and file; perform algebraic data operations such as subtracting a calibration or reference file from a measurement data file; perform curve-fitting on measured data; annotate plots with text and markers; and zoom in on the data. The edited file can be saved and plotted.

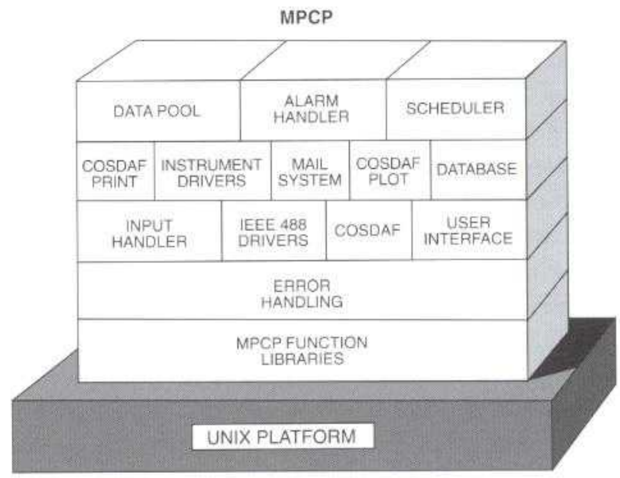


Figure 10. The MPCP is a set of tested software building blocks for constructing IOT systems quickly and efficiently

In the area of automated IOT systems, STD continued development of the Measurement Processing and Control Platform (MPCP), an integrated set of functional software modules and capabilities that are common to individual measurements and computer-controlled systems. Because MPCP is a reusable platform of implemented, tested functions, the development time and cost for building new IOT systems are decreased substantially. MPCP components and capabilities include interprocess/intermachine mail communications, network support, distributed processing system architecture, GUI support, measurement scheduling, a library of microwave instrument drivers, database storage and retrieval, and plotting and printing. Figure 10 illustrates the concept of the modular, layered MPCP implementation. In addition to the modular, reusable components of the MPCP for building IOT systems, the system architecture supports both LAN and wide area networking (WAN) capabilities. Figure 11 shows the IOT system and network architecture, including the capability to support remote access and control. To provide an easy-to-use, flexible user interface to the IOT system, a mouse-based GUI has been implemented. A typical X Window-based user interface for specifying flux density and effective isotropically radiated power (e.i.r.p.) measurements is shown in Figure 12.

Work was also begun on the design and implementation of a new capability—an interactive spacecraft design tool. Once developed, it will present the user with the equivalent of a "what-if" capability for designing transponders by allowing the user to graphically vary the topology, number of transponders or

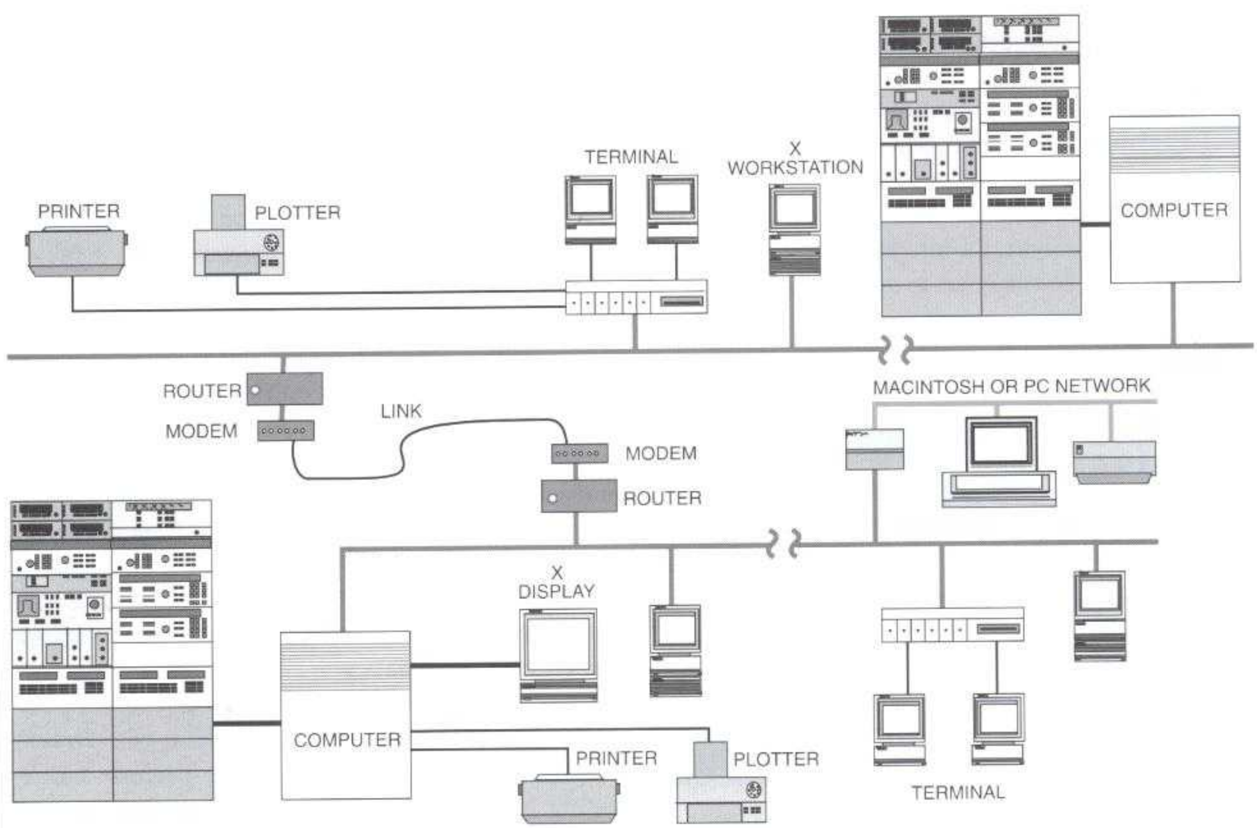


Figure 11. IOT system architecture supports both LAN/WAN in a distributed processing environment

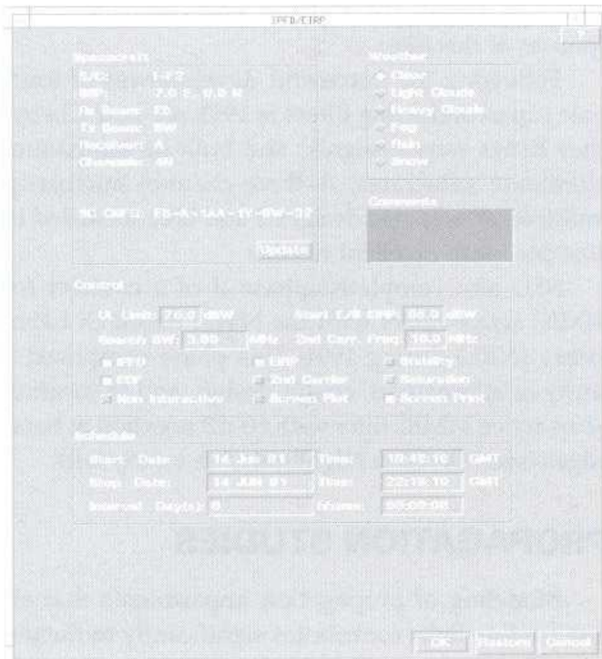


Figure 12. The mouse-based GUI provides an easy-to-use means of controlling IOT system measurements

channels, frequency plan, and other parameters, and to view the resulting effects on spacecraft mass, power, and cost. The tool will use the Graphic Mimic Panel technology developed for the RF Terminal Supervisor (RFTS) in the NASA ACTS Program. The Graphic Mimic Panel (Figure 13) depicts the real-time status of the RF Terminal (RFT), while providing the RFTS with direct control of the station configuration and switch positions via mouse inputs.

For more than 20 years, COMSAT Laboratories has maintained a unique leadership position in the development of microwave filters for satellite communications. Original, innovative research has led to significant savings in transponder mass and volume. Optimum-response filters are efficiently designed and tuned with the aid of COMSAT-developed high-precision mathematical models and software. Recent accomplishments include the design and realization of the first successful high-temperature superconducting microwave filter, the first quadruple-mode multiplexer, and the first hexa-mode filter, as well as pioneering contributions to MMIC active filter design and fabrication. During 1991, STD investigated

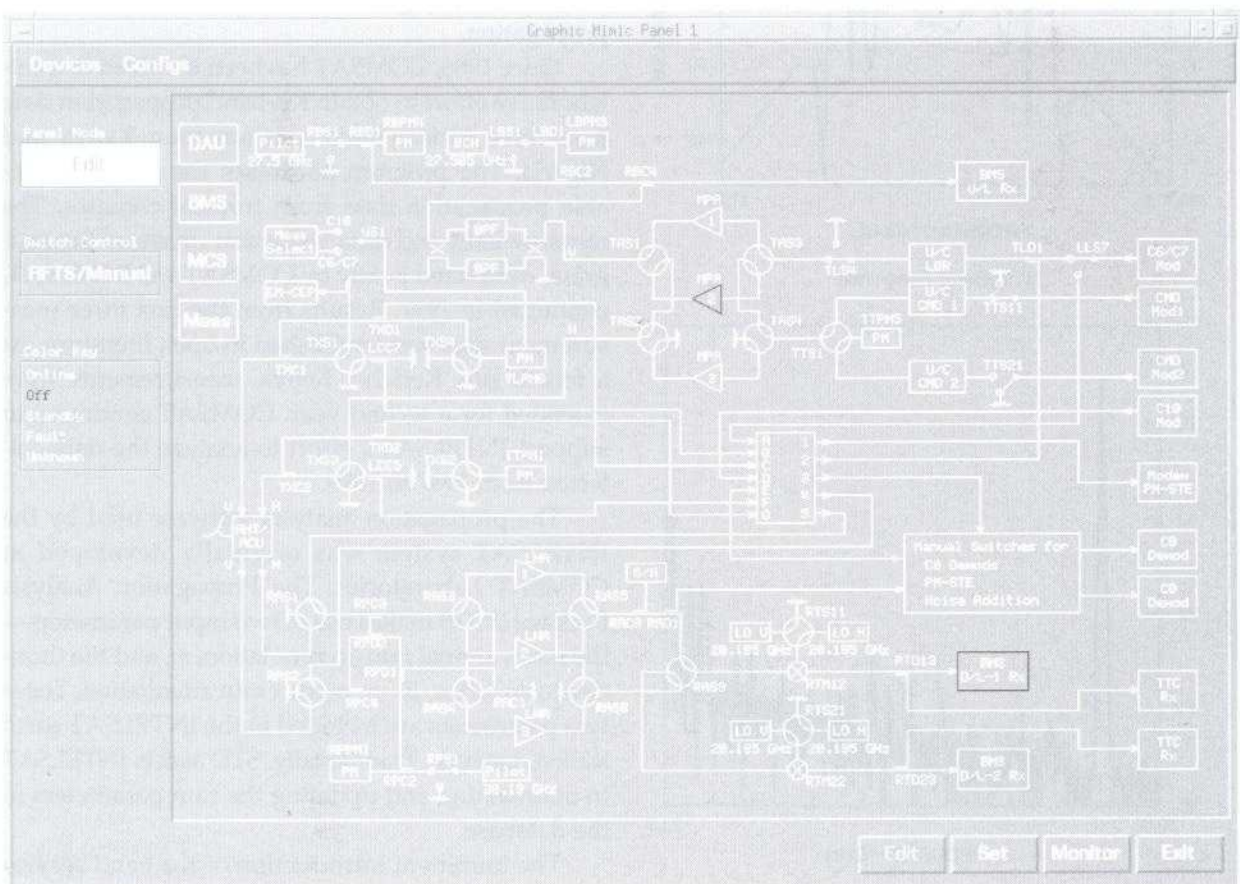


Figure 13. Graphic Mimic Panel provides real-time status of the NASA ACTS ground station and allows the user to configure switch positions by mouse

multimode filter technology, superconducting thin films, and MMIC circuits in an effort to achieve further miniaturization of filters and savings in filter mass.

A new concept for the realization of a narrowband filter with a wide spurious-free response was successfully tested, and a Ku-band filter was designed, tuned, and measured. This filter employs a combination of modes and iris geometry to yield a spurious-free response from 12 to 26 GHz. It can directly replace the combination of a conventional narrow-bandpass filter in series with a low-pass filter (currently used in satellite output multiplexers), resulting in a savings in mass and volume of about 50 percent. A Ku-band wide spurious-free filter is shown in the "Division Highlights," (p. viii, bottom).

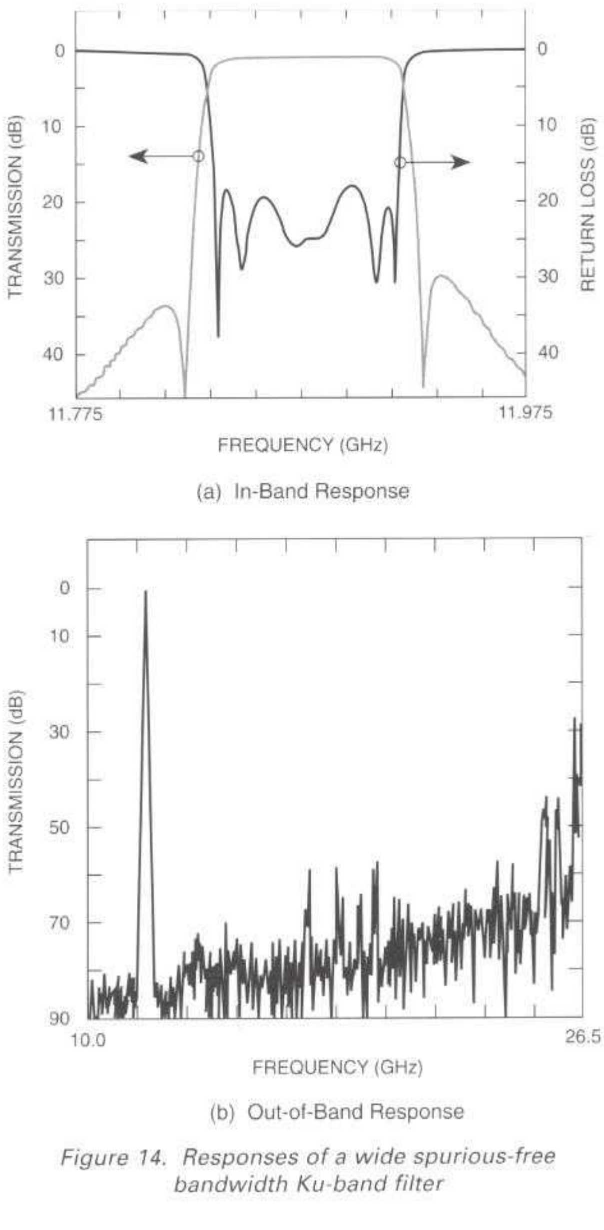


Figure 14. Responses of a wide spurious-free bandwidth Ku-band filter

Figure 14 shows the in-band and out-of-band responses of this filter.

Following the successful development of four-pole superconducting filters in 1991, six-pole Chebychev filters were designed and built on lanthanum aluminate substrates. A three-channel microstrip multiplexer was also designed and breadboarded in alumina, with excellent results.

STD also completed phase II of a contract for MMIC active filters with the Naval Research Laboratory (NRL) during 1991. This phase comprised a study of alternatives, circuit design, and fabrication of an active MMIC filter with 60-dB rejection at band edges (see "Division Highlights," p. ix, top left).

PROPAGATION STUDIES

Modeling of propagation impairments that affect satellite links contributes significantly to the design of reliable communications systems. Accordingly, a number of investigations relating to propagation impairments are being conducted within STD, and include rain attenuation, low-elevation angle clear-air effects, and ground effects on satellite-mobile propagation.

Since 1986, COMSAT has been involved in a collaborative effort to obtain Ku-band propagation data from three African nations—Cameroon, Kenya, and Nigeria. The program addresses the need for reliable propagation data from tropical climates. The measurement and data reduction phase of the program, conducted jointly by COMSAT and INTELSAT, continued in 1991. Results from the first three measurement sites were published in open literature. At a fourth site, Kericho, Kenya, measurements were extended for a second year. COMSAT continued to support INTELSAT's effort to analyze the data collected from 1987 to 1989.

The propagation analysis software used by the INTELSAT system was originally developed at COMSAT Laboratories. The Propagation Analysis Package (PAP) makes use of two input parameters—the mean annual rain accumulation, m, and the thunderstorm factor, β—to predict rain attenuation. These two parameters are included in the INTELSAT earth station database. Traditionally, STD assists INTELSAT in maintaining and updating the rain parameters in the database.

The imminent introduction of Ku-band service in parts of the world where regular heavy rainfall is encountered (*e.g.*, the Pacific Rim and South America) has focused attention on the need for reliable prediction of rain attenuation outages. Although PAP performs adequately in temperate regions of the world, its effectiveness in high rainfall regions has not been examined in detail.

Under contract to INTELSAT, STD used a database containing approximately 125 sets of measured attenuation data at Ku-band frequencies to evaluate the performance of the PAP model in different regions of the world. Although the model dates to the early 1980s, its predictions were found to fall within the range of variability expected from natural causes. Comparison of PAP with the prediction method recommended by the International Radio Consultative Committee (CCIR) indicated that the latter model did not display any significant advantage. Additionally, the PAP model was improved to enhance the scope and accuracy of the depolarization prediction. A database containing the worldwide distribution of surface temperature and humidity was added to the PAP software to enable the prediction of scintillation effects, which become increasingly important at higher frequencies and lower elevation angles.

The extension of satellite coverage to elevation angles well below established norms will result in substantial economic benefit for the INTELSAT system. Propagation impairments will play a dominant role in deciding the operational aspects of such low-elevation-angle links. Investigations covering these concerns were undertaken during 1991, and models were developed for predicting cloud attenuation, gaseous absorption, melting layer attenuation, low-angle fading, and several other clear-air effects.

Very-low-elevation satellite links (less than 5° elevation angle) are not normally used for public switched telephone network applications, but in some cases their use, albeit with reduced availability, may be justified for economic and strategic reasons. The severe propagation impairments encountered at very low elevation angles must be properly understood for the successful design and operation of such links. STD developed a measurement system which can collect pertinent propagation information at several frequencies, and plans are under way to deploy the system in a location close to the equator. The severity of most low-elevation-angle impairments is expected to increase with increased temperature and humidity. The measurement system has the ability to collect data relevant to implementing short baseline diversity, diversity combining, and up-link power control (ULPC).

With the increasing use of higher frequency bands for satellite communications, techniques for overcoming propagation impairments assume a significant role. Open-loop ULPC is one such technique especially suited to international networks such as INTELSAT. For the past 3 years, COMSAT Laboratories has been involved in the development of low-cost ULPC systems. In 1991, STD consolidated the basic system concepts and implemented them in operational earth stations. The ULPC system relies on estimating up-link fade using a measured down-link beacon level. An important element of this system is the separation of down-link propagation effects from equipment-related variations. After isolating the down-link fade, further separation is required to distinguish rain effects from tropospheric scintillations, since the two phenomena require different frequency scaling factors when estimating the up-link fade.

STD has developed and tested two algorithms capable of achieving these objectives. One of the systems, developed under contract to INTELSAT, is being used in a long-term evaluation program involving the continuous monitoring of a satellite link between Clarksburg, Maryland, and Eindhoven, the Netherlands. The second system, developed under corporate funding, has undergone a short test period using the space segment on a domestic satellite. Both systems have demonstrated that they can maintain power flux at the satellite within ±2 dB of the nominal level. Figure 15 illustrates data collected during ULPC trials.

In 1991, under contract to INTELSAT, STD refurbished two sets of radiometric equipment designed and developed at COMSAT Laboratories. The equipment, used for radiometric measurement campaigns in Africa, will be redeployed in Brazil and New Zealand.

As part of COMSAT's extensive involvement in activities of the standards committees of the International Telecommunication Union, STD supports both national and international participation in the deliberation of the International Radio Consultative Committee (CCIR), particularly CCIR Study Group 5 (SG 5), "Propagation in Non-Ionized Media." In 1991, STD provided U.S. representation to international meetings of Working Party (WP) 5B and 5C

COMSAT's interest in radio propagation relates to both fixed and mobile satellite services, which are the concern of WP5C and WP5B, respectively. In relation to fixed satellite services, STD evaluated rain attenuation prediction in an attempt to take advantage of regional differences in rainfall characteristics. In the mobile satellite arena, STD contributed to the formulation of pertinent advice on propagation issues

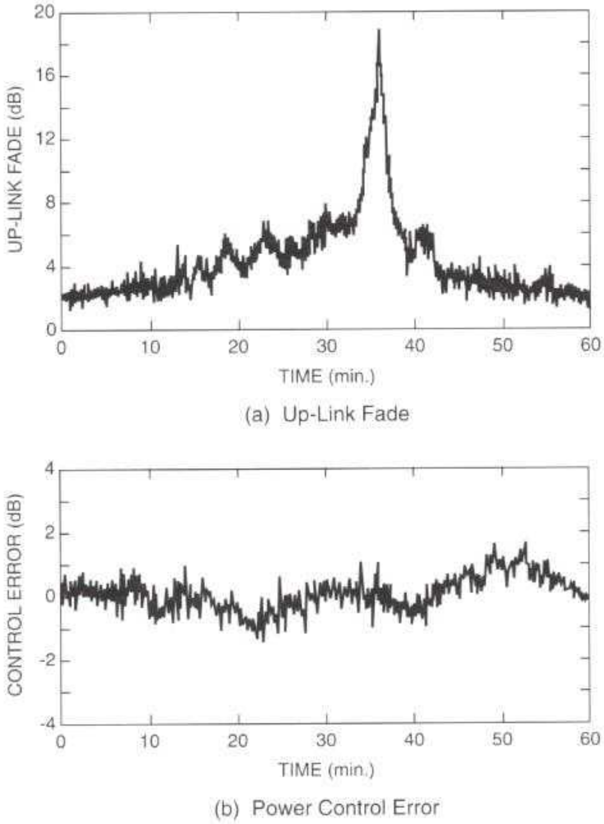


Figure 15. During an up-link fade, the ULPC algorithm maintains power control to ±2 dB

for the user community, and to the creation of an aeronautical mobile database to collate measured propagation data from both U.S. and overseas sources.

DESIGN & FABRICATION CENTER

STD's Design and Fabrication Center (DFC) is a state-of-the-art prototype manufacturing facility that supports both the Laboratories and the Corporation. In 1991, the DFC manufactured stationkeeping hardware for the MicroSat program of Defense Systems, Inc. (DSI). The hardware was installed and tested on seven spacecraft, and the high-pressurization charging system was calibrated. As demonstrated by the successful launch of all seven spacecraft, the system operates within design limits. For another DSI program, the DFC fabricated the spacecraft structure and payload plate for the COMET spacecraft. This structure is undergoing static load tests in STD's Mechanical Testing Cell. Other recent DFC work included the production of an adapter section for another DSI program, the manufacture of microwave hardware for the National Institute of Standards and Technology (NIST) in the Model Shop, and the manufacture of gold-plated solar cell interconnects for the Solarex Corporation in the Plating section.

COMMUNICATIONS TECHNOLOGY

The Communications Technology Division (CTD) made significant progress during 1991 in improving the error performance of satellite links in the INTELSAT and Inmarsat systems. Advances were achieved in transmitting video to ships at sea; compressing high-definition television (HDTV); video multiplexing; specifying future mobile systems; improving speech quality in 4.8-kbit/s codecs; completing facsimile interface units for the Inmarsat-B and Aeronautical systems; and finalizing various national and international standards initiatives. Building on knowledge gained last year, CTD has developed new Reed-Solomon outer codecs for the INTELSAT intermediate data rate 1.5- and 2.0-Mbit/s services to improve the bit error ratio from 10^{-6} to fiber optic quality. Similar improvements were achieved for the 155-Mbit/s modem/codec unit. Digital signal processor-based modems optimized for fading channel operation were developed for first- and second-generation Inmarsat-C services. Super Bowl XXVI was delivered via Inmarsat to U.S. Navy ships, including the USS *Eisenhower*. Other video achievements included significant improvement in the efficiency of encoding HDTV using a simplified vector quantizer approach, and development of a multiplexer that can accommodate three broadcast-quality National Television System Committee (NTSC) and/or phase alternate line (PAL) standard video signals from diverse up-links within a single 36-MHz INTELSAT transponder. Advances in critical technologies for next-generation satellites, which will employ onboard processing, were achieved through the completion and evaluation of the proof-of-concept onboard demultiplexer/demodulator. Also in 1991, CTD standards support culminated in the publication of an American National Standards Institute (ANSI) digital circuit multiplication equipment (DCME) standard and new International Telegraphy and Telephony Consultative Committee (CCITT) draft recommendations (led by CTD Special Rapporteurs) for a 16-kbit/s encoding algorithm and for facsimile demodulation/remodulation in DCME. ■

VIDEO PROCESSING

High-Definition Television

The excellent picture quality and high resolution of HDTV have presented many new opportunities for services that demand high video quality, such as telemedicine, remote sensing, and entertainment applications. However, since satellite transmission of HDTV requires wide bandwidth and high power, minimizing these requirements through data-rate compression of the HDTV signal is very important in order to minimize earth terminal size and satellite power. A basic HDTV compression research effort initiated in 1990 led to a contract award from NASA. As a result of the NASA HDTV Phase I study, subband-based signal decomposition and reconstruction (Figure 1) was proposed to reduce the high-speed processing requirement for HDTV. The LL-band signal is subjected to motion estimation and

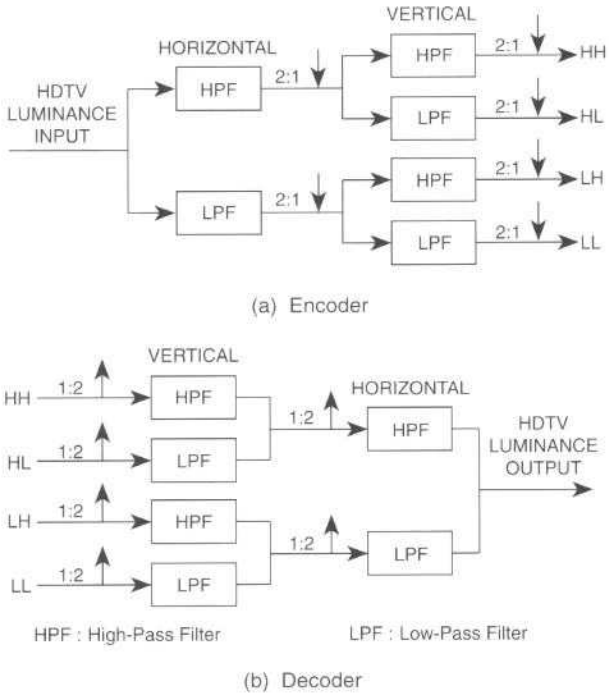


Figure 1. Subband codec reduces high-speed processing requirements

compensation to reduce interframe differences. The subband signals are then compressed by using a simplified vector quantization (SVQ) technique. Extensive software simulations have indicated that the bit rate can be reduced to less than 20 Mbit/s with only a slight reduction in quality. These encouraging Phase I results led to the award of a Phase II contract for hardware development of the subband and SVQ codecs. The simulation facility, consisting of two HDTV monitors and a Magni signal generator, was improved to support HDTV research by the addition of a Sony digital HDTV videotape recorder. To enhance the central processor unit (CPU) power required for software simulation, five high-performance Hewlett-Packard HP700-series workstations were obtained. A Sony HDTV frame grabber now being acquired will further enhance the simulation capability by permitting the use of HDTV sequences.

