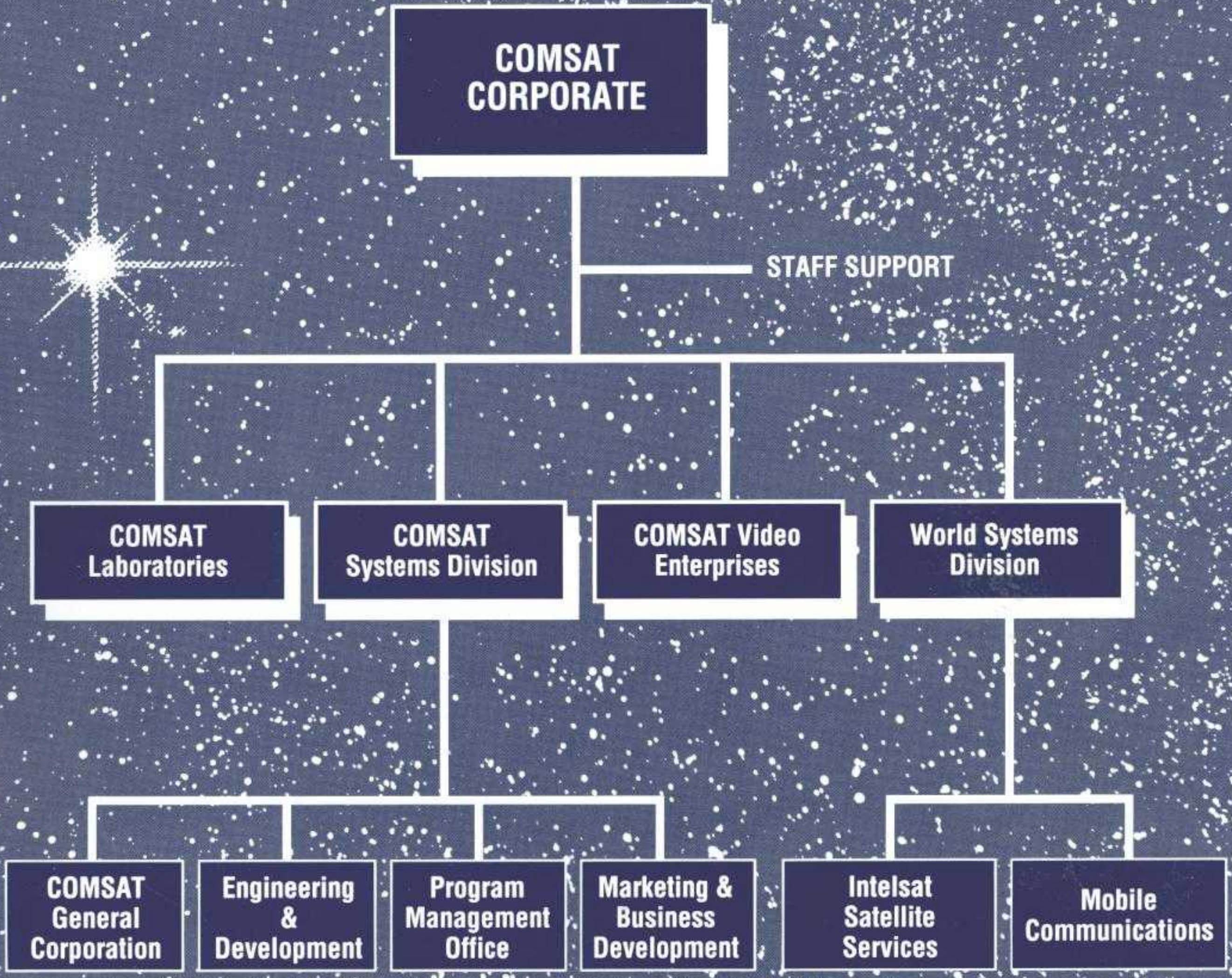
COMSAT LABORATORIES
ANNUAL REPORT 1989



COMMUNICATIONS SATELLITE CORPORATION 1989

COMSAT Laboratories conducts a program of basic research and development to advance satellite communications technology. Elements of the program are funded by Intelsat Satellite Services and Mobile Services (both part of COMSAT's World Systems Division), 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 1989, the Laboratories had an operating budget of $39 million, of which almost 55 percent came from Corporate sources and the balance from outside. Approximately 30 percent of the Corporate funding (15 percent of the total) supported an applied research program with the goal of creating new technology which has the potential of improving communications systems over the long term. A further 50 percent of the Corporate funding paid for development projects, which were undertaken by the Laboratories for elements of the Corporation on a contract-like basis, and have nearer-term applications. The balance of the Corporate funding was for technical support on various projects, studies, and technical issues. The largest effort undertaken for an external customer was for the NASA Advanced Communications Technology Satellite (ACTS) program, although the Laboratories continues to perform a significant amount of development and technical support work 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 seventh in the series, summarizes all of the R&D work undertaken with Corporate support during 1989.

J. V. Evans

J. V. Evans
June 1990

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

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

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

In 1989, the largest part of the work at COMSAT Laboratories was that performed for the regulated activity of international satellite communications, either directly for COMSAT or indirectly for INTELSAT. Additional work was performed for CSD and CVE, mostly with support from the Corporate Shareholders. Efforts funded entirely by sources outside of COMSAT/INTELSAT included activities for the Federal Government and the largest part of this was the work performed on the NASA Advanced Communications Technology Satellite (ACTS) program.

During 1989, there was some regrouping of some departments of the Laboratories, but the number of technical divisions remained six: Satellite Technologies, Communications Technology, Microelectronics, Microwave Components, Network Technology, and System Development. Of these, the first five divisions participate in a research program funded by the Corporation. This program constituted about one-fifth of the Laboratories' activities and included jurisdictional (WSD) business, as well as the nonjurisdictional activities of COMSAT. The former must, perforce, be made public, while the latter is held proprietary.

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

This report summarizes the Laboratories' research and development activities in 1989. It is organized by technology, as defined by the six technical areas represented by each division. The work is further subdivided into the following categories:

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

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The Microwave Components Division (MCD) performs research and development to support COMSAT Corporation's efforts in advancing the capabilities of communications satellites. The key objectives are to significantly increase the available capacity per unit of payload mass, provide flexibility of interconnection, and continue to provide highly reliable communications links. During 1989, the development of a Ku-band active phased-array antenna for on-board satellite applications was successfully completed. This antenna can produce one reconfigurable shaped beam or a scanning spot beam. Extensive testing verified the implementation and operation of this active antenna under ground control, demonstrating excellent correlation between predictions and measurements for several representative coverages. The design and development of a 24-element Ku-band array that will simultaneously transmit four independently steerable beams in each of the two orthogonal polarizations continued in 1989. For this high-power array, low-loss power combining techniques were developed and power-added efficiency of 33 percent was demonstrated over a 1-GHz band for a two-stage 1-W Ku-band solid-state power amplifier (SSPA). Other developments include a C-band, lightweight, broadband 4 x 4 microwave switch matrix, which was assembled with control circuits and tested, and a flight-qualified, electromagnetically coupled patch (EMCP) antenna, which was completed using lightweight, printed circuit radiators. Development of a multibeam, lightweight, high-power and high-efficiency C-band active antenna using the EMCP radiator technique was started. Millimeter-wave low-noise amplifiers and SSPAs were developed, and work on new earth station antennas, compact diplexers, and antenna feed systems continued.

COMSAT JURISDICTIONAL R&D

Ku-Band Low-Power Active Phased Array

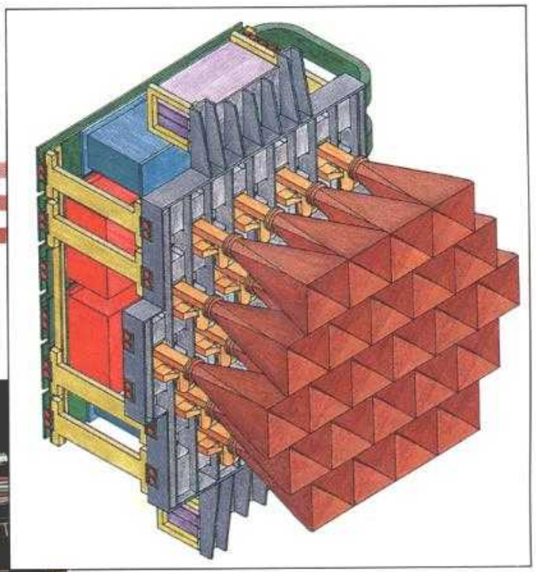
Active phased array antennas capable of generating shaped beams on ground command are very attractive when coverage areas must be modified:

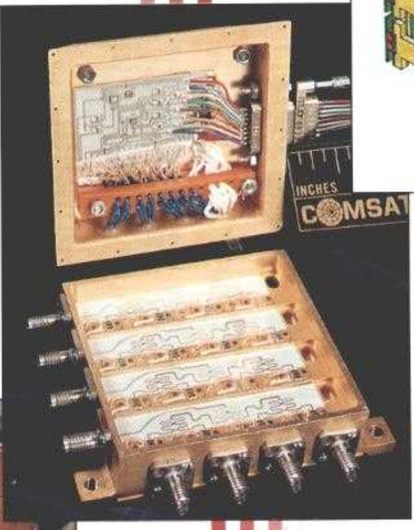
- to maximize the satellite fill-factor by periodically reallocating the available channel capacity for peak daylight operation
- to accommodate changes in long-term growth
- to allow satellite operation from different orbital locations
- to have a single satellite designed for all three ocean regions.

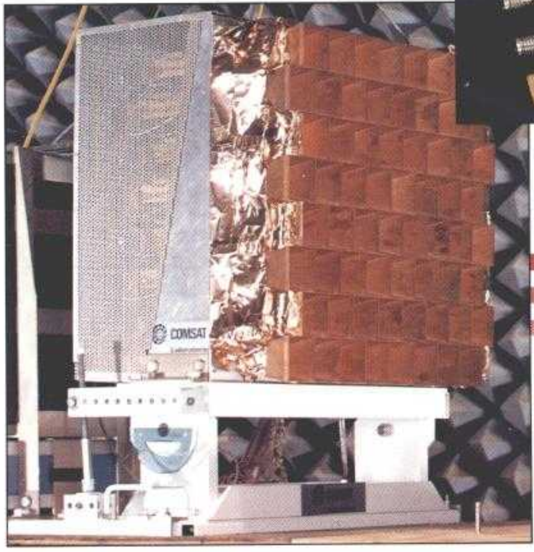
In addition, the capability of dynamically pointing the beams (on ground command) provides the flexibility to increase the useful life of satellites by operating them in inclined orbits.

The development of a 64-element Ku-band active phased-array antenna (shown on the opposite page) which satisfies these requirements was successfully completed in 1989. As shown in Figure 1, this array consists of 64 active transmit subassemblies that are fed by a 64-way power dividing network. Each transmit assembly contains a 5-bit digital phase shifter, a buffer amplifier, a 5-bit digital attenuator, a driver amplifier, and an MIC-to-waveguide transition. The digital phase shifter provides a step size of 11.25° and a range of 360°, and the digital attenuator provides a step size of 0.5 dB and a range of 15.5 dB. A local control module within each transmit assembly interfaces with the array controller to produce the desired amplitude and phase distributions across the array aperture. To maximize the performance uniformity of 64 subassemblies, and to enhance the overall system reliability, the phase shifters, attenuators, and amplifiers were realized using state-of-the-art monolithic microwave integrated circuit (MMIC) technology. Each transmit subassembly feeds one port of an orthomode transducer (OMT) for one polarization which, in turn, feeds the radiating horn. The

MICROWAVE COMPONENTS







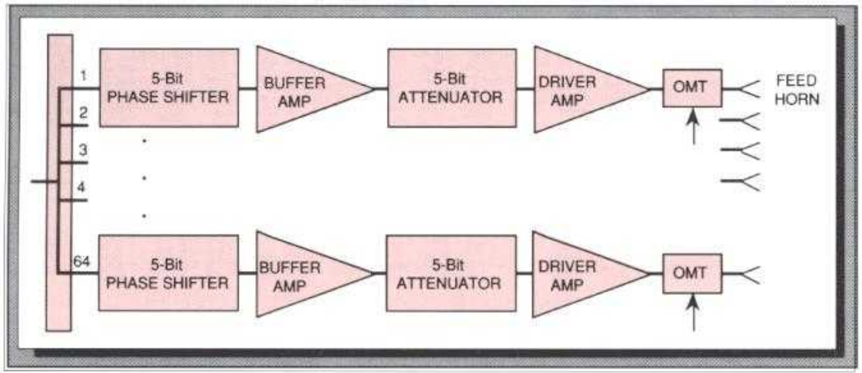


***Figure 1**. Ku-band active phased array consists of 64 transmit assemblies fed by a 64-way power dividing network*

orthogonal polarization is fed to the second port of the OMT through a similar network arrangement. The array assembly also includes control, power, mechanical, and thermal systems.

During the design phase, extensive sensitivity analyses were performed to determine the maximum permissible amplitude and phase variations among the 64 transmit assemblies. To achieve spatial isolation in excess of 30 dB among copolarized shaped beams, the amplitude and phase settings must be within ±1.5 dB and ±10°, respectively, for all 64 paths.

The relative amplitude and phase variations of the fully integrated active array were successively measured between the power divider input and the 64 outputs. These measurements were conducted with all phase shifters and attenuators in their reference states. As can be seen from the results in Figure 2, the relative gain and phase shift are within the allowable values as determined by the sensitivity analyses.

To demonstrate operational flexibility and versatility, several antenna patterns were configured and their measured performance characteristics were compared with theoretical predictions. For example, the radiation patterns of the array were measured when the excitation coefficients were set to successively produce four shaped beams, covering four zones in the Atlantic Ocean Region (AOR) of the INTELSAT system. Azimuth cuts were taken at every 2° in elevation at three frequencies in the 11.7- to 12.7-GHz band, and then measured antenna patterns were compared with the predictions. Figure 3 presents one sample of a pattern cut at 12.2 GHz for the northwestern beam covering North America.

Radiation patterns were also measured for several spot beams within the global coverage area and were compared with computer predictions.

Microwave Switch Matrix

Development of a fully integrated, lightweight, 4 x 4 microwave switch matrix (MSM) was completed in 1989. This project, like the active phased array, demonstrated the use of GaAs MMIC technology for on-board switching applications. A simplified block diagram of the MSM and its control circuits is shown in Figure 4. The dual-gate field-effect transistor (FET) MMIC switch elements provide the required interconnections between the RF input and output ports under the control of the driver logic. The connectivity data are stored in the local control module (LCM), which allows static and/or dynamic interconnections. Dynamic switching is implemented cyclically, i.e., several

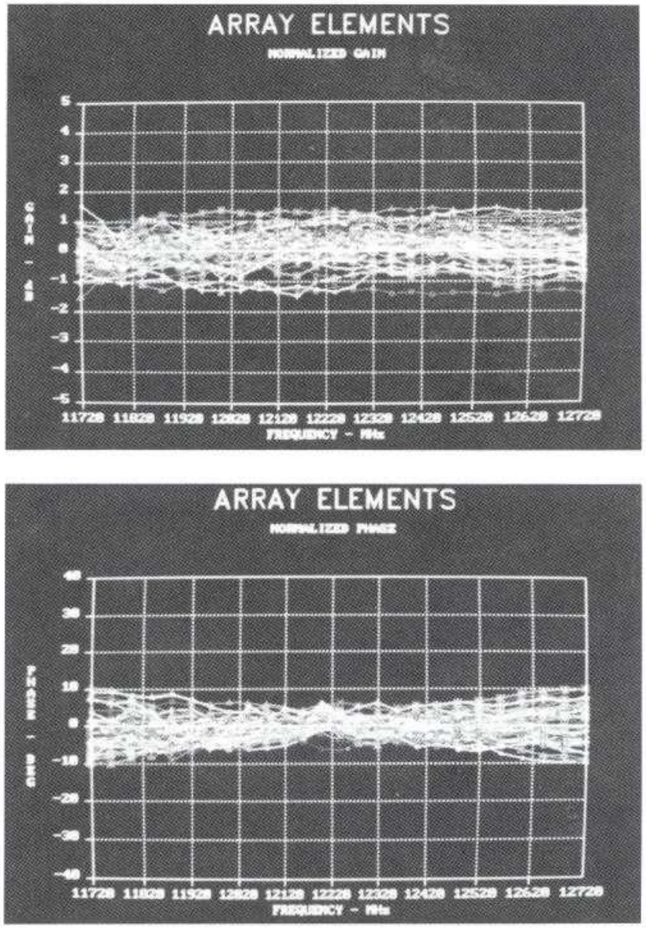


***Figure 2**. Amplitude and phase variations of the fully integrated active array are within allowable values*

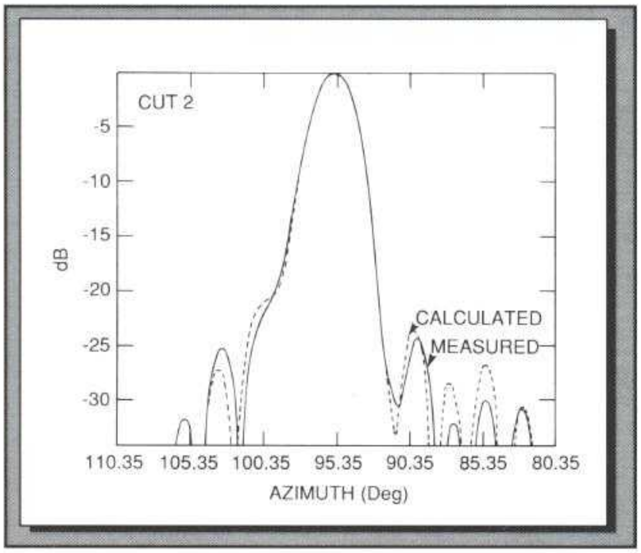


Figure 3. Measured and calculated azimuth pattern cuts (12.2 GHz for North America)

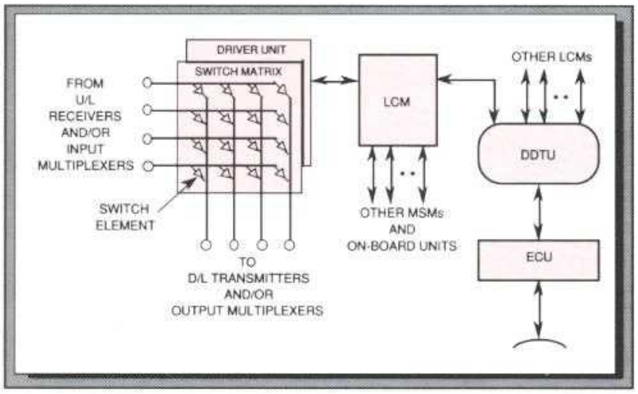


Figure 4. MSM demonstrates the use of GaAs MMIC technology for on-board switching

times during each time-division multiple access (TDMA) frame period. The data distribution and timing unit (DDTU) provides common timing signals for synchronous operation and switchover of control data patterns. The executive control unit (ECU) generates the switch-state data, verifies the telemetry data, and provides the highest level of control. The MSM is shown in the introductory photograph for this section. In this architecture, 16 MMIC switch elements have been integrated with eight power divider/combiners, and 16 RF feedthroughs and driver/control circuits. The GaAs MMIC switch element, which forms the key building block of the 4 x 4 MSM, was designed using two dual-gate FETs. The switch has a gain of approximately 10 dB and on-to-off isolation greater than 50 dB over the 3.5- to 6.5-GHz frequency range.

Measured performance for all 16 paths over 3.5 to 6.5 GHz shows on-state insertion loss within 6.25 dB, path-to-path insertion loss variations within ±0.5 dB, on-to-off isolation greater than 50 dB, phase balance less than ±10°, and measured input and output return losses greater than 15 dB. Functional tests of MSM operation were successful under control of the driver/control circuit.

The MSM development demonstrated high-density packaging of MMICs with driver/control circuits in a lightweight 2- x 2- x 1-in. package. The driver/control circuit can interface with a distributed and highly flexible modular control architecture, allowing other on-board units to be controlled by a single executive controller. The MSM design concept, packaging approach, and control functions are being extended for use in the design of the Ku-band beam-forming matrix (BFM) described below.

Ku-Band High-Power Multibeam Active Phased Array

In 1989, the design concept was developed for an active phased array that can produce one beam per polarization at a time. To produce multiple and simultaneously independent beams using the same array aperture, the beam-forming network (BFN) is replaced with a BFM. In this case, the number of inputs corresponds to the number of beams and the number of outputs equals the number of radiating elements in the array. At the junctions, which connect the input power distribution networks to the power combining networks, variable and controllable digital phase shifters are included to shape and/or scan the separate beams in different directions. As can be seen, the BFM is conceptually similar to the MSM with one exception—the dual-gate FET switch is replaced with a 5-bit phase shifter.

Specifically, the development of the 24-element Ku-band high-power multibeam active phased array (MBAPA) was initiated in 1989. As configured, the MBAPA could simultaneously produce four independently controlled beams per polarization. An SSPA, described in the next section, will be integrated with each radiating element to produce the required e.i.r.p. This project will demonstrate the communications characteristics and operational flexibility of MBAPAs. The power sharing of the SSPAs allows for a very flexible assignment of the RF power to any one beam or any combination of beams.

The dual linearly polarized MBAPA, as depicted in the photograph at the beginning of this section, contains six different subassemblies: OMT/horn, SSPA, BFM, antenna controller, power supply, and thermal/mechanical system with heat pipes. The 4 x 24 BFM, shown schematically in Figure 5, uses 96 five-bit phase shifters. In 1989, 60 phase shifters and eight- and four-way MIC power dividers and combiners were fabricated and tested.

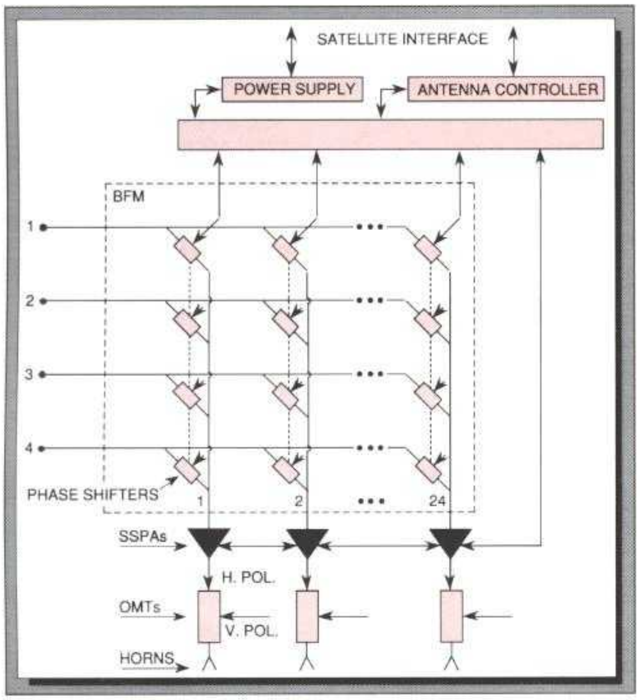


Figure 5. 4 x 24 BFM uses 96 five-bit phase shifters

As configured, the BFM subassembly will also include level shifter circuits and MMAC driver circuits to control the phase shifters. A photograph of part of the BFM subassembly is shown in Figure 6. The 24 outputs of the BFM will be connected to the 24 SSPAs.

The fabrication, assembly, and test of the MBAPA will be completed in 1991.

Ku-Band Solid-State Power Amplifier

A 1-W quasi-monolithic amplifier and two-stage driver MMIC amplifier, shown in Figure 7, and a one-

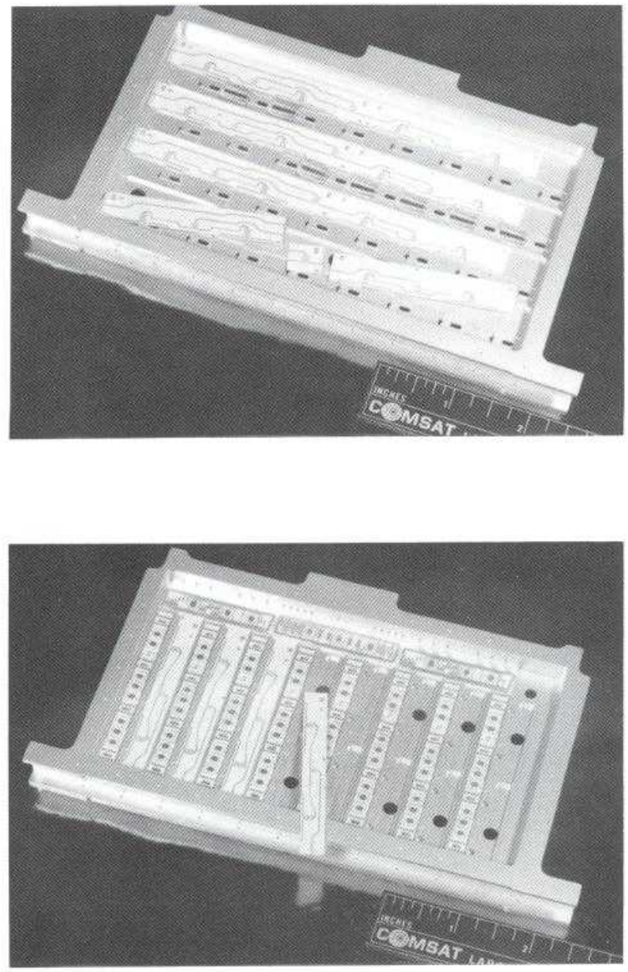


Figure 6. Front and back views of BFM shelves

stage MMIC amplifier, were developed, fabricated, and tested for incorporation into the Ku-band MBAPA antenna. In addition, a breadboard housing with microstrip-to-waveguide transition was designed for the complete SSPA. Fabrication will start in 1990. An input drive level of 18 dBm for the quasi-monolithic 1-W amplifier produces output power of 29.8 dBm, and a power added efficiency (PAE) of 31.5 percent across the 11.7- to 12.7-GHz frequency band. The maximum PAE of 36.1 percent occurs at 12.2 GHz, where the amplifier delivers 31 dBm. For an input drive level of 14 dBm, the single-stage MMIC amplifier exhibited an output power and PAE of 21.8 dBm and 13 percent, respectively.

In 1990, all Ku-band SSPAs will be fabricated, tested, and delivered for integration into the multibeam antenna discussed above.

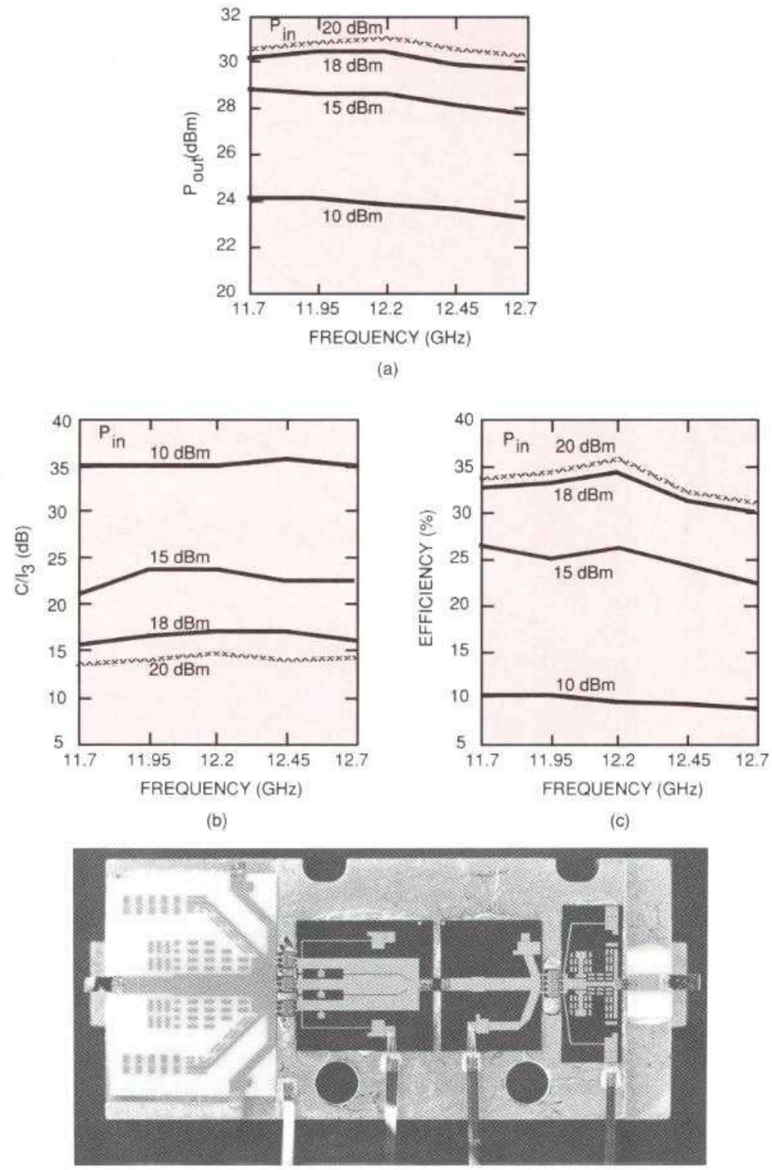


Figure 7. Two-stage driver amplifier will be incorporated into Ku-band MBAPA antenna

High-Efficiency, C-Band, Multibeam Active Phased Array

Much of the knowledge gained in the development of Ku-band arrays is also being used as a foundation for an advanced C-band active array that would be directly applicable to future high-capacity satellites. The emphasis in the C-band program is on producing a lightweight space-qualifiable array that will generate multiple electronically steerable spot beams. The array will use printed circuit radiating elements and will include high-efficiency power amplifiers that are described below. It will generate e.i.r.p. levels equivalent to those produced in an operational INTELSAT system. Critical functions such as heat transfer, array packaging, functional redundancies, and performance monitoring will be incorporated into the design.

In 1989, work on the C-band array concentrated on the EMCP radiating element. Objectives were to widen the radiator's field of view while maintaining a sufficiently high polarization purity to allow for frequency reuse. The objectives were achieved using a four-point fed-patch element with an inherently good polarization purity among each of the four patches. This element and its feed network are shown in Figure 8. This radiator has a very good on-axis axial ratio of about 0.3 dB, and the polarization purity does not significantly degrade off-axis. The high polarization purity of the element exhibited over the wide field of view permits its use for a wide-angle scanned active phased array.

Subsequent work in this program will involve the design and development of a fully operational array to validate the system concept. The proposed coverage would consist of up to eight frequency reuses with 3° spot beams located over the land masses. Each beam would be independently steerable. A tradeoff study comparing a direct radiating array to an array-fed confocal parabolic reflector system will also be performed.

C-Band Solid-State Power Amplifier

The high-efficiency C-band SSPA, consisting of three stages of amplification, was developed in 1988 and later modified for integration onto a silicon motherboard. To reduce circuit losses, the Lange couplers used in the original design of the output stages were replaced with Wilkinson dividers.

To maintain the low-loss properties of the ultra-high-purity and high-resistivity silicon, a new processing technology needed to be developed for the silicon motherboard. Recently, a successful fabrication was completed. Initial test results indicate that the amplifier gain, output power, and efficiency are close to the performance goals.

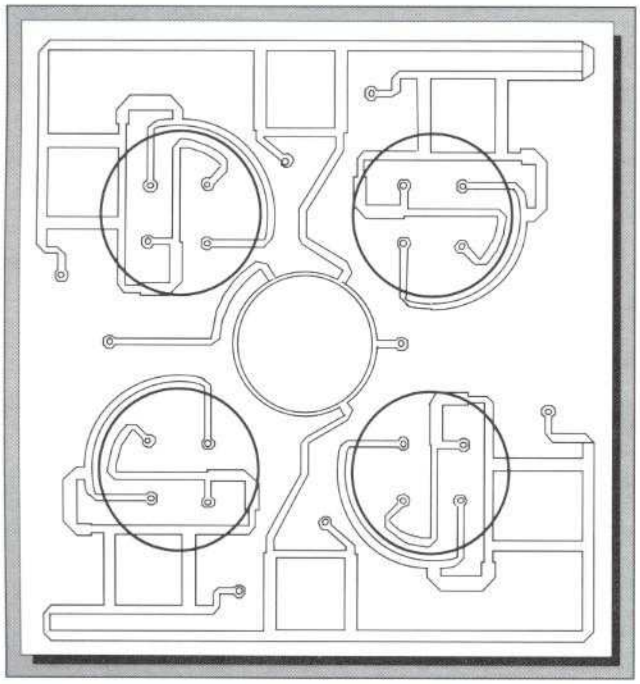


Figure 8. Four-point fed-patch element allows high polarization purity over a wide field of view

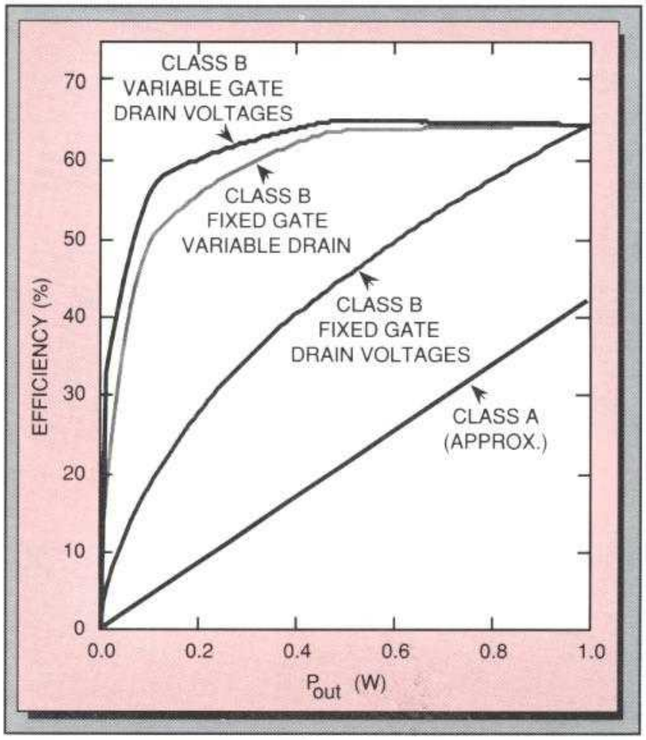


Figure 9. Experimental single-stage amplifier achieves high efficiency with drain and gate bias modification

In 1990, several amplifier modules will be fabricated and tested to verify performance quality and uniformity.