Time-Multiplexed Television

The prototype time-division multiplexed video transmission (TMTV) two-TV multiplexer developed in 1989, and described in previous Laboratories' annual reports, allows the simultaneous transmission of two broadcast-quality video signals through a single 36-MHz transponder. After many successful laboratory demonstrations and field trials, this technology is being produced by a supplier for deployment in television networks. Both the transmit and receive units are compact in size, measuring 13.3 cm high x 48.7 cm wide x 35.6 cm deep.

In 1991, a TMTV-3 NTSC/PAL proof-of-concept system was completed. The system is capable of transmitting three time-division multiple access (TDMA) broadcast-quality video signals in one 36-MHz transponder. An attractive new feature of the system—the ability to transmit any combination of three U.S. (NTSC) or European (PAL) standard video signals from diverse up-link sites—has greatly enhanced system flexibility. Mixed NTSC/PAL operation is expected in many international video transmission applications, as the equipment can operate in global as well as spot/hemi beam environments.

Video Transmission & Compression

COMSAT Video Enterprises (CVE) has been exploring the possibility of transforming its multiplexed analog component (MAC) video distribution system to a digital TV distribution system. The added flexibility and diversity of a digital system would result in a number of potential advantages for CVE. Realizing that a transformation of this magnitude would not take place without a period during which a mix of digital and analog signals would be present in the satellite distribution system, CVE commissioned the Laboratories to investigate the limitations of mixing digital and analog TV signals in a common transponder. This investigation focused on interference between digital and analog carriers sharing a common satellite transponder when the transponder is loaded with a single analog and multiple digital carriers. The results were presented in a form suitable for calculating interference in the CVE distribution system, given various known parameters of each carrier type (*e.g.*, transmit power, satellite used, and nearest neighboring satellite).

The Laboratories also designed a video codec breadboard for CVE to evaluate picture quality at various bit rates. The hardware is based on the proprietary SVQ algorithm. SVQ alleviates computational complexity at the encoder and large codebook storage problems at the encoder and decoder, which are encountered in regular vector quantization, while preserving the advantages of high compression efficiency and low decoder complexity. Along with the SVQ algorithm, many other quality improvements and rate reduction techniques were developed. Extensive software simulations were conducted, and the results show that high broadcast-quality video can be achieved around 10 to 15 Mbit/s, whereas VCR-quality video can be achieved around 2 to 3 Mbit/s.

The Laboratories has been actively involved in implementing COMSAT Mobile Communications' (CMC's) new service offering of live video transmission to ships at sea. This service utilizes highly compressed video signals, operating at around 300 kbit/s, which are transmitted (over Inmarsat satellites) to Inmarsat Standard A terminals on ships. The Laboratories' contributions to this new service include link design, equipment specifications, demonstration, troubleshooting, and assistance with ship installations such as the USS *Eisenhower*.

The video quality of satellite TV transmission has always been an important issue for COMSAT World Systems (CWS). Due to the trend toward digital TV transmission via satellite, increased use of digital video codecs in satellite transmission is anticipated. In order to understand how digital video behaves in the satellite environment, the Laboratories conducted studies using signals from commercial video codecs which were processed through a satellite simulator. The threshold energy-per-bit to noise-power density ratio, E_b/N_o, at which the picture begins to deteriorate sharply was measured under noise, adjacent channel interference, and co-channel interference conditions. NEC and Telettra 45-Mbit/s codecs were used. For thermal noise interference, both codecs exhibited about the same threshold at 15-dB simulator input backoff. When the input backoff was reduced to 6 dB, the threshold increased by about 0.5 dB. In the co-channel interference test, the E_b/N_o was maintained at 10.5 dB and the resulting threshold carrier-to-interference ratios, C/I's, differed by about 1 dB between the two codecs. Adjacent channel interference appeared to have little effect on the thresholds.

BASEBAND ENCODING & COMPRESSION

Voiceband Processing

In 1991, R&D continued on source encoding of speech, sound program audio, and facsimile images at various transmission rates. Work was initiated on development of a 1,200-bit/s speech codec suitable for communications-quality mobile systems. The algorithms that were investigated exploit intraframe and interframe signal redundancies to permit speech coding at low rates with satisfactory quality.

As a first step, the methods investigated derive a representation of a segment of voice (or frame) by means of a set of linear predictive coding (LPC) parameters. This representation is then converted to a vector of 10 line spectrum frequencies (LSFs), which is subsequently split into two subvectors, L_1 and L_2, where $L_1 = 4$ and $L_2 = 6$. For each subvector, a vector quantizer is designed independently, with codebooks of lengths 2^{B1} and 2^{B2}, respectively, such that B1 + B2 equals the desired LSF vector bit rate per frame.

A key concept in the development of a high-quality voice coding system is the rate at which the system parameters are updated over time. Better quality is achieved by updating the system parameters more frequently. This can be accomplished by shortening the frame length, at the expense of a higher transmission rate. Alternatively, more efficient methods can be found for transmitting the same information. To achieve higher quality than previously possible, a frame duration of 20 ms was chosen, rather than the more commonly used 22.5 ms. As a result, the speech representation parameters are updated 50, rather than 44.4, times per second.

To compensate for the increased bit rate resulting from the frame size reduction, a finite state vector quantizer (FSVQ) design was investigated. By exploiting adjacent frame parameter correlations, this design can reduce the number of bits required to represent the two LSF vectors from 20 to 17 bits per frame. In addition, two other nonlinear properties were investigated. The first exploits the LSF local spectral sensitivity, and the second, the characteristic that the human ear cannot resolve differences at high frequencies as accurately as it can at lower frequencies. Figure 2 is a functional block diagram of the encoder.

Computer simulations were conducted to evaluate the performance of the 28-bit/frame voice coder at a frame rate of 50 frame/s. The split vector quantizer yielded an average spectral distortion of 1.15 dB when measured with an independent test set. Informal listening tests showed that the quality of the reconstructed speech was highly acceptable. Future efforts

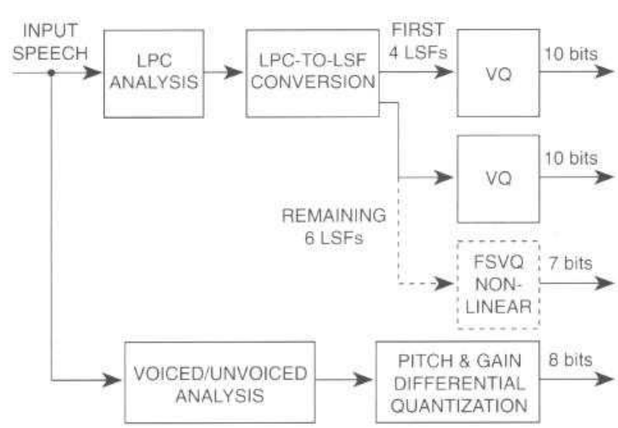


Figure 2. Low-rate voice encoder includes FSVQ to compensate for frame size reduction

will focus on reducing the average spectral distortion of the 20-bit split vector quantizer to about 1 dB and reducing the bit rate, without noticeable degradation in speech quality.

Digital Audio Broadcasting

Under the sponsorship of CMC, two areas of sound program audio received attention. The first relates to the transmission of audio signals in mobile environments, and the second to the transmission of audio signals over the Fixed Satellite Service.

With regard to mobile audio transmission, an audio compression scheme was developed based on the adaptive predictive coding with transform domain quantization (APC-TQ) signal processing technique, which permits encoding of audio signals over a 5.5-kHz bandwidth at a bit rate of 24 kbit/s or less. This scheme was subsequently implemented in real time on a Motorola 96002 digital signal processor (DSP) platform, and its performance was evaluated using expert listener assessments. Initial results confirmed that the quality is very good over a wide range of material. In addition to the real-time implementation, more advanced algorithms based on auditory noise masking and critical band analysis techniques were investigated and their performance simulated off-line.

Regarding the transmission of audio over the Fixed Satellite Service, two areas were studied to support the development of a satellite digital audio broadcasting (DAB) service. Existing digital audio coders were surveyed to identify the features and manufacturers of this type of equipment. This survey showed that currently available coders employ improved source coding/compression techniques which permit the transmission of audio material at significantly lower rates, ranging from 512 kbit/s for near-CD quality to 24 kbit/s for broadcast AM quality.

Another study consisted of parametric link analyses to illustrate the transponder capacity of various satellites (at both C- and Ku-band) for a series of different conditions, including receive earth station size, link margin, and transponder gain setting. The analysis provided space segment *vs* earth station size tradeoffs that can be used in planning DAB systems.

LD-CELP

Recently, a low-delay code-excited linear predictive (LD-CELP) algorithm was selected by the CCITT for the toll-quality encoding of telephone bandwidth voice at 16 kbit/s. For the LD-CELP algorithm to form a credible option for applications such as DCME, operation at rates lower than 16 kbit/s is desirable so that traffic can be accommodated during DCME overload conditions. During 1991, under the Laboratory Engineering Assistance Contract (LEAC) with INTELSAT, a study was conducted to quantify the ability of the LD-CELP technique to operate at various transmission rates and to interconnect with other voice coding standards. The results of this evaluation indicate that operation of the LD-CELP algorithm at lower rates (such as 12.8 kbit/s) provides quality which is subjectively equivalent to that of the 24-kbit/s adaptive differential pulse-code modulation (ADPCM) used during DCME overload conditions. Thus, it appears that the LD-CELP algorithm presents a credible option for inclusion within a DCME and packet circuit multiplication equipment (PCME) overload strategy.

As part of the same study, the quality of interconnected North American Digital Cellular networks employing the 8-kbit/s vector sum excited linear predictive (V-SELP) algorithm with 16- and 32-kbit/s DCME/PCME-based switched telephone networks was quantified. Based on these assessments, it was concluded that cellular networks using the V-SELP algorithm are likely to meet end-to-end quantization distortion allocation criteria when interconnected with the switched network. The results of these tests are presented in Figure 3, which shows the mean opinion score (MOS) equivalent of the above conditions, as well as those of 32- and 24-kbit/s ADPCM.

4.8-kbit/s Codec Improvement

Mobile satellite communications systems for land, maritime, and aeronautical applications are an important part of a wireless world communications

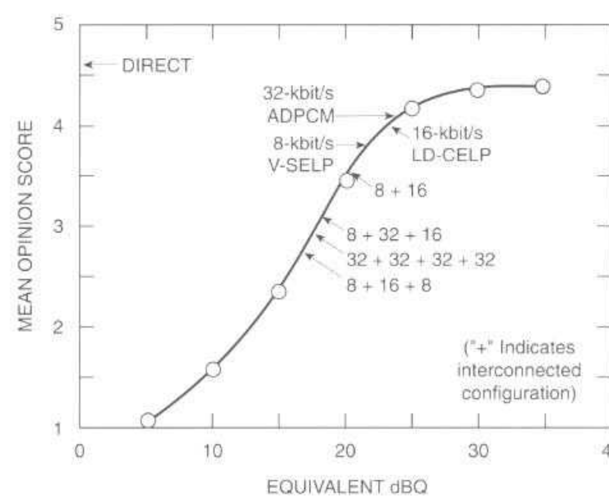


Figure 3. Subjective evaluation provides a quality performance ranking for various codec combinations

network. Critical to successful mobile satellite communications are the efficiency and quality of the low-rate digital coder (or vocoder) technique used for speech transmission. For 4.8-kbit/s, two vocoders have shown the greatest success in producing good communications-quality speech. One is the improved multiband excitation coder (IMBE), and the other is the CELP coder. While these vocoders represent a significant advance in low-data-rate voice coding, audible signal distortions have been noticed during their operation, which indicates that significant benefits could be realized if the factors responsible for the distortion could be identified and removed.

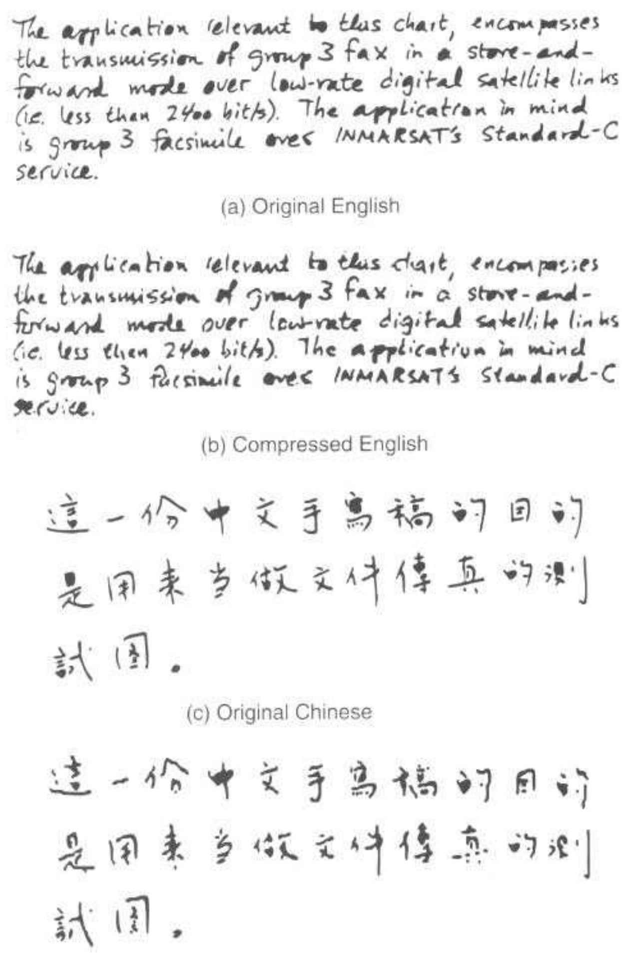
In 1991, an investigation was undertaken on behalf of CMC to identify such algorithmic voice degradation and to develop new schemes or modifications to improve IMBE and CELP vocoder performance. To meet these objectives, an experiment was conducted in which a diagnostic spectrographic analysis was performed on a set of recorded speech utterances. Based on the diagnostic results, two new schemes were developed: the multiband-excited linear predictive coder (MBELPC), and the pitch-tracking CELP (PT-CELP). Subsequently, simulation software was developed for the IMBE and MBELPC coders, and informal expert listening tests were conducted to confirm that the quality of the MBELPC vocoder at 3.2 kbit/s was nearly equivalent to that of the IMBE vocoder at 4.8 kbit/s.

During this study, a problem associated with the transparency of low-data-rate vocoders to dual-tone multifrequency (DTMF) signals was also identified. In response, a novel, very simple software algorithm was devised to enhance DTMF signaling transparency through a general class of linear predictive all-pole filter vocoders. The algorithm relies on the LSF parameters of the vocoder's spectrum filter to distinguish DTMF signals from speech and to identify which tone pair is being transmitted from the end-user. This algorithm can also be used in multifrequency signaling applications.

Facsimile

Compression of facsimile images over and above that possible by standard Group 3 facsimile machines is critical for providing economically viable facsimile services over the low-rate transmission channels that characterize mobile Inmarsat services. Without substantial compression gains, such services become too expensive to the consumer. Two candidate image compression approaches, investigated in 1991 for CMC, were identified as the most promising and were simulated. Both methods seek to retain high image intelligibility, rather than quality, and are based on an analysis-by-synthesis (A/S) technique developed at COMSAT Laboratories in 1989.

In the first approach, a variable-length coding scheme was developed and optimized for the characteristics of handwritten images compressed by the A/S method, resulting in an overall compression gain of 50 to 1, or a factor of 4 better than standard Group 3 facsimile coding. In the second approach, the compressed image resulting from the A/S compression scheme was subjected to a pattern matching process. Combined with a simple variable-length coding scheme, this approach demonstrated that average compression gains in the range of 57 to 115 are achievable, with good text intelligibility for the reconstructed image (relative compression gains in the range of 6.7 to 7.6 over standard Group 3 facsimile coding). Examples of segments of original and reconstructed images are shown in Figure 4. The reconstructed



(a) Original English

(b) Compressed English

(c) Original Chinese

(d) Compressed Chinese

Figure 4. Examples of original and reconstructed text demonstrate good text legibility for compressed gains of 57 to 115

English text was generated from a coded image representation which was compressed by a factor of 57 to 1, and the reconstructed Chinese text was generated from a coded image representation compressed by a factor of 115 to 1.

FACSIMILE & DCME

Inmarsat-B & Aircraft Earth Station Facsimile Interface Units

The importance of communications employing facsimile transmission over public switched telephone networks (PSTNs) is evidenced by the rapid annual growth in the number of end-user Group 3 facsimile terminals. However, the transmission of Group 3 facsimile over narrowband digital satellite mobile networks presents a challenge because facsimile signals, which are transmitted as 9.6-kbit/s voiceband data over the analog PSTN, require the allocation of at least 40 kbit/s of bandwidth when transported over digital links. The user data channel capacity in narrowband mobile digital systems rarely exceeds 10 kbit/s. Thus, the support of such traffic and interworking with terminals connected to the PSTN requires specialized, cost-effective solutions for reducing bandwidth requirements, as well as conversion of facsimile protocols to a format suitable for use over digital mobile satellite networks. These requirements can be met by using waveform demodulation, whereby facsimile signals are converted from the voiceband to the digital baseband domain.

In 1991, COMSAT Laboratories completed a 2-year development effort which began with a protocol specification review and culminated in the implementation of one set of prototype real-time facsimile interface units (FIUs) for operation over the Inmarsat-B, -M, and Aeronautical systems. The FIUs were designed to perform two basic functions: to convert incoming or outgoing signal waveforms from the voiceband to the baseband domain or vice versa; and to perform protocol conversions so that Group 3 facsimile protocols become compatible with the transport channel constraints of the three basic Inmarsat service configurations. The FIUs also incorporate a set of protocols for converting point-to-point Group 3 facsimile to broadcast operation.

This concept was evaluated in terms of channel error performance by using a prototype FIU system developed at COMSAT Laboratories. The results confirm the validity and robustness of the concept as implemented over simulated satellite links.

FAX/DCME Transmission Issues

In addition to activities related to facsimile transmission over mobile systems, a study was undertaken on facsimile communications and protocol interaction with trunked circuit-multiplexed networks. This study focused on the protocol analysis of facsimile calls in a laboratory environment, and investigated potential reasons for call failures. As part of this study, specialized equipment was developed to evaluate the interaction of facsimile with demodulating/remodulating network segments.

During 1991, the implementation of a facsimile test set (variable fax machine) was completed. In addition, facsimile calls were analyzed to assess their compliance with CCITT Group 3 protocols. Where deviations were found, an assessment was made of the manner in which these deviations could lead to interactions with telecommunications networks incorporating facsimile demodulation technology. It was concluded that a significant number of facsimile transmissions fail to meet the requirements set by CCITT Recommendation T.30 (which specifies facsimile protocol), thus leaving the network in an indeterminate state. This deviation from the standard could be the underlying cause of some call failures; however, additional studies are needed to quantify this supposition.

Also in 1991, a four-channel facsimile activity monitor was designed and implemented. The unit is particularly useful for monitoring networks that incorporate facsimile demodulation, and where transmission delay could be a function of signal type and signal transmission direction. In addition, the hardware implementation of a facsimile demodulation test set was completed. The test set can be used to study the interaction of facsimile protocols with demodulating/remodulating equipment under operator programmable conditions, as well as to simulate a variety of end user facsimile terminal protocol conditions in a controlled environment. Finally, a detailed methodology was developed to assess the interaction of DCME and PCME when transporting facsimile traffic.

FAX/DCME Standards Activities

As part of COMSAT's interest in the development and standardization of efficient transmission technologies, support was provided in developing national and international standards for circuit-multiplexed equipment. Under COMSAT's chairmanship in 1991, the U.S. ANSI Specification T1.309-1990 on DCME was completed and published. This specification permits the development of DCME that is backward-compatible with the INTELSAT Earth Station Standards (IESS)-501 DCME specification and CCITT Rec. G.763.

Also in 1991 and under COMSAT's leadership, CCITT completed a specification on the transmission of facsimile over DCME-based networks using demodulation/remodulation technology. In addition, significant effort was directed toward the development of DCME-compatible high-speed voiceband data modems (V.fast) capable of operating at rates up to 24 kbit/s to facilitate future demodulation/remodulation.

ECHO CONTROL

COMSAT provided support in the development and modernization of echo control specifications, particularly the ongoing revision of CCITT Rec. G.165 on network echo cancellation, to improve echo control performance in the evolving digital network and in the presence of voice and non-voice signals. Many of the revisions under consideration are the result of work conducted in 1990 by COMSAT Laboratories under contract with EUTELSAT. In addition, COMSAT initiated the current motion which is progressing through CCITT to declare Rec. G.161, "Echo Suppressors Suitable for Circuits Having Either Long or Short Propagation Time," as obsolete and superseded by Recs. G.164 and G.165.

VOICE & VIDEOPHONE EVALUATION

Videophone Tests

In 1991, a study was conducted for CWS to assess the subjective effect of end-to-end transmission delay in videotelephone environments. While only part of the videotelephone portion of the study was concluded by year-end, the design, administration, and analysis of a pilot (telephone) test was completed. The purpose of the pilot test was to identify the subjective procedures and experimental design to be used in conducting videotelephone tests, as well as to assess the impact of the reference delay condition on circuit acceptability.

The pilot test was conducted by splitting participants into two groups (A and B) and exposing each group to two sets of partially overlapping delay conditions: 0, 400, and 750 ms for group A; and 200, 400, and 750 ms for group B. Pilot test results (Figure 5)

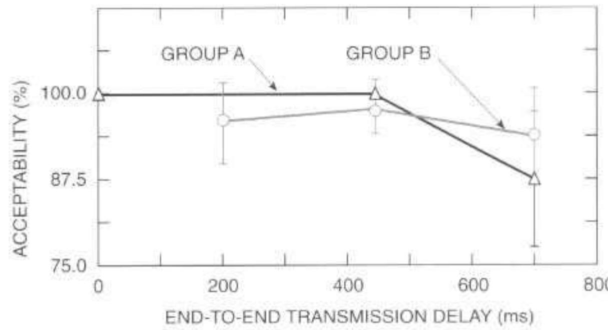


Figure 5. Videophone circuit acceptability improves as lowest delay increases

indicated that communications performance appears to degrade more rapidly with increasing delay as the lowest delay experienced by participants is reduced. This lends credibility to the speculation that communications participants may be less sensitive to delay when they are denied the benefit of a 0-ms delay environment, as is the case in videotelephony.

16-kbit/s Host Lab Support & Standards Activities

Also in 1991, CTD supported the development of international standards in voice coding. Under contract with INTELSAT, COMSAT Laboratories functioned as "host laboratory" for CCITT standardization of an LD-CELP algorithm. As part of this effort, a large database of source speech was processed over a variety of conditions and languages, and forwarded to a number of countries for subsequent evaluation by subjective listener assessments. In addition, the performance of the LD-CELP algorithm with narrowband signals, with CCITT Signaling System No. 5, and with DTMF signaling was assessed and data were provided to CCITT. This effort contributed to the recent adoption of the LD-CELP algorithm by Working Party 2 of CCITT Study Group XV for the toll-quality encoding of telephone-bandwidth voice at 16 kbit/s.

Under COMSAT's leadership, CCITT Rec. P.84 on subjective methods for the performance evaluation of DCME systems was revised. COMSAT also provided data for inclusion as an appendix to the revised CCITT Rec. G.114 on the network planning aspects of end-to-end transmission delay.

TRANSMISSION PROCESSING

The viability of the global satellite system depends on continuous improvement in transmission efficiency, which can be realized in various ways, from improving the bandwidth or power efficiency of existing systems to designing new system architectures such as onboard signal processing. Typically, performance enhancements are first investigated under a corporate research program, where general architectures are derived and performance estimates are established using computer simulations. Detailed system design and hardware implementation are then accomplished under a proof-of-concept development project, and finally, nonlinear channel performance is demonstrated over the satellite simulation facilities in the laboratory or by field testing.

155-Mbit/s Modem/Codec

COMSAT's recently developed 155-Mbit/s broadband integrated services digital network (BISDN)-compatible transmission system was tested over a nonlinear channel in 1991 using COMSAT's satellite simulator, with excellent results. This system employs octal phase-shift keying (8-PSK) modulation, combined with a rate 13/15 multistage codec, and will transmit information at the BISDN rate of 155.52 Mbit/s through a single 72-MHz transponder. This represents a 29-percent increase in capacity over the existing 120-Mbit/s carriers and, more importantly, allows the transmission of BISDN traffic over existing satellite channels.

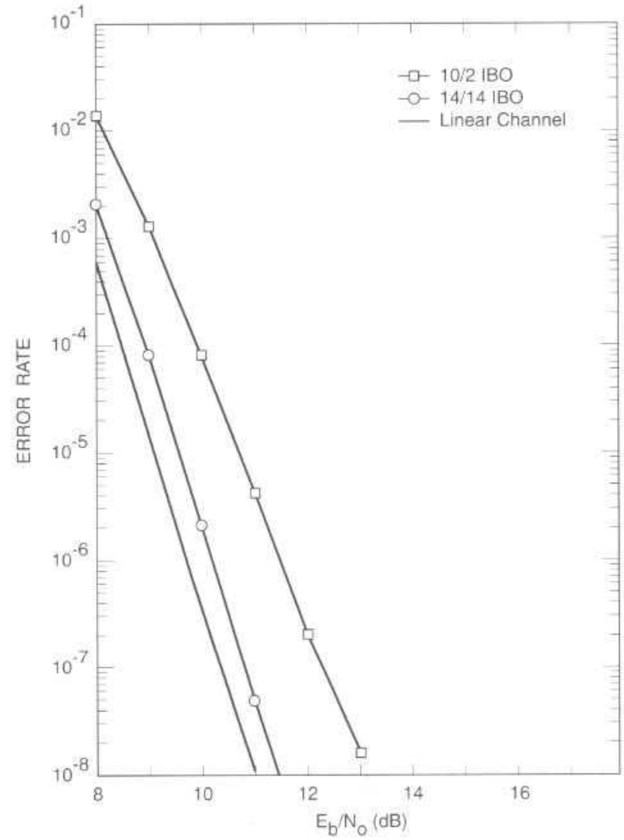


Figure 6. Linear and nonlinear channel BER measurements of the 155-Mbit/s system

Initial testing was performed with the system operating through a linear channel, resulting in data consistent with both theoretical analysis and computer simulation. Nonlinear channel measurements through the satellite simulator were then conducted, using earth station high-power amplifier (HPA) and satellite traveling wave tube amplifier (TWTA) input backoff (IBO) settings of 14/14 and 10/2 dB (HPA/TWTA). The results are shown in Figure 6. The results for 10/2 dB are of particular interest since they represent the values typically encountered under operating conditions. Additional tests performed at the 10/2-dB IBO operating point with co-channel and adjacent channel interferers yielded good results.

In addition to improving the bandwidth efficiency of satellite transmission, the 155-Mbit/s system also improves power efficiency. Comparing the nonlinear channel results with typical 120-Mbit/s quadrature phase shift keying (QPSK) data shows an improvement in power efficiency of approximately 1.5 dB at a bit error ratio (BER) of 1×10^{-7}.

To further improve the power efficiency of the coded 8-PSK, and to obtain fiber optic-compatible BERs, a BER improvement appliqué was developed that applies a Reed-Solomon (RS) outer codec to the baseline 155-Mbit/s system. The addition of the outer codec affords a large link margin, which guarantees excellent performance under degraded link conditions. The system also includes an optional operating rate of 140 Mbit/s, which is supported by a firmware change to the RS outer codec.

The detailed design and construction of the RS outer code was completed in 1991. The core of the design is based on commercially available high-speed RS decoder chips. Minor modifications were made to the 8-PSK modem to support the increased symbol rate. Linear and nonlinear channel performance measurements will be conducted in 1992.

BER Improvement for IDR System

To improve the quality of the 2.048-Mbit/s (and 1.544-Mbit/s) intermediate data rate (IDR) service to INTELSAT customers, a BER improvement appliqué has been developed which can enhance the performance of existing IDR systems by reducing the current 1×10^{-3} threshold BER to 1×10^{-6} without loss of transponder capacity. To function with existing in-service IDR satellite modems, the BER improvement appliqué was designed for low cost with minimal change in the commercial units.

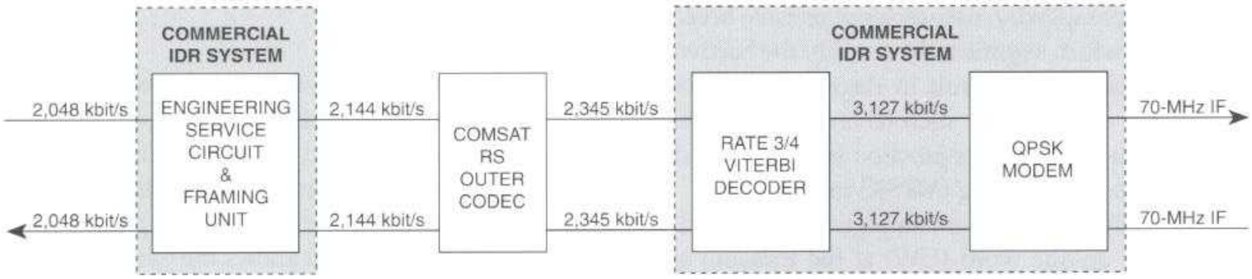


Figure 7. IDR system with outer codec

The developed system utilizes a new concatenated coding scheme that appends an RS outer codec to the baseline 2.048-Mbit/s IDR system, as shown in the block diagram of Figure 7. Various candidate RS outer codes were examined, and their performance with a nonlinear channel in the presence of adjacent channel interference (ACI) was simulated extensively to identify suitable codes that could be implemented inexpensively. From this subset of codes, the nine-symbol error-correcting shortened RS (210,192) code was selected as a representative code which met the design goals and could also be implemented unobtrusively.

The IDR outer codec hardware design (Figure 8), utilizes a low-cost, commercially available DSP and an off-the-shelf RS decoder integrated circuit (IC) to accommodate the IESS-308 (Rev. 5) T1 (1.544-Mbit/s) and E1 (2.048-Mbit/s) data rates. The prototype hardware comprises only 25 integrated devices. Multiple data interfaces are not required for the different IDR systems. Two low-cost, phase-locked, voltage-controlled crystal oscillators (VCXOs) are used to lock the operating speed of the outer codec to each of the T1 and E1 data rates. A single RS decoder IC is shared between the transmit and receive paths to minimize the board cost. All data-framing functions of the IDR outer codec are implemented in software in the DSP.

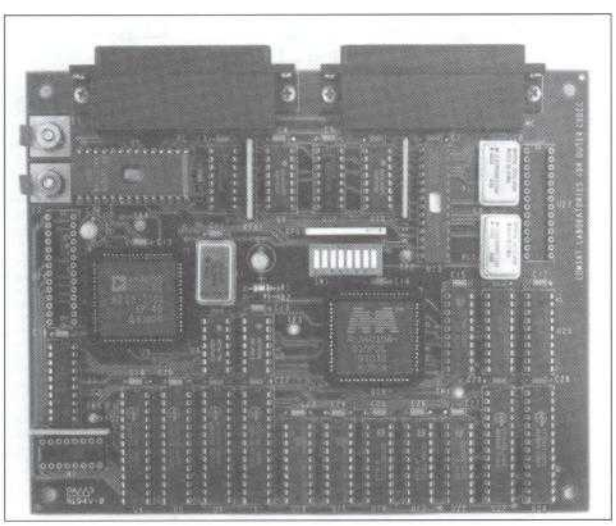


Figure 8. IDR outer codec hardware eliminates multiple data interfaces for different IDR systems

Preliminary laboratory tests of the BER improvement appliqué have been conducted. The results (Figure 9) were derived using an IF loopback test setup to provide linear channel performance data. Performance of the concatenated coding system is expected to degrade by about 0.2 to 0.3 dB when measured through a nonlinear channel under typical ACI and co-channel interference (CCI) conditions.

Differential Encoding

To improve system bandwidth and power efficiencies, modem and codec equipment has become necessarily more complex. In order to counter this

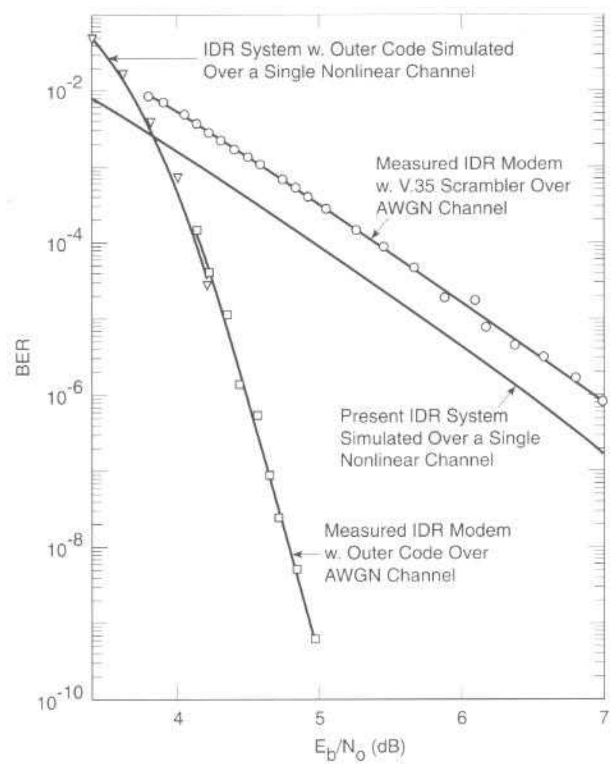


Figure 9. Preliminary tests of IDR system with 9-symbol (210,192) RS outer code (HPA = -14 dB IBO) demonstrate improved BER performance

increasing complexity, new techniques have been investigated which significantly simplify the hardware implementation and result in degradation of only tenths of a decibel. One such technique is differential decoding, used in conjunction with block-coded M-ary phase shift keying (MPSK) modulation.

Typically, carrier phase ambiguity is resolved by inserting a unique word (UW) at the transmit side and detecting it in the demodulator. Although effective, this technique is costly to implement and becomes even more difficult with MPSK formats. Differential encoding of data can also be employed, so that phase ambiguity resolution is not required; however, this causes a doubling of the BER. In digital communications systems utilizing both channel and differential encoding, it is advantageous to perform differential encoding prior to channel encoding (and channel decoding prior to differential decoding) so that the BER doubling results in a smaller signal-to-noise penalty (due to the shape of the BER curves).

Two simple schemes for differential encoding of block-coded MPSK signals have been devised which perform channel decoding prior to differential decoding. This technique has been evaluated using computer simulations which show that both schemes suffer only slight performance degradation compared to the non-differentially encoded case, with a significant reduction in hardware complexity.

Onboard Processing

Onboard processing offers two capabilities that will make future satellite channels more efficient and cost-competitive: onboard demultiplexing and demodulation. Demultiplexing permits switched multibeam operation at high effective isotropically radiated power (e.i.r.p.), which allows the use of low-cost earth terminals with small antennas and provides much more efficient connectivity. Demodulation and retransmission improve the link signal-to-noise ratio, S/N.

In the past year, the onboard demultiplexer/demodulator test facility (Figure 10) was thoroughly debugged, and multicarrier or shared demodulator operation was achieved. BER characteristics for the shared channel are depicted in Figure 11. The three curves illustrate progressively more complex operation: on a single carrier alone, on a single carrier from a group of three carriers, or on all three fully shared carriers.

The next phase of this CWS-sponsored program is to reduce the mass and power required of the prototype hardware through application-specific integrated circuit (ASIC) development. An important technique has been developed which minimizes the hardware complexity required to interpolate samples from the different carriers, in order to provide common timing for the shared demodulator. This technique, called

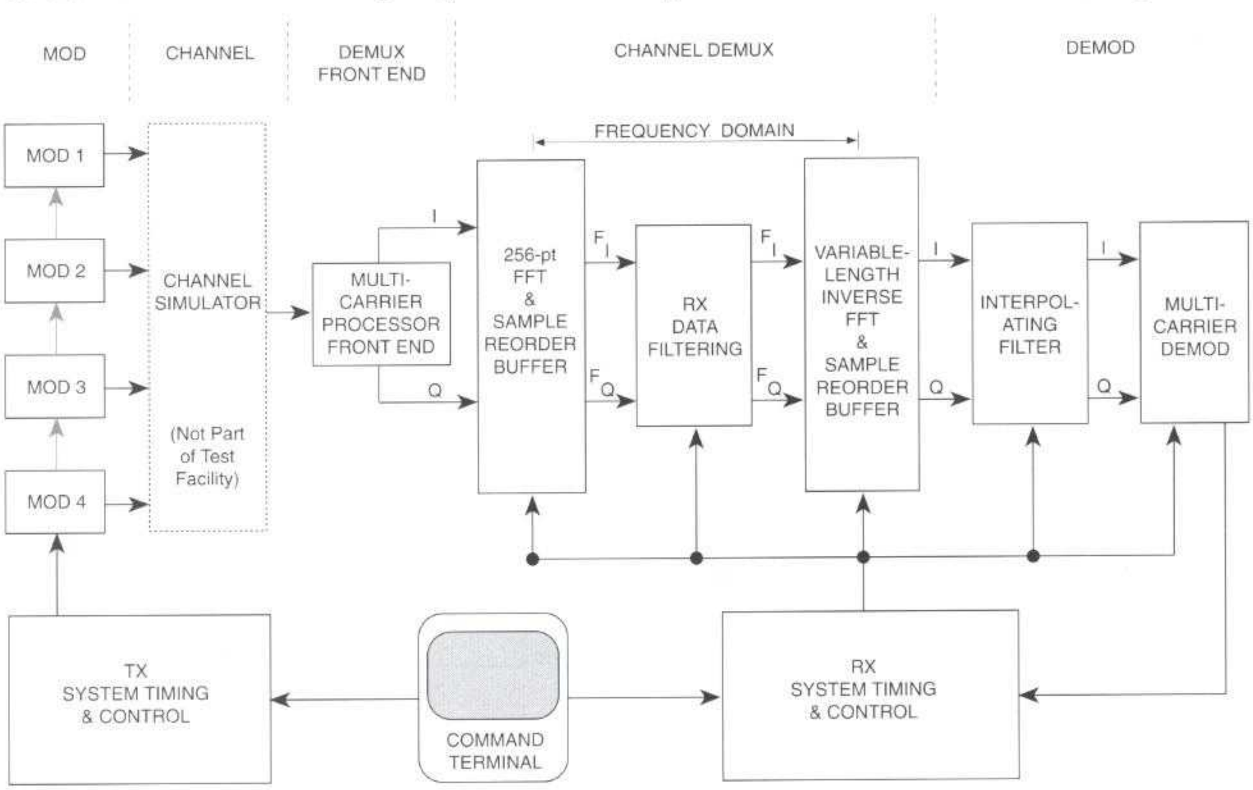


Figure 10. Demultiplexer/demodulator test facility can simulate multicarrier or shared demodulator operation

"detection-transition sample estimation," greatly reduces a major component of the overall hardware requirement.

Programmable Digital Modem

Fully programmable digital modems are now seen as a way of satisfying a requirement for a wide variety of data rates without using a large number of data-rate-specific modems. This solution applies to both onboard and earth station applications.

A very flexible, high-speed, digitally implemented modem is being developed 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. The modulation formats supported are 2, 4, 8, and 16 PSK; 16 quadrature amplitude modulation (QAM); MSK; and offset-QPSK. Operation will be completely programmable in all modes, and no hardware modifications are required. To support this effort, a general-purpose ASIC is being developed which will be used in nine separate locations in the demodulator (Figure 12). Automated test and demonstration equipment is also being developed to exercise the many possible operational modes.

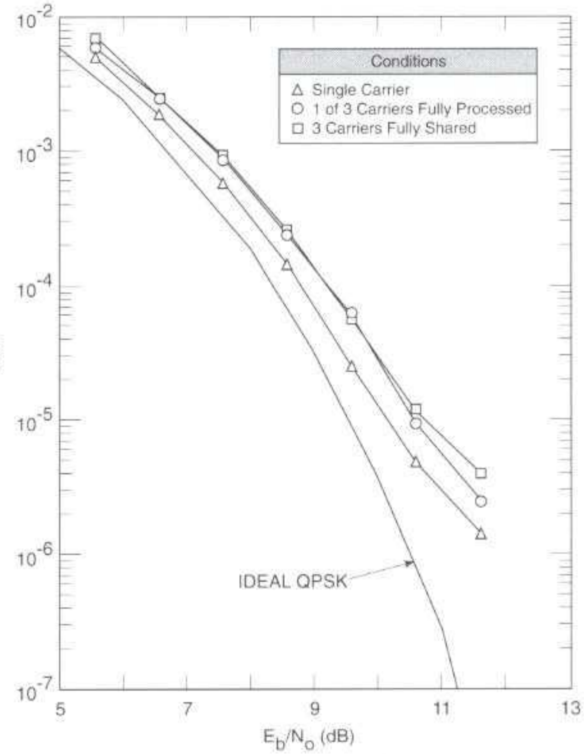


Figure 11. BER performance for single and multicarrier processing shows only a slight increase in degradation with increasingly complex demodulator operation

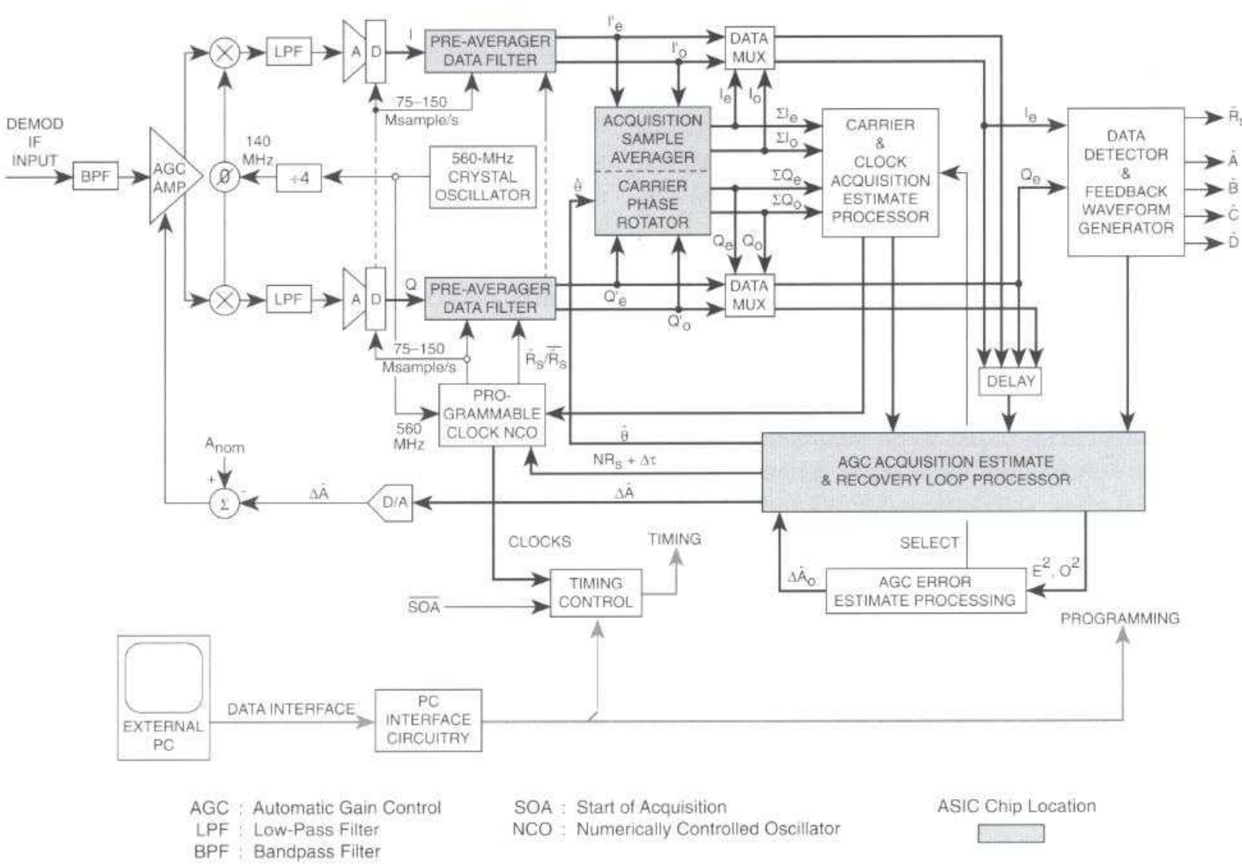


Figure 12. PDM demodulator features ASIC to achieve completely programmable operation in all modes

Extensive emulations of the architecture were completed, and the hardware design was finalized. A menu-driven software package was compiled to provide user-friendly programming via a personal computer, and substantial additional software was written to calculate the internal operational parameters for programmable operation. The modem and test equipment are currently being fabricated, and the ASIC is being readied for layout.

MOBILE & PERSONAL COMMUNICATIONS

Mobile and personal communications systems for land, maritime, and aeronautical applications have become an important part of a wireless worldwide communications network. Delivery of these services via satellite affords high-quality worldwide coverage with no restrictions on receiver mobility anywhere in the satellite beam, unlike limited-range local wireless or radio-based personal networks. R&D in satellite-based mobile communications has been ongoing at the Laboratories, combining diverse capabilities in research, simulation, channel modeling, digital techniques, and speech processing. In 1991, the Laboratories conducted broad-based R&D in the mobile and personal communications area, encompassing advanced research in synchronization techniques and vocoder improvements for mobile terminals, application of direct sequence spread spectrum technology for mobile and portable communications, feasibility studies for integrated mobile services, and enhancements for existing mobile services.

Synchronization of Mobile Channels

CTD's research activities for 1991 included the synchronization of mobile satellite communications. The effects of phase noise on coherent and differentially coherent trellis-coded MPSK modulation schemes, as well as noncoherent modulation schemes such as differential phase shift keying (DPSK) and frequency shift keying (FSK), were studied. It was found that the most important parameters in examining the sensitivity of carrier synchronizers to phase noise impairments were the relationship between bit rate and phase spectral bandwidth, and phase noise levels at the different corner frequencies. Due to the large frequency offsets typically experienced in the mobile environment, the sensitivity of synchronizers to frequency errors is an important consideration. The effects of frequency errors are more pronounced for those schemes that do not track the carrier phase (*i.e.*, differential and multiple symbol differential detection). The sensitivity to frequency errors can be reduced through the use of coarse/fine frequency estimators. An analysis of the sensitivity of synchronizers to symbol timing errors, and the optimization of the rolloff factor in modem pulse-shaping filters to minimize intersymbol interference (ISI), indicated that a root mean square (rms) timing error of less than 5 percent is necessary to keep BER degradation under 0.5 dB at error rates better than 10^{-5}.

Code-Division Multiple Access

A major area of investigation has been the application of direct sequence spread spectrum code-division multiple access (DS-CDMA) technology to satellite-based mobile and personal communications. System designs, link budgets, and other implementation issues have been considered for two classes of DS-CDMA portable terminals: a Ku-band portable "pico" terminal with direct terminal-to-terminal communications, and a C-band portable microterminal with hub-and-spoke communications, both using INTELSAT V satellites. Point-to-point and point-to-multipoint variable bit rate voice and data communications have been investigated for the C-band terminal. Several key technologies, including low-bit-rate voice coding, flat-plate antennas, and advanced signal processing techniques, have been incorporated in the system design. Figure 13 shows the conceptual features of the terminal. The direct sequence spread spectrum modulation for both C- and Ku-band systems minimizes interference to adjacent satellites and terrestrial networks, as well as simplifying network control and operation. The major system parameters, network operation, call setup and takedown, frequency and power control methods, and signal formats have been established by extensive analysis and computer simulations.

Voice I/O Capabilities

In a mobile environment, an operator often needs to send or receive messages while driving a truck, navigating a ship, or piloting an airplane. The feasibility of providing value-added voice input/output (I/O) capabilities to mobile terminals for communications through a low-data-rate channel was investigated for CMC. Communication using direct voice (speaking and listening) instead of a keyboard is desirable in order to avoid distracting the operator. For small, inexpensive terminals such as Inmarsat-C, the information data rates are very low (300/600 bit/s). Current speech coding technology cannot provide

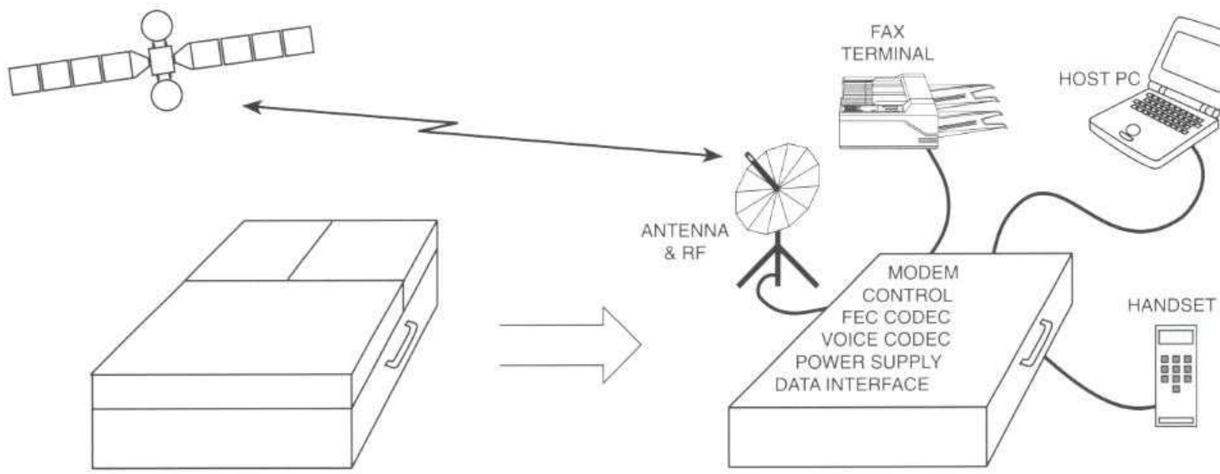


Figure 13. Personal communications terminal incorporates several key technologies

digitized speech with sufficient intelligibility at such low data rates, in a noisy acoustic environment and over a channel with severe multipath fading characteristics. Since the main objective is messaging (not voice fidelity), voice I/O provides a means of achieving this goal, but it must operate in a degraded acoustic *S/N* environment.

Voice I/O involves two speech processing functions. Speech recognition converts outgoing speech into American Standard Code for Information Interchange (ASCII) strings, and speech synthesis (text-to-speech) converts received ASCII strings back into voice. Thus, voice I/O allows direct voice messaging with low-data-rate transmission. In addition, speech recognition and synthesis allow mobile terminal command/control, prompt, and verification. Many other features, including automatic voice warning and various time and status voice reports, can be realized. The low-rate ASCII codes also allow extra error protection to minimize ARQ (as implemented in Inmarsat-C), thus improving system throughput.