High-Efficiency Variable-Gain SSPA

To reduce the radiated power level in the sidelobes of an active phased array, SSPAs must deliver different gains and output power levels to the radiating elements. In 1989, a technique that consisted of modifying the drain and gate bias voltages as a function of output power and reducing the input RF drive was developed to maintain high efficiency over a wide range of output power levels. This allowed the use of a single type of SSPA in all locations of the active phased array.

This concept was validated by automatically controlling the amplifier drain and gate bias and the RF input drive attenuator settings. The measured PAE of an amplifier operated in this mode was then compared to that obtained with the more conventional fixed bias approach shown in Figure 9. For the experimental Class-B single-stage amplifier (PAE of 65 percent at an optimum output of 1 W), the efficiency at 10-dB backoff is 57 percent with both drain and gate bias adjustment, 49 percent with only drain voltage modification, and 18 percent with fixed biasing. A fixed-bias, Class-A amplifier would exhibit an efficiency of about 5 percent under these conditions.

Low-Loss Combiners For High-Efficiency SSPAs

The passive circuits needed to match the impedance of large power FETs become very lossy. Consequently, the output power available from a single GaAs FET is usually limited by the maximum device size that can be matched over a particular frequency band. For amplifier applications requiring high power (> 10 W) at X-band frequencies and above, the amplifier must be designed by combining the power of many units. The combiners (such as the Lange coupler or the Wilkinson combiner) can have significant loss (0.3 to 0.5 dB) thus limiting their usefulness for high-efficiency, high-power applications.

Two novel low-loss combiners have recently been developed, and one is useful for power combining of four hybrid or monolithic circuits. This four-way combiner uses a two-ridged rectangular waveguide to transform the incident electromagnetic waves in four parallel microstrip lines into a TE10 waveguide mode. (The four incident waves should be in phase for proper combiner operation.) Figure 10 shows the insertion and return loss of divider-combiner components connected back-to-back. The insertion loss for the two components and the connecting microstrip lines is less than 0.3 dB and the calculated loss of the combiner is less than 0.1 dB, corresponding to a combining efficiency of greater than 98 percent. This combiner also functions as a waveguide-to-microstrip transition and is being used in the design of high-power amplifiers at Ku-band and X-band frequencies.

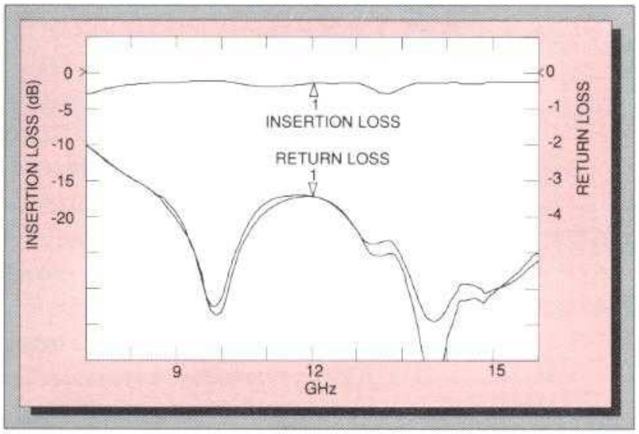


Figure 10. *Insertion and return loss of divider-combiner components*

During 1989, work also started on the design of high-efficiency radial ridged-waveguide power combiners. The ridged-waveguide structure has the advantages of low insertion loss and high power handling capability. In a radial structure, several amplifiers can be combined with good amplitude and phase balance. A prototype ridged-waveguide 16-way power combiner, shown in Figure 11, was constructed for the 3.7- to 4.2-GHz band and will be tested in 1990.

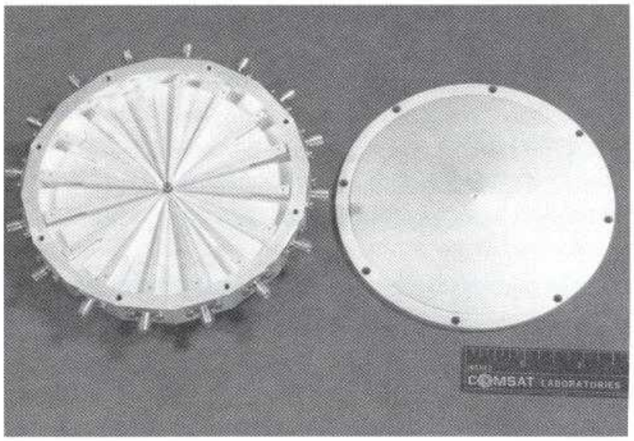


Figure 11. *16-way power combiner using ridged waveguide*

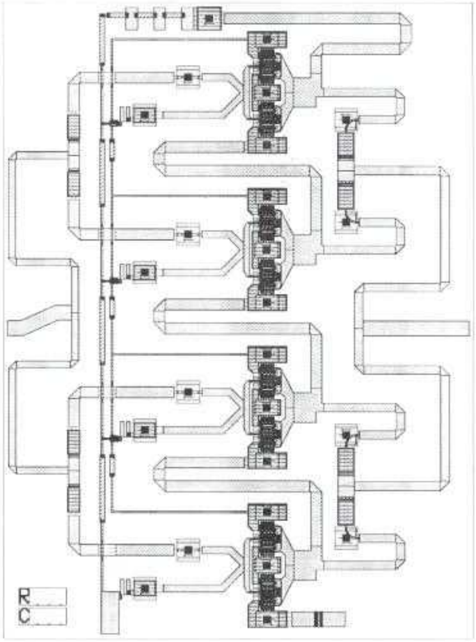


FIgure 12. *2-W X-band HV-FET amplifier*

High-Voltage FET SSPA

To maximize the overall DC-to-RF efficiency of the satellite, the development of MMIC SSPAs using high-voltage FETs continued in 1989. The goal of this project is to achieve a bias voltage close to the bus voltage. The layout of an amplifier designed to operate with a 40-V bias is shown in Figure 12. The circuit design incorporates on-chip biasing, power combining, and a harmonic termination for Class-B operation. This high-voltage SSPA, designed to deliver 2 W at 12 GHz, will be fabricated and tested in 1990.

On-Board Demodulation and Remodulation

In 1989, the miniaturized reverse modulation loop (RML), consisting of a demodulator, a remodulator, and a comparator circuit was characterized. The relative phase shift for all four states of the modulator is shown in Figure 13. The corresponding amplitude balance of the modulator was ±0.3 dB over 200-MHz at 3.95-GHz center frequency. The modulator rise-time was 1.4 ns, which would allow RML operation at a bit rate higher than 120 Mbit/s. The demodulator and comparator circuits of the RML successfully recovered the 120-Mbit/s bit stream.

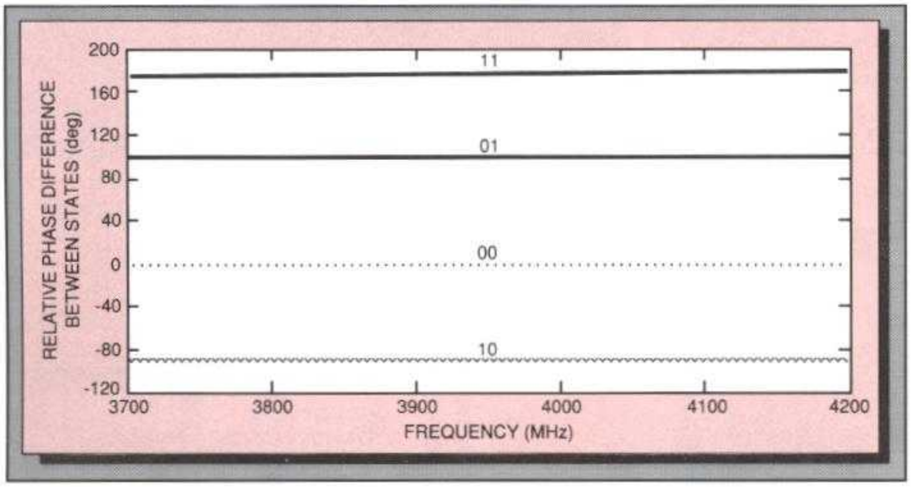


Figure 13. Relative measured phase difference between modulator states

Multibeam Spacecraft Configuration for Mobile Satellites

To increase the capacity of the next generation of INMARSAT spacecraft (INMARSAT 3), L-band e.i.r.p. must be maximized for a given spacecraft mass. This can be accomplished with multiple spot beams which have a higher gain than the shaped global beam presently developed for INMARSAT 2. A study to optimize the spot beams resulted in a seven-beam design that provides continuous coverage over the earth's surface. The seven beams, shown in Figure 14, are designed to provide spatial isolation between nonadjacent beams, allowing for frequency reuse. Separate transmit and receive antennas must be employed to minimize the reception of active and passive intermodulation components that are generated by the transient subsystem. The antenna design can be implemented using either a direct radiating phased array or a focal-region-fed reflector. Using a direct phased array, the number of basic radiating elements is 37. Each element can be implemented with four microstrip patch radiators, for a total of 148 patches. This design achieved a computed isolation of 23 dB between the beam edges of the North American and European coverages.

L-Band Solid-State Power Amplifier

A program to develop an L-band SSPA was started in 1989. The program objectives were to design, fabricate, and characterize a linear, high-efficiency L-band amplifier and thereby establish the practical limits of the critical building blocks for future mobile satellites. As part of this program, a two-stage power amplifier was designed and tested. Devices were selected for high power and high efficiency, based on measured DC characteristics, including low pinchoff and high gate-to-drain breakdown voltages. For maximum efficiency, circuit losses were minimized by using distributed transmission lines in the matching networks, and the device was operated in the Class-AB mode. Good agreement was achieved between measured and computed performance under small signal conditions, as shown in Figure 15.

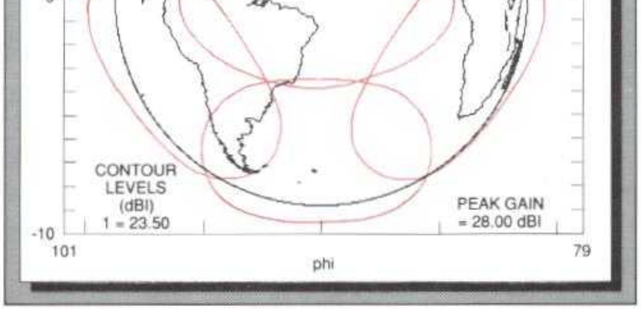


Figure 14. Seven-beam design provides continuous coverage over the earth's surface

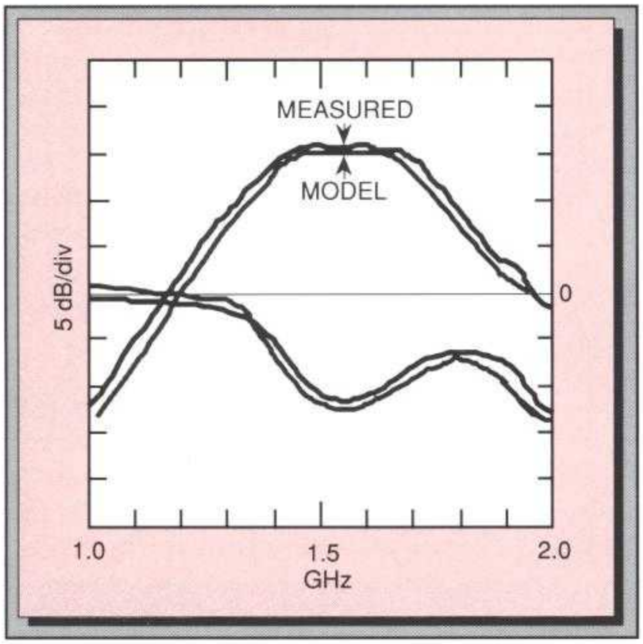


Figure 15. L-band SSPA gain and phase characteristics

Under high-efficiency operation, the amplifier delivered 43 dBm (20 W) with 20-dB gain, 50-percent PAE, and 12-dB C/I_3. Measured results under medium power operation showed an output power of 45 dBm (30 W) with 22-dB gain, 37-percent PAE, and 13-dB C/I_3.

Millimeter-Wave MMIC Technology

MCD is continuing to develop state-of-the-art monolithic integrated circuits up to the millimeter-wave frequencies. For power amplifiers, a metal semiconductor FET (MESFET) device with 0.3-mm gate width was selected for a single-stage V-band MMIC amplifier design. Proper GaAs material recess for the MESFET gate was processed to provide the required breakdown and pinch-off voltages for the specified output power. In the circuit implementation, distributed elements on microstrip structures were employed for impedance matching, achieving low circuit loss and better modeling accuracy. DC-blocking and bias networks were incorporated into the MMIC design to allow for direct cascading of the unit modules into multistage or balanced amplifiers, achieving usable gain and power for system applications. A multistage power MMIC amplifier comprising these single-ended and balanced modules exhibited a linear gain of 16.7 dB and an output power of 250 mW at 57.5 GHz.

MESFET and pseudomorphic modulation-doped FET (P-MODFET) devices have been used to develop monolithic millimeter-wave LNAs. Given the same device parameters, the P-MODFET MMICs exhibit better performance than MESFET MMICs in the 60-GHz band. Both the 0.25-μm gate length and recess contour in the GaAs material for the P-MODFET were optimized to achieve high transconductance and low gate resistance, resulting in improved low-noise characteristics of the device. The millimeter-wave MMIC design approaches for LNAs are similar to those for power amplifiers, except that the input circuit is generally matched to the optimal source impedance to achieve a minimum noise figure. Both DC-blocking and bias networks are included in the circuit designs. An MMIC LNA, containing two dual-stage MMICs with P-MODFETs, has yielded a noise figure of 3.7 dB and an associated gain of 20.7 dB at 58.25 GHz.

Compact 4/6-GHz Diplexer

A compact, 4/6-GHz, dual circularly polarized diplexer for small prime focus INTELSAT earth station antennas is presently under development.The diplexer must be compact and lightweight to allow mounting in front of the reflector. An additional design consideration is to minimize the cost of INTELSAT earth station antenna systems.

During 1989, several breadboard designs were analyzed and critical components were fabricated and tested. A candidate design was chosen for 1990 fabrication.

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

A dual-band feed is being developed to permit simultaneous access to a satellite at both C- and Ku-bands from a single earth station antenna. The design uses a multi-aperture directional, slotted waveguide array to achieve unity coupling at Ku-band from rectangular waveguides into the C-band circular (2.125-in.-diameter waveguide). The 1989 effort was devoted to improving the 14-GHz unity coupler design and developing fabrication techniques capable of providing the required precision and symmetry to reduce cost.

An improved coupler geometry was developed that achieves unity coupling with less than 1-dB loss in the 14.0- to -14.5-GHz up-link band. The coupler design was modified to simplify fabrication and provide the precision and symmetry required to meet the INTELSAT specifications for axial ratio. The design for the prototype to be manufactured permits fabrication of the couplers with a single piece center core containing all the coupling slots and center waveguide. All the 11/14-GHz coupler parts are fabricated on a numerically controlled milling machine, thus substantially reducing the manufacturing costs for the dual-band feed.

The prototype for the dual-band feed is presently being fabricated. Assembly and test of the complete feed, including possible test in a U.S. earth station, are planned for 1990.

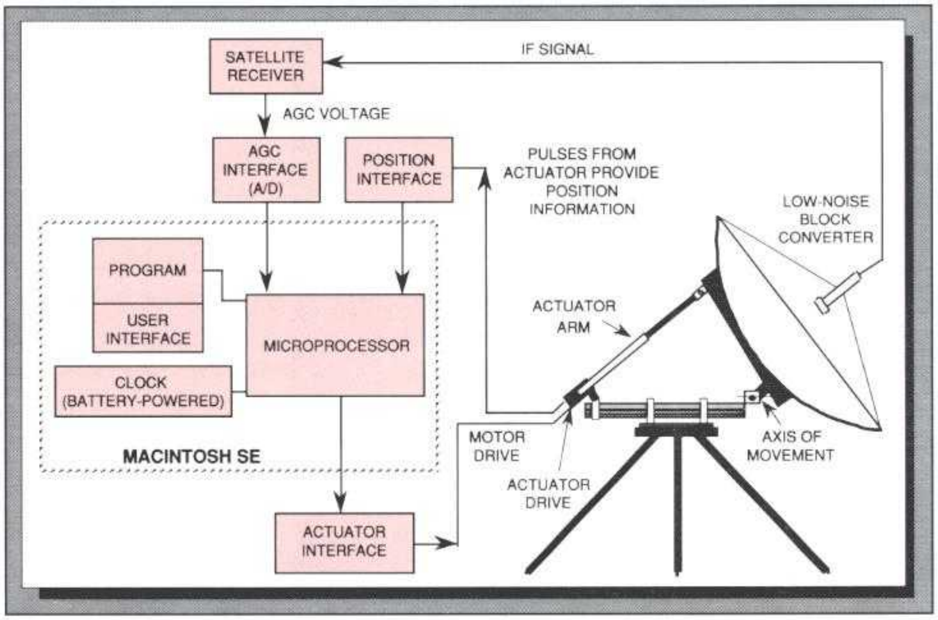


Figure 16. *Block diagram of a low-cost inclined orbit tracker*

Earth Station Antennas for Use With Inclined Orbit Satellites

In 1989, COMSAT Laboratories conducted a study of antenna techniques that could reduce the cost of the earth station antenna tracking for inclined orbit satellites. The techniques studied included the development of antenna pedestals designed for single-axis tracking of an inclined orbit satellite, development of low-cost monopulse tracking for use with inclined orbit satellites, and design of reflectors that use feed scanning for inclined orbit tracking. Because of cost implications, the study emphasized the use of parabolic or other axis-symmetric main reflectors

The first phase of the study examined alternative techniques and designs. The recommended design consists of a single-axis pedestal with a low-cost step tracking system that utilizes the automatic gain control (AGC) output of a video receiver.

In the second phase, the hardware and software designs were implemented and the tracking system was evaluated using the test setup shown in Figure 16. The tracking system used a 3-m-diameter transportable reflector antenna and mount operating at Ku-band and a commercially available video receiver. The system was used to track a carrier on an AOR INTELSAT V-4 inclined-orbit satellite. The performance measurement phase successfully demonstrated the reliability and accuracy of the technique.

NONJURISDICTIONAL R & D

Flat Plate Antenna

Flat plate array development during the past year has concentrated on optimizing the performance of a dual linearly polarized array. The array is applicable to the Fixed Satellite Services (FSS) markets as well as the quasi direct broadcast systems (quasi-DBS) presently being initiated in Europe. It has demonstrated better than 50 percent efficiency in both polarizations for an aperture as large as 77 x 77 cm. Both polarization and port-to-port isolations are better than 25 dB, illustrating the decoupled nature of the array.

Techniques for improving the overall efficiency of the flat plate array have also been investigated. The approach involves integration of a partial waveguide distribution network into the array thereby replacing some of the lossy long stripline runs. Associated with this integration is the development of several highly efficient waveguide-to-stripline transitions.

MCD investigated techniques for integrating active circuits into the array structure. Specifically it was found that the integration of LNAs can improve the overall noise temperature performance, and electronic steerability requires imbedded phase shifters. Low-loss transitions from stripline to MMIC circuits have been designed.

Analog Phase Shifter

MCD began the development of a reflection-type 360° analog phase shifter in 1989 to achieve electronic steerability in the flat antenna. An MIC prototype circuit has been built which operates at X-band and a miniaturized MMIC version of this circuit will be fabricated during 1990. The key component of this phase shifter is a monolithic hyperabrupt varactor that provides the necessary voltage-variable capacitance. Each MMIC circuit incorporates eight varactors. Since the devices are reverse biased, the power consumption is negligible.

Integrated Low-Noise Amplifier

A miniaturized, high-performance low-noise amplifier is being developed for integration into the flat antenna assembly. The first amplifier stage uses discrete high electron mobility transistors (HEMTs) and the subsequent amplifiers use MESFET devices. This compact LNA (70 x 265 mils) has a state-of-the-art noise figure.

COMSAT SUPPORT

Antenna for Mobile Satellite Services

Two L-band reflector antenna systems were developed for the COMSAT Systems Division (CSD) site in Southbury, Connecticut. The first system is a receive only 5-ft reflector mounted behind the subreflector of the C-band Scientific Atlanta 11-m Cassegrain reflector. The second system consists of a transmit/receive 6-ft antenna fastened to a ground-mounted pole. In 1990, the Scientific Atlanta C-band and COMSAT L-band antennas will be converted to an INMARSAT coast earth station (CES) by the addition of appropriate diplexing devices.

A program has also been started at the CSD earth station site in Santa Paula, California, to modify the existing antennas and to install new LNAs for the new second generation INMARSAT service.

L-Band Feed for Korea

In support of a CSD CES contract with Korea, COMSAT Laboratories is designing and fabricating a circularly polarized L-band feed. The feed operates over the transmit and receive frequency bands and is designed for use in a prime focus implementation with a 10-ft reflector. The breadboard feed is shown in Figure 17. Four probes fed in a 0°, 90°, 180°, and 270° phase progression by means of two magic tees and a quadrature hybrid launch the circularly polarized wave. The scalar ring, located outside the horn aperture, provides a circularly symmetric feed illumination, thus achieving maximum gain and low off-axis cross-polarization.

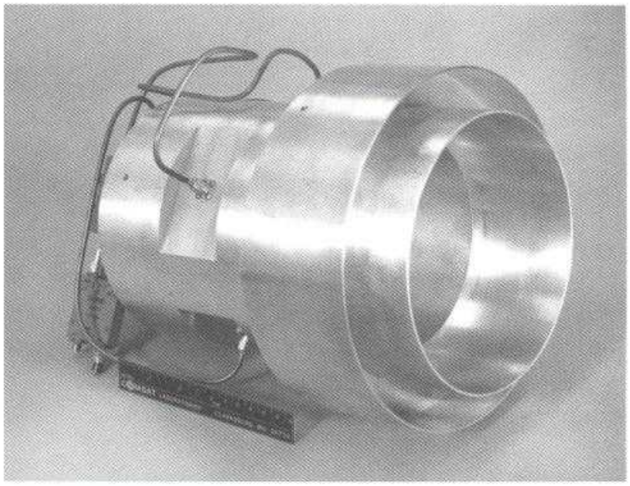


***Figure 17**. Circularly polarized L-band feed for CES*

INTELSAT

INTELSAT K Study

A study was performed to modify the existing SATCOM K (INTELSAT K) to obtain a set of new coverages that were desired by INTELSAT. These coverages included east (Europe), west (North America), and South American regional beams.

Computer modeling revealed certain physical constraints of the antenna system, limiting its ability to achieve the desired coverages. The east and west zones could not be totally covered, and the South American zone could not be covered at all.

Using the existing system, efforts were then focused on optimizing the reconfiguration and achieving the maximum possible coverages of the east and west zones. An additional dedicated antenna system offered a solution for the South American coverage.

Miniaturized SSPA Modules

A multiyear contract with INTELSAT is underway to develop new techniques for the design and fabrication of high-efficiency power amplifiers for communications satellite applications. The original goal was to develop a 2-W, 30-dB-gain module for the 3.7- to 4.2-GHz band using a mix of MMIC and quasi-monolithic circuit techniques. The next phase of the contract focused on the realization of the same three-stage SSPA on a single silicon substrate rather than on several alumina substrates, as was done previously, thus improving reliability, uniformity, and performance. By the end of 1989, the silicon process development had been substantially completed. Figure 18 is a photograph of the silicon substrate showing all three stages, as well as the recesses into which the MMICs and FETs would be mounted. At the close of the year, work started on a 30-W, two-stage power amplifier using the same silicon motherboard technology combined with a novel low-loss radial power combiner.

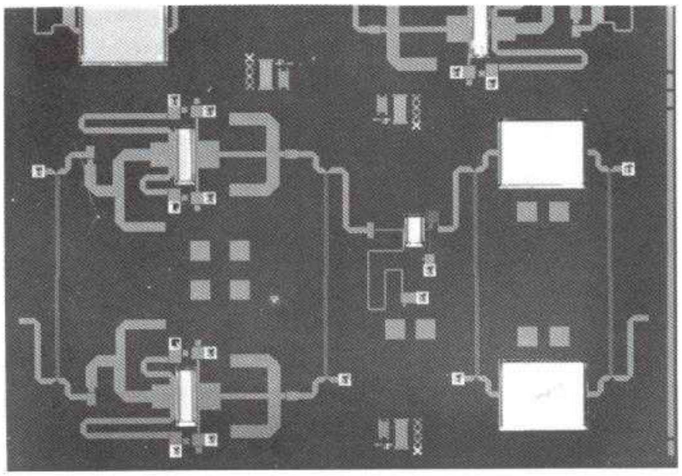


Figure 18. *Motherboard for miniaturized SSPA is realized on a single silicon substrate*

C-Band Steerable Spot Beam Antenna Feed System

MCD is currently developing a feed system for a C-band steerable spot beam satellite antenna. The feed system design will allow the polarization to be switched between linear and circular and will allow operation with high polarization purity over both the 3.7- to 4.2-GHz and 5.925- to 6.425-GHz frequency bands. The feed system will be used with a 1-m-diameter offset reflector, which is mechanically gimbaled to allow the transmit/receive spot beam to be steered to any position on the earth disk. The primary design effort is to develop a lightweight dual-polarized diplexing network and a high-polarization-purity feed horn that operates over the full 500-MHz transmit and receive frequency bands. A breadboard feed system was designed and tested in 1989.

Due to weight constraints and other technical considerations, it was jointly decided by INTELSAT and COMSAT to build a flight representative lightweight model of a circularly polarized feed network. The network will be approximately 40 in. long and weigh about 5 lb. The flight representative feed will be completed in 1990 and tested with a gimbaled 1-m offset reflector. A complete set of electrical data will be measured, including polarization isolation, coverage gain, polarization sensitive beam squint, return loss, passive intermodulation products, and multipactor breakdown. Thermal and mechanical vibration testing at flight representative levels will also be performed.

Compact Feed

A project to develop lightweight, flight-qualified feed elements concluded in 1989. The goal of the program was to use printed circuit radiator technology to realize lightweight, high-polarization-purity feed elements. These elements would replace existing waveguide horns, OMTs, and polarizers which, in combination, make the feed large and relatively heavy. Two types of microstrip radiators were developed and built; one for reflector feed use, and one for direct-radiating array applications. Figure 19 shows the direct radiating element which has an aperture efficiency of over 70 percent and is thus electrically equivalent to a global horn.

The 1989 effort concentrated on evaluating array performance of compact feed elements. An array of seven feed elements was assembled and tested for

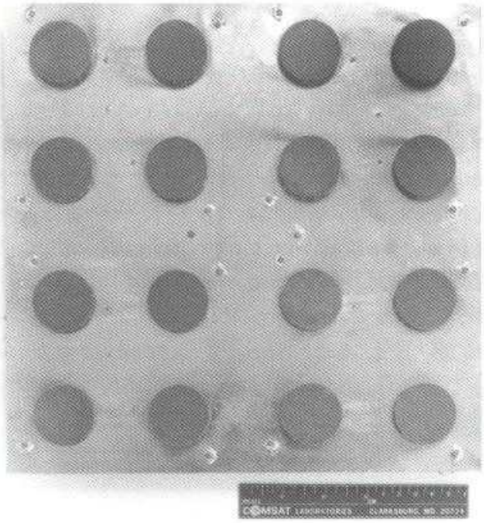


Figure 19. Direct radiating element is electronically equivalent to a global horn

embedded element performance including axial ratios, radiation patterns, and mutual coupling. The performance in the array environment showed that coupling had little effect on element performance.

OUTSIDE CONTRACTS

Superconducting Phased Array

In conjunction with Massachusetts Institute of Technology's Lincoln Laboratories, COMSAT initiated a program to demonstrate a superconducting phased array. COMSAT is designing a four-element linear array fabricated on a dielectric substrate that contains high-temperature superconducting thin film material. Performance of the array will be measured both at room temperature and at 70 K.

Millimeter-Wave Components

A 47-GHz MMIC power amplifier driving an MMIC doubler to produce a power source at 94 GHz is being developed for Hercules. Preliminary measured results of the multistage MMIC amplifier at 47 GHz presents linear gain of 14.4 dB and a power output of 88 mW.

Maryland Industrial Partnership Program

COMSAT has been working with the University of Maryland under the Maryland Industrial Partnerships Program to research the optical characterization of MESFET devices and MMICs, and generate millimeter-wave signals. The conventional network analyzer, photoconductive switch sampling, and electro-optic sampling techniques were used to characterize and compare 28-GHz MMIC power amplifiers.

Gain Standard Antenna

Under a contract with the National Institute of Standards and Technology (NIST), COMSAT Laboratories designed and fabricated 20- and 40-GHz circularly polarized gain standard antennas. The antennas provide both left-hand and right-hand circular polarization states with an axial ratio less than 0.15 dB over the respective 10-percent frequency bands. The 20-GHz antennas with gains of 12, 18, and 24 dBi are shown in Figure 20. The antennas will be gain calibrated by NIST and used as standards to measure the gain of circularly polarized reflector antennas.

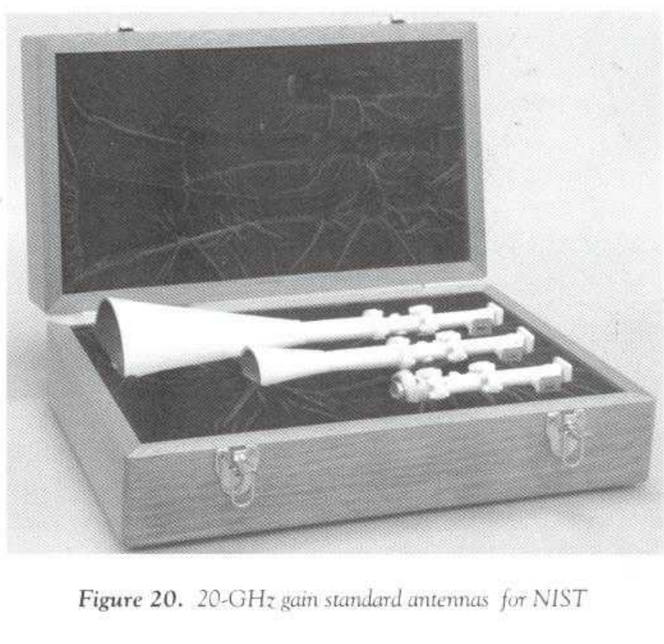


Figure 20. 20-GHz gain standard antennas for NIST

The Microelectronics Division (MED) supports COMSAT's need for state-of-the-art microelectronic components for use in advancing satellite communications systems and promoting its competitive business. Research and development are performed on discrete components [such as field-effect transistors (FETs)], microwave integrated circuit (MIC) technology, and monolithic microwave (and millimeter-wave) integrated circuit (MMIC) technology. General goals are to improve the performance, operating frequency, and reliability of these components. MED capabilities encompass all aspects of this technology, from device modeling and materials growth through fabrication, RF and DC characterization, and reliability evaluation. In 1989, MED developed a 60-GHz pseudomorphic modulation-doped FET (P-MODFET) low-noise amplifier with the best reported noise figure to date (2.9 dB), and a Ku-band amplifier with 27-percent power-added efficiency. The Division also developed P-MODFETs that exhibited a 0.8-dB noise figure at 18 GHz, and power FETs producing power-added efficiency as high as 53 percent at Ku-band. In addition, MED completed the fabrication and delivery of all MMIC chips for a low-power phased-array antenna designed and built by the Microwave Components Division.

COMSAT JURISDICTIONAL R&D

Materials Technology

The 1989 semiconductor materials research effort addressed two areas believed to have a major impact on FET power device performance. First, significant premature power compression was observed in devices that are under increased source-drain bias. This degradation was believed to be caused by an inadequate buffer layer, permitting hole injection into the active channel under large voltage swings. Devices fabricated from vapor phase epitaxy (VPE) material with unintentionally doped n^- buffer layers exhibited this behavior to a greater extent than those fabricated from molecular beam expitaxy (MBE) material. To evaluate this hypothesis, MED investigated the properties of an MBE-grown p^- buffer layer incorporating an AlGaAs/GaAs superlattice. Devices and MMIC chips fabricated from wafers incorporating this improved buffer layer exhibited state-of-the-art performance with minimal premature power compression, leading to significant performance improvement.