From the study, it was concluded that voice input in the Inmarsat-C environment will require a high-accuracy, noise-robust, speaker-adaptive, isolated-word, medium-sized (a few hundred words) vocabulary speech recognizer. For voice output, an unrestricted text-to-speech speech synthesizer is desired for receiving unrestricted ASCII messages. Based on this observation, commercial voice I/O products were surveyed, a truck fleet control task was defined, and a complete voice I/O demonstration unit for the task was developed. The problems of robust speech recognition under noisy conditions and fast speaker adaptation for new users were studied, and an algorithm using speech recognizer model mapping was identified. Finally, baseline hidden Markov model (HMM) speech recognizer simulation software was developed and successfully tested.

Global Positioning

As part of an ongoing effort to improve the position accuracy available to civilian users of the Navstar Global Positioning System (GPS), COMSAT Laboratories is developing the technology necessary to send differential GPS (DGPS) correction signals over Inmarsat satellites. In the proposed system, DGPS correction signals are sent to an Inmarsat coast earth station using either terrestrial- or satellite-based links. These signals undergo time-division multiplexing, and are then sent over an Inmarsat satellite using a single satellite carrier. At the mobile user site, the desired correction signal is demultiplexed from the incoming signal and applied to the DGPS receiver, resulting in greatly improved position accuracy over that obtained with standard GPS.

This system was successfully demonstrated in 1991 in two Inmarsat ocean regions—the Gulf of Mexico in the Atlantic Ocean Region, and off the coast of Hawaii in the Pacific Ocean Region—using an Inmarsat-A-type carrier, with excellent results. Significant progress was also made on a similar setup using an Inmarsat-C-type carrier which, because of its higher satellite transmit power, may be received by a much lower cost mobile terminal than that required for Inmarsat-A service. Computer simulations were performed to model the Inmarsat-C carrier as received by an omnidirectional antenna and to characterize the impact of the multipath fading present in this configuration on the transmission of differential corrections and the resulting position accuracy. These simulations demonstrated the feasibility of sending the correction signals over this heavily faded channel. The software and hardware required to accomplish this are currently under development.

Satellite Paging

The feasibility of several new concepts in personal and mobile communications, including a combined Inmarsat-M and digital cellular radio terminal and a direct satellite paging receiver, were considered for CMC. The combined Inmarsat-M and digital cellular terminal would operate in digital cellular mode in urban areas, and in Inmarsat-M mode in remote areas not served by cellular service. Various issues such as antennas, RF/IF processing, modem processing, baseband processing, and user interfaces for both modes were considered. The conclusion was that a combined terminal is feasible but would be dominated by Inmarsat-M cost, size, weight, and power consumption. Consideration of a direct satellite paging receiver included the system aspects of such a receiver, as well as L-band attenuation characteristics inside buildings and on highways.

SYSTEMS STUDIES, MODELING, MONITORING & SIMULATION

An important function of COMSAT Laboratories is to conduct studies relating to the definition of new satellite systems and the improvement of existing systems. This work complements the R&D activities and hardware implementation that occupy most of the Laboratories' resources. Analysis and study efforts conducted during 1991 include satellite-based cellular universal personal telecommunications (UPT), ground segment specification development, satellite newsgathering (SNG), interference studies, system monitoring, and demand-assigned video TDMA.

Satellite-Based Cellular UPT

It is envisioned that land-based and satellite-based cellular systems must someday become integrated. To help reach this goal, satellite-based system concepts for providing future UPT services must be developed. This study was divided into two areas: a survey of land-based mobile (wireless, cellular, and personal communications network [PCN]) communications systems and their evolution, and the development of a satellite-based personal communications system concept for case study.

The characteristics of cordless telephones, second-generation digital cellular systems (for Europe, the United States, and Japan), and third-generation cellular systems were examined in a land-based mobile system survey. These characteristics included modulation schemes, data rates, allocated frequencies, network architectures, multiple-access schemes, TDMA slot and frame structure, vocoder schemes, and channel capacity.

A system concept was developed for personal communications between handheld units and PSTNs via geosynchronous satellites. Handheld-to-satellite links are provided for land-based users at 20/30-GHz Ka-bands, nominally under clear-sky and shadow-free conditions, and augmented by L- and S-bands under rainy or multipath fade conditions. Dual-mode handheld units are used in regions where heavy traffic is envisaged. For areas where low usage is expected, only L- and S-band handheld units will be available. For aeronautical and maritime applications, larger L- and S-band terminals similar to Inmarsat-M, Aeronautical, and B terminals will be used.

Handheld units employ a patch antenna at Ka-band and a stub antenna at L/S-band to provide antenna gain of 3 dBi. Transmitter power is less than 0.6 W at L-band and 0.8 W at Ka-band. Frequency-division multiple access/code-division multiple access (FDMA/CDMA) is used in conjunction with binary phase shift keying (BPSK) modulation and Viterbi and RS forward error correction coding. An adaptive CELP-based codec at 4.8 and 2.4 kbit/s is employed for low-rate encoding of speech.

Spacecraft antennas of 4 and 7 m are used for the Ka- and L/S-bands, respectively, for communications into handheld units. These antennas generate cellular footprints on the land masses. A 0.5-m Ku-band antenna is used for communications into gateway stations at 14 and 11.7 GHz. Satellites are positioned over land masses to achieve better than a 20° elevation angle for most areas, and hence to minimize potential shadowing problems. Intersatellite links at 60 GHz are provided by horn antennas to interconnect the satellites and thus extend the coverage of gateway stations. Due to the availability of a wideband feeder link at Ku-band, and the fact that all gateway stations are in the same footprints of a particular satellite, bent-pipe transponders can easily be interconnected with the cellular footprints at Ka- and L/S-bands. The nominal capacity of such a satellite is about 30,000 full-duplex channels.

CDMA is used to minimize antenna beam isolation requirements; realize simultaneous demand-assignment of satellite bandwidth and power; achieve natural statistical multiplexing of voice and data at the transponder input; and minimize transmission power spectral density, and hence adjacent satellite interference and intersystem interference. With proper implementation of traffic handoff between cellular footprints, satellite antenna pointing and other stationkeeping requirements of such large spacecraft platforms can be minimized.

Satellite Newsgathering

During 1991, the Laboratories continued to participate in the ongoing work of Task Group 5 of the Committee for Mixed Television and Transmission (CMTT). This joint study group between the International Radio Consultative Committee (CCIR) and the CCITT is working toward the development of CCIR recommendations for various aspects of the use of small earth terminals for SNG.

During the year, the development of a new service offering—small earth terminal spread spectrum communications—for the INTELSAT system was monitored and commented on in the INTELSAT Board of Governors/Technical Advisory Committee (BG/T). This service is used in various SNG applications. A contribution was also prepared and presented at the international meeting of CMTT Task Group 5, and portions of the contribution were included in a new draft recommendation.

Inmarsat Interference Measurements & Studies

During 1991, the Laboratories began a hardware-based program to quantify the effects of intrasystem interference in the Inmarsat system. This work, funded by Inmarsat, focuses on a number of potential interference scenarios and will use both objective and subjective performance measurements to determine objectionable levels of interference. Measurements such as *S/N* or BER are being used to characterize objective performance degradation. An evaluation to be conducted at COMSAT's Subjective Evaluation Facility will provide performance results based on actual human listener perceptions. The results of this measurement program will be extremely useful in future system planning and coordination.

High-Reliability Transmission Modeling

To correct large numbers of input (raw channel) bit errors in an INTELSAT IDR type of transmission system, Viterbi decoders of convolutional codes are used. The decoder usually performs the correction and delivers an essentially error-free output sequence; however, these decoders occasionally fail to decode correctly and produce bursts of errors at their output. These error bursts can cause additional degradation to elements that follow the decoder. Elements such as the differential decoder, descrambler, and any other type of outer coding for either error detection or additional error correction may not function properly when presented with burst errors. These elements are in turn likely to contribute to the creation of more bit errors and longer error bursts.

To avoid a long error burst, some form of interleaving can generally be used to break up or randomize the error bursts. However, if the error burst is unusually long, it may exceed the interleaving span and introduce burst error events to the succeeding processors. These error events, if uncontrolled, would be especially disturbing to DCME control channels that require highly reliable message transfer. Control of such errors involves the use of outer error-detecting codes selected for their high reliability.

A hybrid time domain simulation/analysis approach was developed during 1991 to gain insight into rare or unlikely burst lengths, as well as to aid in accurately predicting the probability of essentially all occurrences of error bursts. This approach not only provides statistics of error bursts, but also generates sequences of error-free burst length and burst error pattern pairs.

Further studies on the effect of burst errors on the DCME control channel (which involves an RS outer error-detecting code) have led to the ability to evaluate the message error rate performance of the control channel. All of these burst error analyzing capabilities have been integrated into highly efficient software modules as part of the Channel Modeling Program (CHAMP).

Comparisons between software simulation and hardware measurements have shown excellent agreement. Results from both areas support the conclusion that the major source of burst errors on IDR channels is the Viterbi decoder.

Packet Switch Simulation

In AT&T's Integrated Access Cross-Connect (IAC) system, a packet switch combines voice, data, and signaling packets. In 1991, various error control and queueing algorithms for the transmission of this packet data over INTELSAT IDR system links were tested using time domain simulation. In these simulations, voice, data, and signaling packets were generated by random traffic generators and then "sent" over satellite links in which transmission impairment models were used, resulting in realistic estimates of traffic throughput. Such simulations can be used to optimize algorithm parameters and compare various approaches to transmission control.

Demand-Assigned Video TDMA

COMSAT Laboratories was awarded an INTELSAT contract to study a demand-assigned video TDMA system. This type of system is intended to support a wide variety of new and existing digital video services, including demand-assigned integrated services digital network (ISDN) video traffic, reservation-type videoconferencing, and broadcast digital TV.

The focus of this study was the design of the demand-assigned video TDMA system, including network configurations; TDMA frame and burst structures; network acquisition, synchronization, and system management; development of protocols for allocating system capacity among earth stations on demand-assigned and reservation bases; communications between different elements of the network; and issues related to terminal design.

Also included in the study was a software simulation of the system design. Based on estimated traffic statistics, a computer program was developed and used to investigate the way in which important parameters such as response times, and cutoff and blocking probabilities depend on factors like the number of participating terminals in the network, level of demand, and type of demand (*e.g.*, the amount of reservation traffic relative to demand-assigned traffic). The final phase of the study addressed operational factors and the kinds of problems likely to be encountered during implementation and monitoring of the system, and assessed the demands the system will place on the network control center.

Transmission Impairment Hardware Simulation

In order to improve hardware simulation, a fading channel simulator was constructed during 1991. The simulator was designed to model, in hardware, the fading and polarization discrimination degradation experienced in Fixed Satellite Service transmission channels. It will primarily be used to evaluate the effects of degradation due to rain and other atmospheric factors on digital transmission. A block diagram of the IF simulator is shown in Figure 14.

Electronically controlled variable attenuators are used to vary the signal strength and the amount of interference due to polarization discrimination

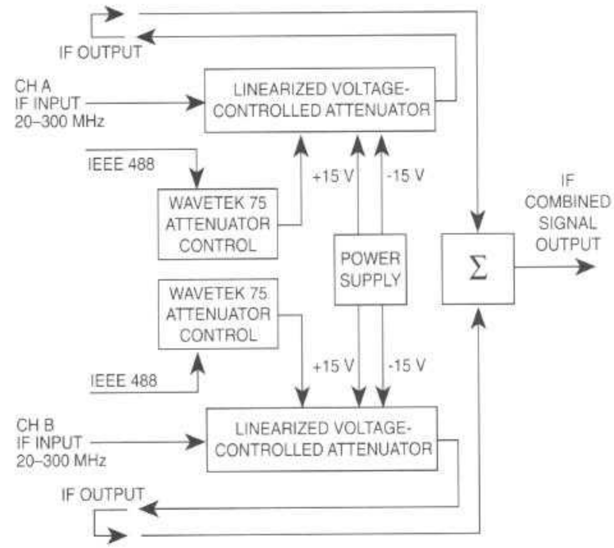


Figure 14. Fading channel simulator will be used to evaluate the effects of atmospheric factors on digital transmission

degradation. The attenuators are controlled by an arbitrary waveform generator programmed to produce a waveform equivalent to a propagation event. This unit is useful over a wide frequency range to model fading channel effects at both C- and Ku-band Fixed Satellite Service frequency bands.

Communications Signal Monitoring

Over the last decade, communications satellite usage has increased dramatically, and the number of different types of services has multiplied. Because of these rapid changes, monitoring of satellite traffic has become increasingly important and difficult.

Monitoring is critical to the ability to provide troubleshooting such as diagnosing equipment malfunctions and identifying interference sources. Under contract with INTELSAT, COMSAT investigated the application of new technologies to the communications signal monitoring effort. In particular, the use of DSPs was studied as a means of increasing the speed and accuracy of monitoring systems. Analytical models were developed to predict the accuracy of various measurements in the presence of noise, and a specific hardware architecture was proposed to implement these measurements. Further, COMSAT developed detailed computer simulations to demonstrate the speed and accuracy of a variety of measurement algorithms. The effects of interference on a variety of different modulations were also explored, including analog FDM/FM and digital carriers.

NETWORK TECHNOLOGY

Work carried out by the Network Technology Division (NTD) in 1991 spans network systems, networking technology, high-performance protocols, onboard processing, and optical communications. Developments in network systems included integrated services digital network (ISDN) earth station switching interfaces, a digital demand-assignment system, and an aeronautical data service gateway. NTD continued to advance networking technology with the development of high-performance, satellite-friendly, internetworking devices such as bridges, routers, and gateways, as well as a prototype neural network that performs resource management for broadband ISDN (BISDN) networks. NTD also continued its development of high-performance protocols, particularly data and ISDN protocols that perform efficiently over satellite links, and its effort to have these protocols accepted as U.S. and international standards. Division efforts in onboard processing focused on the ongoing development of an onboard baseband switch that routes traffic over a high-speed optical ring. The merits of onboard fast packet switching were also examined. In optical communications, NTD continued to investigate the potential savings in mass and size that could be realized by using onboard optical beam-forming for phased-array antennas. Integrated optical devices are currently being designed and fabricated for application to other onboard optical subsystems. ■

NETWORK SYSTEMS

ISDN Earth Station Interfaces

On behalf of COMSAT World Systems (CWS), NTD has investigated integrating ISDN with satellite systems and using ISDN switching interfaces at International Business Service (IBS) earth stations. Since the IBS system supports the transmission of digital carriers for business networks, this interface capability at an IBS earth station offers two major advantages. It provides direct user access to international private networks that offer ISDN services, and it allows more efficient use of both satellite and terrestrial access circuits. Traffic from different users which is destined for the same earth station can be aggregated onto a single satellite link. Likewise, traffic for different destinations can be aggregated onto a single terrestrial access to an earth station.

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) that extracts signaling channels from incoming terrestrial links, commands appropriate cross-connect switching, and formats the appropriate outgoing signaling message. On terrestrial links, the NIP implements the primary rate (23B + D) ISDN user-network interface protocols standardized by the International Telegraphy and Telephony Consultative Committee (CCITT), including Recommendations Q.921 for the link layer and Q.931 for the network layer. On satellite links, a protocol that provides the basic functionality of common channel Signaling System 7 is required to carry signaling information between earth stations. In addition, the NIP implements call control procedures to control and release incoming and outgoing calls, allocate capacity on the satellite links, dynamically switch the digital cross-connect, and perform management functions.

A prototype system developed in 1990 was enhanced and demonstrated live via satellite in 1991. The enhancements increased system flexibility and added new features such as multidestinational capability. Routing and switching functions were added for bandwidth allocation on a call-by-call basis. To support these functions, information on numbering, configuration, and resources was collected and maintained in a database, so that the call control software module could be enhanced to perform numerical analysis for routing and resource management, as well as for switching and dynamic allocation of bandwidth. A control module was added to manipulate the switch matrices of the digital cross-connect and to perform switching.

This system was demonstrated in a joint experiment between CWS and the National Institute for Standards and Technology (NIST). Two nodes—one located at the COMSAT ISDN Application Center (ICA), Washington, D.C., and the other at NIST, Gaithersburg, Maryland—were set up and linked using the Satellite Business Systems (SBS)-2 inclined-orbit satellite. Each node comprised a prototype switch and user equipment. The switch consisted of a digital cross-connect unit (Coastcom DXC II) that supports up to 16 T1 carriers, a D3/D4 channel bank, and a NIP. User equipment included an ISDN private branch exchange (PBX) by Northern Telecom SL-1 with primary rate interface (PRI) modules, digital telephones, and Sun workstations and terminals. In addition, ComStream CM421 modems were used to interface the nodes to the earth station equipment.

The experiment demonstrated the ability to establish switched end-to-end ISDN connections over the satellite and to integrate voice and data services. An ISDN quality of service (QOS) experiment, using the Chameleon 32 protocol analyzer, verified compliance with CCITT Rec. I.352 specifications for call setup and release delays. During 1992, new capabilities will be developed and integrated into the prototype system.

Broadband ISDN

With widespread deployment of BISDN expected in the near future, it is imperative for COMSAT to ensure that BISDN protocols and services can be effectively provided over satellite links. BISDN uses a fast cell switching technique called asynchronous transfer mode (ATM). All services (voice, video, and data) will be provided using the ATM adaptation layer (AAL) and ATM protocol layers.

During 1991, NTD developed for CWS a detailed design and initiated the schematic capture of an ATM/AAL line card. The hardware architecture of this card is shown in Figure 1. Although the hardware is designed to operate at rates up to 155 Mbit/s (STS-3), the initial implementation will support rates only up to 51 Mbit/s (STS-1), due to the unavailability of STS-3 line interfaces and central processing unit (CPU) limitations. Fabrication and testing of this board will be completed in 1992.

Digital Demand-Assignment System

The IBS system is widely used for international private networking. In its present form, the service is offered as an extended-period, fixed-bandwidth leased line interconnecting pairs of customer sites. Marketing research has indicated that a majority of IBS customers have significant fluctuations in bandwidth requirements, even over a period of a day. Additionally, emerging technologies such as ISDN require a bandwidth-on-demand capability. In view of these requirements, NTD designed and developed for CWS the digital demand-assignment system (DDAS) to dynamically allocate IBS circuits.

A centralized network control center (NCC) controls 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

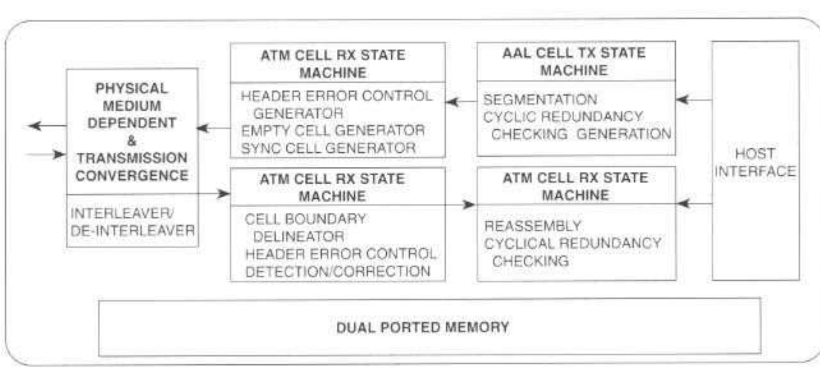


Figure 1. ATM/AAL line card hardware is designed to support rates up to 155 Mbit/s

signaling system, with a single continuous outbound channel from a hub CCU to all remote sites, and a shared inbound channel accessed by remote CCUs in an Aloha (contention) mode. The 1991 effort included the development of network topology displays and a configuration and accounting management system. A field trial of the system, conducted between NIST and CWS in Washington, D.C., demonstrated the integration of the DDAS with the shared IBS/ISDN system. The field trial configuration is shown in Figure 2.

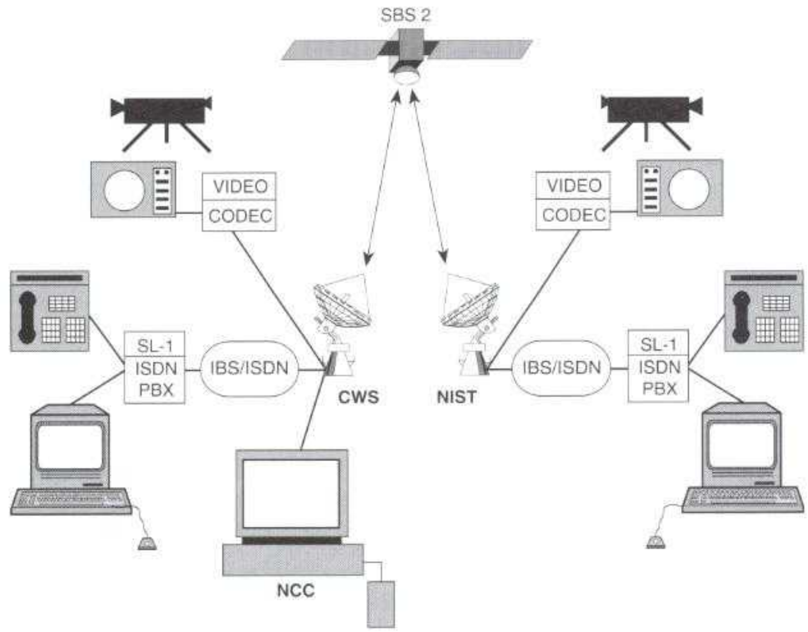


Figure 2. Field trial configuration integrates the DDAS with the shared IBS/ISDN system

Aeronautical Data Services Gateway

The Aircraft Communications Addressing and Reporting System (ACARS) is widely used by commercial aircraft to exchange data messages, such as constantly updated estimated time of arrival (ETA) and fuel quantity reports, with airline operations centers. In the continental U.S. (CONUS), this service is provided by Aeronautical Radio, Inc. (ARINC), and operates in a very-high-frequency (VHF) line-of-sight environment. ACARS messages are physically transmitted and received by a network of ground-based radio stations. Customers (airlines) connect to an ARINC front end processor system (AFEPS), which communicates with the ground station network through terrestrial links.

The Aviation Satellite Communication System (SATCOM) extends aeronautical voice and data services to airborne earth stations (AESs) via L-band satellites in the Inmarsat Aeronautical system. Thus, high-quality voice and data services are available to aircraft on transoceanic flights. Ground earth stations (GESs) that conform to these specifications are installed at COMSAT Mobile Communications (CMC) facilities located in Southbury, Connecticut, and Santa Paula, California.

Anticipating the need to provide an ACARS messaging service to AES-equipped aircraft via CMC GESs, NTD designed and built an interim protocol gateway that would accommodate differences in protocols and addressing used in the two systems. The ARINC network uses a proprietary protocol to deliver data to ground-based radio stations, whereas a GES uses X.25/X.75 interfaces. Likewise, SATCOM uses a CCITT Rec. X.121 data terminal equipment (DTE) address assigned by the International Civil Aviation Authority (ICAO), while ACARS messages are addressed using an aircraft registration mark called the tail number.

As shown in Figure 3, this protocol gateway—which has been implemented, installed, and tested at CMC's Inmarsat GESs—interfaces to modified ARINC ground station equipment using a serial asynchronous port, and to CMC's earth station equipment using a synchronous X.25 port. It accepts log-ons from (and maintains separate X.25 virtual circuits for) "data-capable" AESs. It also performs mapping between ACARS and ICAO addresses, and routes both up-link and down-link ACARS messages. An operator interface is provided to maintain aircraft authorization tables and to display the current status of logged-on aircraft.

The protocol gateway relies on the use of a modified GTC-100, which provides connectivity to the ARINC multidrop communications lines from the

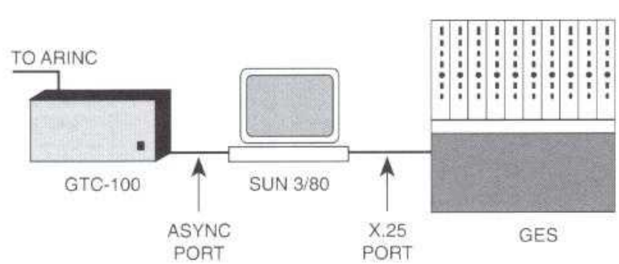


Figure 3. Aeronautical data services gateway accommodates different protocols and addressing for airborne and ground stations

AFEPS. In the GTC-100 used for the gateway application, the VHF controller is replaced by an asynchronous RS232C-compatible serial line driver. The ACARS gateway itself is based on a Sun 3/80 UNIX workstation configured with 8 Mbytes of memory and a 200-Mbyte disk. The hardware configuration is shown in Figure 4.

Onboard Processing System Architectures

During 1991, NTD performed three studies of advanced onboard processing satellite systems for Loral Corporation as part of its support to NASA's Lewis Research Center. Satellite systems to support mesh VSAT, integrated video, and BISDN services were investigated under this study task. Current systems and standards as well as expected future applications for these services were examined. Based on future traffic estimates, satellite system architectures capable of supporting the identified services were developed. Onboard processor design options were then examined before specific payload designs were formulated. In each case, transmission formats, earth station designs, and signaling and network control issues were explored.

In conducting the mesh VSAT study, NTD explored onboard processing satellite architectures that provide mesh connectivity by allowing direct VSAT-to-VSAT communications. NTD investigated four possible architectures that could provide mesh VSAT connectivity. The architecture selected for detailed analysis (Figure 5) employs an onboard processor that performs demodulation/decoding of up-link signals, packet switching, and recoding/remodulation of down-link carriers. The up-link satellite antenna pattern consists of four beams covering CONUS at Ka-band frequencies. VSAT terminals transmit 4-Mbit/s frequency-division/time-division multiple access (FDMA/TDMA) carriers that are frequency demultiplexed and demodulated by a multicarrier demodulator (MCD) using digital signal processing techniques. The packet switch is implemented using a ring topology in which packets are passed from input to output processors via a fiber optic ring. In each switch output processor, a down-link carrier is formatted and encoded before being remodulated for transmission to one of 24 down-link spot beams. The system is designed for a network capacity of 1.6 Gbit/s.

The integrated video study focused on onboard processing satellite architectures capable of providing a wide variety of interactive and distributive video services. A study of existing standards showed that most videotelephony and videoconferencing equipment will require transmission rates that are multiples of 64 kbit/s, ranging from 64 to 1,920 kbit/s. In addition, investigation of anticipated services and compression techniques showed that high-quality video for business applications could be supported by 6-Mbit/s transmission rates.

The network architecture selected for integrated video transmission employs 28 up-link and down-link spot beams covering CONUS. User earth terminals transmit FDMA/TDMA carriers at either 2 or 6 Mbit/s. Onboard MCDs demultiplex and demodulate these carriers, and onboard switching is provided by processors connected via a fiber optic ring, as shown for the mesh VSAT system. The baseband switch is implemented using a ring topology in which packets are passed from input to output processors via a fiber optic ring. Although these video services are primarily circuit-switched, the onboard packet switch can provide point-to-point and point-to-multipoint connectivity with minimal network control complexity. The output processors format and encode two 54-Mbit/s TDM carriers, which are then remodulated and transmitted on the down-links. The Ka-band was selected to meet bandwidth requirements for the expected system capacity of 2.5 Gbit/s.

Satellite networks are expected to play an integral part in future BISDN services, especially in serving remote users and establishing efficient multicast and broadcast services. Two onboard processing

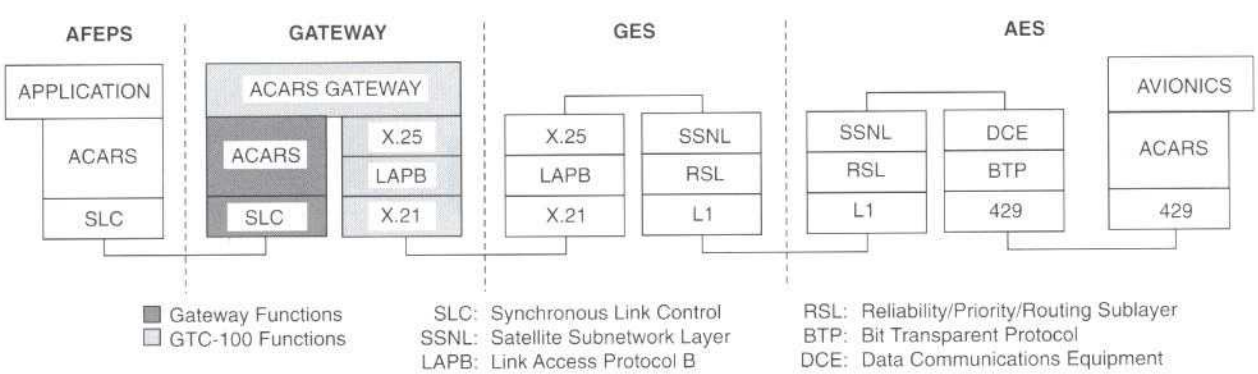


Figure 4. ACARS gateway is based on a Sun 3/80 UNIX workstation

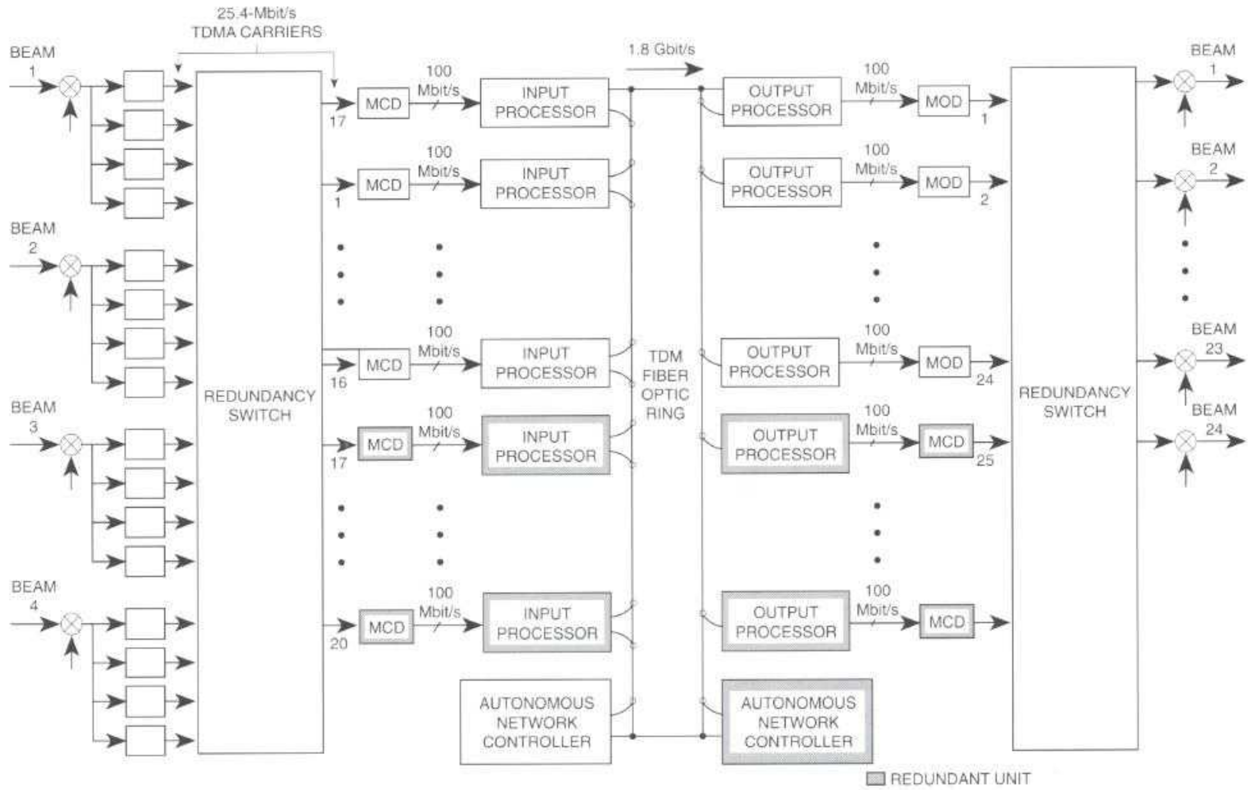


Figure 5. Mesh VSAT network design uses a ring topology

architectures, operating at Ka-band frequencies, were explored. One of these architectures would augment existing terrestrial BISDN, offer access for remote users, and provide a capacity of 1.6 Gbit/s. The other is intended to establish private BISDNs and to serve as the gateway to the public network for these private networks. This latter architecture is based on a satellite system using hopping-beam TDMA and onboard baseband switching to interconnect earth stations. Of several candidate baseband switch architectures, a self-routing, packet-switched crossbar switch with multicast capability was selected. The internal network routing is based on "virtual packets," which contain fields of ATM cells. The total system throughput for this design is expected to exceed 9 Gbit/s. Figure 6 shows the selected baseband processor design.

NETWORKING TECHNOLOGY

High-Performance LAN/WAN Interface Processor

The rapid growth of communications technology is dramatically changing the networking environment. Existing local area networks (LANs) are expected to be replaced by higher speed networks such as the fiber-distributed data interface, which operates at 100 Mbit/s. Wide area networks (WANs) are also rapidly evolving from medium-speed DS-1 to higher speed DS-3 (45-Mbit/s) links. The advent of high-performance microprocessors enables user workstations to exploit the large available bandwidth. These trends, coupled with bandwidth-intensive applications, will tax the switching capabilities of internetworking devices such as routers and bridges. In view of the switching requirements of these high-speed networks (in excess of 30,000 packets per second) NTD has been pursuing an R&D program to develop a high-performance bridge/router.

In 1991, the high-performance CPU MC68040 was incorporated into the router as a packet processor. This CPU is based on traditional complex instruction set computer (CISC) technology, but incorporates features such as dual buses, and on-chip instruction and data caches that are typically provided by reduced instruction set computers (RISCs). The COSMOS operating system was ported to this processor, along with interface drivers and networking protocols. During 1991, a software driver for a high-speed serial board was also developed. This board provides the capability of remote interconnection between routers at speeds up to 4 Mbit/s.

The first-generation high-performance router bridge developed by NTD uses a shared bus architecture for interconnecting the input/output (I/O)

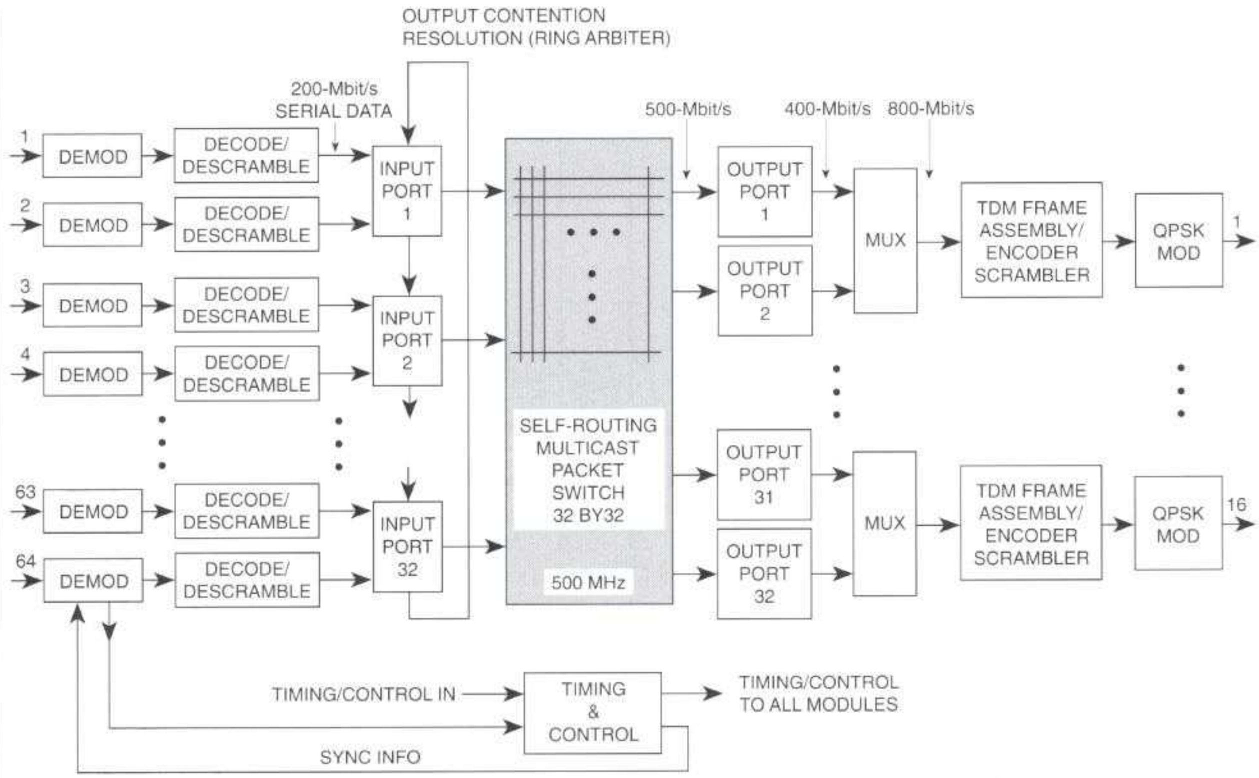


Figure 6. Baseband processor uses a self-routing, packet-switched crossbar switch with multicast capability

and packet processors. The key advantages of this approach are reduced development cost and rapid prototyping that result from the use of off-the-shelf hardware. Disadvantages are the shared bus bandwidth limitations and the less than optimal performance associated with off-the-shelf hardware. In view of these disadvantages, the next-generation router design (Figure 7) is based on custom hardware and a centralized switching module, with I/O processors interconnected via a centralized high-performance parallel interface (HPPI) switch. Custom hardware for this next-generation system will be developed in 1992.

Neural Networks in Resource Management for Satellite BISDN Networks

The first function of network traffic management, and an integral part of dynamic resource management, is call or connection admission. This is especially true of the BISDN network, which supports a large number of services. When a request for a new call or connection is received, this function decides whether to accept or reject the request. A decision to accept the call indicates that adequate bandwidth is available based on the traffic characterization of the call (*e.g.*, mean bit rate, peak bit rate, mean holding time, and peak burst duration) and QOS requirements (*e.g.*, packet loss rate and maximum allowable delay). Acceptance also indicates that existing calls within the system will continue to meet QOS requirements without degradation. Conversely, call rejection means that such guarantees are not possible for the new call and/or for existing calls. For circuit-switched traffic and for constant bit rate services, this is relatively straightforward. For other types of traffic where statistical multiplexing is used to optimize the efficiency of resource allocation, this is a challenge. A conservative call admission function will obviously reduce the level of congestion (not eliminate it completely), but it will also lower the effective utilization of the network. The goal is to maintain a high level of utilization by accepting the maximum number of calls while maintaining traffic congestion at a manageable level.

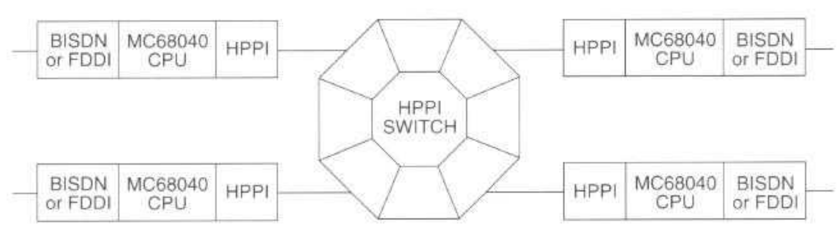


Figure 7. Second-generation high-performance LAN/WAN processor is based on custom hardware and centralized switching

Because of the large number of services in the BISDN network and the large number of calls for each service type, it is impossible to model and monitor all possible network configurations and conditions. NTD's approach to this problem was to develop and implement a model of the network in order to simulate different conditions. This model makes it possible to change a few parameters, such as bit rate fluctuation, call bit rate, and average number of calls in the network, to account for differences in the actual service mix. A classical algorithmic method was simulated, and the results were used to show the relationship between the cell loss ratio, utilization threshold, and bit rate fluctuation which must be quantified and mapped onto a utilization threshold to reject incoming calls for the specified cell loss ratio. Next, a neural network was trained to solve the problem. Test results confirmed that, after training, the neural network could adapt to bit rate fluctuations in traffic to give the desired cell loss ratio without regard to the utilization threshold, as indicated in Figure 8.

HIGH-PERFORMANCE PROTOCOLS

Data Transmission Protocols

The International Standards Organization (ISO) has developed an international standard reference model of open systems interconnection (OSI) as a basis for coordinating standards development for systems interconnection, while allowing existing standards to be placed in perspective within the overall reference model. Since 1983, NTD, on behalf of CWS, and NIST 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 OSI networks.

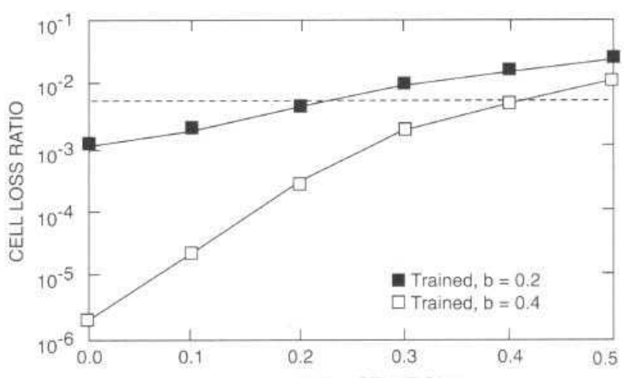


Figure 8. A neural network trained to adapt to traffic bit rate fluctuations gives the desired cell loss ratio regardless of the utilization threshold

Experiments jointly conducted from 1985 through 1990 by NTD and NIST concerned transport protocol class 4 (TP-4); connectionless network protocol (CLNP); session protocol; message handling system (X.400); file transfer, access, and management (FTAM); OSI network management; and distributed transaction processing (TP) protocols. All relevant modifications to TP-4 were merged into the main standard text in 1991, and the merged text will be published as an international standard in 1992. COMSAT has been a key participant in the project, established by ISO/IEC/JTC1 in 1990, to develop enhancements to FTAM standards. The preliminary draft amendment (PDAM) editing meeting was held in November 1991, and the revised text is expected to be issued for the DAM ballot in 1992. Distributed TP has been continuously investigated since 1990. The basic TP protocol suffers no degradation over satellite links. The underlying protocols (commitment, concurrency, and recovery) and the session protocol have also been examined in the context of TP. The requirements for session synchronization agree with COMSAT's 1987 experiment results. This technical contribution, accepted by the ISO in 1991, has resulted in the enhancement of the session protocol so that it is fully compatible with satellite networks.

Since 1990, various OSI architecture issues, including QOS and multipeer data transmission, have been investigated. These critical areas exploit the inherent capabilities of satellite communications. In 1991, specific issues related to the requirements of multipeer protocols and services in various layers were developed, work on high-performance data link protocols was initiated, and the requirements and mechanism of non-blocking transport expedited data service were investigated.

ISDN Protocols

On behalf of CWS, NTD has focused on the design, simulation, and analysis of new data communications protocols suitable for high-speed environments such as BISDN and frame relay networks. In BISDN, an AAL is being defined to run above the ATM layer and to provide additional services to upper layers. Different types of AALs are being defined to support different classes of service. As an example, AAL type 3 is intended to support connection-oriented services with variable bit rates, and in particular, high-speed data applications. It is also intended for signaling at the user-network interface and at the node-to-node interface. In frame relay networks, the CCITT Rec. Q.922 protocol is intended to be used by end users for the data link layer. In both environments, the error recovery function is performed on an end-to-end basis by the user equipment, and not by the network nodes. The exact operation of the error recovery procedures has a significant impact on overall network performance.

The new error control protocol implements a selective retransmission scheme that transmits only negative acknowledgments and distributes the error recovery function between the transmitter and the receiver. The transmitter periodically interrogates the receiver, and the receiver responds with complete status information. Based on this and other information that it maintains, the transmitter retransmits missing frames and frees correctly received frames from its retransmission buffer. This protocol was designed to be robust, efficient, insensitive to network delays, and easy to implement. It was simulated and tested in frame relay and BISDN environments involving satellite links with different bit error rate (BER) characteristics. The simulation results show significant improvement in performance relative to protocols using the go-back-N ARQ method.

In addition to error recovery procedures, user response to congestion notification in frame relay networks, and its impact on performance, have been studied. When congestion is detected, through either retransmission requests or explicit network notification, the user adjusts the input rate to assist the network in recovering from congestion. For window-based protocols, the rate is adjusted by altering the transmitter window size. Different mechanisms for window control have been investigated. Algorithms for increasing and decreasing window size have been simulated and tested to evaluate their performance over satellite and terrestrial links.

Aeronautical Multicast Services Protocol

On behalf of CMC, NTD participated in the design and standardization of a multicast transport protocol for aeronautical applications. This protocol will allow the use of spare capacity on outbound aeronautical time-division multiplexing (TDM) channels (P-channels). Using this protocol, CMC will soon introduce FlightNews™, which will provide news and information services to airborne aircraft through Inmarsat satellites.

An initial study was performed to identify the optimal, minimum-overhead approach to the problem.

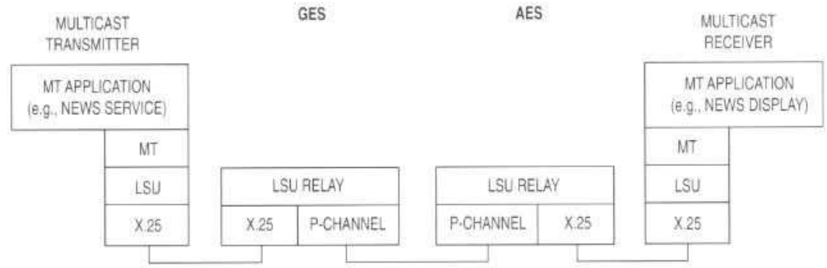


Figure 9. The multicast protocol is designed for sequenced transport of data packets to airborne AESs

As a result of the study, a contribution was developed for the Inmarsat Advisory Committee on Technical Matters (ACTOM), proposing that additional signal unit (SU) formats be defined to support multicast transport service. These formats and the GES-specific broadcast data (GSDB) service definition have since been adopted by Inmarsat as a change notification (CN50) to the Inmarsat Aeronautical System Definition Manual.

The architecture for the multicast transport protocol is shown in Figure 9. The protocol is designed for the sequenced transport of data packets to several airborne AESs. It provides for the detection and rejection of errored packets by the receiver, and makes a best attempt at (but does not ensure) reliable delivery. To transmit a message over the satellite link, the protocol converts application data into a set of P-channel SUs, each 12 octets long and conforming to GSDB SU format. These SUs are transported over an X.25 link to the GES, which queues them for transmission. The GES monitors the use of the P-channel and transmits these low-priority SUs over the outbound P-channel during idle periods. The AES receives all P-channel SUs, and sends those that are identifiable as GSDB SUs to the multicast receiver over the internal data bus. The multicast protocol layer reassembles the received SUs to form an application message for delivery to the appropriate application.

ONBOARD PROCESSING

High-Speed Optical Interconnect

As reported in the *1990 Annual Review*, NTD, under the sponsorship of CWS, has initiated the development of a modular baseband switch capable of providing dynamic interbeam connection for a variety of transmission/service types. The switch will accept traffic from a number of digital satellite services such as INTELSAT intermediate data rate (IDR), TDMA, and IBS.

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 alternate satellite services 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 that are specific to a particular satellite service (service-dependent elements) and elements that are 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.

The overall switch design will consider first the core elements (see Figure 10) and then the service-dependent functions. Two application-specific integrated circuits (ASICs) are being developed for this design: the core processor ASIC, responsible for routing incoming data into memory and for formatting the data-directed packets; and the high-speed switch interface ASIC, responsible for frame synchronization and for delivering data to and from the fiber optic drivers/receivers. The complete core element module is expected to require about 20 ICs and to be fabricated on a 5-in^2 printed circuit board. The design of the high-speed switch interface ASIC was completed and device simulation was started in 1991. Device simulation and fabrication/testing of this ASIC are expected in 1992. The design of the core processor ASIC began in 1991, with simulation planned for 1992, followed by fabrication and testing in 1993.

Onboard BISDN Fast Packet Switching Architectures

BISDN extends the service integration concept to include future high-speed, high-volume network services and to accommodate narrowband ISDN in its infrastructure. The impact of BISDN services on satellite communications can be significant, requiring the same type and quality of service provided by the terrestrial BISDN network. During 1991, NTD conducted a study, sponsored by NASA, to address potential satellite applications, alternate satellite network architectures, system design issues, and onboard switching/processing options for satellite BISDN services.

This study revealed that satellites can play a vital role in future broadband telecommunications services. Satellite-based systems benefit from the inherent capabilities of point-to-multipoint/broadcast transmission: virtually unlimited connectivity between any two points within a beam coverage, short deployment time for the communications facility, flexible and dynamic reallocation of space segment capacity, and distance-insensitive cost. Onboard processing satellites, particularly in conjunction with multiple spot beams, will provide enhanced connectivity, better performance, optimized access/transmission link design, and lower user service cost.

The satellite can support high-speed transmission at a bit rate between 155 Mbit/s and 1.24 Gbit/s using an antenna size between 2.4 m (155 Mbit/s at Ka-band) and 12 m (1.24 Gbit/s at Ku-band). These high bit rates are primarily intended for use in trunking and high-speed circuit-switched applications. A simpler onboard switching payload such as satellite-switched (SS)-TDMA and SS-FDMA (in RF or baseband) may be used for beam interconnection.

The majority of future BISDN users will likely require bit rates between 1.544 and 155 Mbit/s, and flexible interconnection among a large number of user terminals. Flexibility and efficient bandwidth utilization can be achieved by using an onboard fast packet switch to provide an integrated circuit- and packet-switched service. Figure 11 shows an example of a satellite network architecture for BISDN.

Fast packet switching is used to route packetized traffic (packets) from different input ports to different

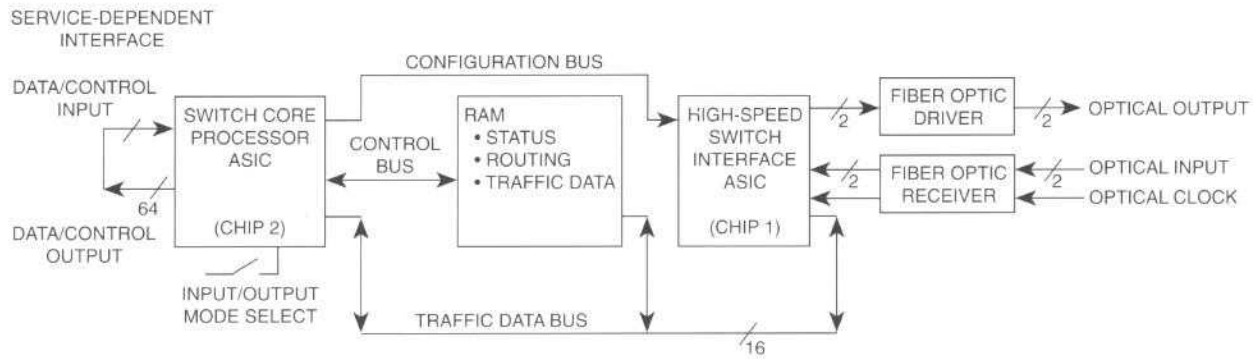


Figure 10. Switch input/core output module requires about 20 ICs, including two ASICs

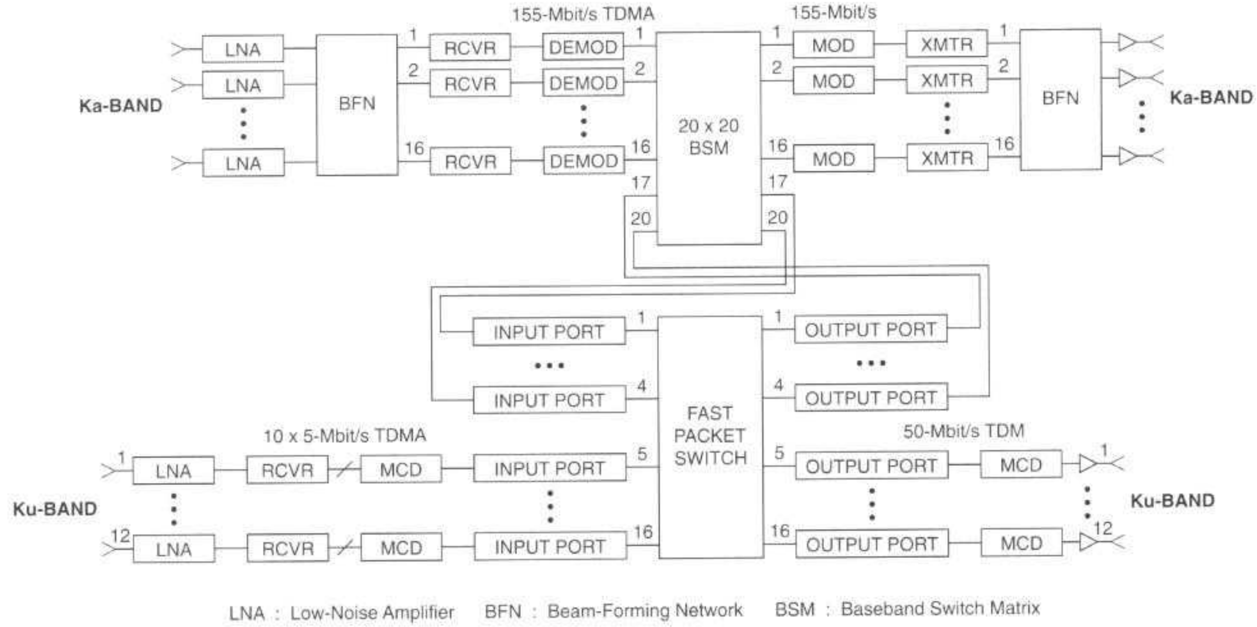


Figure 11. Satellite network architecture for BISDN uses onboard fast packet switch

output ports based on routing information contained in the packet headers. Because the packet transfer protocol and distributed routing functions are performed by a hardware-oriented self-routing architecture, a fast packet switch can handle traffic capacity ranging from megabits to gigabits per second. On the up-link, access and transmission can be optimized for a group of users according to their traffic requirements, while on the down-link, single-carrier TDM transmission can maximize the use of spacecraft power. The fast packet switch can also provide integrated operation of BISDN and non-BISDN traffic.