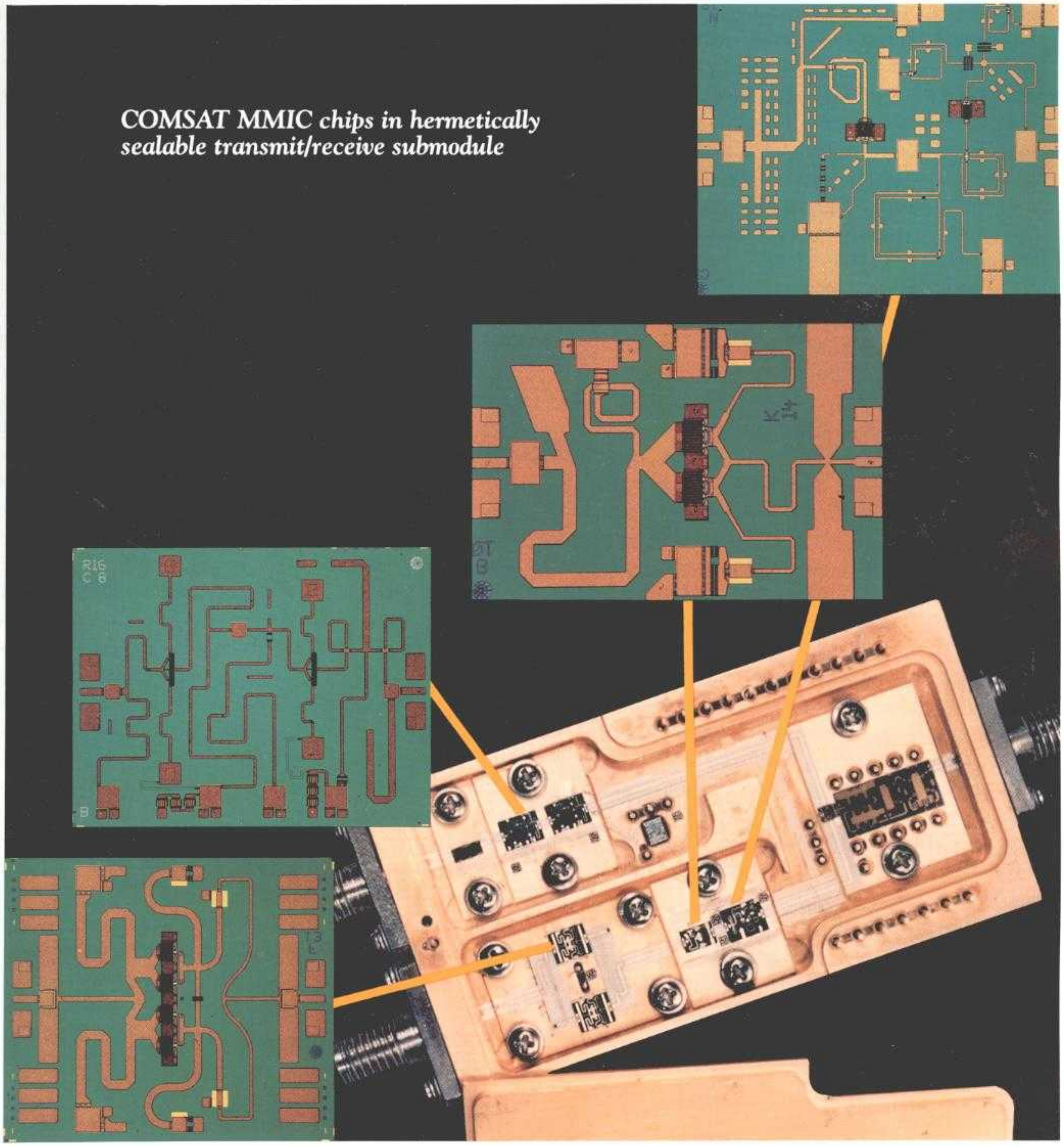
Second, an optimized FET structure was envisioned that would have a minimum gate recess (an area where some of the GaAs has been etched away before the gate metal is deposited) and a deep n^+ layer for ohmic contact formation. Such a structure would increase yield by eliminating the non-uniformities associated with a deep recess etch, and maximize breakdown voltage by minimizing current crowding at the etched corners. A process was developed in which selective ion implantation formed n^+ pockets in an MBE-grown active channel layer. A high-temperature anneal was required to heal the crystal damage and activate the implanted dopant. During the anneal, compensating defects originating in the substrate diffused into the active channel. A series of experiments was performed to identify annealing conditions that produced acceptable activation with minimal active layer compensation. FETs fabricated in this manner produced COMSAT's best power density devices, exhibiting over 600 mW/mm at 12 GHz.

Buffer layers on which active FET material is grown have a direct impact device on breakdown voltage, current confinement, substrate and/or buffer layer charge injection, and back gating. The desired characteristics of a buffer layer are as follows:

- negligible conductivity
- energy band discontinuity at the active layer interface
- p^- type structure
- resistance to defect diffusion.

These characteristics have been incorporated into MBE-grown buffer layers. The layers (p^- type $< 1 \times 10^{15}/cm^3$) are unintentionally doped with carbon from the background carbon monoxide in the MBE machine. The initial 1,500-Å-thick GaAs layer ensures good crystallinity

MICROELECTRONICS



COMSAT MMIC chips in hermetically sealable transmit/receive submodule for the superlattice. The 20-period 2,000-Å-thick AlGaAs/GaAs superlattice forms a potential energy barrier to out-diffusion of defects from the substrate. The final 4,000-Å-thick GaAs layer affords good current confinement and minimizes hole injection into the active channel. This buffer layer has been successfully incorporated into several recent device and circuit wafers.

During the initial effort to form a planar FET, it was discovered that FET channels formed by selective implantation of n^+ ohmic contact regions were completely compensated by diffusing defects when annealed at the optimum condition for implant activation (980°C for 10 s). This required the use of a compromise anneal condition that produced acceptable active layer compensation and maximum implant activation. For the implant conditions used (100 keV, 4×10^{13} Si^+/cm^2), it was found that a 30-s rapid thermal anneal at 850°C caused less than a 7-percent resistivity increase in the active layer and created an acceptable activated implant sheet resistance of 135 $\Omega/\square$. FETs were fabricated from several wafers with epitaxial active channels ($2.5 \times 10^{17}/cm^3$) and selectively implanted n^+ regions. Initial positive results indicate that continued development of this technique will prove fruitful.

R&D efforts in high-temperature superconductivity (HTS) materials have continued with examination of substrate materials for 1-2-3 ($YBa_2Cu_3O_7$) superconducting films. Commercially available crystalline $LaAlO_3$ is the present substrate of choice for research efforts, since it is lattice-matched to 1-2-3 materials and is uniform over large (2-in.) areas. HTS materials measured in the MED's 16-GHz resonance cavity include 1-2-3 film and bulk samples. The bulk samples are comparable to copper in conductivity at 16 GHz and 77 K, while the films are somewhat more conductive than copper under these conditions. Extrapolation of these data suggests that conductivities nearly an order of magnitude greater than that of copper will be obtained at 4 GHz.

The addition of gold into bulk HTS material provides benefits in terms of thermal and mechanical properties. Bulk samples with as much as 20-percent gold show no degradation in microwave performance.

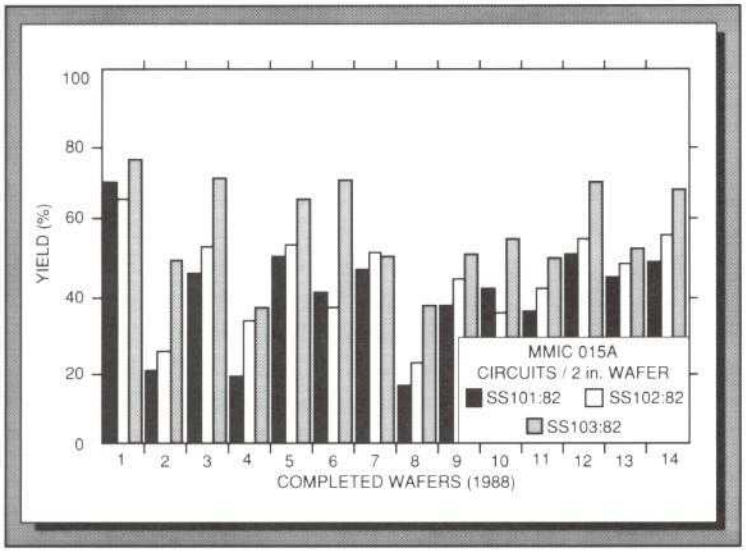
Microelectronic Chip Fabrication

Since its inception in 1983, MED has been aware of the need to continuously develop and refine its GaAs processing technology to produce state-of-the-art FETs and MMICs for advanced communications satellite applications. Fabrication requirements for the multibeam phased-array antenna and other large-scale programs have emphasized the process stability required to reproducibly fabricate highly reliable devices and MMIC chips, and have dramatized the need to implement a "production-like" mode of operation to increase yields, decrease fabrication time, and reduce fabrication costs.

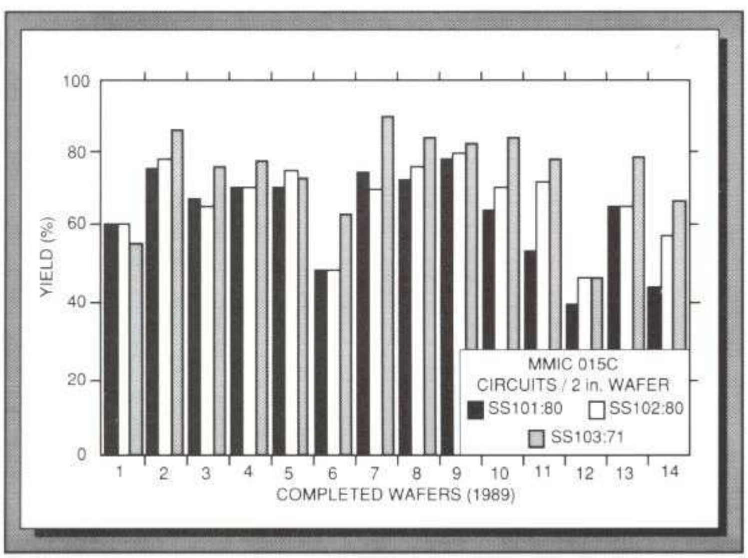
To meet these needs, MED's fabrication capabilities were reorganized at the beginning of 1989. The fabrication efficiency and effectiveness of the new pilot-line style of operation, as well as an increase in professional staff, have enabled the development and implementation of improved processes and have led to the identification and resolution of fabrication problems.

Among these refinements in processing technology is a controlled passivation process with parameter shifts ≤5 percent, making COMSAT an industry leader. Double-recess and shallow-recess gate processes routinely produce breakdown voltages greater than 20 V for power devices, and a newly implemented backside via-hole process realizes nearly 100-percent yield. Implementation of a solution of two related problems—a gate metalization appearance problem and the problem of leaky gates caused by gold metal spuriously coating the titanium and platinum—have also produced a corresponding improvement in yield. Improved wafer thinning technology (lapping and polishing) has increased throughput, while a wafer demount process (after completion of backside fabrication) has reduced demount time. Similarly, tape dicing for "pick and place" chip sorting has nearly doubled the yields at chip pick and clean, and a unique hybrid wet-chemical/mechanical dicing operation has virtually eliminated yield loss due to chipping during dicing (patent filed). Other enchancements include new field-metalization technology and plating-bath chemistry that improved microcircuit electroplating, as well as new automated equipment, such as a wafer-track system for photoresist coating, baking, and developing to improve throughput.

A measure of the initial improvements realized with the pilot-line mode of operation can be obtained by comparing the yield of phase shifter circuits fabricated in late 1988 for the low-power multibeam phased-array antenna (Figure 1a), with the yield of identical circuits for the high-power array fabricated during the initial stages of pilot-line operation in early 1989 (Figure 1b). The average time required to fabricate the phase shifter wafers was reduced by 25 percent. Figure 2 compares the yield maps for a 2-in. phase shifter wafer completed in late 1989 (Figure 2a) and a 3-in. wafer completed in early 1989 (Figure 2b). Although the percentage yield is somewhat higher for the 2-in. wafer, there are nearly three times as many "DC-good" chips on the 3-inch wafer produced with only a slight increase in process time. Matching of 3-in. process line maturity should produce even higher yields than those realized for 2-in. wafers.



(a) 1988 yield



(b) 1989 yield

Figure 1. *Pilot line operation increases turnaround and efficiency of phase shifter circuit wafer fabrication*

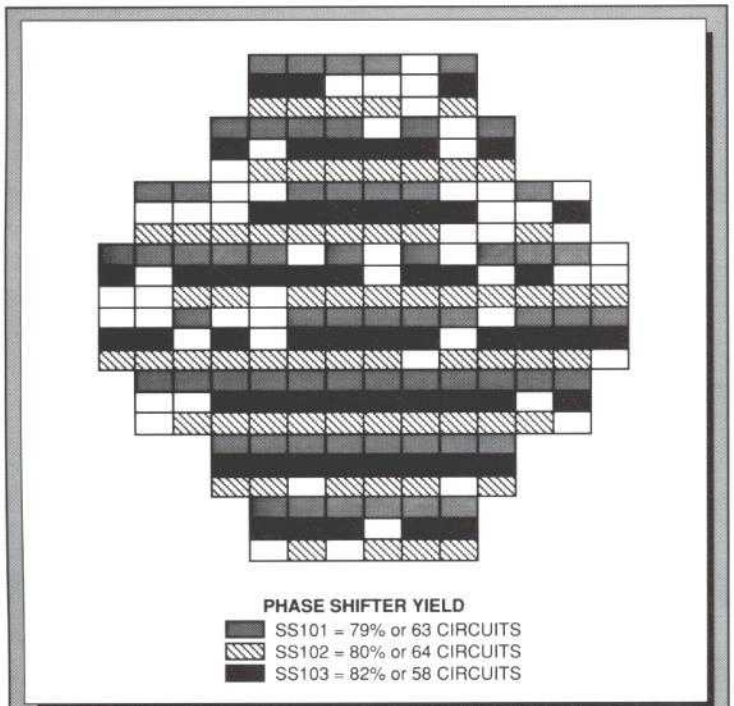
Additional achievements in 1989 include 83-percent DC yield for a C-band driver amplifier wafer, 82-percent DC yield for a 47-GHz power amplifier wafer, and 70-percent DC yield for a C-band low-noise amplifier (LNA) wafer.

The well-established fabrication technology used in the pilot line is under rigorous control. Every process step for FET or MMIC fabrication is documented with detailed process specifications, copies of which are maintained in the work areas. Every GaAs wafer processed through the pilot line is accompanied by a standardized lot traveler, whose entries include step number, a brief descriptive title for each step, critical parameters for the step, and quality assurance criteria. Progress of wafers through the pilot line is monitored by a computerized wafer tracking system. Documentation control and process control are monitored and audited by independent product assurance personnel.

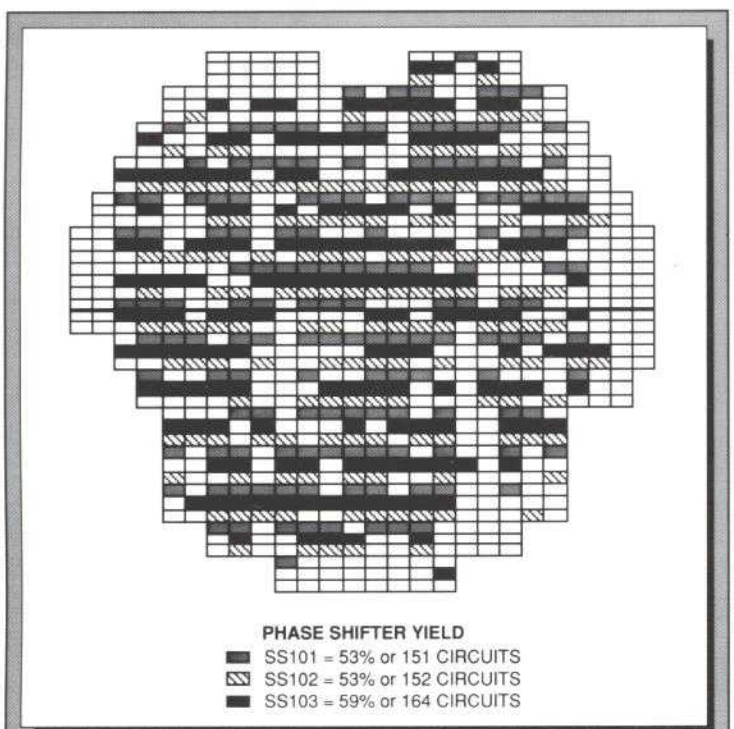
Heterojunction Device Research

State-of-the-art, 60-GHz, low-noise MMICs based on P-MODFETs, with 0.25-μm x 60-μm gates, were developed. Single-stage LNAs exhibited minimum noise figures of 2.9 dB, with 4.1 dB of associated gain at 59.25 GHz. Dual-stage MMICs had minimum noise figures of 3.5 dB, with 10.8 dB of associated gain at 58.5 GHz. Cascaded four-stage LNAs had minimum noise figures of 3.7 dB and more than 20.7 dB of associated gain at 58.0 GHz. Additionally, when biased for maximum gain, the four-stage amplifier exhibited more than 30.4 dB of gain at 60.0 GHz. These results represent the best performance for any millimeter-wave low-noise MMIC reported to date. A comparison between COMSAT's experimental and theoretical predictions of minimum noise figure vs frequency is shown in Figure 3, which includes noise figure results for both discrete devices and COMSAT's low-noise MMICs.

Larger gate width, low-noise P-MODFETs (0.25 μm x 150 μm) were measured for power and efficiency, resulting in a record 71-percent power-added efficiency (the ratio of the difference between the RF output and input power to the DC power used), with an



(a) Yield map for 2-in. wafer fabricated using pilot line operation



(b) Yield map for 3-in. wafer fabricated prior to pilot line operation

Figure 2. *Pilot line operation produces three times as many "DC-good" chips as traditional process*

associated power of 11.7 dBm at X-band. When biased for higher power levels, these P-MODFETs yielded as much as 15-dBm saturated output power.

Varactor Technology

Development work was performed to improve wafer processing procedures in fabricating GaAs MMICs containing varactor diodes. This activity resulted in increased device yield and contributed to realizing high-performance varactor diodes and MMIC voltage-controlled oscillators (VCOs). Improved planar processing techniques in several critical ion implantation steps resulted in greatly enhanced uniformity and reproducibility. Three implant steps were improved by developing plasma processing procedures in the selective implant masking operations. Across-the-wafer uniformity of 99.2 percent, and wafer-to-wafer reproducibility of 99 percent were achieved. Both discrete-varactor diodes and MMIC VCOs closely tracked the improved wafer uniformity in their electrical capacitance vs voltage characteristics.

As a result of this work, additional circuit applications for the MMIC-compatible varactor diode have been identified, including analog phase shifters at 12 GHz, frequency doublers at 94 GHz, VCOs at 35 GHz, and tunable notch filters at 12 GHz.

High-Efficiency Power FET

Power FETs are ideal devices for use in transmitters and in remotely configurable, multibeam satellite antennas such as those described in detail in the Microwave Components Division section of this Annual Report. Such equipment will be needed in future satellites to enhance their competitiveness with optical fiber cable. For this application, it is essential that the FETs have high power-added efficiency. Additional requirements are high operating DC voltage and high power density, which is measured in watts of RF power per millimeter of gate width. Two techniques were optimized to meet these requirements.

To increase operating voltage and power density, and to maintain the high power-added efficiency (over 40 percent) demonstrated in 1988, the gate recess was made as wide as possible for the existing maskset design. However, this wider gate width aggravates the detrimental effects of passivation, which is required for long-term reliability of the FETs. Therefore, the passivation process was adjusted to minimize unwanted side effects.

As a result of these developments, COMSAT's power FET process has improved. The yield of FETs with power-added efficiency greater than 40 percent has increased; power density has risen from 0.35 to over 0.45 W/mm; and operating voltage has increased by 25 percent.

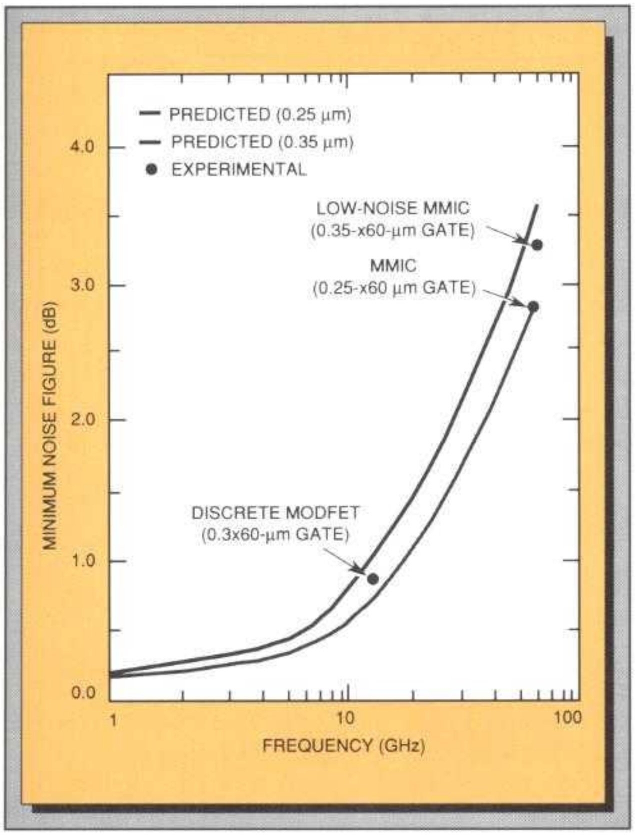


Figure 3. COMSAT's experimental data on minimum noise figure vs frequency shows excellent agreement with theoretical predictions

MMAC Technology

For several years, COMSAT has been fabricating miniaturized microwave active circuits (MMACs) on a variety of substrates. During 1989, COMSAT continued the development of this hybrid circuit technology on high-resistivity silicon substrates for use in high-power, high-efficiency microwave amplifiers being delivered by the Microwave Components Division. A silicon substrate has three advantages over other substrate materials:

- silicon has good thermal conductivity for efficient heat removal in high-power circuit applications
- recesses for mounting GaAs devices are wet-chemically etched into the substrate, thereby reducing the length of bondwires, with a corresponding reduction in parasitic inductance
- via-holes are etched through silicon substrates from the opposite side to provide low-inductance connections to the ground plane. Improvements in process technology have significantly increased the yield of these complex MMAC motherboards.

Electron-Beam Lithography

Low gate resistance and short gate lengths are essential for high-gain, low-noise performance of high-frequency GaAs devices or circuits. Performance is also enhanced by reducing source-to-gate resistance. MED has begun investigations into a technique for obtaining low gate resistance, low source-to-gate resistance, and short gate lengths. A Γ-shaped cross section gate (Γ-gate) structure, in which the small footprint defines the length and the wide top provides a low gate resistance, has been produced. The unique shape of the Γ-gate facilitates the generation of low source-to-gate resistance by allowing the gate to be positioned proximate to the source edge. Figure 4 shows a 0.125-μm Γ-gate placed 0.25 μm from the source edge of a FET.

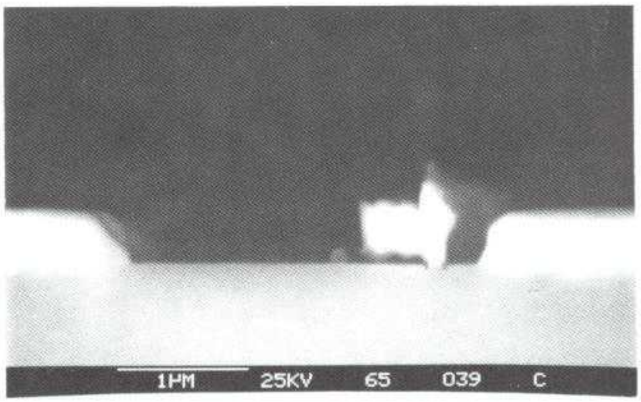


***Figure 4**. Uniquely shaped 0.125-μm Γ-gate placed 0.25 μm from FET source edge provides low gate resistance*

MMIC Packaging Technology

To fully exploit the advantages in performance, size, reliability, and cost afforded by MMIC processing technology, MMIC packaging and assembly techniques must be pushed to a correspondingly high level of development. MED has developed packaging techniques for microwave and millimeter-wave low-noise and low-power MMICs, as well as for multichip, multifunction subsystems. One complex housing (approximately 2 x 4 cm) holds nine MMICs and one silicon control chip, and provides interfaces for RF input/output, DC power, and control signals. Individual MMIC functions are assembled and tested on thin flat gold metalized carriers, and then integrated into the unit housing for submodule testing. This submodule is shown in the opening photograph of this section.

Figure 5 depicts a Ku-band, MMIC, four-stage LNA in a hermetically sealable ceramic package. This LNA achieved a 2.8-dB noise figure with associated gain of 23 dB.

RF and DC On-Wafer Device Characterization

During 1989, MED upgraded its capabilities in on-wafer MMIC/device characterization in two areas. The first was the addition of a system capable of performing full small-signal microwave on-wafer characterization of MMICs/devices at frequencies up to 40 GHz. The system (Figure 6) consists of a Hewlett-Packard 8510 automatic network analyzer, a Rucker & Kolls automatic wafer prober, and a Cascade Microtech microwave probe assembly for the autoprober. Devices are characterized using probes that are miniature coplanar waveguide (CPW) microwave transmission lines. In addition, bias may be applied through conventional needle probes. This capability will enable MED to quickly and accurately determine the microwave characteristics of an MMIC or device wafer earlier in the process than with the normal method of dicing out chips and mounting them for RF characterization. This system will also enable MED to perform microwave characterization on more MMICs/devices per wafer, thus allowing more thorough and timely analysis of process development and feedback to R&D circuit development.

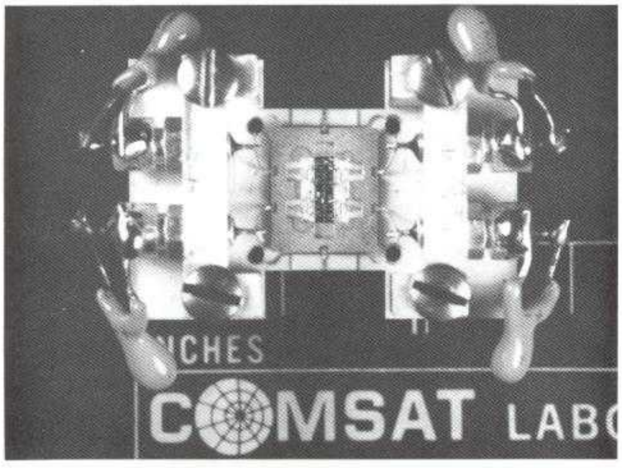


***Figure 5**. Ku-band, MMIC, four-stage LNA in a hermetically sealable ceramic package shown mounted in test fixture*

The second improvement to MED's on-wafer test capabilities is in automatic DC wafer characterization. The addition of a Hewlett-Packard 4062B automatic parametric analysis system in 1989 increased MED's capabilities by adding automatic capacitance, capacitance vs voltage, and capacitance vs time measurements. With these additional capabilities, more material analysis measurements such as carrier doping profiles can be performed routinely. With its built-in library of measurements and simplified probe control software, the system also simplifies test software generation for many types of MMICs.

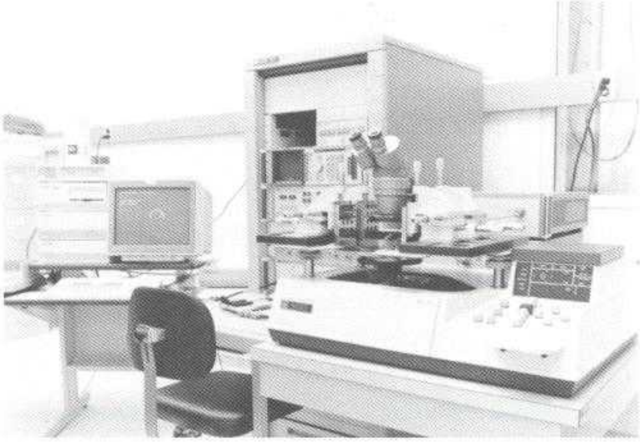


***Figure 6**. On-wafer RF test system provides full-scale small-signal microwave on-wafer characterization of MMICs/devices at frequencies up to 40 GHz*

MMIC Life Test and Reliability

In 1989, the MED designed and assembled an RF-biased life test system (Figure 7). The system has been designed for dynamic control of individual oven

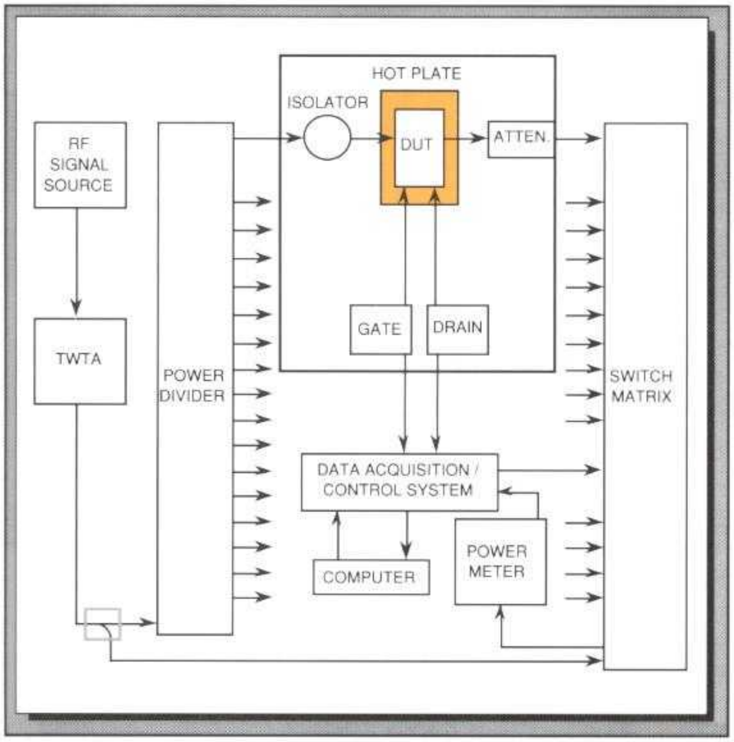


Figure 7. RF-biased life test system enhances GaAs MMIC and FET reliability assessment

temperatures to instantaneously compensate for changes in DC and RF parameters and hence maintain constant junction temperatures. All bias voltages, and the resultant currents, will be monitored and recorded. Initially this system will be configured for 5-GHz operation, but the operating frequency can be increased to 18 GHz by changing only the RF source and traveling wave tube amplifier (TWTA). The thermal portion of the system, the data acquisition system, and the computer are independent of frequency. This system can also be used as a DC-biased life test system by simply disconnecting the RF ports. In conjunction with the present DC-biased life test system, it gives the MED wide-ranging capabilities in GaAs MMIC and FET reliability assessment. The Division will be capable of performing reliability tests on any of the types of devices that have been identified as likely candidates for integration into future satellite systems.

Physicochemical Failure Analysis

Early failure of traveling wave tubes has been traced to poor adhesion of oxide cathodes. A microanalytical study based on Auger analysis of oxide-coated cathodes, initiated in 1988, identified materials characteristics associated with reduced electron emission and areas of peeled oxide. Three materials-chemistry-related phenomena have been identified and related to reduced electrical performance. Through a comparative study of several cathodes with lifetimes between 4,000 and 40,000 hours, a correlation has been established between peeled oxide and areas of nickel- and zirconium-rich glassy material at the nickel substrate/oxide interface. By contrast, interface areas under adherent oxide exhibit a nodular nickel structure that does not contain zirconium. This year, findings of this study include the presence of carbon in the form of a carbonate or carbide, as indicated by Auger lineshape analysis; elemental contamination by potassium and sulfur; and oxidation differences in the nickel button surface between peeled and adherent areas. The results of these oxide-cathode chemistry studies point to relationships among materials selection, manufacturing processes, and TWT performance.

Radiation Studies

Work is continuing on a radiation damage monitor for GaAs devices. Strengths and limitations of the present structures have been studied, both experimentally and theoretically. The damage monitor's response to different radiation sources (energetic electrons and protons) and anneal schedules has been characterized in order to extend applications.

Radiation tests to simulate the gamma ray and energetic ion environment at geosynchronous orbit have been carried out on P-MODFETs and MMICs. The results indicate that these structures are even less susceptible to radiation damage than GaAs metal-semiconductor FETs (MESFETs). Experience gained in radiation experiments on different materials and devices is providing a basis for models used to predict radiation degradation in new materials and under different environments.

MED continues to provide consultation on electrostatic discharge (ESD) effects and prevention techniques for spacecraft systems. The approaching peak in the 11-year solar flare cycle has raised concerns, despite many years of relatively trouble-free operation. Such concerns are warranted, since three anomalously large solar flares did occur in 1989. These flares caused spacecraft communications interruptions (from ESD) and solar array degradation (from energetic protons).

The increasing intensity and incidence of solar flares have prompted a review and assessment of resultant high-energy particle impact and "hot" plasma-induced ESD on communications satellites. COMSAT, as U.S. Signatory to INTELSAT, presented a position paper to the INTELSAT Board of Governors/Technical Advisory Committee (BG/T) recommendating reevaluation of the ESD protection on INTELSAT VII. MED personnel also briefed Ford Aerospace on the technical issues and participated in discussions on ways to improve the tolerance of INTELSAT VII spacecraft. A database was set up to correlate spacecraft anomalies on INTELSAT V with solar flare activity.

MMIC Design Manual and Library

MED has developed a design manual and associated cell library for power and low-noise FET and MMIC processes. The manual contains the information circuit designers need to perform RF design of MMICs containing FETs, resistors, capacitors, and inductors, as well as the design rules used by mask designers in laying out new MMIC masksets. Power FETs, inductors, and capacitors of various sizes, which are capable of being RF-probed without dicing and bonding individual elements, have been designed. Wafers fabricated using these masksets will provide statistical data on the reproducibility and uniformity of the MED pilot line.

INTELSAT SUPPORT

As part of the Laboratories' support to INTELSAT, MED has measured the ultraviolet (UV) degradation of silicon solar cells and studied the optical properties of a new type of optical solar reflector (OSR). These new OSRs have such low absorptance that special care must be taken in calibrating the equipment and in conducting the measurements. Future work will include particle and UV damage experiments on the OSRs.

Satellite battery lifetimes can be extended with improved materials selection and testing procedures. Migration of active material in the positive plates of nickel-hydrogen cells has been associated with redistribution of electrolyte and loss of storage capacity. Computer analysis of backscattered electron images of cross-sectioned positive battery plates has been used to quantitatively relate the change in cell performance to changes in positive-plate chemistry, and to suggest means for improved manufacturing and operating conditions. A new potential failure mechanism involving platinum migration in INTELSAT VI Ni-H_2 cells has been uncovered and investigated. The impact on cell performance is now being studied.

In seeking to understand possible causes of the INTELSAT V solar array anomalies, MED has used electron beams to simulate space plasma charging effects. The results of these tests, before and after vibration and thermal testing, indicate that ESD will probably not occur on sensitive regions of the array, and, even if it does, it will not produce the type of damage observed in the I-V array. Other ESD-induced damage mechanisms will be investigated in 1990.

OUTSIDE CONTRACTS

Air Force Transmit/Receive Module

COMSAT is a subcontractor to a Fortune 500 defense contractor in the development and production of 75 transmit/receive (T/R) modules for a phased array antenna. In this program, C-band receive and transmit chips developed at COMSAT are integrated to form a T/R submodule, as shown in the color photograph at the beginning of this section. The receive chain consists of a cascaded four-stage LNA that delivers 1.8-dB noise figure (Figure 8). The transmit chain consists of a balanced power amplifier and a driver amplifier combined to produce 3 W of output power. A single chip of the power amplifier in the transmit channel has delivered over 2 W of output power with 36-percent power-added efficiency (Figure 9), while the driver amplifier has exhibited 1-W output power with 40-percent power-added efficiency. These are state-of-the-art results for submodules. Several prototype modules have been delivered on schedule.

Externally Supported R&D

COMSAT is under contract to a Fortune 500 defense contractor to develop an X-band power module. The development program includes process techniques that

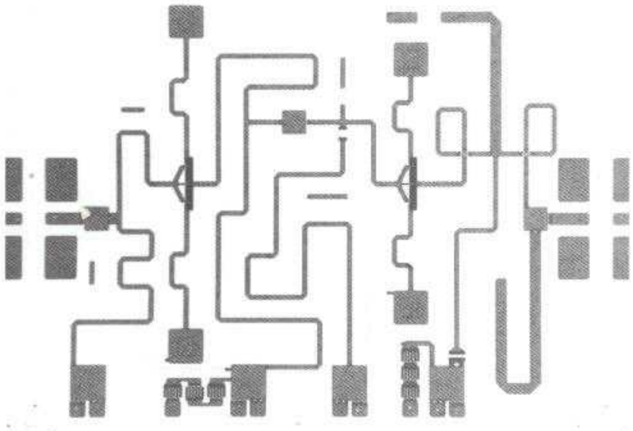


Figure 8. A cascaded two-stage section of four-stage LNA that delivers 1.8-dB noise figure

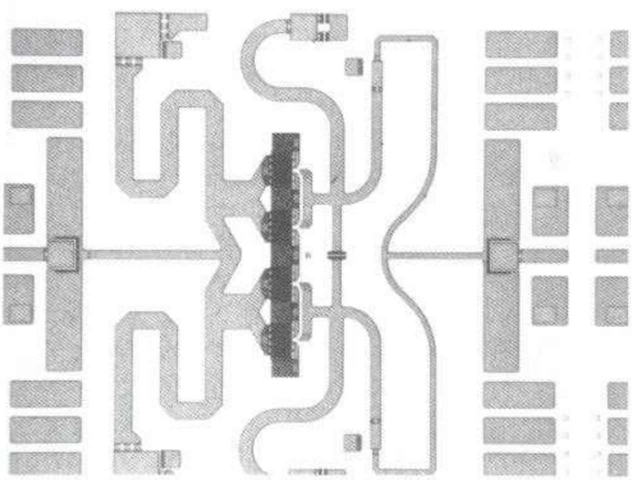


Figure 9. MED's balanced power amplifier delivers over 2 W of output power with 36% power-added efficiency.

will improve power-added efficiency, power density (output power per millimeter of gate width), and linearity (constant gain as a function of output power). Several techniques have been investigated.

The use of a shallower gate recess etch depth is expected to increase power output density by increasing the maximum allowable drain voltage. This process will also prevent burnout due to source-drain breakdown caused by current crowding at the ohmic contacts. The recess must be deep enough to prevent burnout, but as shallow as possible to maintain a high gate-drain breakdown voltage and to maximize the yield of FETs with the correct current voltage characteristics. Therefore, the thicknesses of the conducting layers in the GaAs wafer used to fabricate the FETs must be accurately controlled.

Another technique, selective ion implantation, can completely eliminate the recess etch requirement. In this technique, the conducting layer required under the gate is either epitaxially grown or ion implanted to have the correct thickness and conductivity. Then, to prevent current crowding, a separately masked ion implant creates higher conductivity areas on which ohmic contacts will be deposited.

A very different technique for increasing maximum drain voltage, and therefore power density, is the use of a superlattice (alternating thin layers of epitaxially grown GaAs and AlGaAs) to prevent certain defects from diffusing from the GaAs substrate into the epitaxially grown buffer layer where they can cause source-drain breakdown.

One technique to increase power-added efficiency and linearity is to confine the FET drain current to a very thin layer at a small depth below the gate. This is accomplished by an MBE growth technique called delta-doping, in which the epitaxial growth of GaAs is interrupted, while the dopant atoms (used to make GaAs conducting) accumulate in a partial crystal plane on the GaAs surface; growth is then resumed.

Promising results have been obtained for all four techniques. Excellent RF power and efficiency have been measured on a FET using a wafer with both a shallow recess and a superlattice diffusion barrier. At 12 GHz, the power density is 450 mW/mm and the power-added efficiency is 50 percent. Figure 10 shows the power output and power-added efficiency as a function of input power.

An X-band (8.8 to 9.6 GHz) solid-state power amplifier (SSPA) has been designed using two MMICs, a 0.5 W power-amplifier chip with 40-percent power-added-efficiency, and a driver amplifier chip to increase the amplifier gain.

Hughes MMIC and VCO/NRL Varactor Diodes

COMSAT successfully completed development contracts with the Naval Research Laboratory (NRL) and Hughes Aircraft Company on GaAs ion-implanted hyperabrupt varactor diodes and MMIC varactor diode VCO circuits. Discrete varactor diodes developed for NRL met the contract requirements of less than 2-Ω series resistance, quality factor (Q) greater than 10 over the full voltage range, and capacitance ratio greater than 10:1, all measured at 10 GHz. The fabrication process developed was demonstrated to be compatible with MMIC GaAs circuit fabrication by inserting the varactor diode in VCO circuits for Hughes Aircraft Company. Four different VCO circuit designs, each containing two to four hyperabrupt varactor diodes, were fabricated and delivered to Hughes for characterization. The VCO's bandwidth and frequency range depended on the specific design. The largest bandwidth measured was 5.4 GHz. Measurements on three of the four designs showed VCO performance covering the frequency range between 13.7 and 24.1 GHz, with bandwidths of 3.3 and 5.4 GHz. Output power up to 5 dBm was measured.

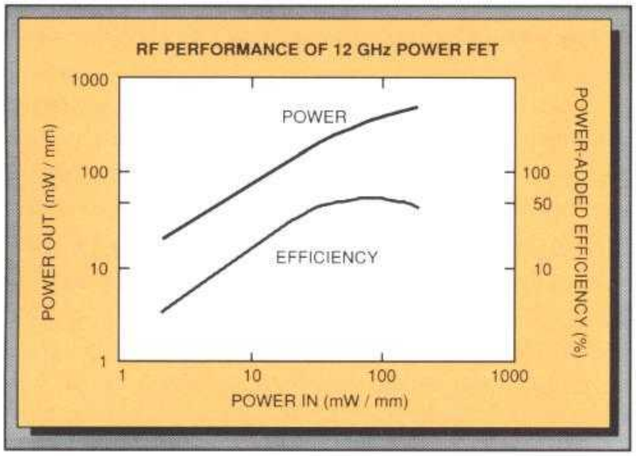


Figure 10. A shallow-recess, 2.25-mm power FET with a superlattice buffer layer produces 450 mW/mm at 12 GHz with 50% power-added efficiency.

MMIC Phase III

MED was awarded a prime contract from the Defense Advanced Research Projects Agency (DARPA) / U.S. Army under the MIMIC Phase III program, "Optical On-wafer Characterization of MMICs," to investigate the potential of non invasive optical on-wafer characterization. In particular, as the operating frequencies increase into the millimeter-wave region (above 26 GHz), the use of contacting RF test probes will prove to be less accurate, less reliable, and more costly. MED's technical approach is to replace the contacting CPW probes with optical beams generated by an ultrafast pulsed laser. Signal generation and sampling are accomplished by photoconductive switches printed on the wafer itself. A laser beam activates the DC-based switch, and thereby launches a short-duration microwave pulse along a 50-Ω transmission line to the MMIC. Another photoconductive switch, activated by a time-delayed synchronous laser probe beam, is used to sample either the reflected or the transmitted signals from the MMIC under test. Data acquisition and signal processing are performed, and the results converted into S-parameters which are easily understandable by microwave engineers.

Foundry Services

MED has a continuing program to fabricate MMICs for the Canadian Research Centre (CRC). Drawing on COMSAT's established expertise in microwave and millimeter-wave MMIC design and fabrication, a foundry course was taught to representatives of CRC and several Canadian firms. Each student selected an MMIC for design and was provided with sufficient data to complete the chip design and layout. Currently, the class maskset is being finalized, with fabrication and delivery of wafers scheduled in 1990.

In addition, MED successfully completed a contract from Hittite for the fabrication of 6- to 18-GHz MMIC circulators, with greater than 50-percent yield achieved. These wafers represented some of the most dense MMIC chips fabricated to date by COMSAT. Four wafers were delivered and accepted by Hittite.

COMSAT's foundry services extend to hybrid MMACs on alumina and silica. SPAR, a Canadian aerospace company, used COMSAT's MMAC foundry service to develop a reliable and cost-effective MMAC process to produce amplifiers that could be qualified for space applications. In this program, passive elements for the amplifier (resistors, capacitors, inductors, air bridge connections, and transmission lines) were fabricated on the substrate to eliminate costly, labor-intensive assembly. Via-holes were ultrasonically drilled through the substrate and metalized to produce low-inductance connections to ground. Larger openings were ultrasonically drilled through the substrate to permit the active elements (power FETs) to be mounted directly onto the carrier for heat removal.

Direct-Write Electron-Beam Lithography Service

COMSAT's electron-beam lithography facility continues to supply direct-write lithography foundry services to commercial customers. This service entails gate-level-only writing and overlay on 3-in. GaAs wafers provided by the customer. To date, MED has processed over 40 wafers and has contracts for approximately 100 more in 1990.

Hercules MMIC Development

During 1989, Hercules Corporation contracted with MED to provide a custom MMIC development program for 35- and 47-GHz power amplifiers. A 35-GHz, four-stage MMIC power amplifier was successfully designed, fabricated, and tested by MED. The first two stages, which consisted of driver chips with 0.4-mm gate width, were cascaded with two balanced power chips, each with a total gate width of 0.8 mm. Figure 11 is a photograph of the complete four-stage power amplifier module. As shown in Figure 12, excellent millimeter-wave performance was achieved. A linear gain of 14.6 dB with saturated power of 295 mW was obtained from 4 to 36 GHz.

Using MMIC chips fabricated by MED, a five-stage amplifier producing 12.8-dB gain and 87-mW saturated power was designed by the Microwave Components Division and successfully fabricated, assembled, tested, and delivered to Hercules.

Miscellaneous

COMSAT's well-known expertise in evaluating radiation and UV damage in solar cells has resulted in outside contracts from customers including the Applied Physics Laboratory, Solarex, and Mitsubishi. A byproduct of these tests is a better understanding of the INTELSAT and INMARSAT solar array performance predictions.

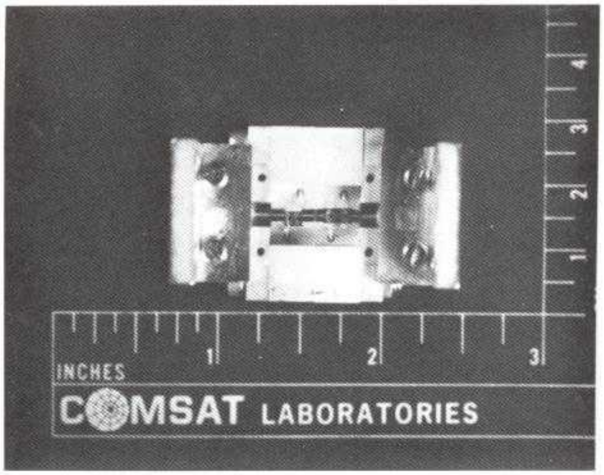


Figure 11. *A 35-GHz four-stage power amplifier has been successfully designed, fabricated, and tested by MED*

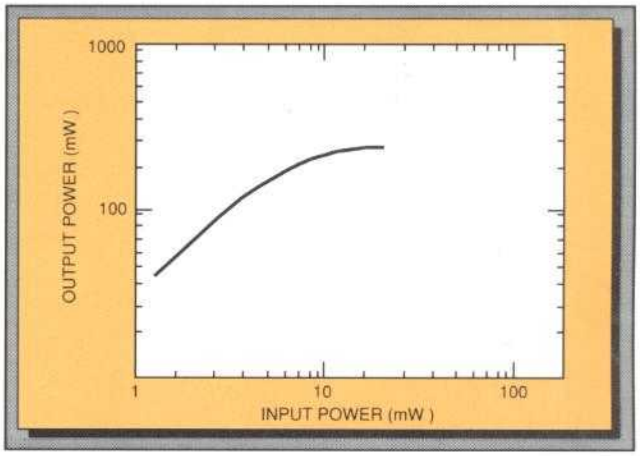


Figure 12. *MED's 35-GHZ four-stage power amplifier exhibits excellent millimeter-wave performance with a linear gain of 14.6 dB and a saturated power output of 295 mW*

The Satellite Technologies Division (STD) of COMSAT Laboratories conducts research, development, and support activities in a number of technical areas important to the Corporation, including technological developments in advanced communications satellite concepts that use numerous pencil beams as well as on-board processing. The Division provides a broad range of engineering skills in disciplines such as satellite attitude control and dynamics, structures, telemetry and command, mechanisms, thermal control, power systems, energy conversion and storage, and environmental and qualification testing. Specifically, in 1989 STD developed a common pressure vessel (CPV) nickel-hydrogen battery and continued work on microwave and superconducting filters, CPV battery life testing, satellite monitoring and in-orbit testing, and microwave propagation studies.

JURISDICTIONAL RESEARCH AND DEVELOPMENT

Multimode Microwave Filter Technology

Past work concentrated on the development of microwave bandpass filters using multiple degeneracies in high-Q cylindrical microwave cavities. For example, 6-pole filters have been built from combinations of two triple-mode cavities, and a contiguous-band multiplexer has been built from a single quadruple-mode cavity per channel. However, extending the concept of multiple degeneracies in cylindrical cavities to more than four modes creates new problems because independent tuning and coupling of the desired modes are difficult to control. Alternatively, the rectangular cavity provides one extra degree of freedom (viz, the a/b ratio) compared to the cylindrical cavity. In 1989, work concentrated on exploring rectangular multiple degeneracies. Analysis allowed identification of practical degeneracies and development of prototype filters using these degeneracies. A narrowband response of a single-cavity hexamode filter is shown in Figure 1. Future work will exploit these sixfold degeneracies in multiple cavity filters.

Superconducting Filter Technology

Stripline microwave bandpass filters using high Tc superconducting lines are being developed both on an internally funded program and a joint development effort with Lincoln Laboratory. The successful development would greatly contribute to the state of the art of satellite payload input multiplexer technology, possibly replacing bulky cavity filters with printed circuit technology. Two dielectric substrates particularly appropriate for this application are lanthanum aluminate and galate. STD designed, fabricated, and tested both 2- and 4-pole gold film circuits at 4 and 7 GHz. Figure 2 shows typical high Tc (HTS) 4-pole stripline filter response at a room temperature of 300 K and at liquid nitrogen temperature of 77 K. From these results, the dielectric constant and loss tangent of the substrates can be accurately computed as a function of temperature.

Analytical Techniques

Under this task, STD continued to improve its analytical techniques through development of new software, enhancement of existing programs, conversion of programs to the most efficient computer system, enhancements to the local area networks (LANs), and education and training of user personnel. Several industry standard analysis programs were enhanced, and training was provided on the upgraded programs.

Propagation Studies

COMSAT Laboratories pursues a variety of experimental and analytical studies of radio wave propagation related to satellite communications. Investigations are

SATELLITE TECHNOLOGIES

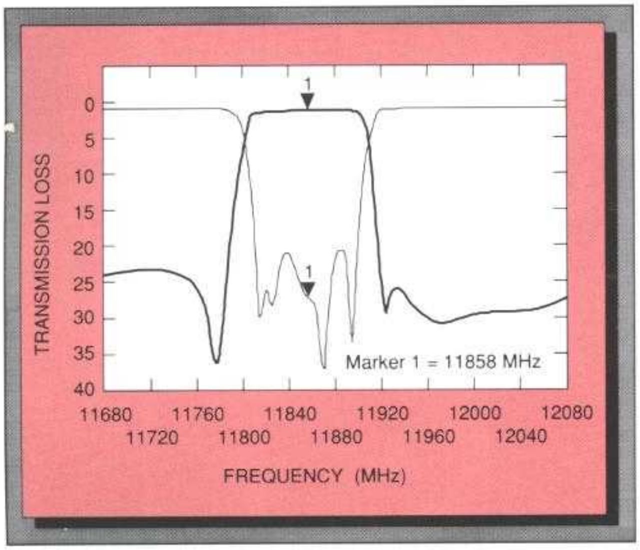


Figure 1. *Narrowband transmission response of single cavity hexamode bandpass filter*

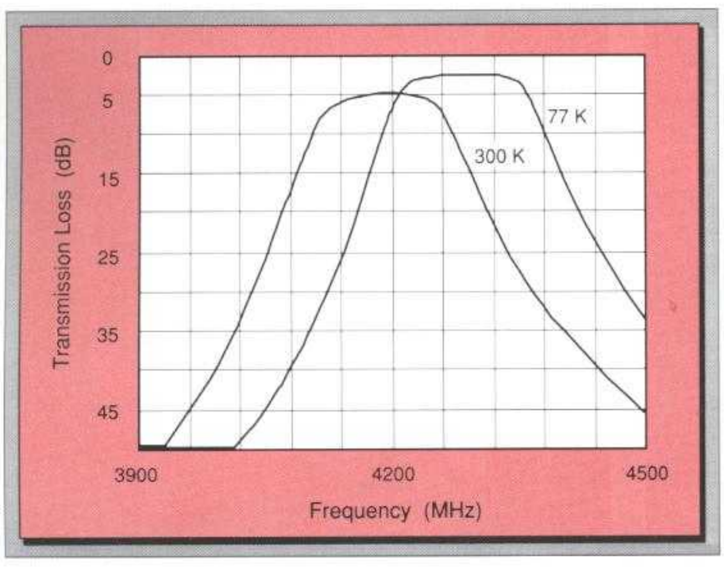


Figure 2. *Four-pole microstrip bandpass HTS filter—transmission response at 300 K and 77 K*

often related to emerging trends in satellite communications systems (small-margin systems, adaptive techniques for responding to signal impairments, and mobile-satellite systems). In 1989, a joint study with INTELSAT assessed propagation requirements of small-margin (low-availability) systems, such as very small aperture terminals (VSATs) and business service terminals.

Small, preferably nontracking antennas are a necessary ingredient in low-cost earth terminals, but corresponding power margins achievable with such systems are currently limited. Low-level fading on the propagation path caused by clouds, tropospheric scintillation, and low-intensity rainfall, which may persist for a significant percentage of the time, is an important consideration in the design of these systems. Some systems specify unavailability times of 1 to 5 percent of the year, at which point user perceptions of quality are strongly affected by details of the performance impairments, such as duration of fade and intervals between individual outages.

It has been concluded that new prediction models are needed that estimate cloud and rain attenuations when time percentages are greater than 1 percent of the year at frequencies above 10 GHz, because existing rain rate statistics are generally unreliable at these time percentages. Fading specifics (such as number of fades at a given fade level and fade duration statistics) are needed.

The combined effects of rain attenuation and tropospheric scintillation on overall cumulative distribution of path fading is also of interest, since degradations caused by scintillation may be of almost equal importance in some systems. Uplink power control to counteract moderate fading is under active development at COMSAT Laboratories, as described below.

MMIC Thermal Control Techniques

During 1989, a detailed analytical thermal model was defined of a monolithic microwave integrated circuit (MMIC) device, a C-band amplifier power driver chip, which developed a heat dissipation density of approximately 4,000-W/cm^2 gate area. The thermal model incorporates a large number of nodes in this gate area. Each layer of the integrated circuit chip is modeled separately, leading to a three-dimensional thermal model. The goals are to predict the operational temperatures of the chip in the gate regions, and to identify mechanisms by which the maximum gate temperatures can be reduced.

In conjunction with the above effort, an infrared (IR) microscope was acquired and used to obtain thermal temperature maps of operational MMIC chips. Because the resolution of the IR microscope is approximately 20 to 30 micrometers, compared to MMIC gate dimensions of 1 micrometer or less, an effort was started to evaluate methods to correlate IR temperature maps with analytical model predictions.

Computer-Assisted Microwave Measurement Techniques

For many years, COMSAT Laboratories has designed and developed in-orbit test (IOT) systems to measure the post launch communications performance of satellites. These software-controlled systems embody over 20 years of COMSAT's measurement expertise. The recent trend toward multiuser systems with remote terminals has resulted in a need for a new operating system. Based on previous IOT experience, STD completed the implementation of a computer operating system, the Multi Purpose Programming Package (MPCP II), that provides a platform for developing user-friendly, efficient software to control microwave instrumentation. The new MPCP II accommodates multiple users at separate workstations within a computer network. It is UNIX-based and uses the industry standard X Window interface developed at the Massachusetts Institute of Technology (MIT). This work, completed in 1989, included several enhancements to accommodate the ACTS Control and Status and EUTELSAT IOT systems, both of which use MPCP II as a platform.

Multibeam Phased-Array Antenna

During 1989, the design of the multibeam phased-array antenna (MBA), initiated in 1988 and shown in Figure 3, was realized in a proof-of-concept module that is spacecraft compatible. It has 24 feed horns, configured in five unequal rows in a staggered pattern to facilitate the interleaving of modules and form a complete array. To minimize the temperature gradient between the highly dissipating field-effect transistors (FETs) and the heat pipe vapor, the high-power amplifiers (HPAs) are mounted directly to ammonia/aluminum heat pipes which carry the heat to a remote thermal radiator to be rejected into space. With the exception of the power supply, each component of the MBA, including the structure, was designed and is being fabricated. During 1990, the module will be assembled and tested.

The design of the controller for the beam-forming matrix (BFM) was completed in 1989, and the first test parts fabricated. It comprises three different alumina board substrates, a driver, and two level shifter boards. Twenty-four driver boards and nine level shifter boards are used in the BFM. Each has complementary metal-oxide semiconductor (CMOS) integrated circuit chips

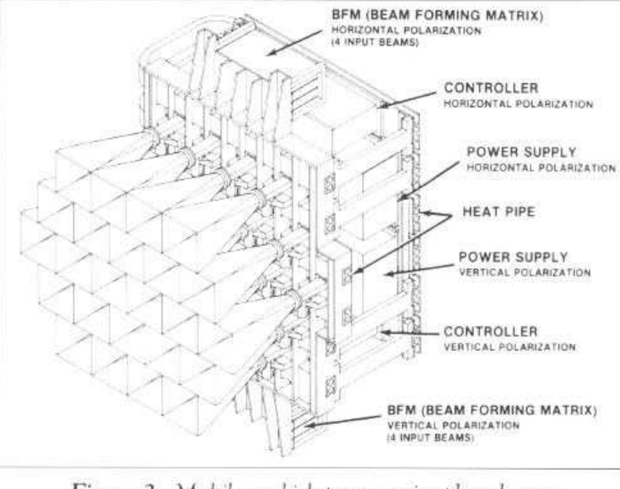


***Figure 3**. Multibeam high-power active phased array*

with surface mounted resistors and capacitors. Over 200 integrated circuits will be used in the BFM to control the 96 phase shifters. Development of test software for these boards was also started this year.

During 1989, a 350-W high-density power converter was developed to supply the drain voltage of the 24 MBA solid-state power amplifiers (SSPAs). It achieved a power density of approximately 25 W/cm^3 and peak efficiency of approximately 89 percent. To control, monitor, and distribute the power to the array, a microprocessor-based power monitor was developed, whose graphical interface gives the user direct control of power to individual array elements. Comprehensive monitoring of the power flow, along with automatic, sequential shutdown, will help protect the SSPAs and isolate failures.

Advanced Structures Concept

STD has completed a preliminary design for a communications spacecraft with an MBA payload. A modular concept was developed in which the module consists of 24 horns and their MBA elements. Each module is a separate thermal control entity with a common interface for transferring heat to the spacecraft bus. The thermal interfaces between the MBA module, capillary-pumped loop, and radiator panel have been designed and optimized. A design featuring capillary-pumped two-phase cooling loops was implemented for a planned 1991 flight experiment based on engineering data developed by NASA's Goddard Space Flight Center (GSFC).

The spacecraft heat rejection to space is accomplished by fixed conductance heat pipes embedded in honeycomb radiator panels. The heat pipe networks inside these radiators have been optimized to provide maximum heat transport capacity with minimum mass. The spacecraft dimensions have been selected for compatibility with a 3.6-m-diameter launch vehicle shroud. The overall spacecraft size is slightly larger than INTELSAT VII and can accommodate a power dissipation of up to 7.5 kW.

A dual reflector design with seven MBA modules has been selected as the initial payload configuration. Six capillary-pumped cooling loops transport the MBA waste heat to north and south radiator panels. The weight and area requirements for the spacecraft thermal control system have been calculated as a function of the dissipation requirements. The thermal weight per kilowatt of payload dissipation has been determined as 24 kg/kW, comparable to the thermal designs now planned or in orbit. A 3-axis stabilized spacecraft utilizing these design parameters has been developed.

Thus it is clear that the thermal design for a spacecraft using MBA elements is of great importance and may require a sizable portion of the spacecraft mass.

Advanced Stationkeeping

The interaction between the spinning spacecraft body and the large liquid fuel mass fraction for propulsion systems can result in spin instability as the properties of the body change due to liquid consumption during rocket motor fire. STD's advanced stationkeeping work attempts to analytically predict the dynamic effect of the liquid and compute the parameters in Guibert's criterion for static stability. The computer program developed was successfully validated against the stability results for INMARSAT 2.

The large amount of propellant mass required for satellite stationkeeping (INTELSAT VI has over 400 kg) has long motivated a search for higher specific-impulse propellent/thrusters. These goals have followed the diverging paths of bipropellant, ion, and electrothermal monopropellant. Bipropellant, once considered unusual, has become common on contemporary communications satellites; therefore, evaluating the progress in ion and electrothermal monopropellant systems was emphasized in 1989. Ion propulsion might save hundreds of kilograms of propellent mass on INTELSAT VII. Flight experiments are scheduled on European and Japanese spacecraft in the early 1990s.

Electrothermal monopropellant thrusters are augmented hydrazine thrusters. They increase the temperature of the decomposed hydrazine products by ohmic heating, raising thruster exhaust and specific impulse. Even higher temperatures, and thus higher specific impulse, can be achieved by striking an arc between a cathode and an anode in the decomposed hydrazine, resulting in more ohmic heating. Specific impulses of about 5,000 N-s/kg have been achieved. This arcjet concept, unlike ion thrusters, is more easily integrated onto a spacecraft already using hydrazine thrusters, but is more difficult for a spacecraft which uses a bipropellant propulsion system such as INTELSAT VII.

Bearing Cage Instability Investigation

The ball bearings used in the spacecraft momentum wheel, which is part of the attitude control system, can suffer from an abnormality wherein the ball separator or cage vibrates violently. This abnormality can dramatically reduce momentum wheel lifetime and cause spacecraft control problems. It is a difficult phenomenon to control. As momentum wheel lifetime requirements have increased—INTELSAT VII demands 16 years—an analytical model of the dynamic performance of the ball bearing is needed so that parametric studies can be conducted, because empirical testing becomes impractical for extended missions. Parametric studies can evaluate the propensity of a ball bearing cage to become unstable using parameters such as temperature, lubricant type and quantity, bearing and cage dimensions, and wear rates.

A computer program capable of dynamically modeling a ball bearing that operates at high speed is ADORE, (**A**dvanced **D**ynamics of **R**olling **E**lements). ADORE is particularly refined for cage dynamics and was modified to model the novel geometric features of the INTELSAT VII momentum wheel bearing cage. The model will be extensively exercised in 1990 under this continuing effort.

Early Failure Detection of TWTs

This project seeks to develop an electronic test that would, before installation on a spacecraft, detect a subtle type of anomaly that may occur in the oxide cathodes of space TWTs. It has been found that a small proportion of cathodes has been failing at three to five years, instead of the theoretically expected 15 years, due to the parts of the oxide layer slowly separating from the supporting metal base. The effect seems to develop after only 5,000 to 10,000 hours of operation, appearing as sensitivity to TWT turn-off. A complicating factor is the lack of a suitable diagnostic test that is applicable after the TWT has been integrated with its power supply to form a traveling wave tube amplifier (TWTA).

Because traditional forms of oxide-cathode screening do not reveal this defect, the electrical fluctuation (noise) characteristics of the TWT cathode current were examined for signatures that would show anomalous behavior. A background of theory and observation reveals that the current noise is affected by physical and chemical effects in the cathode. At low cathode emission, the dominant effect is ballistic "shot" noise arising in the electron flow away from the cathode, but at normal emission, this effect is greatly modified by space-charge and cathode-dependent effects.

For theoretical reasons, it was initially thought that low-frequency noise (10 to 100 Hz) would most likely show correlation with peeling, but after many experiments, it appeared impractical to identify fluctuations due to cathode effects in the presence of noise from power supplies, etc. At higher frequencies (3 to 15 MHz), it has proven possible to identify the shot and transition noise in the cathode current by choosing a part of the frequency spectrum with low local spurious signals and, preferably, a screened environment.

When the filament power is turned on and off again with high voltage applied, the emitted current rises to the operating value and falls back to zero. The accompanying cathode current noise is illustrated in Figure 4: the noise increases with the current (shot noise) as the warming cathode starts to emit, then peaks and starts to fall as smoothing processes operate, and finally stabilizes at the normal value. When the filament power is switched off, the process reverses, although more quickly. The same noise data are shown in Figure 5, plotted against the cathode current. The next step in the program is to further develop this type of test to apply it to suspect TWTs and seek characteristic anomalies.

Expert Systems Applications

As the INTELSAT system expands to include more satellites of varying designs it places a heavier burden on the ground operational system. The goal of this project is to take advantage of advances in knowledge-based systems (expert systems) to operate the system safely and cost effectively. Specifically, the purpose of this project is to determine the best approaches in command, telemetry, and operation to minimize the risk to INTELSAT satellites and their communications services, as well as to lower the cost of satellite operations by using expert systems.