Onboard baseband switching interconnects user earth stations operating at different bit rates and with different access schemes. Circuit switching is most efficient for handling circuit-switched traffic in which assigned time/frequency slots are fully occupied by a constant flow of traffic. Fast packet switching, on the other hand, not only efficiently accommodates packet-switched traffic with variable destinations but also supports circuit-switched traffic. In some situations, a mixed switch configuration, consisting of circuit and packet switches, may result in an optimal onboard processor architecture.

There are several architectural alternatives for a fast packet switch design. NTD has designed two modules that can be used as basic building blocks for fast packet switching fabrics. Breadboard implementations of a batcher sorting module and a multicast banyan module are presently being tested. These modules are implemented using an off-the-shelf erasable programmable logic device that can be interconnected to produce various sizes of multicast fast packet switching fabrics. NTD will develop and evaluate the performance of a 16 x 16 switching fabric.

Technology assessment based on a detailed switch design indicates that the power consumption of a multicast packet switch is currently about 9 W per port, and is likely to be reduced to approximately 3 to 4 W in the near future. For a 16 x 16 fast packet switch, this will result in a total switching subsystem power of 48 to 64 W, which is a small fraction of the total onboard baseband processor power of several hundred watts.

Information Switching Processor Contention Analysis & Control

For a fast packet switch, output contention occurs when several packets are destined to the same output port at the same time. The technique used to resolve output contention depends on the switching architecture employed. Two types of fast packet-switching architectures were considered in a study performed by NTD for NASA: a contention-free switch and a contention-based switch.

Three implementation techniques were investigated for a contention-free switch: a TDM bus with distributed output memories, a fiber optic ring switch, and a common memory switch. The capacity of these switching architectures is limited to several gigabits due to shared hardware operation.

Allowing output contention to occur in the switch (or even internal blocking within a switching fabric) can ease hardware complexity and speed requirements compared with those of the contention-free switch. Based on the output contention resolution scheme (or packet transfer scheduling algorithm), two types of contention-based switch architectures can be identified. For the first architecture, output contention can be resolved by scheduling packet transfer at the input ports (using an output port reservation scheme). Alternatively, for the second architecture, in each packet transfer cycle a set of non-contending packets is chosen from the input ports (using a path setup strategy). These packets will not collide in the switching fabric or the output ports.

Simulation models were developed and experimental sets run to analyze switch throughput performance. An example of simulation results for a point-to-multipoint switch (Figure 12) illustrates the effectiveness of increasing switch speed to attain higher throughput.

As indicated by this study, the contention problem in a self-routing fast packet switch is not a major concern. It can be completely eliminated by using a contention-free switch architecture or, for a contention-based multistage switch, it can be resolved by using either the output port reservation scheme or the path setup scheme. However, these schemes reduce the switch throughput by 20 to 40 percent due to scheduling efficiency and head-of-line blocking at the input queue.

OPTICAL COMMUNICATIONS

Optical Space-Fed BFN

Future multibeam satellite systems using phased-array antennas will require a complicated beam-forming network (BFN) consisting of a large number of feed lines and phase shifters to distribute RF power to the various phased-array antenna feed elements. The use of optical BFNs can result in reduced size and weight, as well as less susceptibility to crosstalk problems. The low loss of the optical fibers allows remote positioning of the phased-array antenna elements from the satellite main body.

In 1991, NTD designed, fabricated, and assembled a proof-of-concept optical space-fed BFN consisting of a four-element antenna array which allowed up to 27° scanning. Figure 13 is a block diagram of the prototype system. A set of four RF signals (C-band) electro-optically modulates laser diode transmitters, and the resulting optical signals are optically switched/coupled to the desired input ports of the optical space-fed BFN. The BFN (see Figure 13) uses fibers of different lengths to create the required phase shifts at the output ports of the BFN. The signals at the output ports of the optical BFN are combined using 4 x 1 couplers and fed to an array of photodetectors to recover the electrical RF signals, which then excite the phased-array antenna elements.

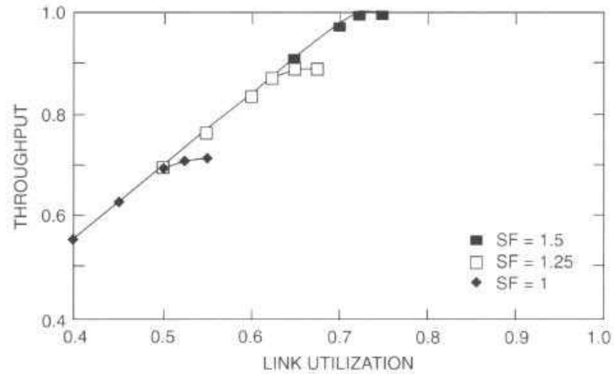


Figure 12. Point-to-multipoint switch performance is improved by increasing switch speed

The BFN is arranged in a modular format consisting of four trays, each containing four connectorized fibers. Each of these optical fibers was cut to within 1-mm accuracy to create the requisite phase delays. The optical losses were essentially the same as for the connectors and couplers, and were uniform to within ±0.5 dB. The measured relative phase shifts of various fibers were found to agree closely (to within ±5°) with the theoretical values.

The fabricated optical BFN has dimensions of 7 x 5.5 cm (radius) and weighs 800 g. The major contributors to the weight and size of the BFN are the optical connectors. With fusion splicing, the dimensions

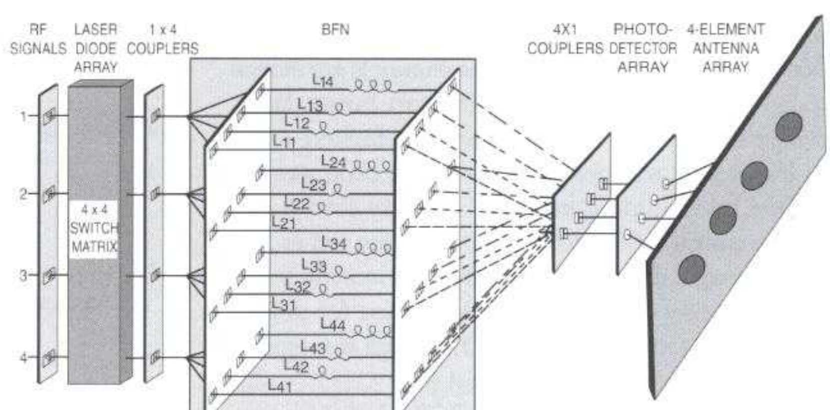


Figure 13. 4 x 4 optical space-fed BFN consists of a set of 16 fiber true time delay lines feeding a four-element antenna array

could be reduced to a few centimeters and the weight to a few grams. In 1992, NTD plans to combine the optical BFN with the phased-array antenna elements and measure the radiation pattern. Methods to further reduce the size of the optical BFN will also be investigated.

Integrated Organic Optical Waveguide Devices

Future generations of advanced communications satellites will make increasing use of onboard processing. The emerging concept of integrated photonics has the potential for realizing lightweight, low-power, and compact onboard processing subsystems. At the Laboratories, development of integrated optical (IO) devices based on nonlinear organic material for C-band, lightweight, phased-array satellite antennas continued in 1991. This effort focused on the design, fabrication, and performance testing of organic optical waveguide phase shifter devices.

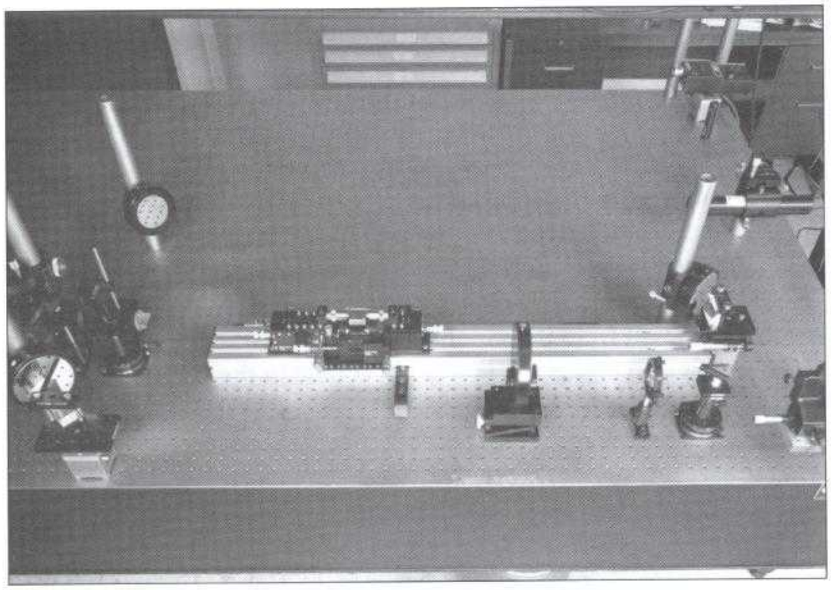


Figure 14. Optical test bench includes micropositioners to establish the fine alignment of integrated optical devices

IO devices use a three-layer (buffer/core/buffer) stack of organic NLO material that is electro-optically active. Prototype electro-optical channel waveguide phase shifters are fabricated on silicon wafers. Each of the fabrication steps is complex and requires meticulous inspection.

Typically, the NLO core is corona-poled before channel fabrication. The post-poling processing parameters are carefully selected to prevent degradation of the poled electro-optical coefficient. To reduce the optical scattering losses resulting from the RIE sidewalls of the core channels, the phase shifters are also fabricated using a strip waveguide design. For strip waveguide devices, the channels are etched to an appropriate depth on the top buffer layer, where the difference in the effective refractive index of the etched and non-etched regions produces the optical waveguiding mechanism. Since corona discharge poling of the core layer has often led to surface damage, the strip waveguide devices are poled by an applied electric field. A technique for polishing the end facets of organic IO channel waveguide devices has also been developed.

The propagation loss, mode-field distribution, and V-π (voltage required for an electro-optically induced 180° phase shift across a 1-cm-long device) of the fabricated devices have been measured in the Laboratories' optical test facility. A Mach-Zehender interferometer measures the V-π of the phase shifters. Figure 14 shows the optical test bench, complete with micropositioners for fine alignment of the IO device and light sources and photodetectors. For the strip waveguide design, the loss is typically lower (approximately 2 dB/mm *vs* approximately 3 to 4 dB/mm for the RIE core channel waveguide at a 0.83-μm wavelength). For a longer wavelength (1.3 μm), the loss is reduced to 0.5 to 1 dB/mm. The mode-field distribution is single-mode in the transverse plane (Figure 15). The measured V-π of the phase shifters corresponds to a 3- to 10-pm/V linear electro-optical coefficient. NTD continues to investigate the high RF (GHz) modulation capability of the electro-optical devices.

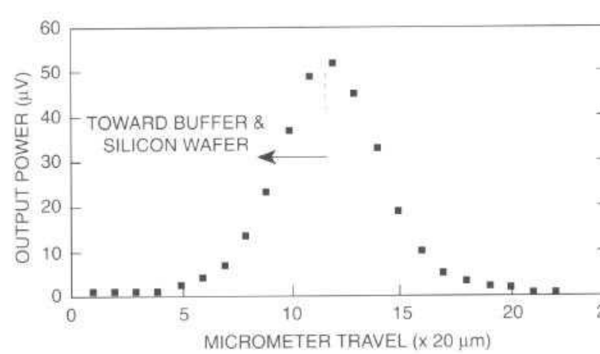
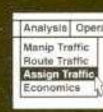


Figure 15. Mode-field distribution in the transverse plane of the waveguide exhibits symmetrical single-mode behavior (near-field scan at 100X magnification)

SYSTEM DEVELOPMENT

The System Development Division's (SDD's) major accomplishments for 1991 included completion of the initial version of the AXIS user interface development environment and its application to several major software development programs. Engineering workbenches were designed and implemented for COMSAT Mobile Communications (CMC) and COMSAT World Systems (CWS), and an interactive version of the General Antenna Program was realized. SDD provided frequency planning support to CWS and INTELSAT. The year also saw completion of the Inmarsat-M/B Network Coordination Station operator interface. Systems integration support was provided to the Advanced Communications Technology Satellite (ACTS) Program, and systems engineering studies and analyses related to mobile satellite systems were conducted. ■



AXIS USER INTERFACE DEVELOPMENT ENVIRONMENT

During 1989 and 1990, SDD developed AXIS, a user interface development environment (UIDE) which is being applied to create sophisticated graphical user interfaces for software applications. Based on the X Window System and Open Software Foundation (OSF)/Motif, AXIS provides software libraries, productivity tools, and application templates to improve user interface consistency, programmer productivity, and software quality.

The initial version of AXIS was put into production during 1990. Its major components include the AXIS Toolkit, a library of user interface software; XWARE, a screen designing and code-generating facility; and the Motif Clip Art library, a collection of drawings used to design and document user interfaces.

In 1991, several major enhancements were made to the AXIS software libraries and productivity tools. A new version of the AXIS Toolkit was completed which is based on an enhanced architecture that supports future system expansion. Several new user interface objects ("widgets") were added, including a work-in-progress box (Figure 1), a graphing widget, and a polyline segment widget. In addition, a record manager dialog (Figure 2) was implemented for use in applications, to allow an operator to define and edit information stored in records (*e.g.*, data in a database). Other functions added to the AXIS Toolkit include support for multiple-column lists and text file parsing. Numerous utilities that support rapid prototyping were included in the latest version.

The major enhancements to XWARE include the addition of a C-code generating capability and a widget hierarchy display. Several other upgrades were made to increase programmer productivity and support the additional rapid prototyping capabilities added to the AXIS Toolkit. In combination, these features enable a programmer to create a user interface prototype with virtually no programming.

ENGINEERING WORKBENCHES

An engineering workbench is a software system that provides a common, interactive interface to a database of technical system parameters and a suite of analysis programs that operate on the data in these databases. In 1991, engineering workbench tasks were initiated for both CWS and CMC. The software systems will run under the UNIX operating system on engineering workstations and will support the daily activities of CWS and CMC engineering, operations, planning, and marketing personnel.

The user interface to both workbenches is menu- and dialog-driven, and is based on the style conventions provided by OSF/Motif. Even though the CWS and CMC workbenches access different databases, they have several common features. Both workbenches perform the following functions:

- View and report data in the technical database, including earth station, satellite, signatory, traffic, and frequency planning data.
- Create maps of the world with user-selected projections, labels, elevation and azimuth contours, antenna coverage patterns, and traffic links between earth stations.
- Calculate elevation angles, azimuth angles, beta factors, and earth station pointing angles for a specified earth station and satellite location.
- Calculate the effects of inclined orbits.
- Compute link budgets.
- Perform frequency planning analysis.

In 1991, the user interface was designed for both workbenches, and portions of it were implemented using the X Window System, OSF/Motif, and AXIS. In addition, SDD developed a preliminary version of the general mapping feature,

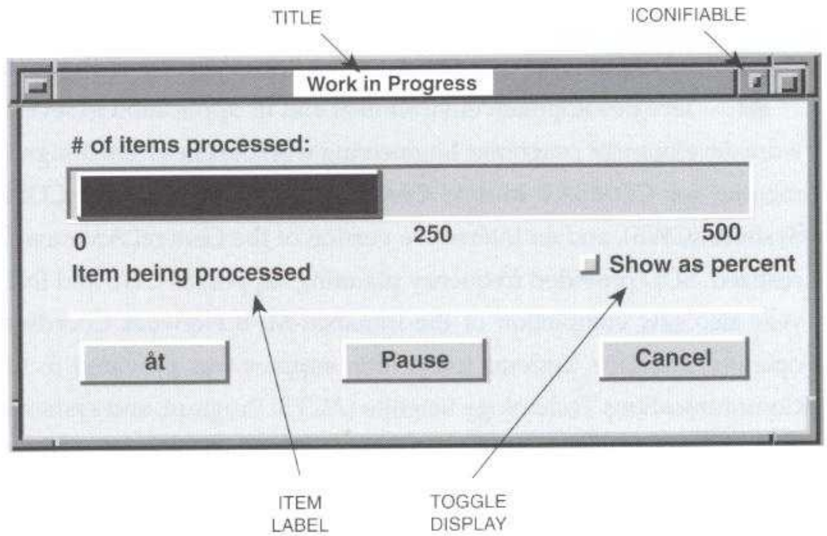


Figure 1. Work-in-progress box

which allows a user to interactively generate and customize maps of the world by selecting options from a set of menus. These options include map projection (orthographic, Mercator, equirectangular, and perspective), state and country borders, and lines of latitude and longitude. The user can also plot contours of constant elevation and azimuth for a specified

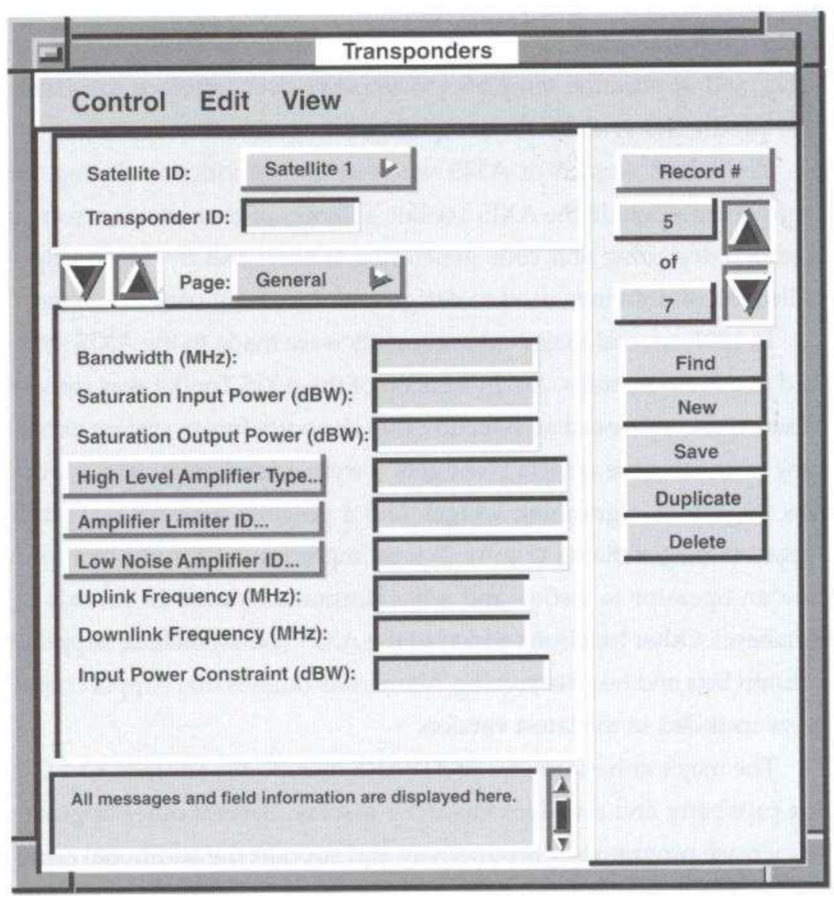


Figure 2. Standard record manager dialog

satellite location. Earth stations and satellites may be plotted from the database, or new locations may be entered for planning purposes.

The CWS Workbench includes the functions listed above, as well as functions to calculate the effects of rain and sun outages, perform traffic manipulation and forecasting, and plot INTELSAT antenna coverage patterns. In 1991, the CWS Workbench provided access to all the earth station and satellite data stored in the Intelsat Satellite Services (ISS) Database Management Facility (IDBMF). Figure 3 shows a standard report-generation dialog. This particular dialog allows the user to generate a report of earth station data. The user may quickly view the types of data that are available from the database, and then choose a subset of data fields to include in the report. In addition to report generation, the workbench enables the user to quickly find all the information stored in the IDBMF concerning a particular earth station or set of earth stations via a quick-find dialog. Figure 4 depitcs a typical quick-find dialog. A similar dialog exists for satellite data. This feature will be available for all data categories in both workbenches.

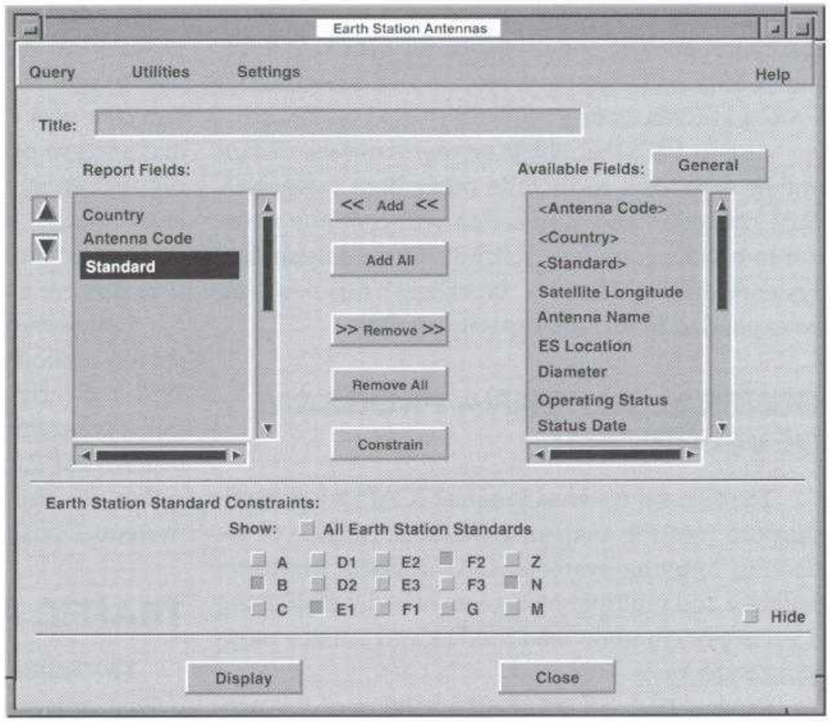


Figure 3. Standard report-generation dialog

The CMC and CWS workbench tasks differed in that CMC did not have an existing database or suite of analysis programs. For CMC, the task included developing the workbench as well as a database of mobile system parameters and a suite of analysis programs to operate on the stored data. A prototype of the database and software system was built in 1991, and the parameters associated with coast earth stations (CESs), mobile terminals, and satellites were identified. The mobile system database was designed and implemented for CES and satellite data, and data collection and entry were initiated for these two data categories.

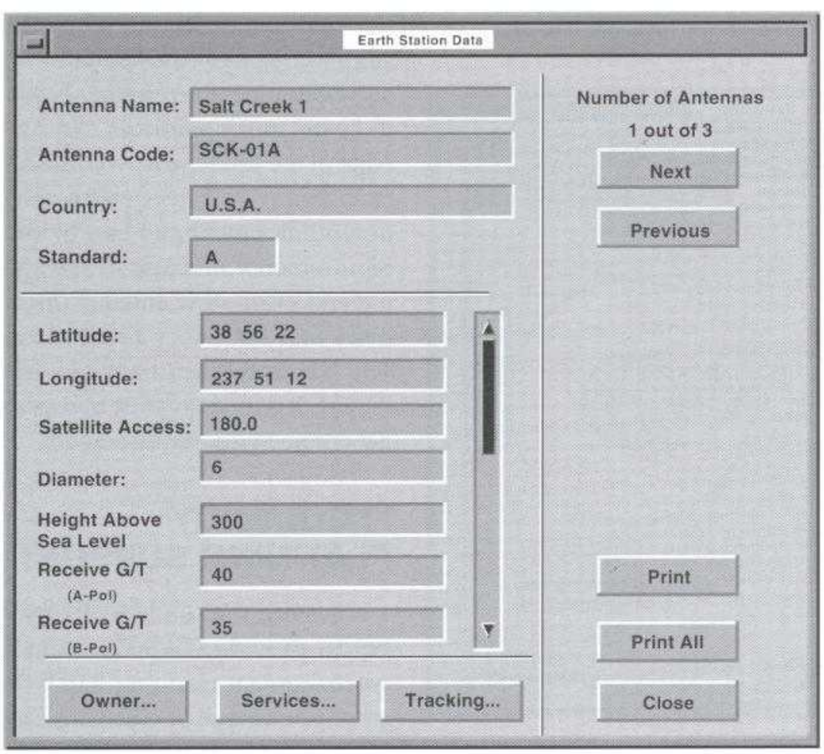


Figure 4. Typical quick-find dialog

In 1992, the common functions of the workbenches will be expanded to include calculation of azimuth and elevation angles, enhanced mapping features, viewing and reporting of other data categories, and computation of link budgets. Both systems will have a full set of documentation, including a user manual, theoretical manual, and programmer manual. A training course will also be prepared and presented to CMC and CWS users.