SATCAM, a prototype expert system that assists operators in conducting critical maneuvers, has been developed and tested. It validates proposed command sequences for maneuvers, verifies satellite readiness to execute maneuvers, and monitors satellite performance during maneuvers. The Laboratories' Attitude Control Simulator was used to provide real-time telemetry and

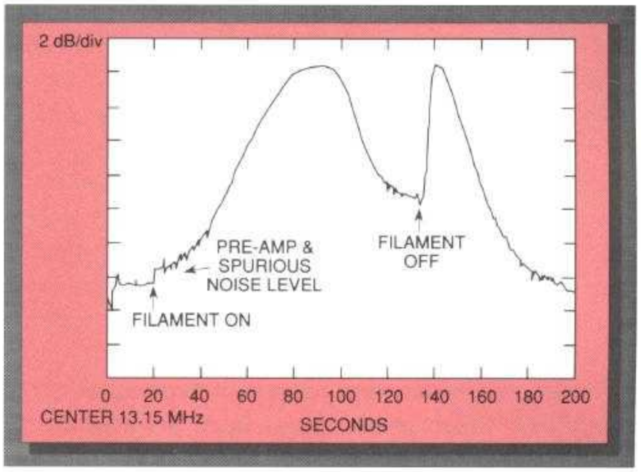


Figure 4. Noise variation as cathode heats up and cools again

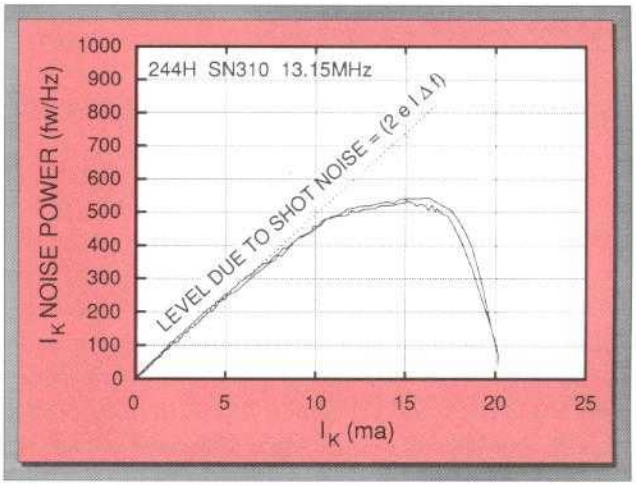


Figure 5. Noise levels of Figure 4 plotted against cathode current

command responses during development and test of SATCAM. In the design of an expert system for a given application, choices are made in representing the human expert's knowledge and reasoning strategy, and the system control structure. A study was conducted to determine if a mapping exists between the type of expert system application and the most appropriate choice in each of the above areas, thus lessening total development costs. Unfortunately, one study conclusion is that no such mapping currently exists. Therefore, the design solution must be selected as part of the overall design process. An architecture for semi-independent but cooperating expert systems has been selected for this project. It is believed that the most appropriate architecture for cooperating systems is one modeled according to how human experts are organized to monitor and control satellite systems and how they use their expertise to reason about flight anomalies.

Power System Life Extension Studies

The possibility of greatly extending the life of INTELSAT spacecraft encouraged the study of durability and performance of Ni-Cd and $Ni\text{-}H_2$ batteries and solar arrays. A battery performance model is used to calculate the voltage and life expectancy of all batteries on board INTELSAT satellites. Efforts continued during 1989 to augment the prediction model to reflect differences in battery cell design. An accelerated cycling test of flight-type $Ni\text{-}H_2$ cells was initiated to determine the mean time to failure to further refine this model. The average cycle life under test conditions was determined to be 5,292 and 7,303 cycles for INTELSAT V and VI, respectively. Destructive physical and chemical analyses of failed cells offered insight into the degradation modes involved and can lead to better designs.

For solar arrays, investigation of solar string failures has been the primary emphasis. A total of 18 solar strings have failed in the INTELSAT V series of satellites, the latest in June 1989 on Spacecraft 512, launched in September 1985. These failures are abrupt and have been encountered at any time, from right after launch to varying lengths of time in orbit. A series of tests performed in COMSAT Laboratories' Solar Wind Simulation Facility observed the response of solar cells to electrons with energies comparable to those experienced during active periods at geosynchronous earth orbit (GEO), before and after vibration and thermal cycling to determine if shorts could be introduced by high voltages. Results obtained thus far indicate that solar string failures are not caused by vibration, thermal cycling, or electrostatic discharge.

Propagation Measurements in Africa

Current propagation prediction models do not provide sufficient accuracy when applied to tropical climates. To address this deficiency, COMSAT initiated in 1986 a propagation measurements campaign in Africa, in collaboration with Cameroon, Kenya, and Nigeria; INTELSAT; the U.S. Telecommunications Training Institute; the National Telecommunications and Information Administration; the U.S. Agency for International Development; and the U.S. Information Agency. The measurements phase of the program, conducted jointly by COMSAT and INTELSAT with the three African nations, continued into 1989. As of midyear, two years of rain rate data and 11.6-GHz radiometric sky-noise data had been collected at Douala, Cameroon; Nairobi, Kenya; and Ile-Ife, Nigeria. Data processing and analysis were then initiated. Activities to date were presented to the International Radio Consultative Committee (CCIR) Study Group 5 in late 1989. Data analysis will continue in 1990, and the results will be reported in 1990.

Ku-Band Up-Link Power Control Development

Up-link power control (ULPC) is a viable technique combatting propagation adversities at Ku-band. Previous measurements at COMSAT Laboratories showed that reliable open-loop control is possible for fade levels of 7 or 8 dB, and operational principles have been under development. During 1989, attention was focused on the requirements for an operational ULPC system deployed in earth stations. Investigations included practical methods of down-link beacon monitoring for a reference signal for use in up-link transmit power control and development of control algorithms for use in unattended operational environments. Developments have been very promising, indicating reliable and effective Ku-band ULPC systems offering much improved performance are feasible. Future efforts will concentrate on development of a prototype ULPC system.

Effects of Scintillation on Satellite Communications

This project, initiated in 1989, addresses the impact of signal scintillations on satellite communications systems. Effects include associated signal fading on communications channels, especially important for small-margin systems using propagation paths at low elevation angles, and fluctuating signal levels, which also create problems for many types of antenna tracking systems. Work initially focused on effects of tropospheric scintillation on antenna tracking and associated operational problems. Information on slant-path scintillation phenomena and antenna tracking methods was compiled, scintillation mechanisms categorized, and evaluation of effects of signal fluctuations on antenna tracking and pointing systems initiated.

Small Earth Station Tracking Verification

North-south stationkeeping of a satellite in orbit expends a significant amount of propellant. Foregoing north-south stationkeeping and using propellant only for attitude control, longitudinal corrections, and de-orbit control saves propellant. However, the satellite orbit inclination increases 0.75° to 0.95° per year. The diurnal motion of the satellite as projected on the earth is a figure "8" whose magnitude depends on the orbit inclination error (see Figure 6). An earth-based antenna system tracking the satellite would eliminate the need for north-south stationkeeping.

A 4.5-m C-band antenna was upgraded with an azimuth and elevation position system, diagrammed in Figure 7, which permitted both program tracking and step tracking. Performance was evaluated using an INTELSAT satellite with large orbital inclination. The program tracking used the POINT program of INTELSAT Earth Station Standard (IESS) 412, by inputting ephermeris data to determine the position of the satellite and the antenna pointing angle. The step tracking used the maximum signal strength of the satellite beacon to position the antenna.

Both program and step tracking were performed over several months with the INTELSAT IV-A F4 inclined-orbit satellite. Test results showed the maximum pointing error of program tracking was 0.4° (see Figure 8), which translates into a maximum power loss of 2 dB

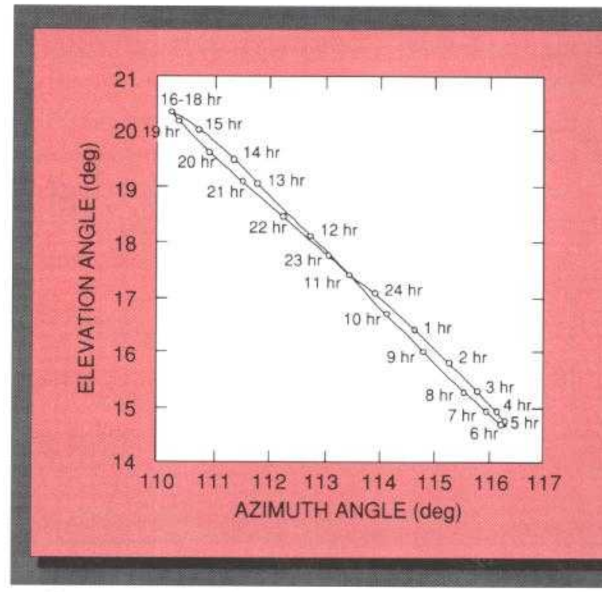


***Figure 6**. Measured pointing angles of INTELSAT IV-A F4 (338.5°E)*

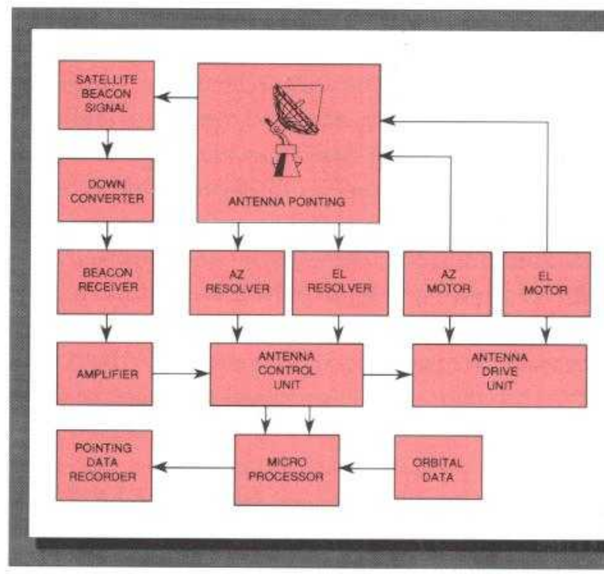


***Figure 7**. Tracking system block diagram*

for the 4.5-m C-band antenna. These data can also be used to modify POINT to improve antenna pointing.

PROPRIETARY DEVELOPMENT

Ni-H_2 Aerospace CPV Battery

During 1988, a project was initiated in STD to develop a prototype test module of the Ni-H_2 CPV aerospace battery to take advantage of achievements

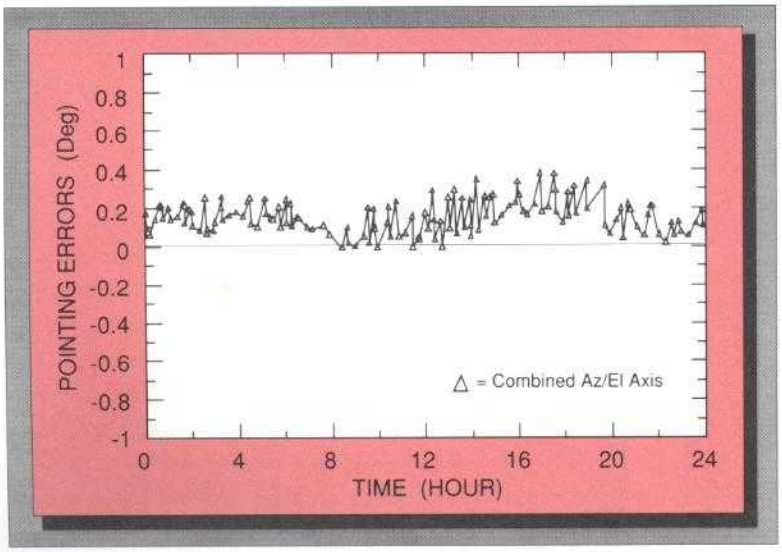


Figure 8. Pointing error of POINT program

derived from a previous development for Sandia National Laboratory of a terrestrial CPV battery. After thermal modeling studies, a cylindrical design that allows for the passive removal of heat was selected. A lightweight Inconel pressure vessel was designed and fabricated using a laser welding technique developed for final vessel closing. Final assembly of a 26-cell 22-Ah aerospace CPV battery in February 1989 was followed by initial characterization. The battery was then placed in an accelerated cycling regime to remove 44 percent of its energy on each discharge before recharging (for 4,000 cycles of very stable voltage performance in 1989). This CPV technology offers significant improvements in energy per unit weight and energy per unit volume.

Efforts to produce a new synthetic separator, a key component in the Ni-H_2 cell, to replace the current asbestos and zirconium-oxide separators have paralleled the CPV development. Phenomena such as rapid hydrogen-oxygen recombination, electrolyte redistribution, and migration of electro-active materials are directly attributable to the nature and type of separator. A new proprietary structure, which appears quite promising, was identified in 1989.

COMSAT SUPPORT

INMARSAT II Support

In support of the COMSAT Systems Division (CSD), STD staff members provided support to INMARSAT on the INMARSAT II Program including experimental evaluation of soldering processes and electroformed waveguide for the L-band transmit antenna, evaluation of mechanical deployment hardware, and support of the protoflight thermal vacuum tests at Toulouse, France. COMSAT personnel were asked to participate in an audit of the INMARSAT II program, and reported to the INMARSAT Council during the July meeting.

INMARSAT III Study

This technical support to the U.S. Signatory during the development of the RFP for the INMARSAT III satellite highlighted the following key areas:

- design of the multiple spot beam antenna, especially the achievable gain and spot-spot isolation
- mechanical layout of the multibeam antenna
- characteristics of solid-state L-band amplifiers and their connections to the antenna
- design and configuration of the payload
- thermal design
- total mass model of the spacecraft and the sensitivity of the L-band e.i.r.p. to changes in spacecraft lift-off mass.

Results from this study showed that, for the larger spacecraft bus assumed for the study, both global and spot beam coverages can be realized with reasonably large capacity. A global e.i.r.p. of 39 dBW and spot e.i.r.p. greater than 45 dBW may be achieved if the L-band amplifier is used efficiently and if partial operation is assumed during satellite eclipses.

CCIR Activities

As part of COMSAT's extensive involvement with standards committees of the International Telecommunication Union, STD supports both national and international participation in the CCIR, particularly CCIR Study Group 5 (SG5), Propagation in Non-Ionized Media. In 1989, STD activities included Chairmanship of Ad Hoc Committee 5F, aspects relative to space telecommunication systems, of U.S. SG5; U.S. representation to an Interim Working Party 5/2 meeting in Tokyo; and provision of a U.S. Delegate to the SG5 Final Meeting in Geneva during September and October.

Battery Support

Representative batteries from the COMSTAR and Satellite Business System (SBS) satellites continue to be life tested in a charge and discharge cycling regime to simulate real-time battery operation in orbit. Results allow modeling of in-orbit performance and lifetime expectancy on-board COMSTAR and SBS satellites, projecting performance and end-of-discharge voltage on the longest eclipse day. COMSTAR batteries have completed 28 eclipse seasons (13.5 years), and SBS batteries 18 seasons (8.5 years). Real-time life test and performance projections are the basis for estimating battery capability when these satellites are operated up to and beyond their contractual lifetime.

Serial Port Failure

STD's technical expertise helped COMSAT Video Enterprises overcome the persistent problem of failures of its central equipment in hotel installations. Lightning and line voltage differentials caused many of these failures. COMSAT Laboratories helped identify an inexpensive method of greatly increasing effectiveness of lightning suppressors previously installed in hotels, and aided in the development and test of a new data converter for hotel installations to avoid these problems.

INTELSAT CONTRACTS

INTELSAT V Momentum Wheel Life Test

The antenna-pointing performance of INTELSAT V/V-A satellites critically depends on the life of the momentum wheels. Long-term effects of speed and temperature cycling on the momentum wheel motor, electronics, and bearings were not fully known prior to the launch of the first INTELSAT V satellites. COMSAT Laboratories is continuing its evaluation of the long-term performance of two engineering model (EM) wheels. The life-test program has accumulated over 18 wheel-years of running time. The control wheel operates at ambient conditions at a nominal 3,500 rpm, while the other 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 wheels have shown normal performance to date. These tests provide an empirical critique of the current momentum wheel generation, and have produced a valuable database for future designs.

INTELSAT VI BAPTA Life Test

The engineering model of the INTELSAT VI bearing and power transfer assembly (BAPTA) which started life tests in January 1989 included the bearing assembly and the electrical contact ring assembly (ECRA). Performance of the bearing assembly and the ECRA is critical in sustaining the life of the satellite because neither assembly has a redundant backup. The BAPTA is being tested in a thermal vacuum environment to simulate in-orbit conditions. Parameters continuously monitored include temperatures at several locations, bearing lubrication film condition, spectral analysis of the torque signal, and ECRA power brush noise. The BAPTA friction torque is computed from the drive motor voltage and the current. The BAPTA has performed normally to date.

In addition, an accelerated life test on an ECRA is being conducted by increasing the speed to 300 rpm from a normal of 30 rpm, and increasing the current to 36 amps from a normal of 18 amps. The equivalent of 11 years of operation in a thermal vacuum environment has been accumulated so far.

INTELSAT V and INTELSAT VI Battery Life Tests

COMSAT Laboratories has extensive experience in real-time life testing of Ni-Cd and Ni-H_2 aerospace batteries, including testing for all INTELSAT series of satellites. In 1989, testing included real-time life tests of batteries for INTELSAT V and VI. This testing is performed within a dedicated facility by STD.

INTELSAT V Ni-Cd and Ni-H_2 batteries have been life tested by simulating electrical and thermal parameters of in-orbit power subsystems. The Ni-Cd battery has been tested for 20 eclipse seasons (9.5 years), and the Ni-H_2 battery for 16 eclipse seasons (7.5 years). These tests provide a baseline for performance data, an early look at the effects of wear, and an opportunity to develop procedures to correct for anomalous performance in-orbit. Two such situations have occurred during the INTELSAT V program: one from a battery short-circuit in a battery structure, and the second from the development of high impedance for some cells of several batteries. In both instances, the life test provided a means to generate methods that could circumvent the problem and continue operation.

The INTELSAT VI Ni-H_2 battery life test, simulating real-time battery operation in orbit, began in 1986 and has continued through 1989. The method of pre-charge was the major variable under investigation. The batteries have completed seven eclipse seasons and have shown excellent electrical performance.

Due to extended preflight storage of INTELSAT VI flight batteries, cells from a flight battery were analyzed for storage-related degradation and found to be sufficiently impaired that remaining flight batteries had to be rebuilt using newly manufactured cells. The degraded battery cells suffered from migration of active species into and across the separators, loss of charge efficiency and stand capability, and storage-related capacity fading. Their replacement will substantially improve energy storage system reliability on future INTELSAT VI spacecraft.

TWTA Enhanced Reliability

Continuing efforts by STD to increase reliable operating lifetimes of TWTAs on spacecraft include completion of the test and analysis phase of a program in which multiple-stress testing was applied to twenty 10-W Ku-band TWTAs built for the INTELSAT VI series of spacecraft. Under a contract with INTELSAT, this program demonstrated the practicality and potential usefulness of this stringent form of screening in TWTA manufacture by highlighting anomalous behavior indicative of defects that might lead to premature failure.

In pairs, the TWTAs were subjected to one-week of thermal cycling during which all variable parameters were systematically varied and all commandable functions exercised, under computer control with frequent samples of operating data recorded for subsequent plotting and analysis. Since the TWTAs were all flight qualified, it was not expected to find many anomalies. However, subsequent data analysis revealed a slow random drifting of gain and helix current as a function of temperature, seen in the data in Figure 9 (originals were plotted in color to enhance the clarity).

In an extension of this contract, life-test equipment racks with control and monitoring instrumentation are being built for delivery to INTELSAT. Evolution of the TWTA performance will be closely watched to establish the relation between life performance and test observations, and to determine if the stressing possibly "overtested" the amplifiers.

Thermal Model Conversion

Thermal computer models obtained from Aerospatiale, Ford, and Hughes for the INTELSAT V and VI spacecraft were converted to the SINDA thermal analyzer program format for use by INTELSAT. Software was written to translate the models to SINDA format and command procedures formulated to execute the models. Models that were incomplete or did not consider the postulated orbital conditions were modified or recreated. More than 150 SINDA models were created to simulate orbital and operational conditions for the INTELSAT V and VI spacecraft.

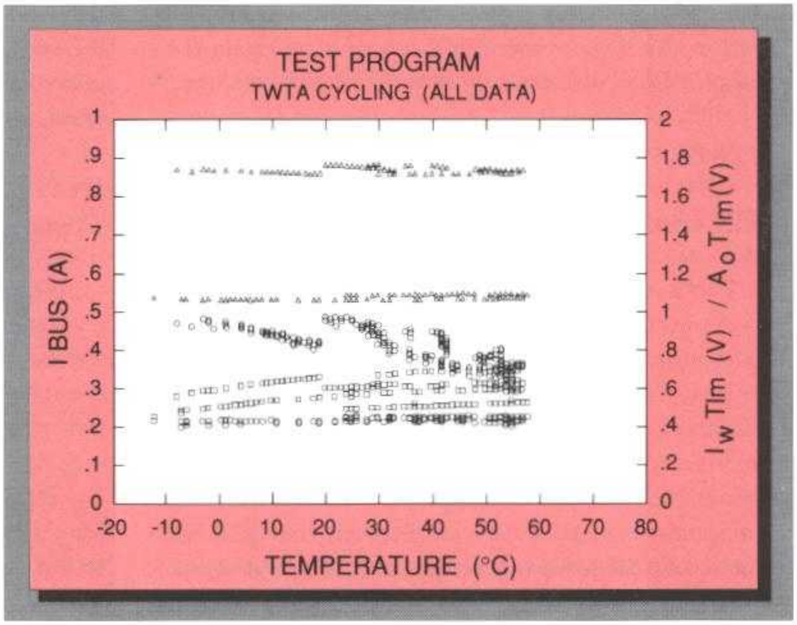


Figure 9. TWTA enhanced reliability

With these models, INTELSAT can now evaluate thermal consequences of proposed operating modes or anomalies. Prior to the launch of the first INTELSAT VI, some of these models were used to predict unit temperatures for some nonstandard operating modes during the preoperational checkouts.

INTELSAT VI Earth Sensor Test

An essential spacecraft instrument is the earth sensor, which identifies the position of the earth with respect to the spacecraft. The earth sensor on the spin-stablized INTELSAT VI has a telescope that focuses a small area of the earth onto a tiny temperature-sensitive resistive flake. The spacecraft rotates once every two seconds, rapidly warming the flake as the leading edge of the earth enters the field of view and cooling when the trailing edge leaves the view. The effect is converted into a voltage pulse output, approximately 80 ms long, from the sensor electronics; the timing of the two edges of the pulse provides the relative position of the earth.

The timing accuracy depends on the noise output of the earth sensor, which is dominated at low frequencies by the flake noise (i.e., spontaneous resistance fluctuations). Fluctuations longer than about 1 second will affect both edges equally and do not affect accuracy, except perhaps during launch. Thus noise spectral components down to about 1 Hz in frequency are the main concern for in-orbit operations.

It was found that some sensors showed erratic noise characteristics after delivery, and at least two were reworked after failing tests during the spacecraft integration period. This led to concerns that erratic behavior might indicate risk to long-term reliability of these sensors, so COMSAT Laboratories tested an evaluation-model sensor. It was maintained in a vacuum chamber with the telescope masked for over 5 months, while electrical noise output was recorded continuously and the spectral distribution recorded daily.

This sensor also gave variable bursts of noise for the first two weeks, but then settled into a regime of random jumps between several different mean levels of noise output over several days. The level never exceeded the noisiest originally seen, and no long-term trend of increasing noise appeared, i.e., no apparent deterioration.

The noise spectrum could be characterized by three regions as illustrated in Figure 10. Of interest is that all shifts in noise were associated with spectral components below about 50 Hz, interpreted as fluctuations of flake resistance in the class of a general, nonthermal type called "1/f noise," so called because of the characteristic rate of falloff with frequency, a common feature of low-frequency fluctuations in general.

Within the project scope, it was not feasible to investigate the mechanisms that gave rise to the variable character of the noise, but it was concluded that no evidence existed of some prospective form of failure for the sensor.

INTELSAT Technical and Engineering Support

During 1989, STD provided engineering support to various INTELSAT projects, including the following:

- INTELSAT VI battery cell tests
- evaluation of the effectiveness of an INTELSAT VI multilayer blanket at high temperature (300°C)
- monitoring and recording of deployments at launch
- analysis of the deployments following a successful launch
- a study of suitability of the CPV battery for INTELSAT VII
- thermal vacuum test support for the INTELSAT VI IRTV test
- support for a variety of design reviews
- development of test procedures for INTELSAT VII heat pipes.

Ku-Band Up-Link Power Control Development

In late 1989, COMSAT Laboratories was awarded a contract to perform sophisticated Ku-band up-link power control (ULPC) development and verification for INTELSAT.

Field Support and Miscellaneous

Under INTELSAT contract, field support and consultation services were provided to radiometric measurement sites in Australia, Cameroon, and Nigeria (the latter two discussed previously). Such services are a vital outgrowth of COMSAT's long involvement in development and deployment of propagation measurements worldwide.

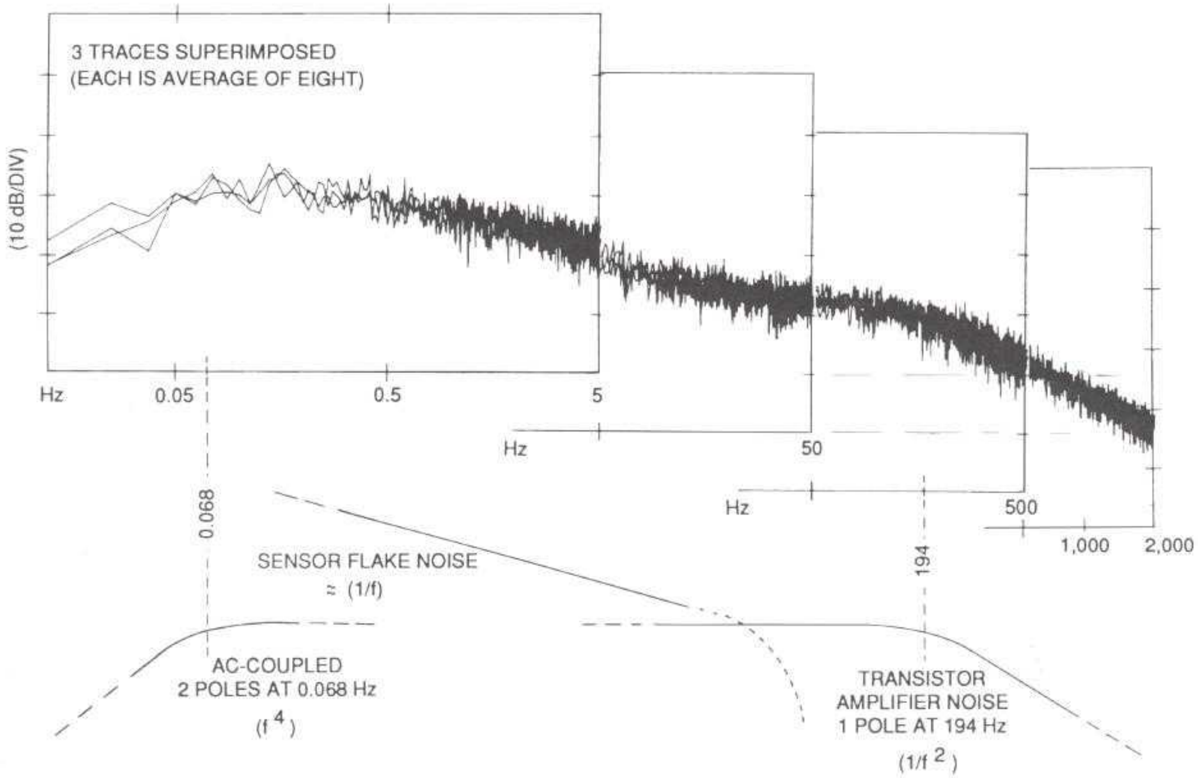


Figure 10. Measured noise spectrum with breakdown into three regions

Further, rainfall parameters in INTELSAT's Propagation Database were updated for new earth stations.

OTHER CONTRACTS

ITALSAT Attitude Control System Flight Simulator

COMSAT contracted to Telespazio to design, build, deliver, and test the ITALSAT Attitude Control System Flight Simulator (IAFSIM). The IAFSIM facility is intended to aid ground controllers and engineers in operating the ITALSAT spacecraft as follows:

- to provide better understanding and evaluation of real-time spacecraft dynamics and attitude control operations and performance
- to facilitate development of operational sequences for transfer orbit and geostationary orbit
- to validate ITALSAT control center software
- to train spacecraft ground controllers
- to support failure analysis.

The simulator combines spacecraft attitude control processing electronics and software models of the rest of the spacecraft. Models include sensors, thrusters, momentum wheels, attitude dynamics, disturbance torques, and orbital mechanics. The simulated attitude control system responds to commands to generate the dynamic telemetry responses. Static models of other spacecraft telemetry are combined with the dynamic telemetry responses to form the complete spacecraft telemetry stream. The IAFSIM can be operated either in standalone mode or, when connected to the control center data network, from the actual control center consoles.

Failure modes can be simulated and triggered during a simulator run. This feature, combined with the fact that all redundant equipment is modeled or included in control processing electronics, allows failures and corrective action to be emulated. Thus, failures can be analyzed, and recovery or workaround procedures can be evaluated and practiced. Work in the past year included system design and documentation, hardware and software design, development, and test. Electrical and mechanical integration of the system was completed, and system checkout started.

Microwave Monolithic Active Filter (NRL)

The purpose of this contract was to design and fabricate a GaAs monolithic active bandpass filter over a passband between 4 and 8 GHz and with a stopband of greater than 20 dB below 3 GHz and above 9 GHz. To achieve this, cascaded, lumped, and distributed inductance-capacitance (LC) elements isolated by a feedback amplifier were used. Isolating the elements with an active circuit permitted a significant reduction in element sensitivity with respect to response variation. A schematic of the 60- x 120-mil circuit is shown in Figure 11, and typical wideband transmission and return loss response in Figure 12. This circuit is a significant improvement in the state of the art and its development is an important milestone in the effort to miniaturize microwave bandpass filters.

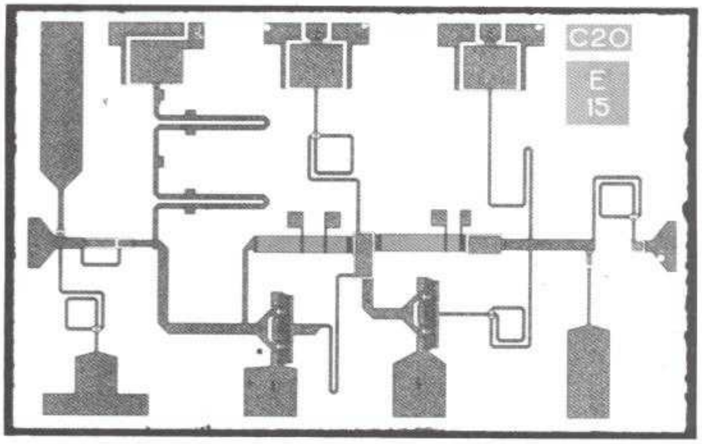


Figure 11. Photograph of 60- x 120-mil active bandpass filter circuit

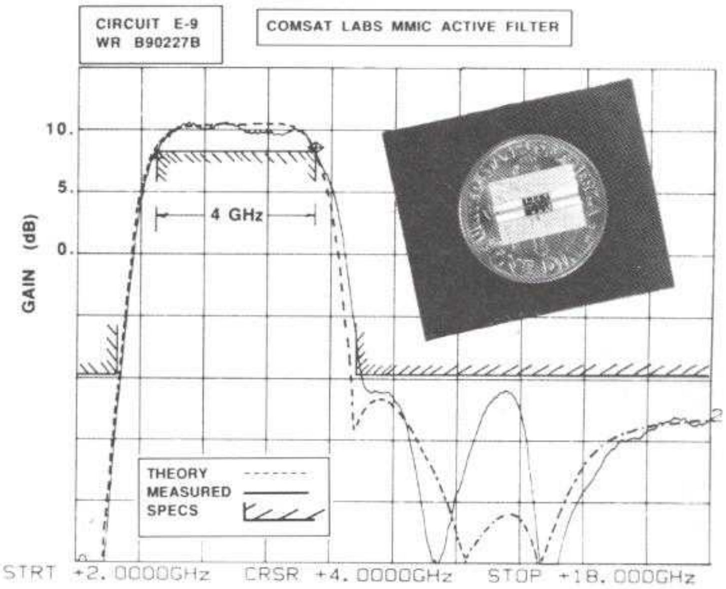


Figure 12. MMIC filter response, measured and theoretical

IOT/ESVA System (EUTELSAT)

In April 1988, COMSAT Laboratories was awarded a contract by EUTELSAT, the European communications satellite consortium, to develop a fully integrated IOT and communication monitoring system. In addition to the traditional IOT measurements, this system will perform a number of new measurements, including those wherein the IOT station verifies the performance of other earth stations using a satellite path. Simultaneous measurements can be performed from several remote locations. The IOT/ESVA system required a substantial software effort and uses the MPCP II, developed at the Laboratories and based on the UNIX operating system. The system was completed in 1989 and shipped to an earth station near Paris, France, where it will be installed in 1990. The system passed a thorough acceptance test before shipment. It has a graphical, user friendly interface based on the X-Window System developed at MIT, which allows operator interaction via pull-down menus, dialog boxes, and a mouse used as a pointing device.

The Communications Technology Division (CTD) conducts research and development and provides technical support for transmission, video, and voice-frequency band processing; systems simulation; and systems analysis and synthesis. Advanced communications systems architectures and technologies are used extensively to achieve the lower equipment costs and improved transmission efficiency necessary to maintain the competitiveness of satellite communications. These advanced architectures and technologies depend, in turn, on widespread application of digital signal processing techniques. During 1989, significant progress was achieved for on-board digital processing, facsimile image compression, unintrusive analysis of digital circuit multiplication equipment performance, preambleless burst demodulation, transmission of two network-quality video channels via one 36-MHz transponder, and development of a 155-Mbit/s modem/codec for broadband integrated services digital network (ISDN) applications. Several ISDN demonstrations via satellite were conducted, as well as a high-definiton TV field trial, which highlighted the potential role of satellite distribution for these important new services. Significant advances were made in characterizing digital link bit error distributions and impairments to analog video signals, and in a comparative analysis of code division multiple access vs frequency division multiple access in a mobile environment. Other activities included study of modulation and coding for mobile gateway earth station applications; development of a 4,800-bit/s voice codec, 16-kbit/s voice codec, and adaptive differential pulse code modulator (ADPCM) speech detector; and studies of a 2-GHz on-board processor.

COMSAT JURISDICTIONAL R&D

Advanced On-Board Digital Processing

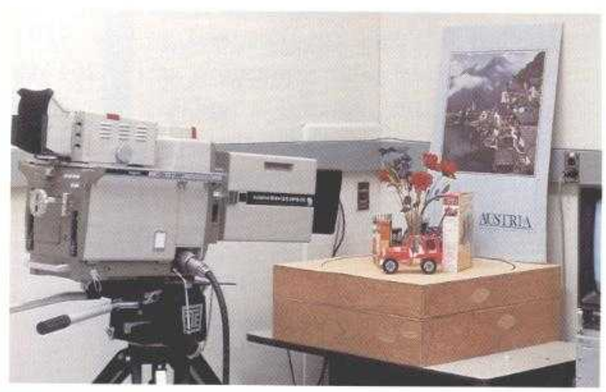
The purpose of this program is to develop a proof-of-concept model of an on-board, programmable, multichannel, demultiplexer/demodulator unit and associated special test equipment to enhance the efficiency of the overall satellite system. When developed, this technology will improve the link signal-to-noise-ratio efficiency and provide improved interconnectivity in a multibeam environment. Potential benefits include using smaller and lower-cost earth stations, maintaining satellite transparency to intermediate data rate (IDR) and INTELSAT Business Service (IBS) users, and continuing the flexibility of frequency plan changes.

The system architecture was defined in 1986, and simulations were conducted to establish detailed design parameters. Hardware design was initiated in 1987, with refinements to the design continuing as new components became available. During 1989, the hardware fabrication was completed, all boards were successfully tested, and integration of most subsystems was started. The final integration will be completed in mid 1990, followed by test and evaluation. The test bed can generate a number of carriers at various bit rates and carrier frequencies to demonstrate the capabilities of the demux/demod.

The demultiplexing function of the on-board processor is performed by a fast Fourier transform (FFT), digital filter, and inverse FFT (IFFT). Both the FFT and IFFT require high-speed, radix-4 butterfly stages followed by a delay/switch/delay (DSD) stage. The shared nature of the IFFT also requires inclusion of radix-2 butterfly stages, as well as a butterfly bypass mode. All these requirements are satisfied with a common butterfly structure, shown with its associated DSD circuitry in Figure 1. A total of eight such boards is required for the FFT/IFFT. The DSD application-specific integrated circuit (ASIC) chips, developed by COMSAT, represent a substantial reduction in hardware size relative to a discrete implementation.

A second-generation on-board processor is now being planned. This system will focus on a reduction of weight, power, and size, as well as an implementation that employs space-qualifiable, radiation-hardened components.

COMMUNICATIONS TECHNOLOGY



Split-screen demo of time-multiplexed video transmission (TMVT) before and after the 3 TV per transponder processing

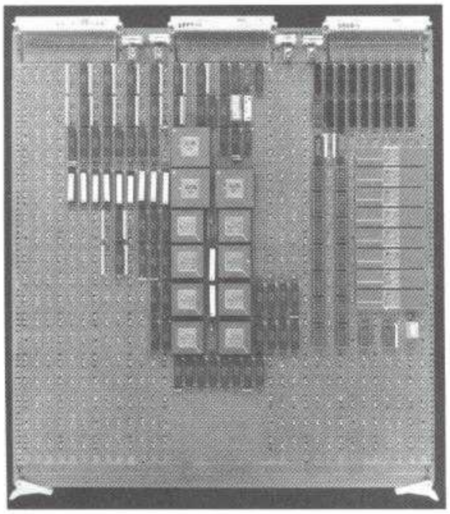


Figure 1. Butterfly/DSD board for FFT and IFFT

155-Mbit/s Modem/Codec Development

To facilitate broadband ISDN operation via satellite and enable fiber optic cable restoration, COMSAT is developing a versatile, high-speed combined modulation and coding system that uses octal phase-shift keyed (8-PSK) modulation combined with a multistage variable rate code. Shown in Figure 2, the system will transmit information at rates of 155.52 or 139.264 Mbit/s through a single 72-MHz transponder. A rate 13/15 code is implemented in the multistage codec when transmitting broadband ISDN information and a rate 7/9 code when supporting cable restoration at 139.264 Mbit/s. After an extensive simulation and study effort completed in 1988, these codes were selected for their superior performance from other viable candidate codes. To support these codes, the 8-PSK modem operates at approximately 180 Mbit/s or 60 Msymbols/s, which results in a spectrum that is well within the available bandwidth of the 72-MHz transponder.

During 1989, the system-level design, which includes the modem, codec, and special test equipment (STE), was mostly completed. Particular attention was given to providing a manufacturable engineering model and incorporating the features necessary for operational deployment. To achieve the reconfigurations necessary to accommodate the dual information rate, extensive programmable logic was employed in the digital codec design. The system design also included a Doppler buffer to enable information transmission over satellites with inclined orbits of up to 3°.

The personal-computer-based STE under development for this system uses a custom circuit to interface between the lower-speed personal computer data and the high-speed data from the unit under test. It will be able to perform a wide variety of system level tests, as well as codec and modem self-tests. The STE will be useful for initial troubleshooting during development, for system calibration, and for future fault isolation.

The successful completion of this system will provide an appropriate interface to broadband ISDN terrestrial optical fiber systems and will help to ensure that satellites are included in future broadband ISDN networks. The 140-Mbit/s information transmission capability will enable COMSAT to offer fiber cable restoration services.

DCME Performance Analyzer

COMSAT has developed a performance analyzer for use on digital circuit multiplication equipment (DCME) built in accordance with CCITT, ANSI, INTELSAT, and EUTELSAT recommendations or specifications. It unintrusively monitors key DCME performance parameters such as gain, average bits/sample, bearer channel usage, and traffic load characteristics to

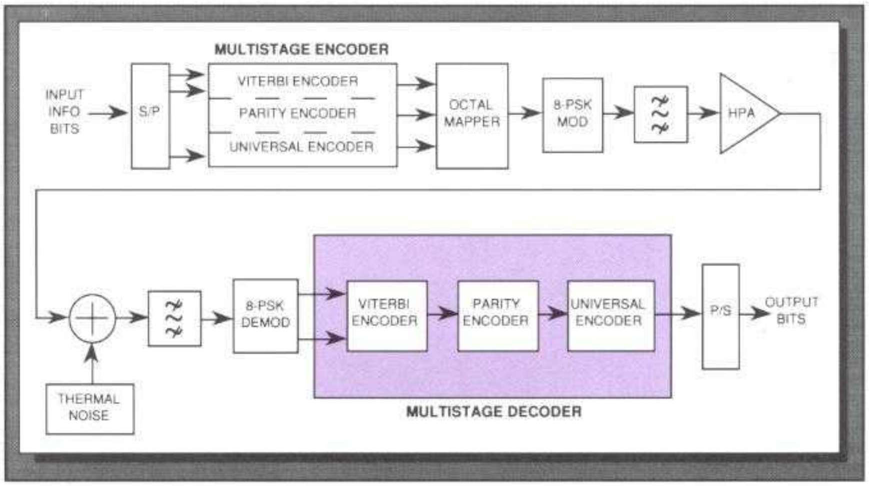


Figure 2. Versatile high-speed combined modulation and coding system

provide valuable information to traffic planners on bearer channel usage and traffic load characteristics and to enable service carriers to optimize derived circuit yield while preserving the quality of service with different traffic mixes.

The performance analyzer is a personal-computer-driven monitoring system programmed by the operator to intercept and analyze the DCME control channel (CC). It can display the DCME gain and the average bits/sample as a function of time and record bearer channel usage, traffic load characteristics, and system alarms in real time.

As shown in Figure 3, the DCME performance analyzer consists of two functional blocks: a bearer storage unit (BSU) and a personal computer control unit. The BSU interfaces with the DCME at its standard 2.048-Mbit/s bearer port in a bridging mode and allows the operator real-time access to the assignment messages that are carried in the DCME CC. The BSU can be programmed to trigger on specific assignment messages and store them for subsequent analysis or to display the DCME performance in real time.

The DCME performance analyzer has been developed to monitor INTELSAT IESS-501 type DCMEs. However, other DCME systems can be monitored by modifying the BSU to accept the specific DCME frame format to be tested and making slight alterations in the performance analyzer software.

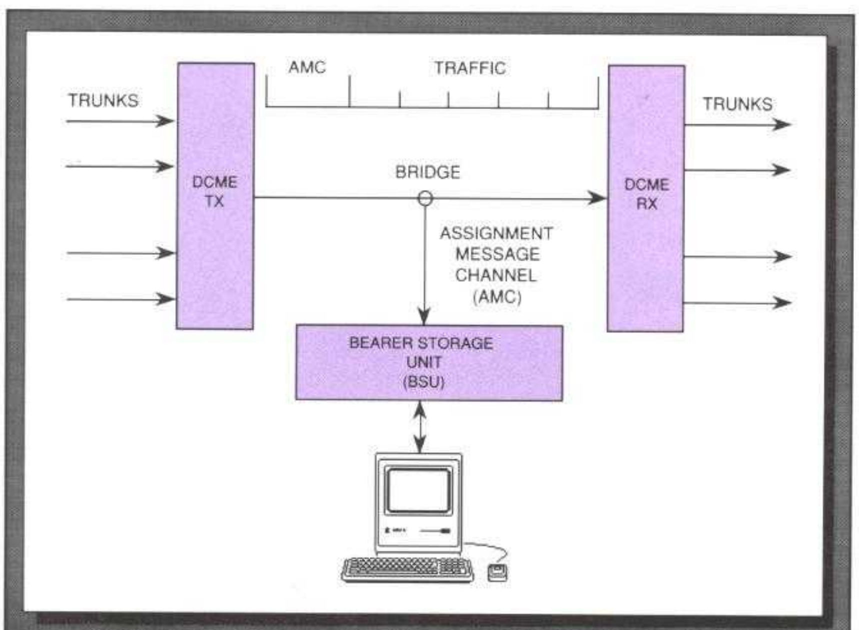


Figure 3. DCME performance analyzer

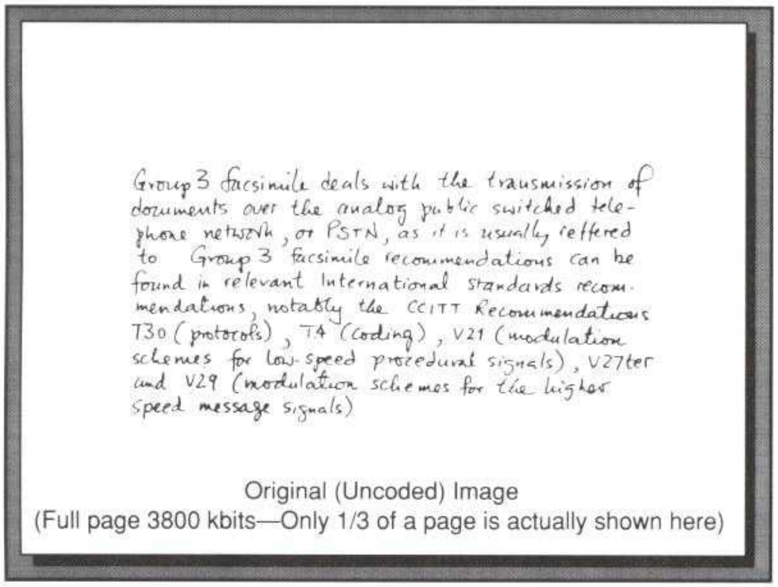
Standard-C Facsimile

The emerging use of low-rate digital voice coding in mobile satellite communications has emphasized the need for telematic service transparency over the same circuits. To accelerate facsimile transmission over a low-data-rate channel such as INMARSAT Standard-C, a project was initiated in 1989 to compress the total amount of bits needed to send Group 3 facsimile.

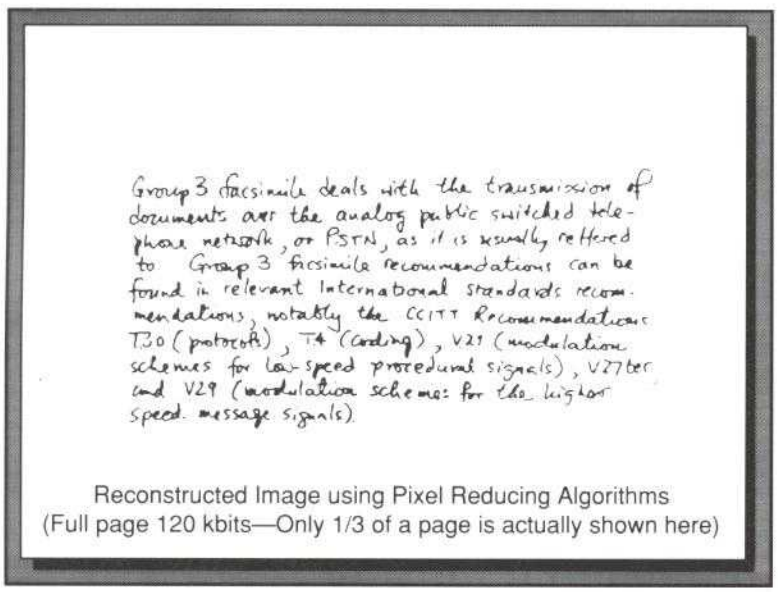
The techniques developed focus on the implementation of a low-cost interface unit (IFU) suitable for facsimile communication between low-power mobile earth stations and fixed earth stations for point-to-point or point-to-multipoint transmissions. This interface may (but is not required to) be colocated with the transmitting facsimile terminal equipment and function in conjunction with standard Group 3 facsimile terminals. The actual techniques used are based on the interception and store-and-forwarding of facsimile messages; however, they can also be used to operate in real time over user data channels at communication rates ranging from 800 to 2,400 bit/s.

The algorithms developed can achieve a compression of approximately 35 to 1 relative to the original (uncoded) image and were designed to emphasize the intelligibility retention of handwritten and line drawing (e.g., map) images. These algorithms offer high reconstruction intelligibility with slight degradation relative to standard resolution facsimile, which offers compression ratios on the order of 12 to 1. Figure 4 compares a typical compressed facsimile to the original.

The algorithms have been implemented and tested in a bit-error environment using a facsimile system test bed specifically designed for this purpose. Because mobile applications are primarily concerned with the intelligibility retention of transmitted text, a new subjective test, called the Text Intelligibility Diagnostic Test, has also been designed to quantify the



Original (Uncoded) Image
(Full page 3800 kbits—Only 1/3 of a page is actually shown here)



Reconstructed Image using Pixel Reducing Algorithms
(Full page 120 kbits—Only 1/3 of a page is actually shown here)

Figure 4. *Typical compressed facsimile compared to the original handwritten message*

subjective performance of the techniques developed. Further facsimile compression will be performed in the future.

16-kbit/s Codec Development

During 1988, a 16-kbit/s codec was implemented based on a novel technique called adaptive predictive coding with transform domain quantization (APC-TQ). The performance of this codec met the basic requirements of delivering high-quality speech while providing satisfactory performance on other voiceband signals. During 1989, development and testing of this codec continued. Codec performance for CCITT 5 Interregister Signaling waveforms, tested in the presence of channel impairments, was found satisfactory. To test the performance of the codec in the presence of channel bit error impairments, its implementation was modified so that the encoder and decoder were fully separated by a serial transmission path operating at 16 kbit/s. Bit and frame synchronization methods were implemented, as were two codec units with separate encoders and decoders to facilitate participation in standardization activities. Codec performance on speech signals was studied in the presence of random bit errors. Results indicated that the codec is robust to channel errors, with satisfactory speech quality up to a bit error rate (BER) of 10^{-5} and acceptable speech quality up to a BER of 10^{-4}.

Some variations of the APC-TQ coding technique were studied to further optimize its performance, so that the signal sampling rate could be increased from 6.4 to 8 ksample/s, while maintaining the bit rate at 16 kbit/s to permit comparisons with other telephony voice codecs, such as 64-kbit/s pulse code modulator (PCM) and 32-kbit/s ADPCM. The greatest improvement was achieved by a scheme using vector quantization of the optimum step sizes for transform coefficient quantization.

Preliminary tests were also conducted to assess the performance of the APC-TQ technique for music signals. The results are very promising, indicating that with some reoptimization, the APC-TQ technique can lead to high-quality audio coding at low rates.

Work will continue in the area of APC-TQ optimization for music distribution via satellite.

Mobile and Portable Terminal Technology

This project, initiated in 1987, has as its goal the development of a 4.8-kbit/s communications-quality voice coder and an associated modem and forward error correction (FEC) codec unit for transmitting the 4.8-kbit/s signal over a 5-kHz multipath fading channel.

Previously developed algorithms were revised to cope with the severe time-delay constraints imposed on the vocoder. Effective error protection schemes for robust operation under fading mobile channels were also developed. A digital signal processor (DSP)-based implementation of the vocoder will be completed in early 1990.

The proof-of-concept vocoder hardware is based on the advanced floating point Texas Instruments TMS320C30 DSP. The encoder, shown in Figure 5, uses a single TMS320C30 processor with 32K x 32 memory capacity. The decoder uses one TMS320C30 processor with 48K x 32 local memory and 8K x 32 expansion memory.

For the modem/FEC codec, computer simulations were conducted to assess the performance of the proposed differentially encoded, trellis coded, 8-PSK with partially coherent detection versus the coherently detected offset quadrature phase shift keying (QPSK). As shown in Figure 6, these simulations indicated that phase coherent detection is sensitive to both channel fading and channel-induced phase noise and that the partially coherent scheme proposed by COMSAT is preferable.

A DSP-based implementation of COMSAT's modem/FEC codec was initiated. A software emulation of the hardware, including energy detection, unique word detection, filtering, frequency acquisition and tracking, symbol timing acquisition and tracking, and partially coherent detection and decoding, was performed. In addition, a frequency tracking algorithm using a discrete Fourier transform branch metric correlation in a trellis was designed.

In 1990, the DSP implementation of the modem/FEC codec will be completed and will be integrated with the 4.8-kbit/s vocoder.

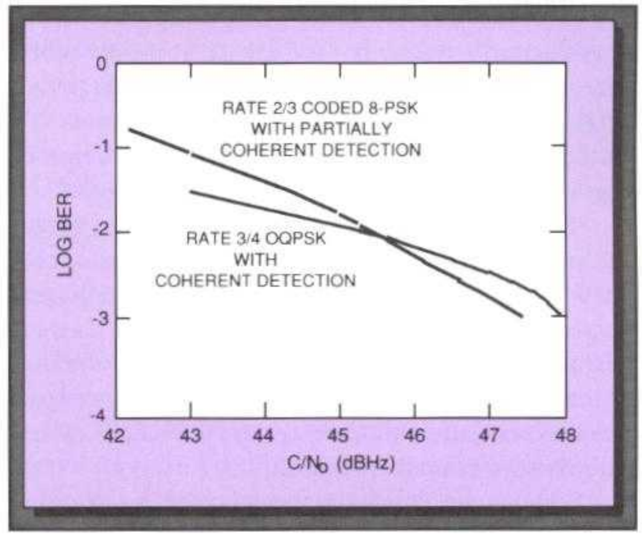


Figure 6. *Performance comparison for land mobile fading channel with a Rice factor of 10 dB, using INMARSAT transmission format*

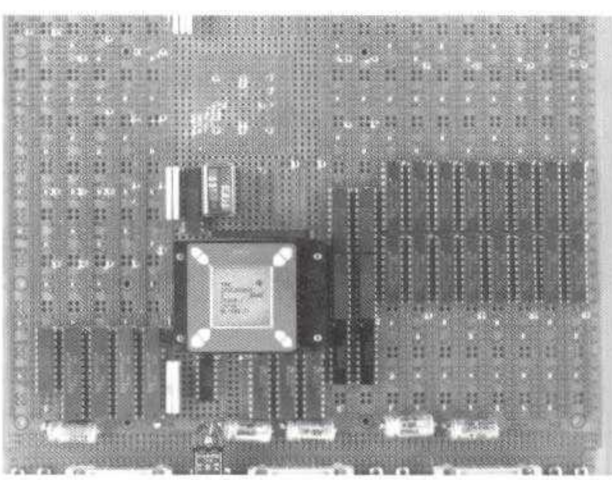


Figure 5. *The 4.8 kbit/s communications-quality voice encoder board*

Transmission Impairment Modeling

The purpose of this project is to model the impairments experienced by digital and/or analog carriers over a satellite transmission system.

To characterize the bit error statistics of the IDR or IBS system, a novel bit error data collection technique has been developed. This technique uses a bit error test set, a personal computer, and hardware developed at COMSAT Laboratories to encode the entire received bit error pattern from a digital carrier by a run-length coder over a certain period of time. This encoded, received bit-error pattern is stored in a file on the personal computer, where it can be retrieved, decoded, and completely reconstructed for statistical evaluation of bit error occurrence or for laboratory simulation of equipment performance.

A statistical evaluation software package has also been developed to evaluate files that were stored using the data collection hardware. This package decodes the previously stored data files and calculates the probability density for such parameters as error-free interval, burst error length, and instantaneous bit error rate. The output from this analysis is then used to generate histograms, an example of which is shown in Figure 7.

To date, this bit-error data collection and analysis package has been used to compile bit-error statistics for a 2.048-Mbit/s digital carrier that operates in a thermal-noise-limited channel. The results of this hardware evaluation agree very well with those of a computer simulation of this same case. Work is continuing to expand the hardware measurement results to include cases of interference-limited channels.

With regard to analog carriers, FM transmissions of composite video signal formats (NTSC, PAL, and SECAM) via satellite to small earth stations are becoming increasingly important. In these situations, overdeviation of the TV/FM carrier (i.e., bandwidth-limited transmission) is necessary to achieve acceptable TV signal-to-noise ratios.

During 1989, software packages based on analytical impairment modeling techniques were developed to quantify linear and nonlinear distortions associated with the FM transmission of NTSC test waveforms through bandwidth-limited channels. Types of distortion include chroma-to-luma intermodulation, chroma gain and phase nonlinearities, differential gain and phase, and steady-state gain/frequency characteristics. The analysis also included evaluation of threshold carrier-to-noise ratios associated with the onset of impulses in the received TV picture when a 75-percent saturated color bar signal is transmitted. All results predicted by software were validated by hardware measurements.

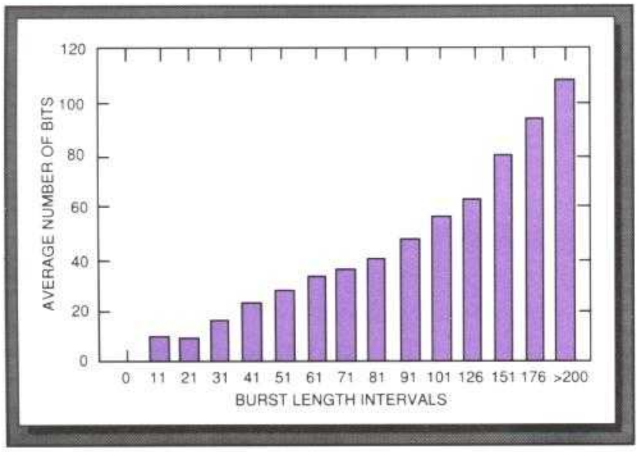


Figure 7. Average number of error bits for the burst length interval

Video Transmission Processing

For cost-effective transmission of digital high-definition television (HDTV) to a small earth station, the information transmitted must be reduced or compressed. A conditional replenishment technique can be used to help compress the data. To prove this concept, a simple conditional replenishment technique has been used on the NTSC signal. In this experiment, each frame of active luminance signal is divided into 4 x 4 blocks. Each pixel is compared with the same pixel of the previous frame. If the absolute difference exceeds a threshold, T, the pixel is considered to be moving. If the number of pixels within the block considered to be moving exceeds a second threshold, N, then the block must be updated. Threshold T eliminates any false detection caused by the camera and other noise in the signal, and threshold N is based on the fact that changes in a small number of pixels within a block are often ignored by human perception. By properly adjusting the two thresholds, very good quality motion pictures can be transmitted by sending only a small fraction of the total number of blocks within the frame at one time. COMSAT's computer simulation shows that the fraction of blocks that need to be updated generally resembles a normal distribution as a function of the two thresholds, T and N.

Figure 8 is a histogram plot for a particular 12-frame sequence. Since each set of T and N values has an associated picture quality degradation and data compression efficiency, a good conditional replenishment scheme can be designed by optimizing T and N values for a given data compression efficiency. Computer simulation results showed that this scheme can achieve compression by a factor of 4:1 to 5:1 without significantly degrading the perceptible picture quality.

This general technique can be further expanded to accommodate limited motion compensation. In addition to a comparison with the same block in the previous frame, blocks shifted by one pixel (or two), in four or eight directions, may also be computed to find the best match. (The number of directions and the amount of shift will be limited by computational complexity.) The difference between the two frames with the best match is tested by the two thresholds, and the block is updated if it still tests as moving. Otherwise, a motion vector or a no-change indication is transmitted. This expanded technique can further reduce the number of blocks that must be updated for a given threshold T or N, or can improve the quality for a given compression factor by reducing T and N. A histogram of the same video sequence using eight motion vectors is shown in Figure 9.

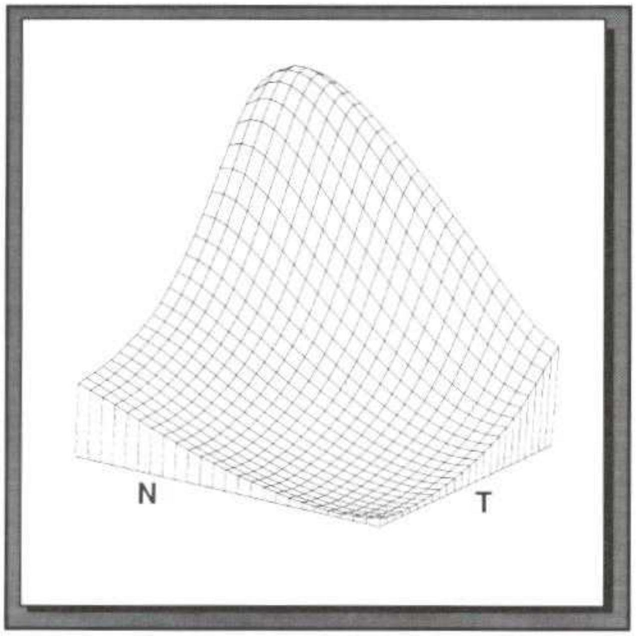


Figure 8. Histogram plot for a 12-frame sequence of blocks

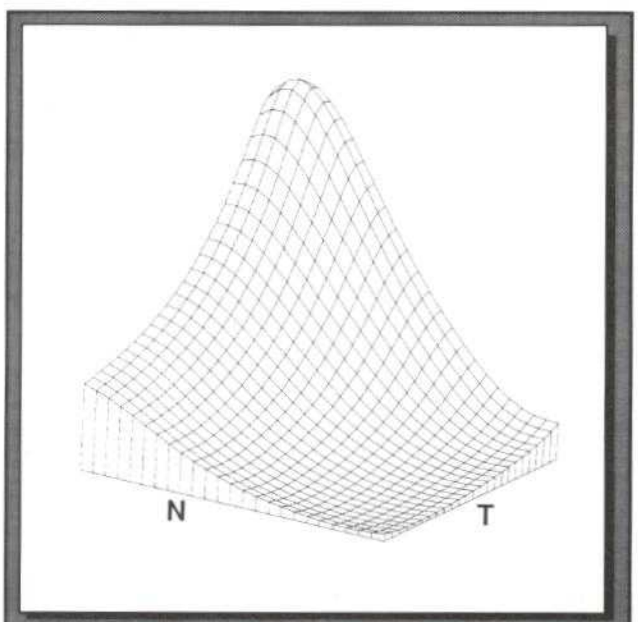


Figure 9. Histogram of the same sequence of blocks shown in Figure 8 using eight motion vectors

Combining the conditional replenishment/motion compensation scheme described above with a good spatial coding algorithm is expected to yield a total data compression efficiency of 16:1 or better for an HDTV signal.

COMSAT NONJURISDICTIONAL DEVELOPMENT

Network Quality Two-Video TV

Previous phases of the time-multiplexed analog television (TMATV) development have been reported in the 1985, 1987, and 1988 Annual Reports . Following the successful completion of a prototype capable of transmitting three broadcast-quality television signals within a single 36-MHz transponder, COMSAT Laboratories has licensed the technology to Ikegami, a world-class professional video equipment manufacturer. A similar prototype was built and demonstrated at the International Broadcast Equipment Exhibit (INTER-BEE) in Tokyo, Japan, in late 1988.

Within the continental United States, major television networks have been distributing one television signal per satellite transponder to achieve a signal quality limited only by their studio equipment. The quality objectives demanded by major networks are difficult to meet with the frequency-division multiplexing technique of conventional half-transponder television or the time-division multiplexing technique of three television signals per transponder. A new video multiplexer that multiplexes two network-quality television signals in a single satellite transponder was developed to improve the space segment capacity utilization by 100 percent for domestic network television distribution.

The new video multiplexer was designed with maximum care to minimize signal distortion or artifacts, which was accomplished by using an improved algorithm that emphasized precision for signal input quantization and arithmetic and used longer and sharper digital filters. The improved algorithm is actually simpler to implement than the original one, as less processing removes less information and introduces less distortion. This new video multiplexer also uses the state-of-the-art programmable gate-array and high-speed first-in-first-out buffer technologies to significantly reduce the parts count of the digital video processor at both the transmit and receive sides. The new video multiplexer carries up to four channels of high-quality digital audio in the horizontal blanking interval instead of the vertical blanking interval (VBI), thus leaving the VBI intact for other purposes.

After the prototype was completed, a loopback test was performed via an inclined-orbit Satellite Business Systems (SBS) satellite. The signal was transmitted from a transportable earth station outside the Laboratories with a 5-m antenna. The video quality received from the transportable earth station was measured objectively and observed subjectively as successfully meeting the network requirements. The same signal received by a 2.8-m antenna with open loop tracking also exhibited excellent video quality. The received signal-to-noise ratio using the 5-m antenna and the transmission parameters are summarized in Table 1. Those of a full transponder television are also included for comparison.

***Table 1**. Comparison of received weighted signal-to-noise ratio (S/N_w) performance between the two-for-one video multiplexer and a full transponder TV*

	2-for-1 Video Mux	Full Transponder TV
C/N_o (dBHz)	98.0	98.0
IFBW (MHz)	36.0	30.0
C/N (dB)	22.4	23.2
f_m (MHz)	7.4	4.2
Δf_{pp} (MHz)	33.6*	21.6
(S/N_w) (dB)	56.0	58.2

*4 dB over Carson's rule.

Advanced Signal Processing

The purpose of this project is to capitalize on current advances in digital processing architectures and hardware technologies and emphasize parallel and pipeline processing and fault tolerant operation. Research in these areas will lead to faster, cheaper, and more reliable processing of speech, video, and data signals for ground terminals and satellite on-board processors.

Discrete linear systems are best characterized in terms of matrices, and several important matrix operations lend themselves to parallelism in their execution. In particular, the decomposition of a matrix into the product of an orthonormal and triangular matrix is an attractive method for providing an accurate and stable solution to the linear least squares problem and for solving eigenvalue and singular value problems. In 1989, methods to reduce the computational complexity of the parallel execution of this decomposition were examined, and several fault tolerant schemes for detecting and correcting transient or permanent errors were investigated. Computer programs to emulate and test such matrix processors were also developed. Future efforts will use the outcome of this study for image and video processing applications.