Also in 1992, the mobile system database design will be expanded to include other data categories. Data collection and verification will continue in order to build a complete, accurate, up-to-date mobile system database. The CMC Workbench functions will be expanded to include capacity analysis.

GENERAL ANTENNA PROGRAM DEVELOPMENT

The General Antenna Program (GAP) is a general-purpose tool for analyzing the performance of reflecting antenna systems. GAP models multiple-reflector and multiple-feed geometries by employing a variety of common feed models and surface modeling techniques.

During 1991, an interactive version of the program was developed for an X Window environment. The interactive interface—called the Interactive General Antenna Program (IGAP)—is based on the OSF/Motif interface standard and was implemented using the AXIS UIDE developed by SDD. This interface is designed to enhance user productivity while minimizing errors. The complex geometry of a reflector system with multiple surfaces and feeds can be defined graphically, eliminating the need for the user to derive complex surface equations and feed geometries. Figure 5 shows a screen that enables the user to graphically define a Cassegrain reflector system. The user can select input geometry, and output and analysis options by using a mouse for direct manipulation, in conjunction with a keyboard for text entry. Output plots and tables are displayed in scrollable, resizable windows. The system also allows the user to save and recall complete work sessions.

Complete documentation for the new command-driven version of GAP (Version 2.0) was completed in 1991 and includes a theoretical manual, a user manual, a programmer manual, and a test report. In addition, GAP 2.0 was installed on HP9000 series computers for use by the Microwave Technology and Systems Division (MTSD).

TRAFFIC ANALYSIS PROGRAM

The Traffic Analysis Program (TRAP) is a menu-driven program that allows a user to interactively specify and edit a world map, satellite antenna beam parameters, and other satellite-related information. TRAP was developed from the existing code of the Interactive Antenna Coverage Program (IACP), and runs on engineering workstations and computers under the UNIX operating system.

TRAP calculates the up-link and down-link traffic volume for user-defined circular beams on a map of the earth, given the earth station locations and the station-to-station traffic matrix. It also determines the resulting beam-to-beam traffic matrices. Knowledge of the total traffic volume for each beam aids in determining down-link power and bandwidth requirements, and also in specifying and evaluating antenna directivity and frequency reuse plans. The beam-to-beam traffic matrix (Figure 6) is used to define transponder connectivity requirements.

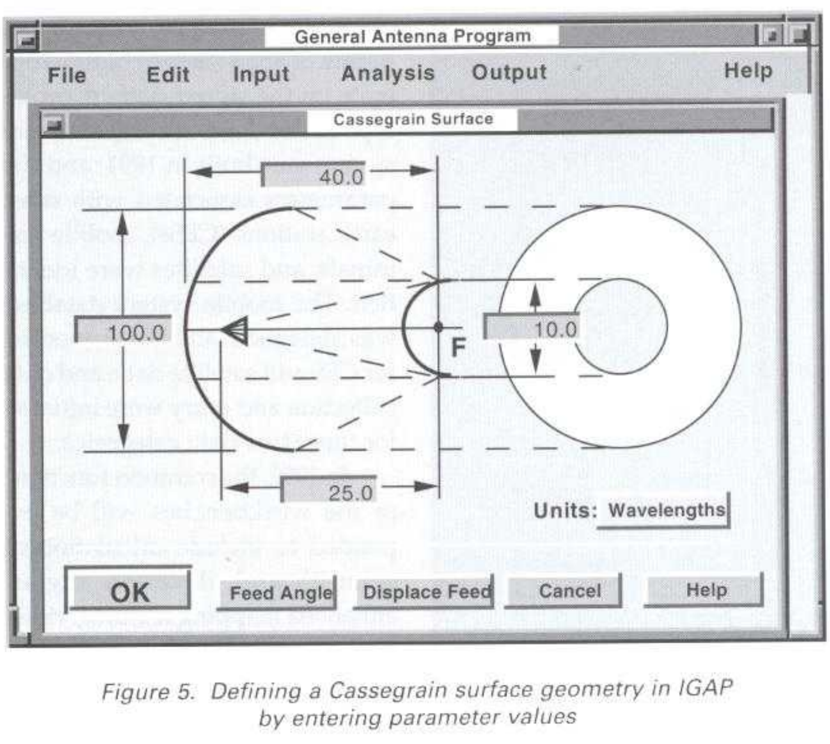


Figure 5. Defining a Cassegrain surface geometry in IGAP by entering parameter values

FREQUENCY PLANNING SUPPORT

In 1990, SDD undertook a project to provide CWS Operations space segment planning staff with an environment of software and supporting documents that would aid in generating and evaluating

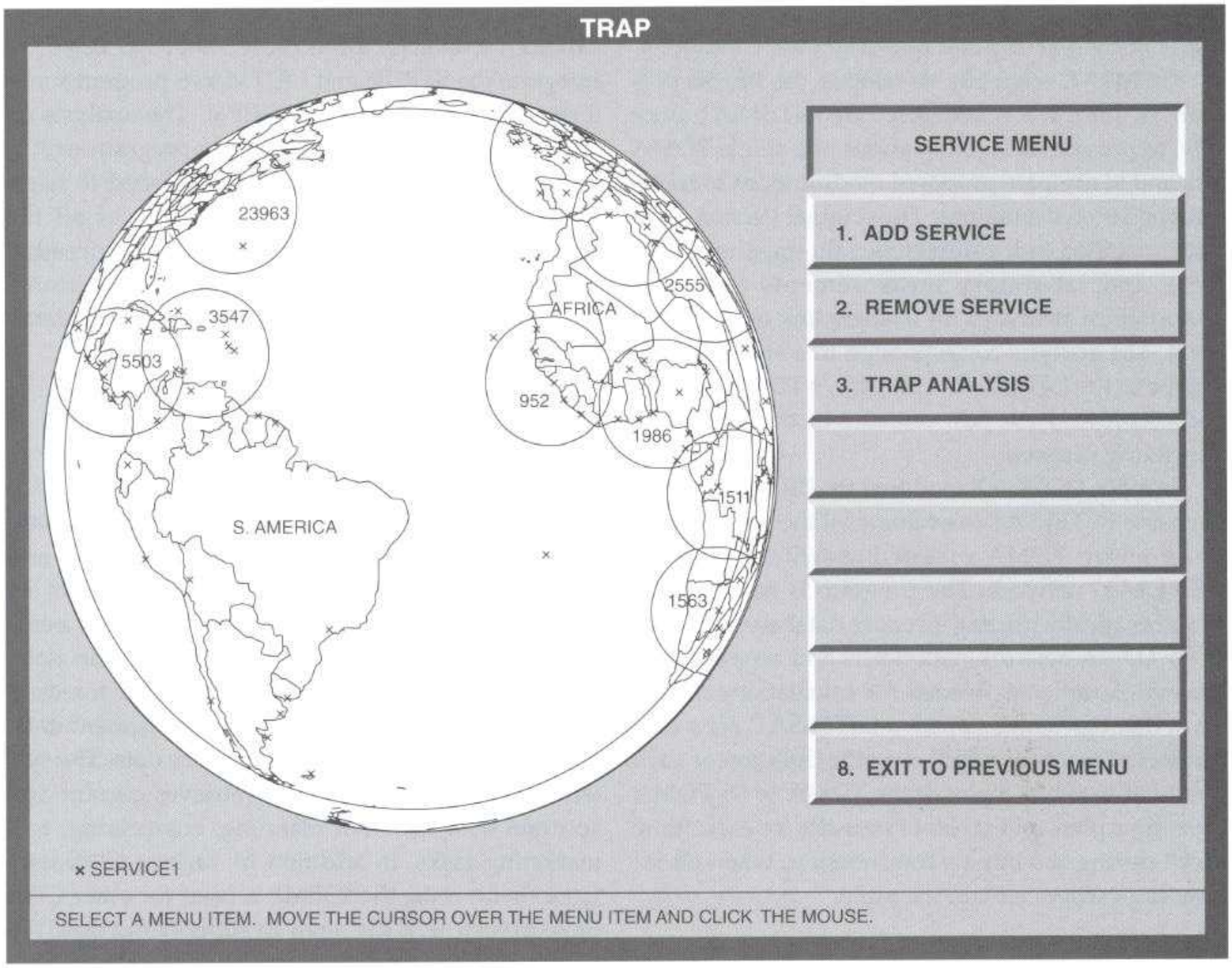


Figure 6. TRAP screen

transmission plans for leased segments of INTELSAT transponders, and in obtaining current carrier assignments on INTELSAT satellites. This capability is necessary for managing space segment capacity, particularly in transponders leased for unrestricted use.

The support consisted of acquiring current frequency plan data from INTELSAT, documenting guidelines for generating or modifying transmission plans, and developing or modifying existing software tools to enable the CWS Operations staff to readily access and evaluate INTELSAT frequency plans. In 1991, SDD provided CWS Operations with monthly plots and weekly reports of the current carrier assignments on all INTELSAT satellites of interest.

An error-checking system was added to the Interactive Satellite Transmission Impairments Program (ISTRIP) to filter out errors in input specifications. Other modifications to ISTRIP included enhancements to the plot of the frequency plan, enlargement of data storage, an analysis capability to recalculate the transponder operating point when a carrier is added, and a new algorithm to reduce calculation time when intermodulation effects are modeled for a large number of carriers. A version of the Satellite Transmission Impairments Program (STRIP) was created to provide rain impairment analysis results for the transmission plans, and software routines to automatically interface ISTRIP with the IDBMF were written.

Draft documentation for the frequency planning tools and procedures was completed in 1991. In addition, specifications were provided to the IDBMF database administrator for loading INTELSAT frequency plans and frequency planning data into the IDBMF.

BEEFS PROGRAM

The Bit Error Rate/Error-Free Seconds (BEEFS) program is a satellite transmission analysis program that computes estimates of bit error rate (BER) and percentage of error-free seconds for INTELSAT time-division multiple access (TDMA) transmission under both clear-sky and rain-degraded conditions.

COMSAT originally developed the BEEFS program in 1983. It has been used by INTELSAT since 1986 to provide detailed analyses of a single TDMA link and to evaluate proposed modifications to transmit and receive antennas. The original version combined detailed link parameters, rain impairment effects, and laboratory measurements to obtain performance estimates for a single link on a TDMA burst. The analysis corresponded to a single instant of time in the INTELSAT 120-Mbit/s TDMA system, and considered the rain statistics of the target and interfering carriers.

In 1991, COMSAT modified the BEEFS program to enable INTELSAT to evaluate all the unique links in an entire TDMA or satellite-switched TDMA (SS-TDMA) network. The program is now capable of automatically reading an entire database of TDMA or SS-TDMA network parameters and accessing additional parameters needed for calculations from a set of databases maintained at INTELSAT. New output includes average BER over the duration of each burst indicated on a plot of the TDMA or SS-TDMA burst time plan, and tables of statistics for each "time slice" during the burst's transmission, when all interfering carriers remain the same.

STRIP6I

Two software programs that have been used regularly at INTELSAT to evaluate and optimize frequency plans for multiple-frequency-reuse satellites are STRIP, Version 6 (STRIP6), and the Outage Margin and Time Program (OUTMAT6). STRIP6 analyzes the performance of all the carriers in a specified frequency plan in clear weather. It can also be used to adjust the up-link power levels of all the carriers to ensure that their clear-weather performance levels meet or exceed INTELSAT's performance criteria. The program can be applied to any geostationary communications satellite operating with fixed earth stations, and allows the use of frequency-division multiplexing/frequency modulation (FDM/FM), digital signals (including TDMA), FM television, single channel per carrier (SCPC)/FM, companded FDM/FM, and companded single sideband (SSB), as well as bands of small digital and SCPC/FM carriers.

OUTMAT6 processes the STRIP6 database to analyze the effect of rain impairment on carrier performance. Both programs operate on the INTELSAT IBM ES/9000 computer.

During 1991, with support from the Communications Technology Division (CTD), SDD began to integrate the STRIP6 and OUTMAT6 programs into a single software system: STRIP6I. The analysis algorithms were modified to speed program execution, and a new algorithm was developed to iteratively adjust the up-link power levels of all the carriers until the requirements for both clear-weather performance and protection against rain impairment are met. Development of this algorithm will continue in 1992.

ISS DATABASE MANAGEMENT FACILITY

The IDBMF originated as the ISS Database Management Facility on the IBM mainframe in 1987, and is now being migrated to the UNIX environment for CWS. The software system provides CWS with a central repository of INTELSAT satellite system data, including frequency planning data, traffic forecasts and actuals, earth station data, space segment data, and Board of Governors and signatory data. The system stores, manipulates, and retrieves current and accurate data for CWS planning, engineering, and marketing tasks. In addition to various CWS user requests for data, the IDBMF is used for other CWS projects such as STRIP analysis support and the CWS Workbench.

Several modifications to the IDBMF in 1991 have strengthened its accuracy and usefulness. The database design was documented, and a significant amount of additional data was included. Several software utilities were developed to process the large amount of data provided by INTELSAT for validation and direct loading into the database, and all modules were enhanced for more accurate and efficient user response. As part of the STRIP analysis support task, the frequency planning module of the database was extensively revised based on additional information obtained regarding INTELSAT frequency planning procedures.

Next year, SDD will complete the migration of the IDBMF from the IBM mainframe to the UNIX environment, and additional database administration functions will be automated. Regular user meetings and formal user training based on the new environment will be conducted, and documentation will be updated. SDD will continue to respond to changing data sources, advanced technology, and user application requirements to secure the IDBMF as a leading-edge facility for CWS.

LOW-EARTH ORBIT MOBILE SYSTEMS STUDY

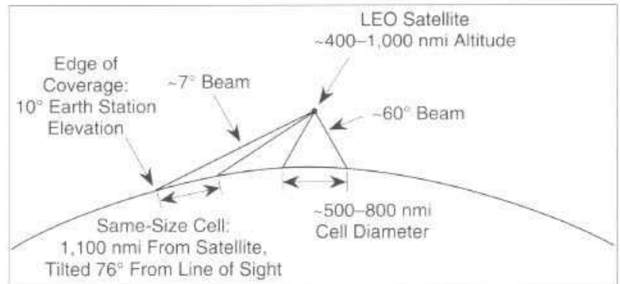


Figure 7. Matched-beam size from a LEO satellite is large, though variable—a small phased array can meet the requirements

On behalf of CWS, SDD conducted a study of low-earth orbit (LEO) satellite communications systems, with the basic goal of understanding their performance potential and the top-level engineering tradeoffs affecting their capacity and cost. The study also investigated how the performance of LEO systems could be matched using satellites in geostationary earth orbit (GEO).

Mobile communications systems comprising tens of satellites in low orbit have recently been proposed by several organizations. In concept, these systems are like a cellular telephone system, inverted; that is, the cells move with the satellites, while the users remain relatively fixed. The cells are hexagonal and hundreds of miles in diameter, and each is covered by one spot beam from a multibeam satellite antenna. Such systems promise high performance (power and bandwidth efficiency), and there appear to be no insurmountable technical barriers to providing approximately 4.8-kbit/s digital voice service to handheld or small portable subscriber units from LEO at L-band. However, other issues that are still open and subject to continuing lively debate include market size, link margins needed for marketable service quality, and economic feasibility.

The study showed that the high performance promised by LEO cellular systems results from small cells, not low orbit altitude. Power and bandwidth efficiency vary with the inverse square of the cell diameter, C, because all major resource requirements per user (bandwidth, satellite down-link transmit power, and handheld unit up-link transmit power) increase with C^2 for a given minimum elevation angle. Bandwidth and satellite power can be kept within technical, regulatory, and economic limits by trading-off system capacity (number of users) *vs* $1/C^2$. However, when subscriber unit transmit power is at its limit, the up-link cannot be closed (and the service cannot be offered) if the coverage cells are made any larger. Thus, there is a maximum-coverage cell size at which the up-link from a handheld transceiver can be closed. This maximum size depends critically on the link margin for shadowing, multipath, and user movement required for a marketable service, and on the maximum safe power from a handheld transmitter next to a human head. While these numbers are difficult to determine, and no firm consensus exists, SDD's studies indicate that, with reasonable assumptions, the maximum cell diameter is something on the order of 800 to 1,000 nmi.

The most significant advantage of LEO for a cellular satellite system is that it allows small cells to be realized with relatively small satellite antennas (Figure 7). Rectangular apertures on the order of 2 m long allow cell diameters under 1,000 nmi. Also, the number of cells required per LEO satellite is moderate (typically 19).

The greatest disadvantage of LEO is that the area covered by each satellite is small (approximately 2 to 6 percent of the earth) and moving—circling the earth about every 2 hours. These moving coverage areas present several requirements, including the need for call handover between cells and satellites; deployment of all satellites in orbit to initiate full-availability service; and either a large number of either gateway stations, or intersatellite links (crosslinks) for other than relatively localized coverage. These requirements are technically feasible, but novel and complex.

The well-known advantage of GEO—nonmoving coverage of approximately 30 percent of the earth from any one gateway station using one satellite—has driven satellite communications for 25 years. Also, handover is needed no more than once per hour, if at all, even for jet aircraft and small cells. Technically, a GEO satellite could provide the same small cell area as a LEO satellite, and thus the same high performance with handheld transceivers (see Figure 8).

The main disadvantage of GEO is that the antenna aperture required to provide sufficiently small cells is very large, on the order of 10 to 15 m. This size is a compromise: more than required for small cells directly under the satellite (Figure 9), but less than needed near the edge of coverage to offset stretching of the cells caused by both geometry and the inevitable degradation of off-axis beams from a reflector antenna (Figure 10). Also, each satellite must

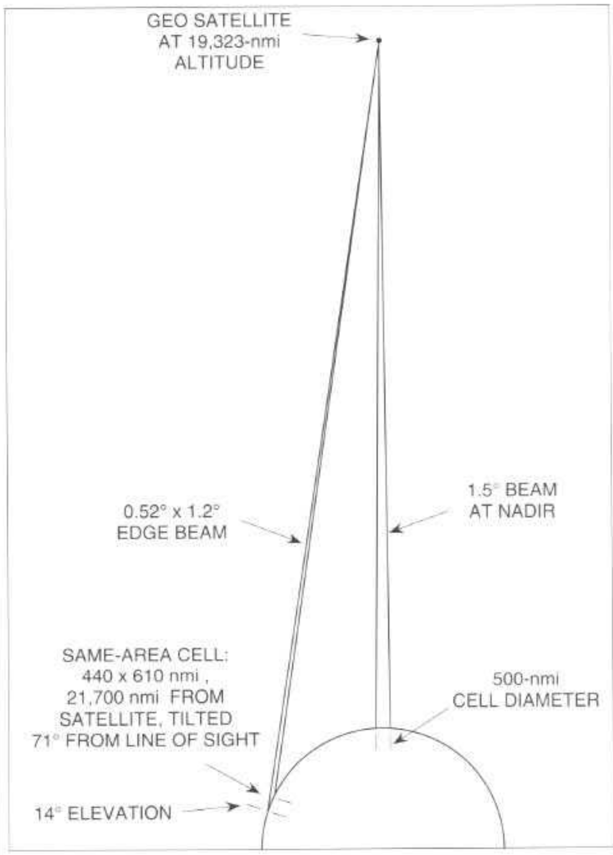


Figure 8. Matched-beam sizes with fixed cell area from a GEO satellite

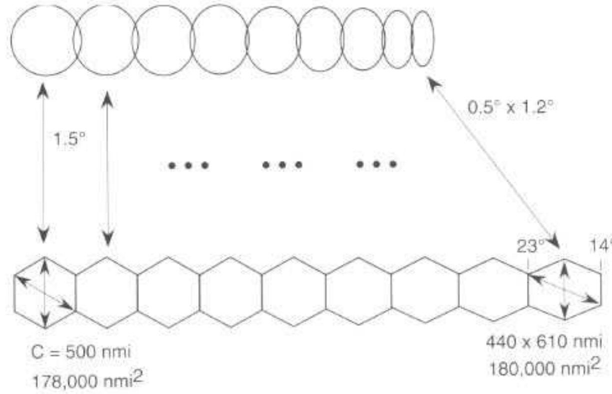


Figure 9. Impractically small elliptical beams at edge from GEO would be needed to produce constant-area cells on earth

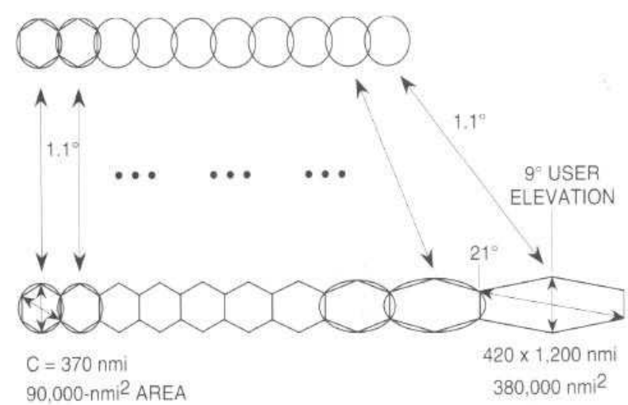


Figure 10. Constant-size beams from orbit produce stretched cells on earth (example: 1.1° beams from GEO, 0.95° spacing)

provide approximately 120 cells to cover even a fraction of the area it can see (*e.g.*, the fraction that is on land). Because of the large satellite size and complexity, only a portion of proven and available GEO technology is applicable.

The study concluded that a LEO system for service to handheld or portable transceivers is technically feasible and offers the substantial advantage of high performance with small satellite antennas. Also technically feasible is a large GEO spacecraft delivering performance comparable to that obtainable at LEO, with the major advantage of using a few nonmoving satellites. Much work remains to be done to define LEO and GEO mobile systems that combine high performance with economic and operational feasibility.

Since 1984, the NASA Advanced Communications Technology Satellite (ACTS) Program has been the single largest program at COMSAT Laboratories, involving skilled engineers and technicians from virtually every division. In 1991, three major program milestones were achieved. All NASA Ground Station/Master Control Station (NGS/MCS) subsystem integration and acceptance testing was completed, and test results and specification compliance were presented to NASA at the Ground Segment Final Design Review. Construction of the NGS 5-m antenna was completed, and antenna acceptance testing began. Also, development of the integrated services digital network (ISDN) interfaces for the NGS and ACTS low burst rate (LBR-2) earth stations was initiated.

These milestones represent the climax of the NGS/MCS development phase at COMSAT, and the beginning of the final phase—the full integration of the ACTS subsystems into a complete and operational system. ■

NGS/MCS INTEGRATION & TEST

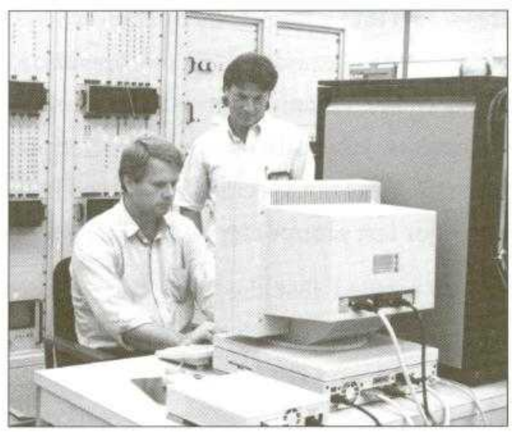
During 1991, the ACTS Program at COMSAT focused on the integration and test of the NGS RF Terminal (RFT), NGS time-division multiple access (TDMA) terminals, and MCS subsystems into a final, fully operational system. Detailed test procedures were developed which exercised all the operational features of the integrated equipment, and characterization procedures were devised which defined the various measurements needed to ascertain the performance characteristics of the integrated system in areas not specifically covered in the contract performance specification. The major test groups can be summarized as follows:

- *MCS/CBS Interface Tests* verified that the MCS correctly implemented the specifications governing its interface with the General Electric (GE)-supplied telemetry, tracking, and command (TT&C) equipment.
- *MCS TT&C Operations Tests* verified correct implementation of the MCS TT&C functional requirements.
- *RFT Performance Tests* verified RFT compliance with all RF performance requirements. These tests also included additional characterizations to be used during installation of the equipment at GE Astro-Space and NASA Lewis Research Center (LeRC), and provided a performance benchmark for calculating overall system performance.
- *Modem/RFT BER Characterization Tests* characterized overall system bit error rate (BER) performance using COMSAT RF/IF equipment paths and NGS modem equipment provided by Motorola Government Systems Group.
- *TDMA Interface Tests* verified the compliance of NGS TDMA equipment with all terrestrial user interface requirements.
- *RFTS Operations Tests* verified compliance of the RFT Supervisor (RFTS) computer and software with their functional and performance requirements.