Self-diagnosis and self-healing for pipeline FFT processors were also investigated. A scheme that permits locating and circumventing a faulty module in the pipeline without disturbing its continuous-mode operation was developed. This scheme is highly efficient because it relies on the addition of a single module to the pipeline. Future efforts will incorporate this fault-tolerant FFT pipeline into the digital multicarrier demultiplexer/demodulator currently under development for satellite on-board processing.

Mobile Gateway Earth Station Technology

This project was initiated in 1988 to develop earth station hardware technology for mobile satellite communications networks that used a subset of the INMARSAT Standard-C specifications for design parameters. To adapt the INMARSAT standard, a 600/1,200-bit/s binary PSK (BPSK) burst packet with no preamble was required for the signaling channel, and a quasi-continuous 600/1,200-bit/s BPSK burst packet with a short preamble was required for the message channel. In 1988, simulation programs to validate the digital demodulator algorithm were developed and the IF sections were designed and constructed.

The project goals were refocused in 1989 to develop complex digital technology utilizing full-specification Standard-C demodulators, which would be installed at selected U.S. coast earth stations (CESs). This technology will be used to support new maritime and mobile communication services.

Major progress was achieved in all areas of this project in 1989. The simulation programs were first expanded to include channel modeling of Doppler and multipath impairments. A sliding FFT-based technique was devised and successfully simulated that provided reliable coarse carrier frequency estimation in the presence of noise, Doppler, and multipath fading, with or without an acquisition preamble in the burst packet.

Innovative Doppler estimation and tracking routines were devised and verified via simulation. Block interpolations were used to smooth out the Doppler corrections, and an efficient phase estimation algorithm was conceived that was relatively immune to cycle slips at low operating E_s/N_o values. Symbol timing routines were developed that estimated timing over blocks of samples for the duration of the packet, and symbol timing corrections were performed in the software by sample adjustments instead of external clock adjustments. Noncoherent and coherent unique word (UW) correlations were used for slot synchronization and phase ambiguity corrections, respectively.

The prototype demodulator hardware design and construction were completed following the verification of all critical demodulator algorithms. The demodulator design used the Texas Instruments TMS320C25 advanced fixed-point DSP. All demodulator algorithms were implemented digitally in DSP assembly language. Figure 10 is a photograph of the prototype demodulator board.

The preambleless signaling demodulator was tested with a special personal-computer-based test setup over the following range of parameters:

- frequency offsets ranging between ± 1,450 Hz
- sinusoidal Doppler shifts of 65 Hz/s with a range of ± 50 Hz
- E_s/N_o values of 2 dB and 6 dB, as well as without noise
- symbol timing offsets from ± 180° in 45° steps
- slot timing uncertainty of ± 27 symbols.

Without noise, the demodulator successfully recovered the data with no errors under all the above conditions. With noise, the demodulator successfully recovered data with few errors. At the specified operating E_s/N_o of 4.7 dB, an average of 2.7 raw errors per packet (of length 316 symbols) were detected. The error statistics indicate that no packet errors will be experienced after Viterbi decoding (to be performed by the MC68000 host processor). The successful completion and test of a full-specification Standard-C preambleless demodulator represents a significant achievement for the Laboratories and a major milestone in the project.

Future work for 1990 includes testing the message channel demodulator, converting the prototype demodulator hardware designs to production printed circuit board versions, interfacing them to the IF unit and the MC68000 host processor, performing the system integration with the CES control processor, and finally, performing field installation and tests at the CES sites.

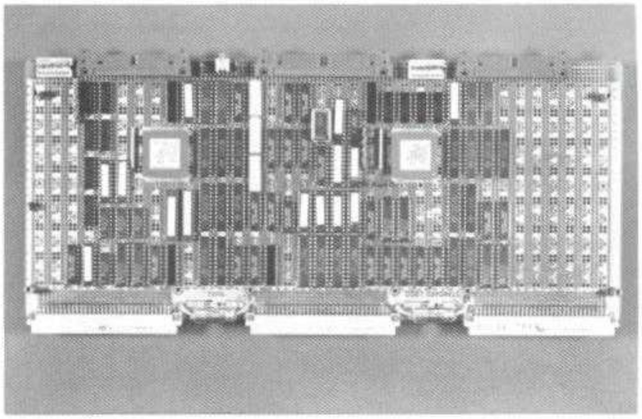


Figure 10. *Prototype demodulator board*

Spread Spectrum System Simulation and Design

Extensions and improvements were made to the COMSAT Laboratories' SPREAD program, which performs time-domain simulation of direct-sequence pseudonoise (DSPN) and frequency-hopping (FH) waveforms. Coding techniques were identified and simulated for two classes of spread spectrum waveforms: M-ary frequency shift keying (FSK) for low-data-rate applications and phase-continuous FSK for high-data-rate transmission. For M-ary FSK, convolutional codes for nonbinary alphabets have been simulated for the high-rate application. Investigations into signal analysis have included the implementation of cyclic spectral analysis. Figure 11 shows typical results for BPSK, QPSK, staggered (or offset) QPSK, and 8-ary phase shift keying where all signals have the same symbol rate, R_s. This technique can potentially reveal signal features and allow discrimination between signals, which would not be possible in the power spectrum domain.

COMSAT SUPPORT

Standards Activities

Standards activities at COMSAT support the development of national and international standards and recommendations compatible with satellite

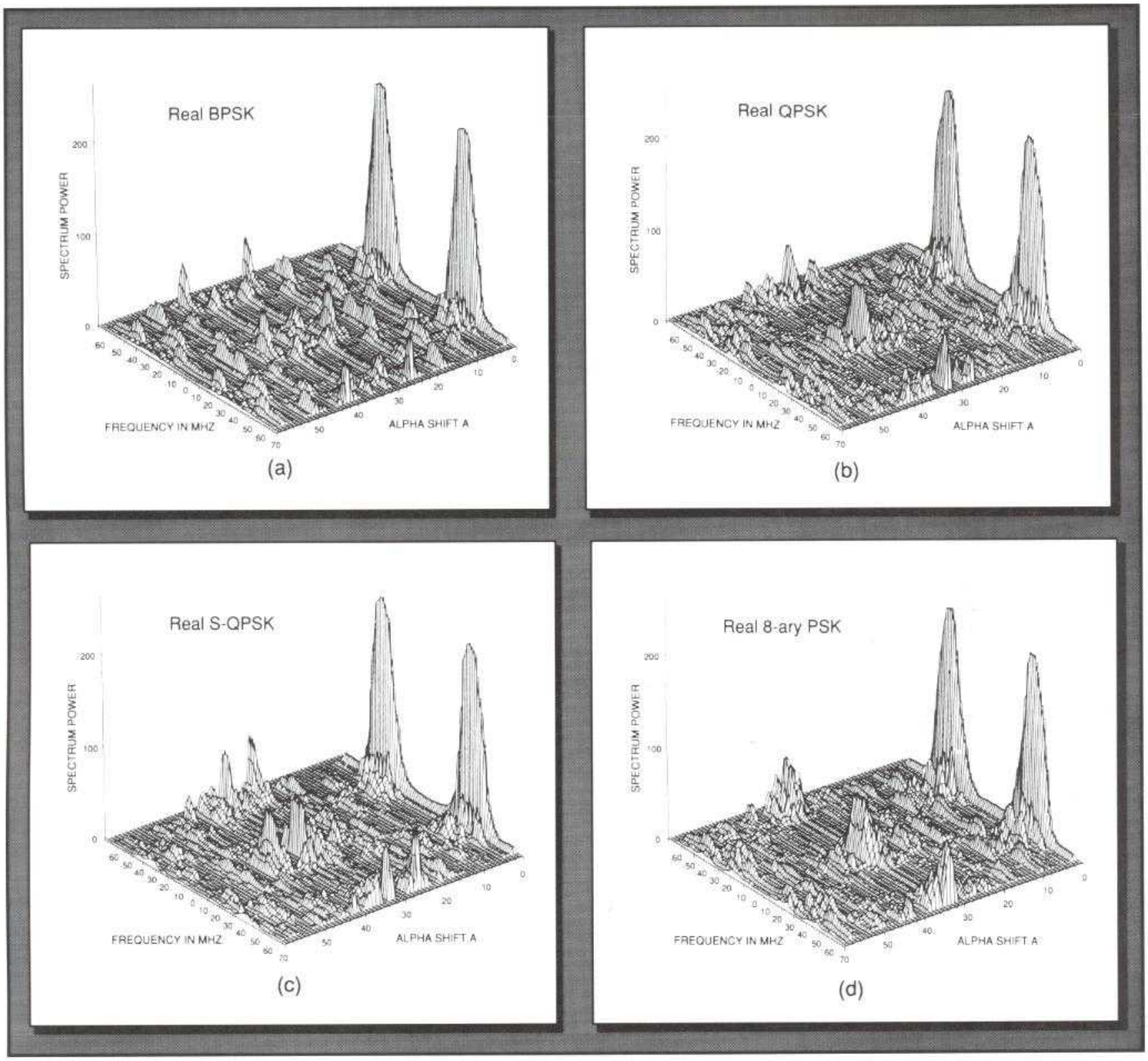


***Figure* 11.** *Cyclic spectra for complex data with signals at* $2 \times R_s$

communications systems operation. CTD activities focus primarily on four study groups of the CCITT: SG VIII, Telematic Services; SG XII, Quality; SG XV, Transmission Systems; and SG XVIII, Networking. The CCITT works on a 4-year cycle, and 1989 was the first year of the new study period.

COMSAT was instrumental in leading the compromise to accept the frame structure defined in the INTELSAT DCME system specification and optional use of 16-kbit/s encoding for overload control. This breakthrough has permitted the working group to focus on developing a recommendation of sufficient detail to permit compatible operation of units designed by different companies.

COMSAT is also leading the group that will select a 16-kbit/s encoding algorithm. In addition, COMSAT is performing the host test-laboratory function and conducting the processing of speech samples that will be used in the extensive subjective evaluations planned for 1990.

With the rapid growth of facsimile traffic, some latent problems are becoming visible, and COMSAT is leading the effort in SG VIII to find solutions to these recently unmasked problems.

In the U.S. National Standards Committee T1, COMSAT played a significant role in the development of a DCME interface standard. This standard, modeled after the INTELSAT IESS-501 DCME equipment specification, was tailored to meet the special requirements of the North American telephone network.

Since both the T1 and the CCITT DCME standards have been developed around the INTELSAT IESS-501 equipment specification, the users and manufacturers of DCME will begin enjoying the benefits of a standard that has worldwide acceptance. The use of DCME built in accordance with the T1, CCITT, or INTELSAT standards will not only simplify the task of networking DCME, but will also reduce the costs associated with the installation, operation, and maintenance of unique equipment.

CDMA vs FDMA

Code division multiple access (CDMA) and frequency division multiple access (FDMA) were compared within the context of current and future INMARSAT satellites. Parameters considered included the e.i.r.p. and antenna coverage of the first- and second-generation INMARSAT satellites, planned increases in e.i.r.p., provision of spot beam coverage, and frequency channelization for the third generation. Both forward and return link performance were studied, including the effects of co-channel interference from adjacent satellites, signal level imbalances, and mixtures of remote station G/T and data rates. Typical results are shown in Figure 12 for the relative bandwidth efficiency of the two techniques.

In the current and anticipated INMARSAT environment, FDMA gives from two to four times the capacity of CDMA for forward links into INMARSAT-A (G/T = -4 dB/K) terminals. For smaller INMARSAT-C terminals (G/T = -24 dB/K), the two access techniques give approximately the same performance, so a choice between the two for these low-data-rate applications would be based on other criteria, such as cost, flexibility, and compatibility.

Similar trends in relative performance have been noted for the return links, provided that up-link operating conditions are selected to allow for expected power-level imbalances.

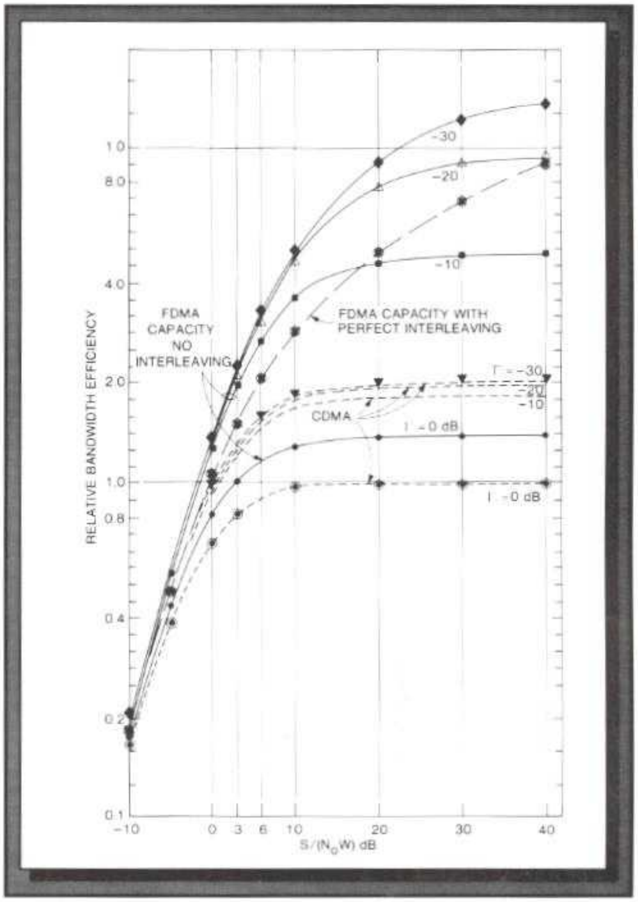


Figure 12. Relative bandwidth efficiency of FDMA and CDMA vs $S/(N_0W)$

Commercial Low-Cost Earth Station Services

In 1989, a study of system architectures that provide low-cost commercial service in the INTELSAT system was conducted in support of the COMSAT World Systems Division. Low cost was emphasized, thus requiring very small, unsophisticated earth terminals. These terminals must operate through INTELSAT satellites, i.e., IS V, VI, or VII, which are not particularly suited to small remote terminal operation. As a result, star network operation is assumed (i.e., operation through a central hub station), and relatively low-data-rate operation is likely.

Tradeoff analyses were conducted that illustrated the cost tradeoffs from variations in data rate, terminal size, and hub station size for various INTELSAT satellites. CTD, in cooperation with the Network Technology Division (NTD), designed small earth station networks intended for specific applications as another part of this project.

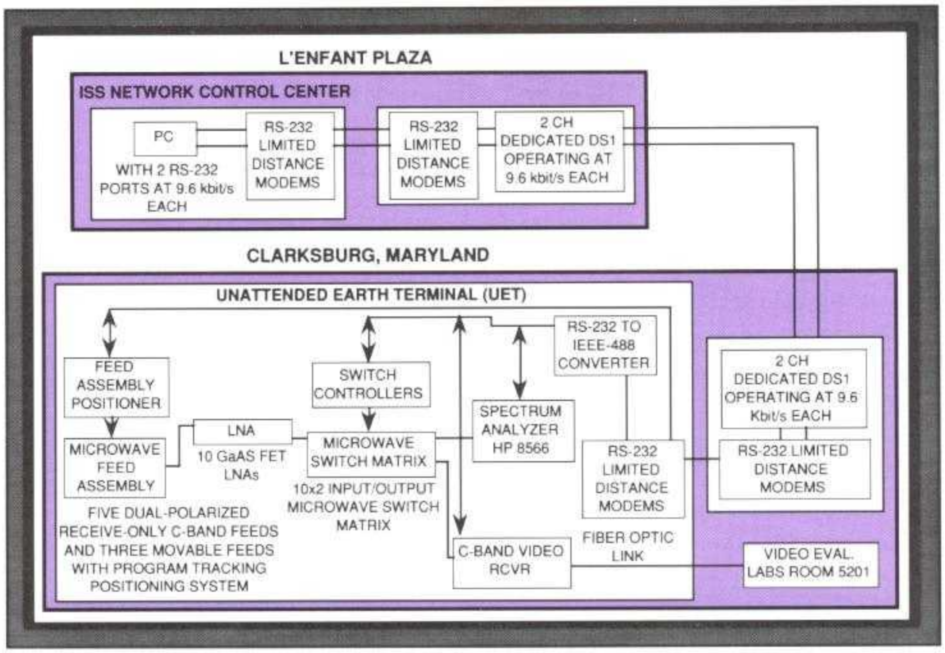


Figure 13. *Block diagram for AOR C-band monitoring system*

32- Foot Application to ISS Down-Link Signal Power Monitoring

The role of the Intelsat Satellite Services (ISS) Network Control Center (NCC) in network control, coordination, and problem resolution has increased significantly in recent years. This increase in responsibility for the NCC has led to a strong need for a remote spectrum analyzer capability. Through the Atlantic Ocean Region (AOR) remote C-band monitor task, COMSAT Laboratories has provided the ISS NCC with a real-time remote spectrum analyzer capability for five INTELSAT satellites in the 325°E to 342°E segment of the geosynchronous arc.

A block diagram of the AOR remote C-band monitor is shown in Figure 13. The system is centered around the 32-ft torus antenna located at COMSAT Laboratories; the remote site is linked to the ISS NCC at L'Enfant Plaza via two 9.6-kbit/s phone lines.

All of the RF equipment for the AOR C-band monitor is housed in the UET shelter and includes five dual-polarized C-band feeds, all of which were designed and fabricated at COMSAT Laboratories; a microwave switch matrix; a spectrum analyzer; and a C-band video receiver. All of this equipment can be completely controlled by the remote NCC operators. Also included as part of the RF receive system is a feed positioning system capable of program tracking three of the five RF feeds. This capability is useful for tracking satellites with inclined orbits up to approximately 2°; all of the software that accomplishes the program tracking was developed at the Laboratories. Periodic down-loading of updated pointing information for the positioning system can be accomplished via a phone line.

The AOR remote C-band monitor system retrieves spectrum analyzer display information from the remote site and presents this information to the NCC operators on a graphics CRT display. The typical spectrum analyzer revisit time for display information retrieval is approximately 1 s, and the resulting CRT display at the NCC looks very much like the display on the actual spectrum analyzer. A printout of a typical CRT display, illustrating a 30-MHz video carrier, is shown in Figure 14.

In addition to being able to retrieve remote spectral display information, the system operator has complete control over all spectrum analyzer control settings. Such common settings as center frequency, resolution bandwidth, and video bandwidth are easily accessed through a control menu. The control of the microwave switch matrix is also integrated into the system so that the operator can choose between different polarizations and satellites for monitoring. Finally, a video receiver is included in the system to allow identification of unauthorized video carriers by monitoring their demodulated program content.

HDTV Field Trial

To demonstrate the feasibility of transmitting HDTV signals through satellite channels, a field trial was conducted jointly by COMSAT, Kokusai Denshin

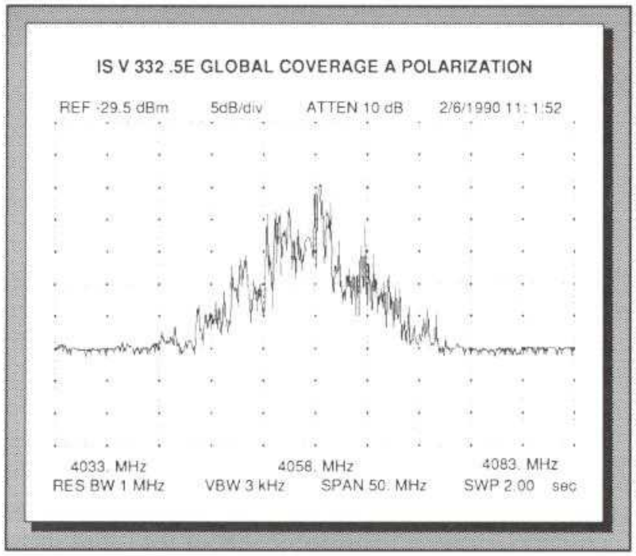


Figure 14. Typical AOR remote C-band monitor display at 30-MHz video carrier

Denwa Company (KDD), AT&T, and INTELSAT. HDTV signals were transmitted from the AT&T Triunfo Pass Standard-A earth station outside of Los Angeles to KDD headquarters in Tokyo during Phase 1 of these tests. During Phase 2, signals were transmitted between Triunfo Pass and KDD's Kamifukuoka R&D Laboratories. Additionally, loopback tests were conducted at both sites. Two small earth stations (INTELSAT E1 and E2) were used in Japan to demonstrate the practicality of transmitting and receiving from portable earth stations. The configuration of the transpacific tests is shown in Figure 15.

These tests demonstrated that high-quality HDTV images can be transmitted via satellites using the COMSAT-developed 140-Mbit/s coded octal PSK (COPSK) modem system and the KDD HDTV codec.

The COMSAT modem allows the transmission of 140-Mbit/s data over a standard INTELSAT 72-MHz transponder and was described in the 1987 Laboratories Annual Report. The KDD HDTV codec reduces the bit rate required for the transmission of HDTV to 140 or 120 Mbit/s. Both live and recorded HDTV pictures were transmitted with good quality between Triunfo Pass and Japan.

ISDN Demonstrations

In 1989, COMSAT Laboratories provided technical support for three ISDN demonstrations conducted by COMSAT ISS. These demonstrations took place between the following sites:

- Honolulu, Hawaii, and COMSAT Headquarters at L'Enfant Plaza in Washington, D.C., in conjunction with the 1989 Pacific Telecommunications Conference
- COMSAT Laboratories and COMSAT Headquarters in conjunction with the dedication of the ISDN Test Bed
- San Diego, California; Sydney, Australia; and Singapore, in conjunction with the 1989 Telecommunications Association Show.

These demonstrations showed that communications satellites can play a key role in the development and expansion of ISDN.

Pacific Telecommunications Conference

All of the demonstrations used similar ISDN application equipment. The Pacific Telecommunications Conference demonstration and the Telecommunications Association Show demonstration used similar transportable earth stations at the remote locations.

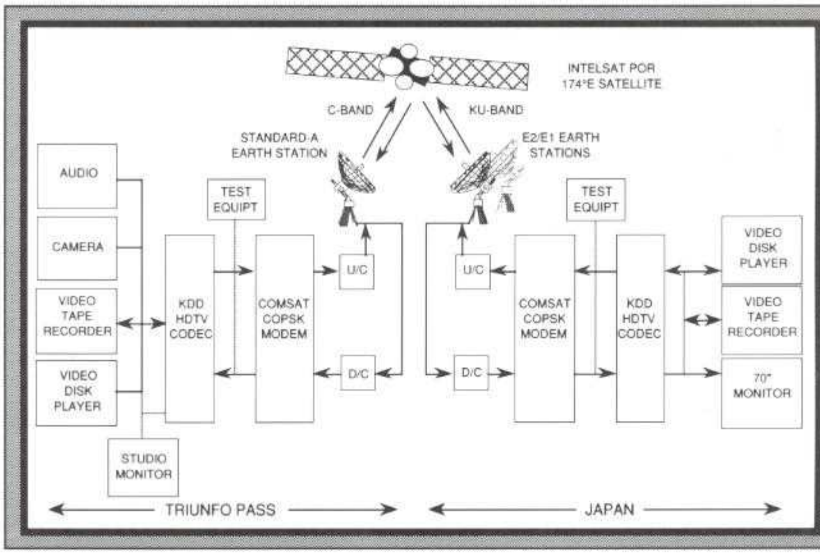


Figure 15. United States/Japanese HDTV field trial equipment configuration

The first ISDN demonstration of 1989 was conducted at the Pacific Telecommunications Council Meeting (PTC) held in Honolulu, Hawaii, from January 11 to 17. In addition to the usual digital telephony, slow scan video, computer-to-computer file transfer, and Group IV facsimile ISDN applications, a GPT IRIS-Phone limited-motion color video telephone was demonstrated.

The Honolulu demonstration used a 2.9-m, prime focus fed, parabolic reflector antenna with a K-band transmit gain of 50 dB that was built especially for COMSAT Laboratories. It used a Ku-band feed fabricated at COMSAT Laboratories and a 150 K low-noise amplifier. The transmit traveling wave tube amplifier (TWTA) had a maximum output power of 50 W. Frequency conversion from the 70-MHz IF to the Ku-band transmit and receive frequencies was accomplished with synthesized up- and down-converters. All of the RF equipment, with the exception of the data modems, was assembled on the lawn of the Sheraton Waikiki, immediately adjacent to Waikiki Beach, as seen in Figure 16. The data modems were manufactured by Fairchild Data Corporation, operated at an information rate of 2.048 Mbit/s, and employed rate 3/4 FEC coding.

The GSTAR II spacecraft of GTE Spacenet was used to provide the space segment for this demonstration as it involved domestic U.S. links.

The L'Enfant Plaza rooftop earth station provided satellite access for the Washington end of the circuit. The Plaza rooftop earth station used a McMichael 2.8- x 5.6-m elliptical reflector antenna (51.3-dB Tx gain) equipped with a 170 K low-noise amplifier and a 300-W TWTA. The effective gain of this antenna was equivalent to that of a 3.0-m circular reflector. The station also used synthesized up- and down-converters for frequency conversion. An identical Fairchild Data Corporation modem was used to interface the RCU to the RF equipment.

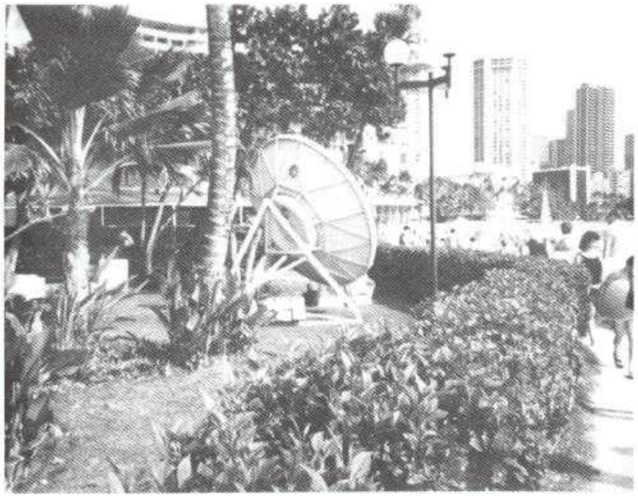


Figure 16. PTC antenna and RF equipment installation

ISDN Test Bed Dedication

The ISDN test bed located at COMSAT Headquarters at L'Enfant Plaza was formally dedicated on August 28, 1989. In conjunction with the dedication of the test bed, an ISDN demonstration was conducted via satellite between L'Enfant Plaza and COMSAT Laboratories. The ISDN applications demonstrated included digital telephony, Group 4 facsimile, computer-to-computer file transfer, and slow-scan video.

Satellite access was provided by the rooftop earth station at COMSAT Laboratories, which consisted of a 4.5-m prime focus fed parabolic reflector, via the INTELSAT 307 spacecraft to the L'Enfant Plaza rooftop earth station.

Telecommunications Association Show

The third ISDN demonstration of 1989 was conducted at the Telecommunications Association Show (TCA) held in San Diego, California, from September 26 to 28. The demonstration linked three sites through multiple ISDN applications via satellite: San Diego, California; Sydney, Australia; and Singapore. The ISDN applications used were similar to those used at the previous demonstrations. A transportable earth station was used in San Diego to communicate with Sydney via the 177 E spacecraft, which was in inclined orbit. This represented the first use of an inclined-orbit spacecraft for ISDN transmission and the first ISDN that linked three continents.

In Sydney, the demonstration with San Diego used the permanent Standard-A earth station of the Australian Overseas Telecommunications Corporation (OTC) located in French's Forest, north of Sydney, and was connected to the downtown demonstration site via terrestrial links. The demonstration with Singapore used OTC's permanent earth station in Ceduna, located approximately 2,000 km west of Sydney, also connected to the demonstration site via terrestrial links.

NASA Advanced Modulation Technology Development Gate Array

Practical implementation of high-speed Viterbi algorithm decoders is limited by the speed at which the add-compare-select (ACS) function can operate. COMSAT developed a general-use versatile gate array implementation of the ACS function in the design of high-speed Viterbi decoding systems to greatly improve the ACS speed bottleneck. During 1989, the ACS gate array was fabricated and incorporated into the design of the ACS subsystem for the NASA Advanced Modulation Technology Development (AMTD) down-link decoder.

The ACS gate array design uses a 1.5-μm emitter-coupled logic (ECL) macro cell array, and contains two independent four-way ACS functions and a single eight-way function. The gate array operates at speeds up to 140 MHz and replaces more than 40 standard ECL components.

Eight gate arrays were used in the design of a 16-state ACS circuit for the 200-Mbit/s 8-PSK down-link decoder for NASA, as shown in Figure 17. The original NASA 200-Mbit/s rate 8/9 decoder employed hybrid circuitry to implement the ACS function. COMSAT's new circuit realized significant system improvements in terms of speed, power, cost, circuit density, and reliability.

The ACS circuit board uses microwire technology to allow for dense wire routing with very good signal impedance characteristics, and is especially suitable for surface-mounted components. ECL flat pack surface mount component (SMC) devices are used exclusively for the interface and metric normalization logic. These devices greatly improve the circuit density of the design when compared with conventional dual in-line package (DIP) devices. The gate arrays are socketed on the board to allow for easy replacement should one fail.

The ACS gate array and the ACS circuit design were successfully tested and integrated into the NASA AMTD system. The ACS board design operates with a significant speed margin, thus showing great promise for the ACS gate array in future high-speed decoding applications.

DCA/DSCS Follow-On Study

This study, performed under contract with the Defense Communication Agency, developed the concept of a very wideband on-board processor. The procesor uses a very efficient FFT computation algorithm that can process a bandwidth as great as 2 GHz and can select and demodulate a mix of 8-ary FSK and differential binary phase shift keying (DBPSK) carriers of various bit rates. This on-board, digitally implemented satellite waveform processor represents a significant advance for implementing the sophisticated Transec measures needed in future jamming and nuclear scintillation resistive military communications. A possible application resides in the DSCS Follow-On and related efforts.

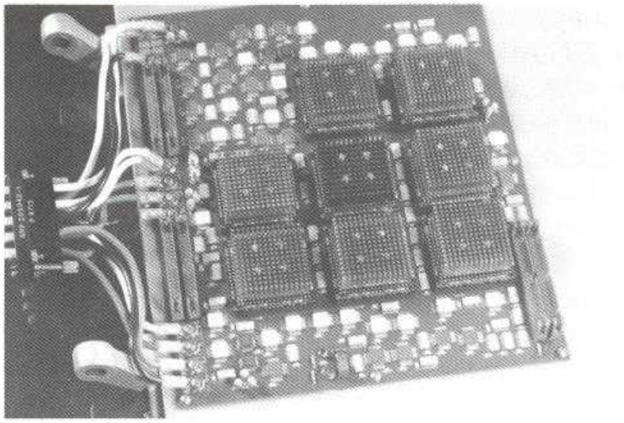


Figure 17. *16-state ACS circuit for the NASA down-link decoder*

The entire signal spectrum is presented continuously in terms of discrete complex-valued frequency coefficients spaced on a grid with frequency spacings equal to the reciprocal of the hopping period of the high-hop rate carriers. This allows the frequency hoping applied to the transmission of an earth terminal to be tracked by simply selecting the FFT coefficients from appropriate frequency locations known to the Transec system on board the satellite. Neither frequency hopping tracker/converters nor their attending frequency synthesizers and mixers are required to recover the signals. Demodulation of the wanted signals is accomplished by recombining dehopped/depermuted FFT coefficients. Furthermore, the panoramic view of the entire spectrum permits easy identification of the frequency locations in hostile jammers, which can then be used to implement adaptive jammer avoidance strategies.

All earth terminal transmissions are timed so that all up-link signals arrive at the satellite synchronized to and within the FFT window, accomplished by means of early/late messages sent to each station from the on-board processor. For multiple hops per symbol operation, the contributions from the appropriate number of tandem

T-duration hops are coherently combined to detect individual symbols.

To make the implementation tractable, the entire 2-GHz band was divided into five overlapping subbands of 500 MHz each, shown in Figure 18. Each subband processor consisted of four parallel FFT pipeline processors as shown in Figure 19. The outputs of these four pipelines were then combined to provide the FFT coefficients of a nominal 500-MHz subband. The outputs of the five subbands were then combined after proper alignment to cover the entire spectrum.

Computer simulations were conducted to assess the performance of the processor. The results showed that resulting impairments for 16-bit fixed point arithmetic are only a few tenths of a dB less than a theoretically perfect operation. Estimates of power required, using current technology, indicate that a subband FFT unit would require about 480 W. When the technology that is expected to appear in the next five years is used as a basis for the estimate, the power is reduced to 160 W.