Rodney Knight, ACTS Ground Segment Program Manager (NASA LeRC) with William Schmidt, COMSAT ACTS Program Director

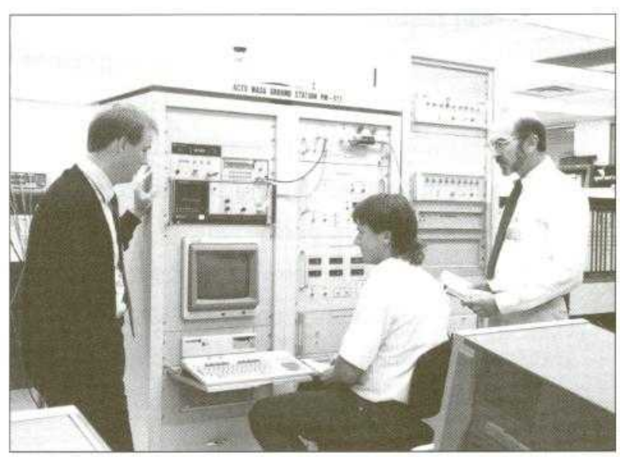
On December 5 and 6, 1991, COMSAT formally presented the acceptance test results and statement of specification compliance to NASA at the ACTS Ground Segment Final Design Review. NASA personnel attending the review concurred with COMSAT's claim of full compliance. For COMSAT, this event represented the climax of the ACTS Program, which began on September 5, 1984. Despite annual replanning due to budget cuts, delays resulting from the Challenger *disaster, hundreds of specification changes, and a major contract restructuring, COMSAT personnel successfully completed a fully compliant system months before it was needed by the program, and at several million dollars less than the COMSAT budget allocation!*

RFT is configured for test

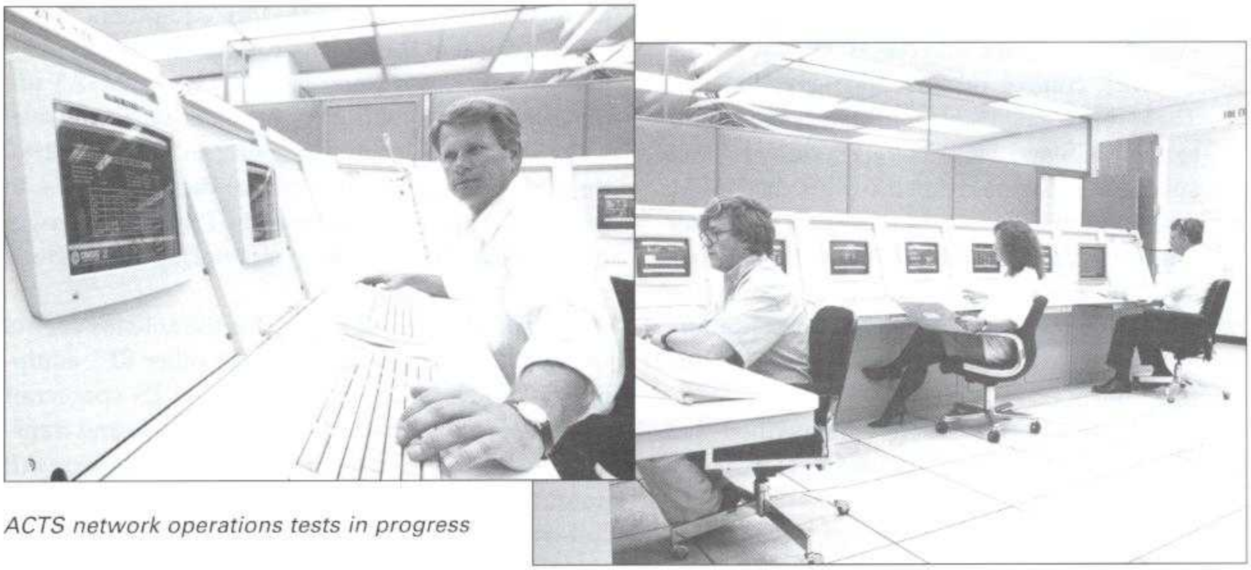


COMSAT ACTS TDMA equipment is prepared for test

NASA engineers witness TDMA network test performed by COMSAT engineer



NASA ACTS resident engineer Ed Taylor (right) witnesses system BER measurement tests

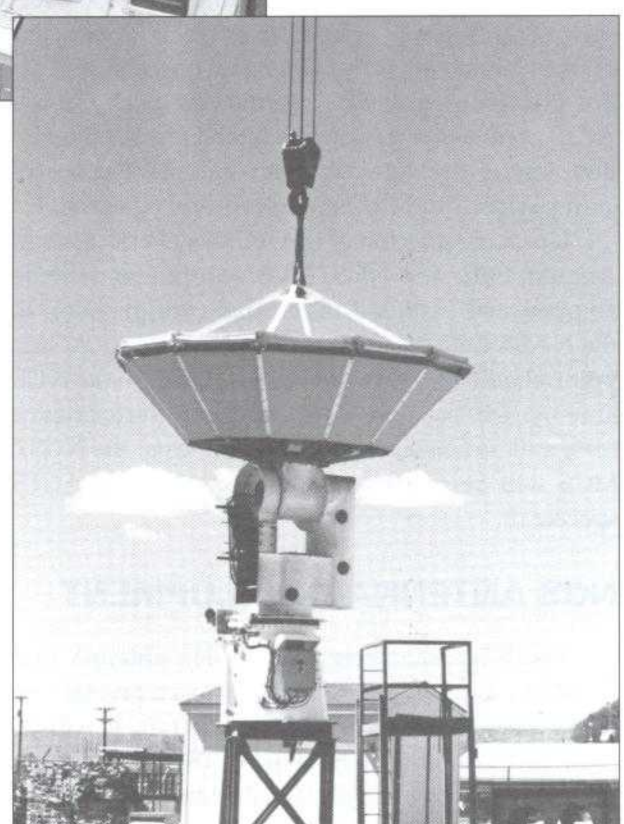


ACTS network operations tests in progress

NASA and COMSAT attendees at ACTS Ground Segment Final Design Review

Dr. Richard Gedney, NASA LeRC ACTS Program Director (left), accepts the "keys to the NGS/MCS" from Dave Meadows, COMSAT ACTS Systems Engineering Manager

ACTS 5.5-m antenna is hoisted by crane to its permanent location atop Building 55 at NASA's LeRC



- *LBR Network Operations Tests* verified overall system compliance with the ACTS LBR TDMA network control performance specification. These requirements were primarily applicable to the MCS and NGS TDMA terminals. This suite of tests verified that the MCS, the TDMA terminals, and the ACTS baseband processor interacted correctly in performing terminal acquisition and synchronization, call connection and disconnection, rain fade compensation, and associated monitoring and data collection functions.
- *Experiment Data Processing Tests* verified that the MCS correctly implemented its experiment data processing functions.
- *NGS Antenna Tests* verified that the NGS antenna met its performance requirements.

All of the above tests were completed by November 1991 and performed before NASA witnesses, in strict conformance with configuration management and quality assurance requirements. The testing demonstrated conclusively that all COMSAT equipment fully complies with all of the specifications and design goals.

Current plans are to disassemble the NGS/MCS equipment and ship it to the GE Astro-Space Division in Princeton, New Jersey, in April 1992. The equipment will be integrated with the ACTS spacecraft, and a series of systems tests will be conducted prior to launch to verify full system operability. This test phase is required due to the complexity of the ACTS system and its unprecedented level of interaction among the network earth stations, the spacecraft payload, and the network control equipment.

Upon completion of the ACTS systems tests in August 1992, the NGS/MCS equipment will be shipped and installed in its final configuration at the NASA LeRC facility in Cleveland, Ohio. At this point, the RFT equipment will be mated to the NGS antenna for the first time. After RF performance tests and antenna control function tests, the NGS/MCS will be ready for operation with the ACTS spacecraft.

NGS ANTENNA DEVELOPMENT

The 5.5-m-diameter, 20/30-GHz antenna that COMSAT is providing to NASA plays a pivotal role in the operation of the ACTS spacecraft. It will be used to transmit and receive ACTS TT&C signals and LBR network traffic signals. Since the NGS is the primary TT&C facility for ACTS, the performance of the antenna and associated RF equipment in this role is critical to the ACTS program mission.

The antenna is being procured by COMSAT under subcontract with TIW Systems of Sunnyvale, California. From contract signing in February 1990 through preliminary and critical design reviews in May and August of that year, the Program Management Office (PMO) has been monitoring the vendor's progress and performance.

Included in the subcontract is the antenna control unit (ACU) which, along with the other RFT equipment, will serve as the primary ACTS spacecraft tracking facility. This facility will generate and transmit the continuous up-link signal that the spacecraft autotrack receiver will use as part of its attitude control, as well as the precise azimuth and elevation data that GE will use for ACTS spacecraft orbit determination. The ACU can be controlled remotely via the RFTS. Through the RFTS computer network, antenna status and control capability will be available at the GE Satellite Control Center in East Windsor, New Jersey, permitting GE personnel to operate the antenna during off-hours, when the NGS is not staffed.

The NGS antenna includes a dual-band, dual-polarization diplexer developed at COMSAT Laboratories. After thorough measurement and test in March 1991, this component was provided to TIW for incorporation into the antenna package. TIW designed and fabricated a feed horn, and integrated and tested the feed horn and diplexer at its Sunnyvale facility. In April 1991, the main antenna structure was erected at TIW's Albuquerque, New Mexico, test range, and mechanical alignment and tests were initiated. Concurrent with this activity, the ACU and servo mechanisms were finalized, and witnessed testing took place in May and June at Sunnyvale. Final mechanical and servo measurements were conducted in October and November, respectively, at Albuquerque, and will culminate with RF performance tests in January 1992 using an 18-mi test range.

The antenna will be delivered to NASA LeRC and erected on the roof of Building 55 in March 1992. Final tests will be conducted to ensure its readiness for the arrival of the rest of the NGS/MCS from GE in September 1992, and the launch of the spacecraft in February 1993.

ISDN INTERFACE DEVELOPMENT

The ACTS LBR network will soon become ISDN-compatible with the addition of ISDN interface equipment being developed at COMSAT Laboratories. This equipment is designed to function with both the NGS equipment manufactured by COMSAT and the very small aperture terminal (VSAT) experimenter terminals being developed by Harris Corporation.

The ACTS ISDN implementation will facilitate the connection of ISDN primary rate interfaces (PRIs) to the ACTS LBR network. Operating at 1.544 Mbit/s, the ISDN PRI provides 23 bearer channels (B-channels) and one common signaling channel (D-channel), with channel data rates of 64 kbit/s. With the addition of commercially available ISDN multiplexing equipment, the LBR TDMA network will also be able to service ISDN basic rate interfaces (BRIs). The COMSAT development effort includes a demonstration of the BRI interface capability using a Teleos IAP-6000 to provide BRI-to-PRI concentration.

COMSAT's design approach, which emphasizes low recurring cost, adds an ISDN signaling processor to the VSAT to facilitate ISDN operation. Figure 1 is a simplified block diagram of the ISDN equipment configuration at the VSAT. For ISDN compatibility, the modular switching peripheral (MSP) associated with the experimenter VSATs is configured to include a B8ZS T1 interface. Each COMSAT-developed ISDN signaling processor consists of a Macintosh IIci computer with two off-the-shelf 68000-based Nu-Bus co-processor boards hosting COMSAT's ISDN software. Experimenters can use any Macintosh II computer with two available Nu-Bus slots for the signaling processor application. One co-processor operates as an X.25 packet handler, while the other services ISDN signaling messages on the D-channel. Figure 2 is a simplified functional diagram of the ISDN signaling processor software.

With the capability to dynamically switch individual 64-kbit/s channels in the onboard baseband processor, ACTS is uniquely suited to serve as an ISDN backbone. Both single-channel and multichannel ISDN calling are supported through ACTS. For the transport of X.25 packet traffic, the ACTS ISDN will establish a 64-kbit/s packet trunk on the LBR network from each ISDN VSAT to the NGS. The NGS TDMA reference terminal is modified to serve as an X.25 packet router hub, simultaneously servicing up to 23 ISDN-equipped LBR TDMA terminals. Both B- and D-channel X.25 packet traffic is supported.

High channel throughput efficiency in the transport of X.25 packet data on the LBR TDMA network is made possible through COMSAT's proprietary

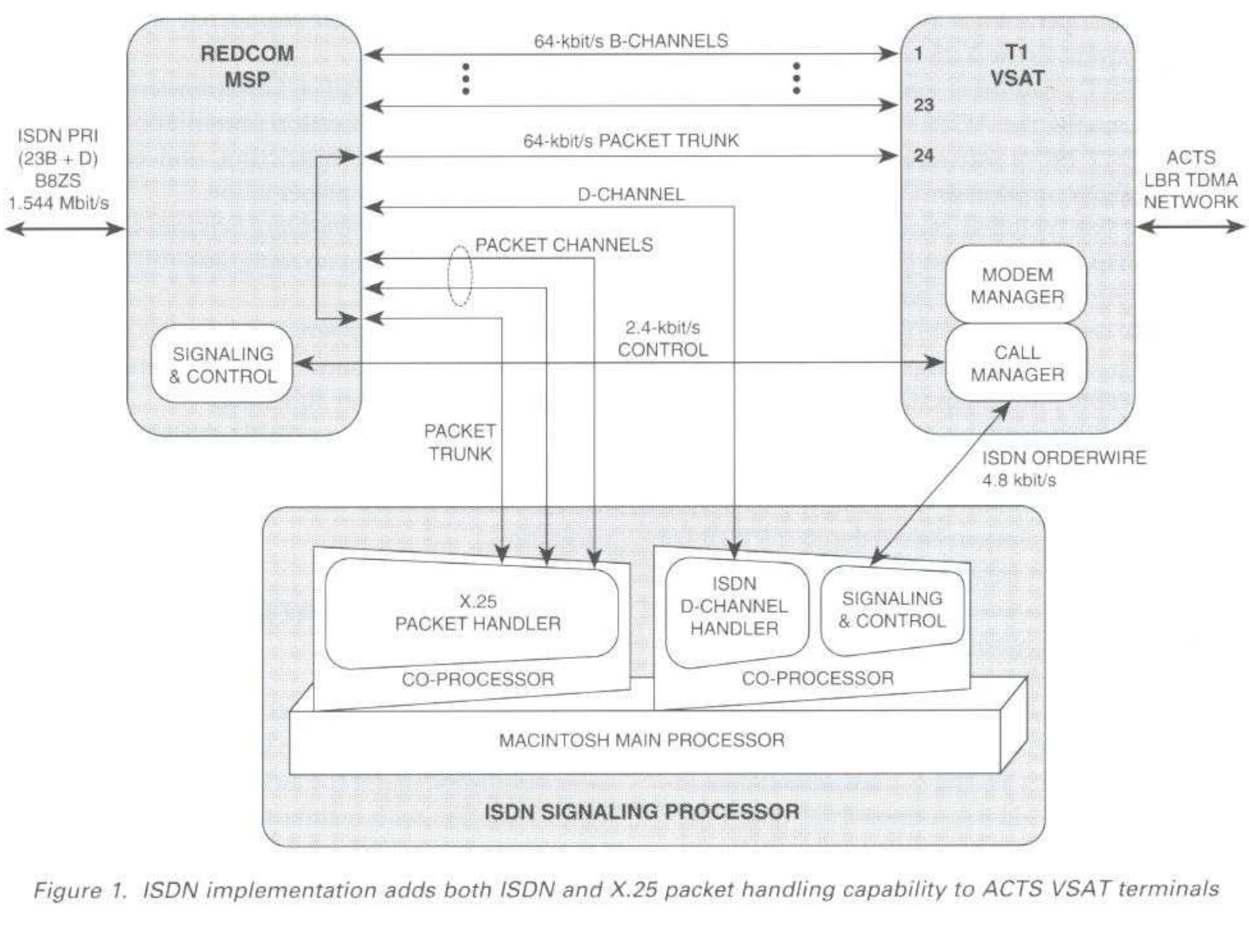


Figure 1. ISDN implementation adds both ISDN and X.25 packet handling capability to ACTS VSAT terminals

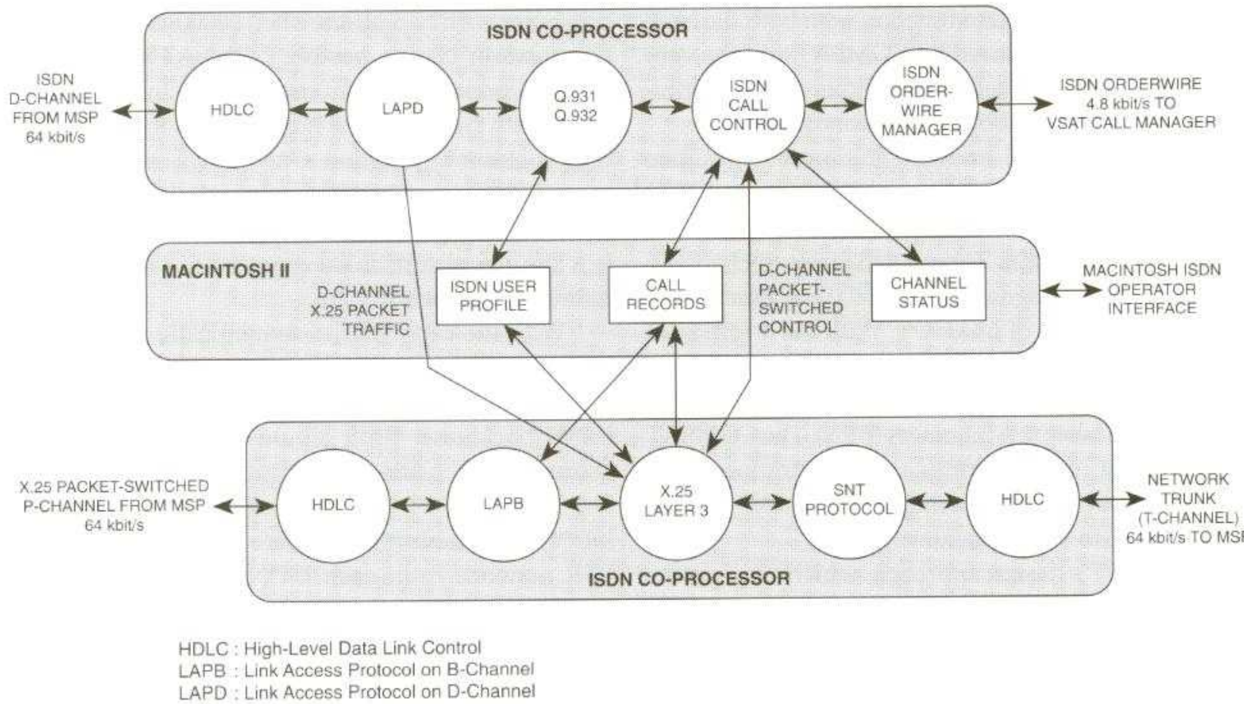


Figure 2. COMSAT's ACTS ISDN software utilizes many previously developed field-proven models

Satellite Network Transport (SNT) protocol. The SNT protocol is a field-tested, selective-repeat protocol specifically designed for satellite applications. COMSAT's SNT protocol operation is internal to the ACTS ISDN and transparent to the X.25 user.

COMSAT's extensive experience in digital networking benefits the ACTS Program because existing COMSAT ISDN software modules are used for the ACTS ISDN application. COMSAT's recent ISDN experience has included providing ISDN interfaces for the INTELSAT Business Service and supporting ISDN experiments with the National Institute of Standards and Technology (NIST). COMSAT Laboratories is currently designing a local area network (LAN)-to-ISDN interconnection facility, including an Ethernet-to-ISDN bridge.

Since it does not implement International Telegraphy and Telephony Consultative Committee (CCITT) Signaling System No. 7, the ACTS ISDN operates as a private network, supporting bearer and supplementary services. The essential and additional bearer services supported by the ACTS ISDN are:

- *Circuit-Mode Bearer Services*: speech, 3.1-kHz audio, 64-kbit/s unrestricted data interchange, alternate speech/64-kbit/s unrestricted data interchange, 2 x 64-kbit/s unrestricted data interchange, 384-kbit/s unrestricted data interchange, and 1,472-kbit/s unrestricted data interchange.
- *Packet-Mode Bearer Services*: virtual call and permanent virtual circuits (X.25) on B- and D-channels.

Supplementary services supported by the ACTS ISDN are:

- *Numbering Identification Supplementary Services*: calling line identification presentation, calling line identification restriction, and connected line identification presentation.
- *Call Offering Supplementary Services*: call transfer, call forwarding no reply, and call forwarding unconditional.
- *Call Completion Supplementary Service*: call hold.
- *Additional Information Transfer Supplementary Service*: user-to-user signaling.

With these capabilities available through the ACTS LBR TDMA network, the ACTS ISDN will provide the ISDN community with a unique tool for experimentation.

PROGRAM MANAGEMENT OFFICE

The overall technical and business management of the ACTS Program within COMSAT Laboratories is accomplished under the auspices of the PMO. This office is staffed with technical management experts for each major work breakdown structure (WBS) element, as well as management and staff responsible for cost and schedule control/reporting activities. The PMO serves a dual role by providing direction to all elements of COMSAT Laboratories engaged in work under the contract, and functioning as the principal liaison with NASA to address all planning, management, and performance reporting activities required by the ACTS contract.

All performance aspects of the contract are continually monitored and controlled by the PMO to ensure that the program will be successfully completed on schedule and within budget. In addition, any proposed amendments to the contract are evaluated and priced by the PMO prior to approval by NASA and implementation by COMSAT.

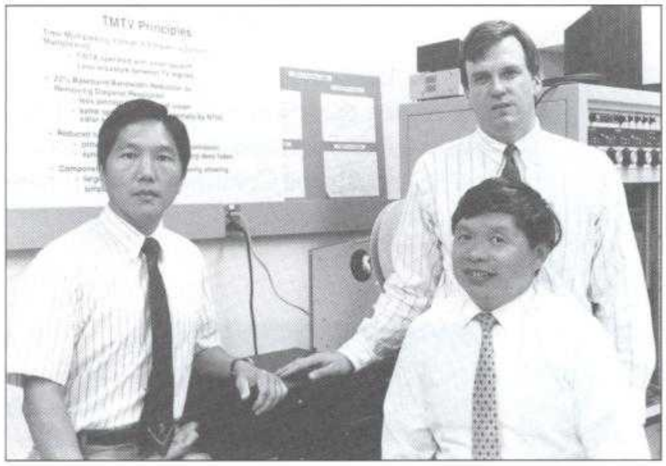
Each month the PMO, with the assistance of the cost account manager responsible for a particular element of technical work under the program, assesses the progress achieved *vs* that projected by the work plan. Cost and schedule variances from the plan are determined for each account, and corrective action is taken when necessary to bring performance back on target, or appropriate workaround plans are proposed.

The PMO conducts a monthly formal internal review of those accounts in which cost or schedule variances exceed a predetermined threshold. It then reports this information to NASA, along with an assessment of the overall impact on the program and any corrective action necessary. The PMO also holds a monthly Program Status Review to keep the customer informed of all significant programmatic and technical issues, together with the overall progress of each WBS element in the program.

Originally established to serve the NASA ACTS Program, the PMO now also supports the U.S. Army Universal Modem System/Interim System Planning Computer (UMS/ISPC) program as a subcontractor to Magnavox Corporation. Thus, the PMO provides COMSAT Laboratories with the general capability to manage large-scale government programs in accordance with Department of Defense (DoD) Instructions 7000.1 and 7000.2.

COMSAT LABORATORIES RESEARCH AWARDS

The COMSAT Laboratories Research Award is presented annually to individuals whose outstanding contributions to the field of satellite technology prove to be of strategic importance to COMSAT Corporation.



Tashin Lin, Don Power, and Lin-Nan Lee, developers of the award-winning multiplexer

The award for 1988 was presented to Lin-Nan Lee, Tashin L. Lin, and Donald W. Power of the Communications Technology Division for the Two- and Three-TV per Transponder Video Multiplexer. This device provides two 56-dB, or three 51-dB, S/N-quality NTSC television signals in a single 36-MHz bandwidth transponder. The ability to carry multiple TV channels permits the satellite transponder to operate at significantly greater power, with no intermodulation distortion or adjacent channel interference. The result is significantly enhanced television quality. The method uses time compression and expansion buffers to perform the multiplexing and demultiplexing, and the signal is carried by wideband FM. The multiplexer offers significant advantages to both CSD's and CVE's TV businesses.


Anil Agarwal and Dilip Gokhale with the NetMCC workstation

Recipients of the 1989 award were Anil K. Agarwal Dilip S. Gokhale, Srinivas Pyda, and John Anderjaska of the Network Technology Division for their development of the LAN/WAN Network Management and Control Center (NetMCC). The NetMCC manages a wide mix of PCs, workstations, minicomputers, and multivendor, multiprotocol LAN/WAN interconnection equipment. Management of these networks requires tools that allow network operators to determine faults, take corrective action, track the usage of links and devices, and configure device parameters. If the network is managed improperly, the operator can be overwhelmed by information. The NetMCC, hosted on a SUN workstation, allows operators to manage large, heterogeneous networks in an orderly, user-friendly manner. This accomplishment is important to CSD in its information communications businesses.

FELLOWS OF IEEE

In 1991, the Institute of Electrical and Electronics Engineers (IEEE) awarded the rank of Fellow to Drs. Lin-Nan Lee and Amir I. Zaghloul of COMSAT. IEEE is the largest professional engineering society in the world, and the grade of Fellow is a singular professional distinction conferred by the Institute upon persons of extraordinary qualifications and experience.

Lin-Nan Lee

Dr. Lee was raised to the level of Fellow for his contributions to applying coding theory, cryptography, and digital signal processing to commercial satellite communications. He joined COMSAT in 1977 and was Principal Scientist in the Communications Technology Division, prior to accepting his current position as Chief Scientist with COMSAT Systems Division.

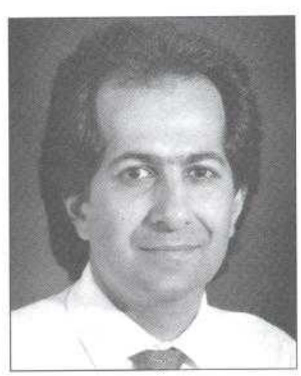
Amir I. Zaghloul

Dr. Zaghloul was awarded his Fellow for contributions to the application of phased-array antennas to communications satellite systems. He joined COMSAT Laboratories in March 1978, and is currently Manager of the Satellite Antennas Department in the Microwave Technology and Systems Division.

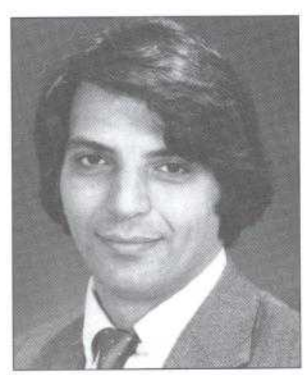
SENIOR MEMBERS OF IEEE

Mr. Thomas C. Ho of the Microwave Electronics Division, and Dr. Spiros Dimolitsas and Dr. Farhad Hemmati of the Communications Technology Division were elected to the grade of Senior Member of IEEE.

Thomas C. Ho



Spiros Dimolitsas



Farhad Hemmati

The following is a list of 1991 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, Maryland 20871-9475. The patents listed were issued to employees (or former employees) of COMSAT Laboratories during 1991. ■

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