INTEL 760 ADPCM Speech Detection

In this recently completed INTELSAT-sponsored contract, a voice detection algorithm for 32-kbit/s adaptive differential PCM (ADPCM) that conforms to CCITT Recommendation G.721 was developed and realized in hardware. The objective of this contract was to prove the concept that signal activity detection and speech/data discrimination could be achieved by using a 32-kbit/s ADPCM-encoded signal without reconstructing this signal back to a PCM signal. A signal activity-detection algorithm was developed using the ADPCM quantizer scale factor, Y_l, directly derived from the

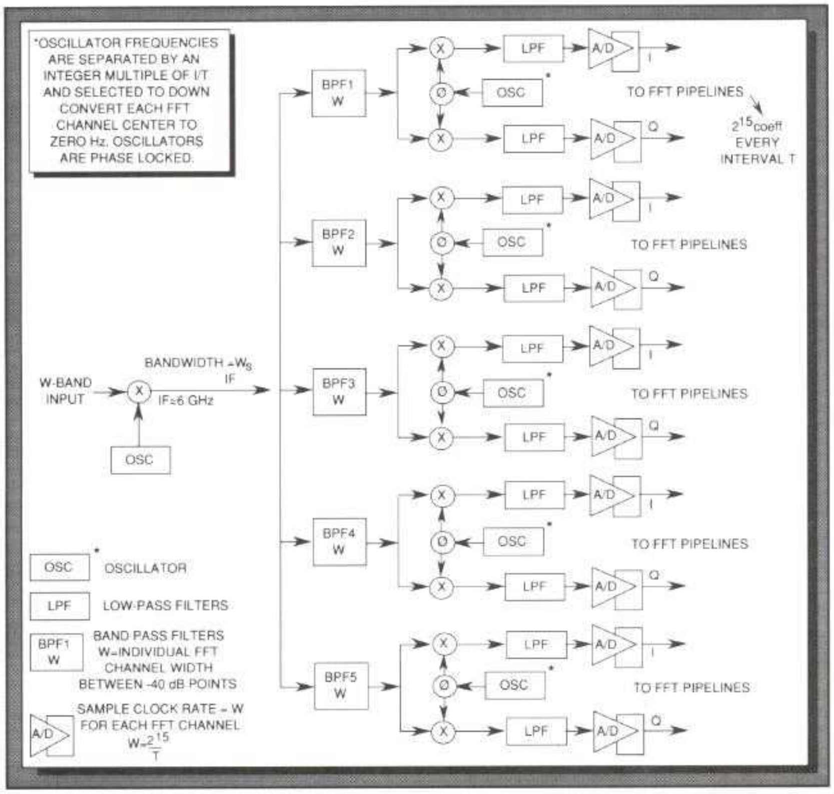


Figure 18. *FFT processor frequency conversion and sampling*

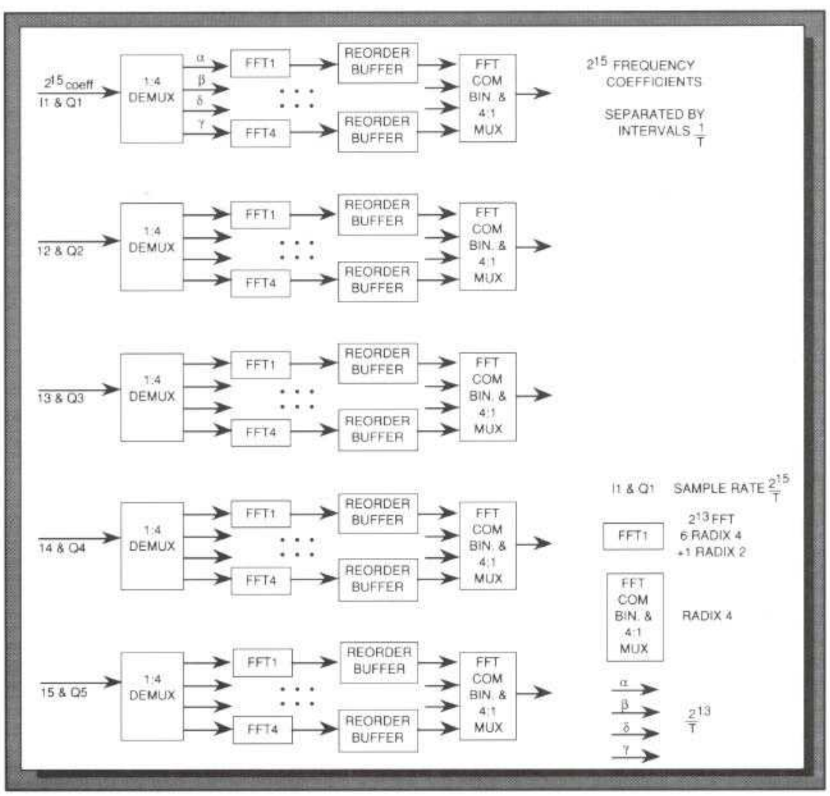


Figure 19. *Complete FFT processor*

ADPCM-encoded signal. The quantizer scale factor closely follows the envelope (magnitude) of the input signal to the ADPCM encoder. A new threshold for activity detection is calculated every two seconds using Y_l. Using this threshold, activity/no activity is determined once every 16 ms. Signal activity is assumed when the sum of the square of Y_l during a 16-ms interval exceeds the threshold. A hangover time of 32 ms is activated and maintained while the signal is active.

The voice detector developed under this contract can also discriminate between speech and voiceband data signals. The ADPCM utilizes an adaptation speed control parameter, A_p, to blend in the fast and slow quantizer scale factors so that the ADPCM algorithm can accommodate transcoding signals with different characteristics. The parameter A_p, derived from the ADPCM encoder output, tends toward a value of 2 for speech and noise signals. For data signals, the value of A_p approaches zero. Using A_p and Y_l, it is possible to discriminate speech and data signals with a high degree of accuracy, ranging from 96.5 percent to 99.9 percent.

The activity detection algorithm and the speech/data discrimination algorithm were both implemented in hardware using a TMS320 digital signal processing chip (see Figure 20). The performance of the ADPCM voice detector, when compared with continuous ADPCM encoded speech, was found to introduce a slight quality degradation. In a monosyllabic intelligibility test, the voice-detected ADPCM speech scored about 5 percent lower than continuous ADPCM speech.

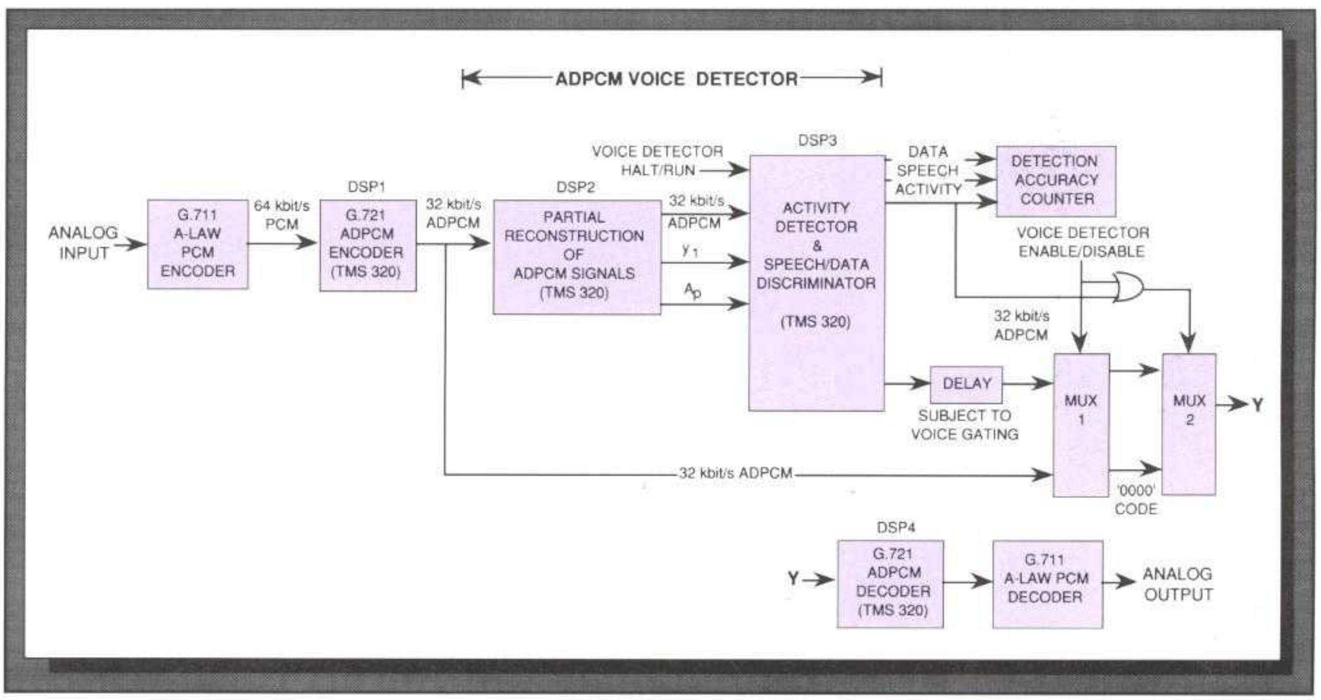


Figure 20. Voice detector for 32-kbit/s ADPCM

The Network Technology Division (NTD) performs R&D related to the analysis, design, development, and testing of advanced satellite- and terrestrial-based communications networks. Application areas include satellite networks, data communications and protocols, optical communications, integrated services digital networks (ISDNs), expert systems, on-board baseband processing, and time-division multiple accessing (TDMA). Specific projects carried out in 1989 included the development of an on-board baseband switch architecture; a value-added service which provides digital demand-assigned service; NASA Advanced Communications Technology Satellite TDMA; ISDN protocols; analysis and testing of data communications protocols; expert systems for network planning, diagnostics, and control; ISDN earth station interfaces; optical integrated circuits; an integrated local area network/wide area network test bed; and a high-performance interface processor for data switching. Technical support was provided in the areas of packet-switching quality-of-service field trials, satellite-switched frequency-division multiple access capacity, and ANSI/CCITT/ISO standards activities.

COMSAT JURISDICTIONAL R&D

On-Board Baseband Switching and Processing

On-board baseband switching, when used in conjunction with other on-board processing functions such as demultiplexing, baseband decoding, remultiplexing, and recoding, can provide enhanced service capability and functionality, which can lead to reduced earth station cost and complexity. In addition, on-board switching can be coupled with multiple spot beams to provide interbeam carrier and channel routing in a system architecture that is efficient in terms of spacecraft mass and power. This in turn can lead to lower spacecraft and launch vehicle costs.

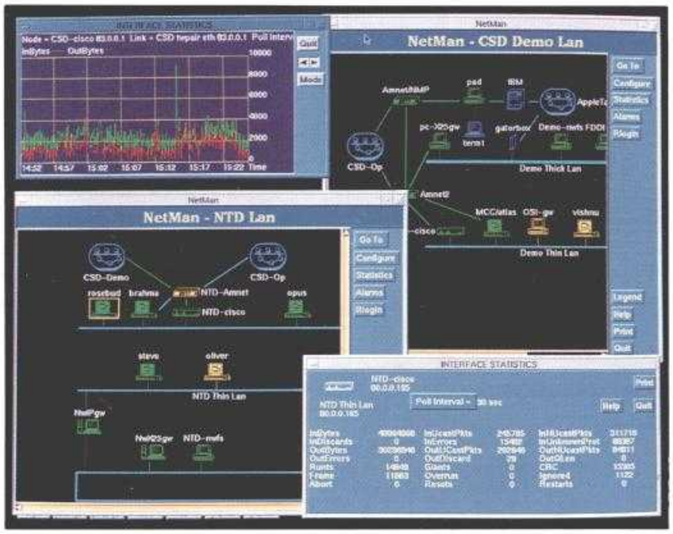
NTD has initiated the development of a modular baseband switch and its associated baseband processing functions. The switch will accept traffic from a number of digital satellite services, including INTELSAT intermediate data rate (IDR), TDMA, and INTELSAT Business Services (IBS). It will demultiplex the traffic to extract its baseband channels, switch them to the appropriate output module(s)/down-beam(s), and remultiplex them for transmission to the ground. Figure 1 is a functional block diagram of the input and output modules required for the INTELSAT TDMA service and the frequency-division multiple access (FDMA) IDR service. The actual interconnection of input to output modules will be provided over a high-speed fiber optic bus operating in a TDMA mode, as shown in Figure 2. The switch under development will support six input and output modules and has a throughput of 1 Gbit/s.

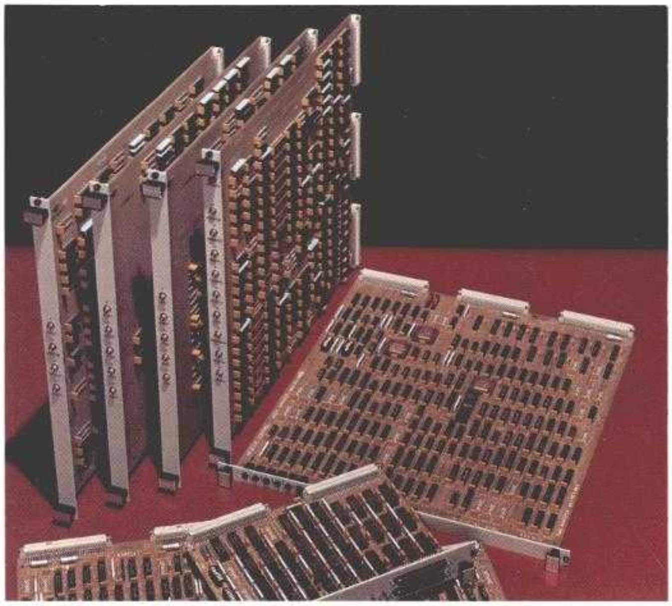
Commercial Low-Cost Service Development

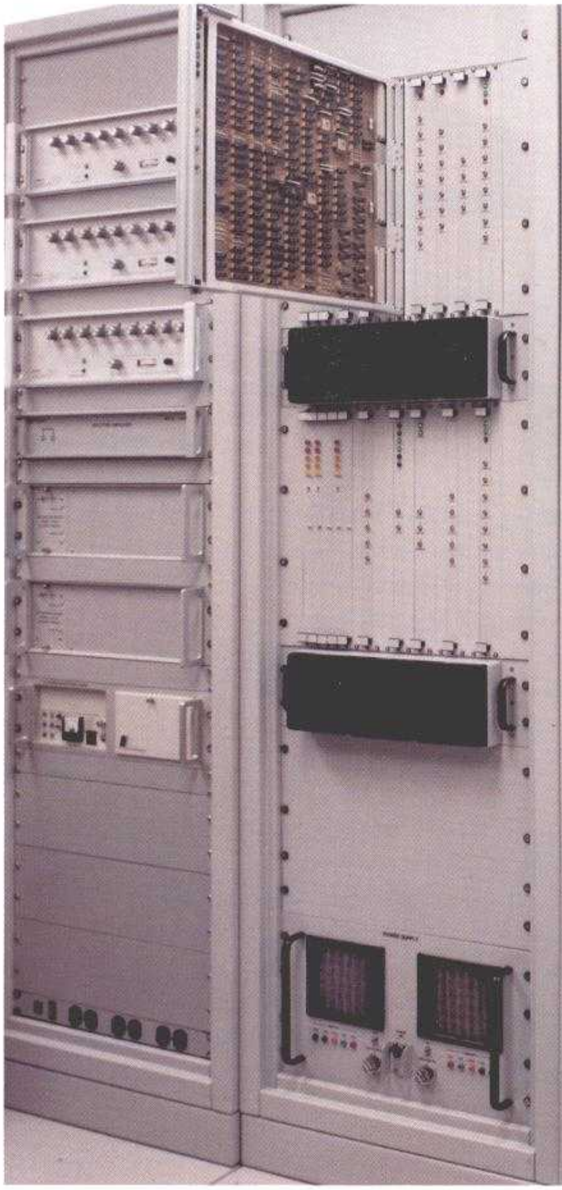
INTELSAT currently offers low-cost data services to international and domestic users through INTELNET I (data distribution) and INTELNET II (data collection). To enhance international low-cost services, a study was conducted on very small aperture terminal (VSAT) network architectures, transmission performance, network topologies, network types, and service costs for data and low-rate encoded (LRE) voice. Because of the limited RF equipment capabilities of a user terminal, most VSAT applications employ a star network in which a large number of small user terminals communicate with a large earth station known as the hub. International VSAT networks can be used for such applications as news gathering and distribution, data communications between a central data processing center in the United States and a number of overseas branch offices, and direct banking at overseas locations. VSAT networks may be implemented according to geographic areas based on INTELSAT satellite beam coverage, as shown in Figure 3.

The most commonly used VSAT access schemes are random-access TDMA (RA-TDMA), code-division multiple access (CDMA), and single channel per

NETWORK TECHNOLOGY







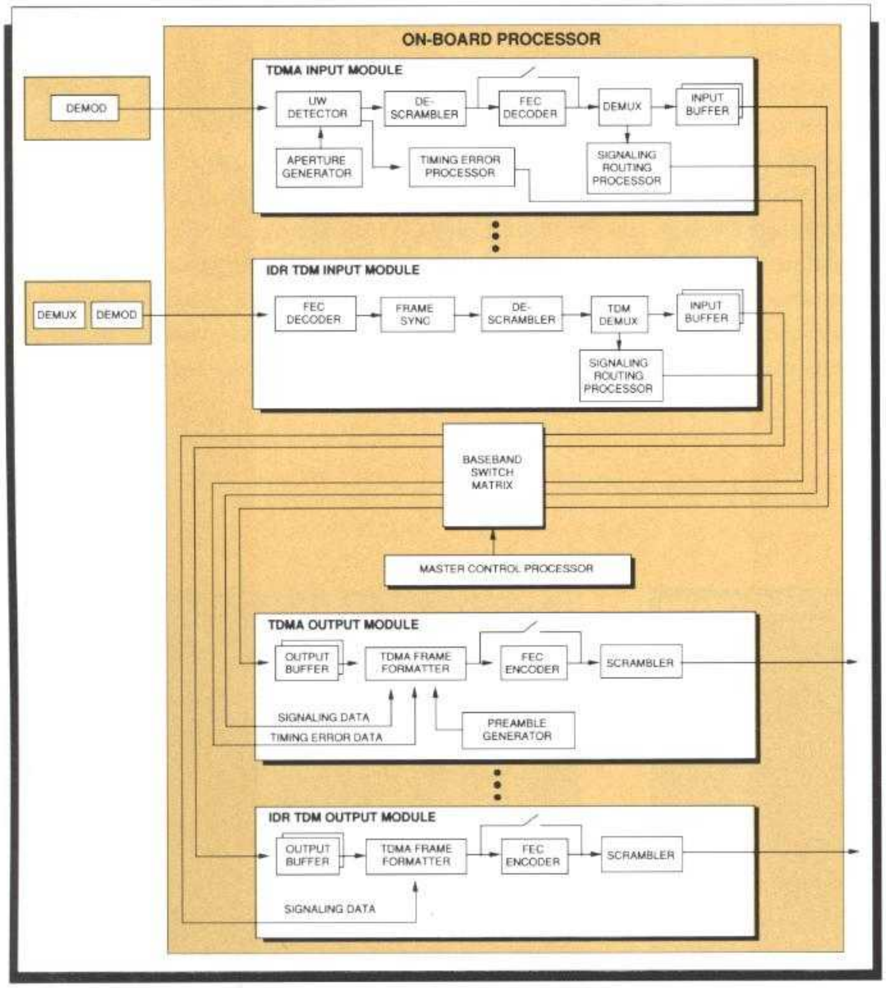


***Figure 1**. NTD's modular baseband switch accepts and processes traffic from multiple services*

carrier (SCPC). RA-TDMA is characterized by efficient space segment utilization, accommodation of LRE voice, small queuing delay at user terminals, ease of expansion, and high hub equipment cost. It is well suited for high-data-rate applications with a large number of remote sites (e.g., >100). CDMA features a low user data rate (up to 9,600 bit/s), smaller antenna size, low user equipment cost, and large bandwidth, and is cost-effective for a network with a large number of low-data-rate users. For a VSAT network with a small number of user sites (e.g., ≤50), SCPC may be the lowest cost solution, as it does not require sophisticated VSAT equipment at the hub. However, its multicarrier operation at the remote site is very limited.

A cost analysis was performed for transactional data and LRE voice, with traffic volume, a number of remote sites, and an access scheme as parameters. The results indicate that data service cost varies from 4¢ to 8¢ per transaction for 100 to 1,000 VSATs, with an average transaction rate of 1,000 per day per site using RA-TDMA. The incremental cost of voice service (a value-added service to VSAT data networks) ranges from 34¢ to 50¢ per call minute, with an average of 90 call minutes per day per site. Voice cost will be significantly higher (about $1 per call minute) for a voice-only VSAT network. These cost figures are based on six business hours per day, a peak-to-average ratio of 2 (data) and 1.2 (voice), and the use of hemispheric beams. A normalized cost breakdown fo r data services is shown in Figure 4. The contribution of hub equipment, space segment, and operations and maintenance (O&M) costs to the overall data cost rapidly decreases as the number of remote sites increases, and user equipment cost becomes the dominating cost factor.

Expert System for Diagnostics in SS-TDMA Networks

The INTELSAT VI series of satellites incorporates satellite-switched TDMA (SS-TDMA), which has led to increased network complexity and the need for additional on-board digital hardware, as shown in Figure 5. As a result, the real-time diagnosis of network failures has become increasingly difficult, if not impossible, for the network operator. An expert system was developed to assist the operator in carrying out this task.

During 1989, NTD developed a rule-based expert system (Figure 6) to analyze network information consisting of status messages from reference terminals and diagnostic receivers, messages from the satellite, and the detection of TDMA unique words (UWs) and other alarms. The expert system identifies the source of the fault as occurring in the traffic terminals, the reference terminal equipment (RTE), or an on-board component of the SS-TDMA payload. If no single cause can be

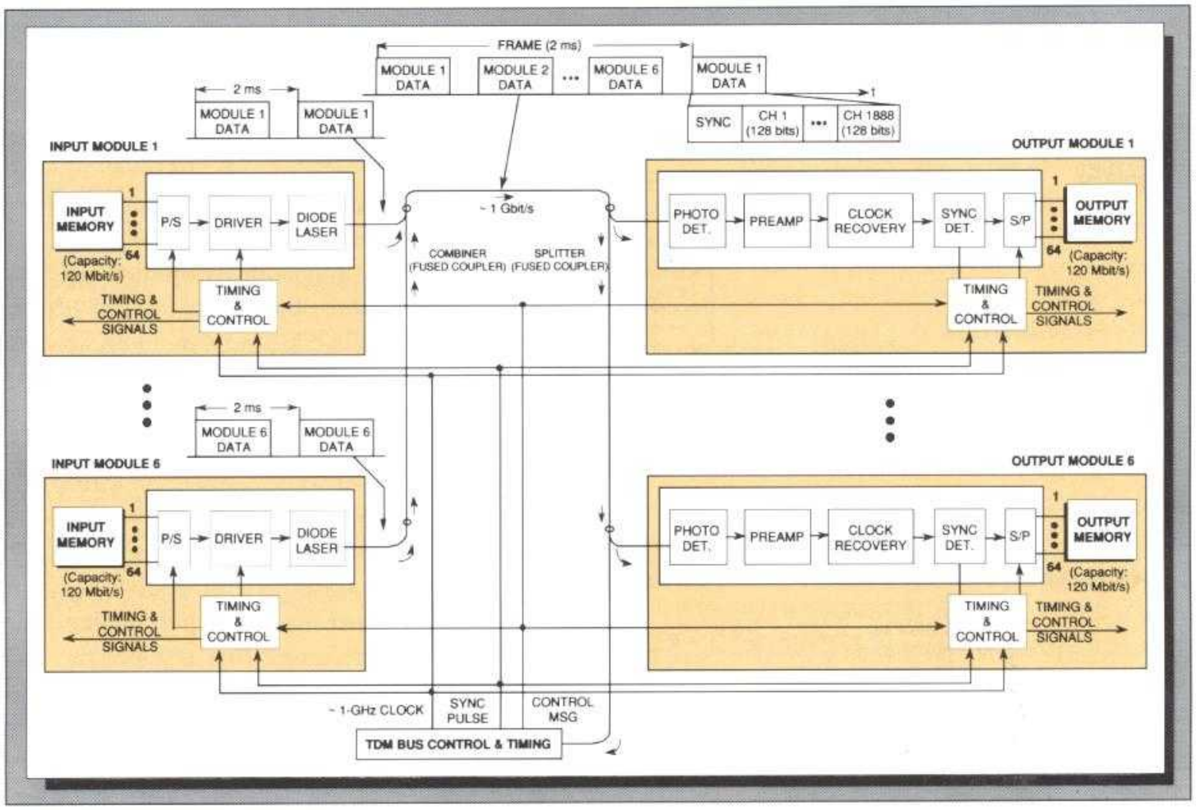


Figure 2. Input/output module interconnection using an optional high-speed bus

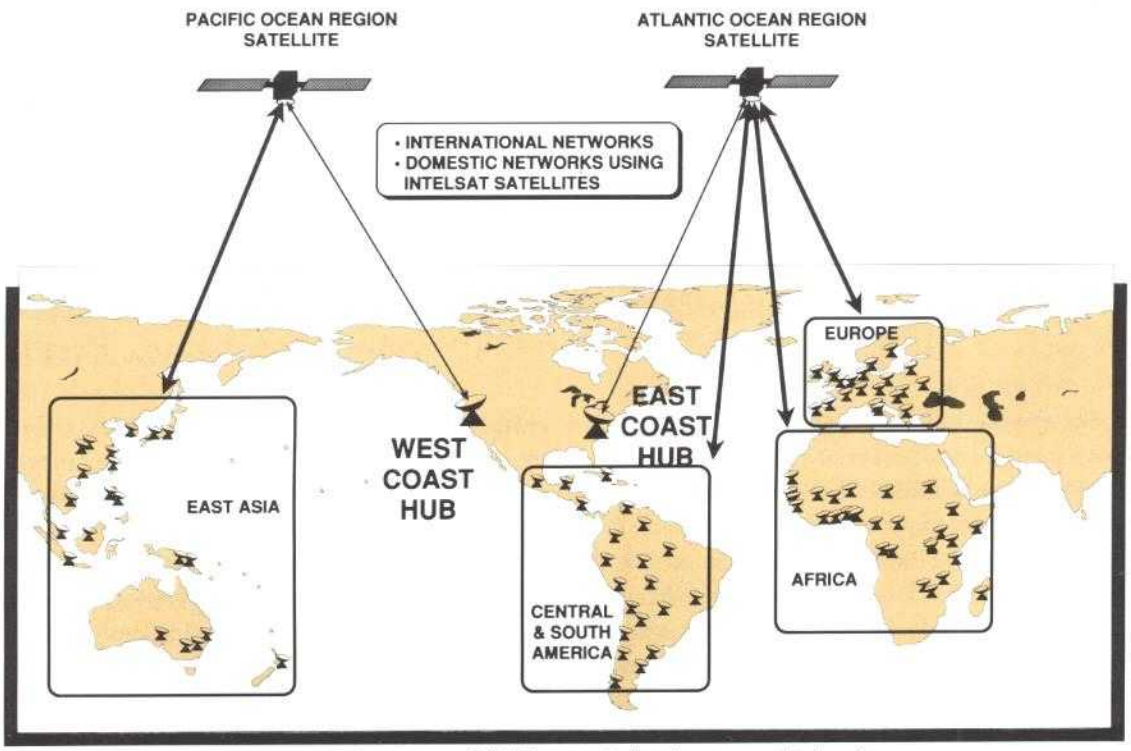


Figure 3. International VSAT networks based on geographical regions

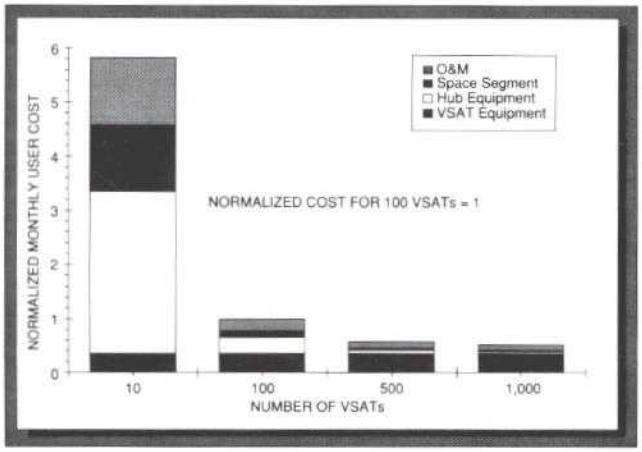


***Figure 4**. Cost breakdown for VSAT data transaction*

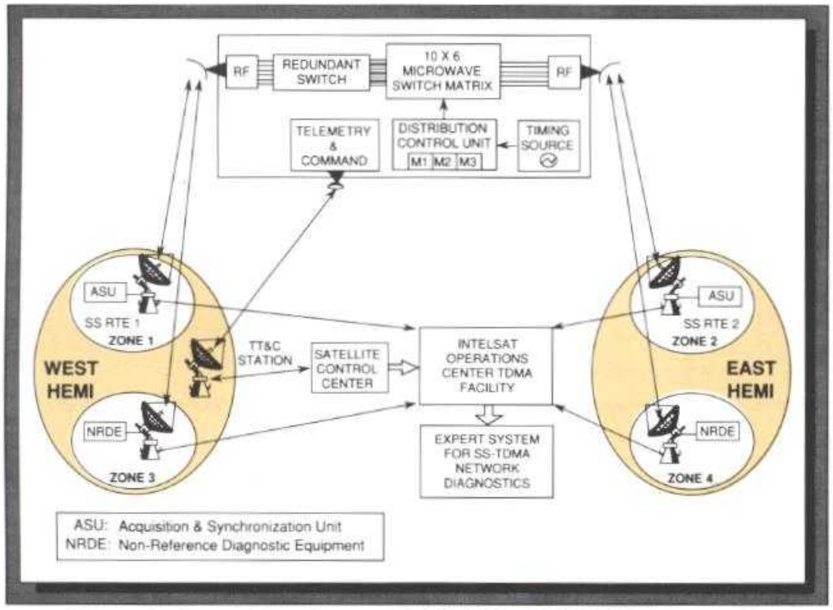


***Figure 5**. Increased complexity of the INTELSAT VI SS-TDMA network makes fault diagnosis more difficult*

identified, the system determines the most likely cause, together with the degree of certainty, depending on the predicted failure rates of individual components and the actual history of malfunctioning. When appropriate, the system also suggests an action to alleviate the problem. This may be in the form of a telemetry command to the satellite or a network control command. The expert system uses a frame-based knowledge representation structure and employs forward reasoning on five rule-sets. It was developed on the Symbolics 3640 workstation with the Knowledge Engineering Environment (KEE) expert system shell. Knowledge refinement and performance evaluation of the system will continue in 1990.

Expert System for Satellite Systems Planning

An expert system for satellite systems planning is being developed which can facilitate long-range satellite network planning and address operational needs for service changes. One objective of the task is to develop an expert system that can automate many aspects of the planning process. The 1989 effort concentrated on evaluating the feasibility of using a knowledge-based expert system to perform three planning functions: traffic routing (assigning traffic to satellites within a region), satellite switch setting (based on traffic routed to the satellite), and transponder loading (assigning traffic to a transponder), as shown in Figure 7. The expert system can produce a tool that reduces the expertise required of the user and eliminates much of the tedium involved in planning, while yielding improved or more nearly optimal system planning results. The knowledge base—a set of rules and procedures that provides a solution for each of these tasks—was developed, and an initial expert system implementation of the satellite switch setting and transponder assignment tasks was completed. Evaluation of the performance of this implementation, and additional development, are planned for 1990.

ISDN Protocols

The ISDN frame relay service uses a window-based protocol to control network congestion. This window size represents the maximum allowable number of outstanding unacknowledged information frames. During periods of network congestion, the amount of traffic offered to the network is decreased by reducing the window size. Because of the longer propagation delays experienced in satellite systems, it is important to use as large a window size as possible to maintain a high rate of link utilization. As a result, satellite systems normally operate with large window sizes (on the order of 40), while terrestrial connections operate with small window sizes (typically 7).

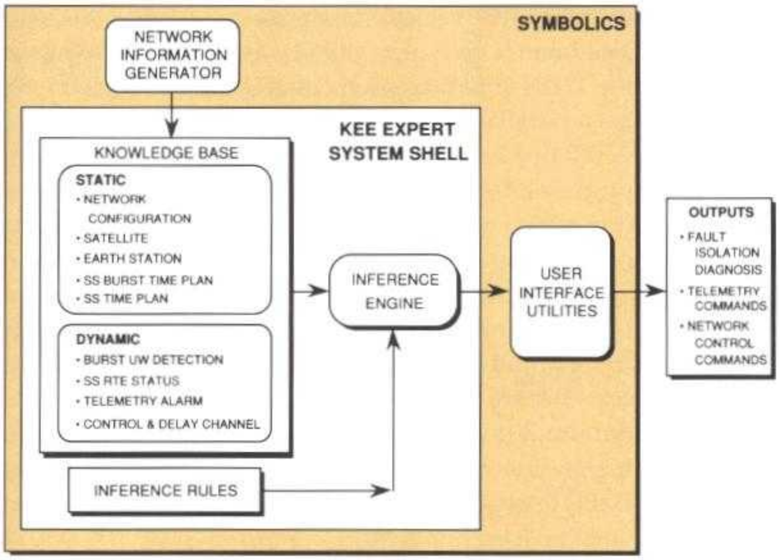


Figure 6. NTD's expert system for SS-TDMA network diagnostics

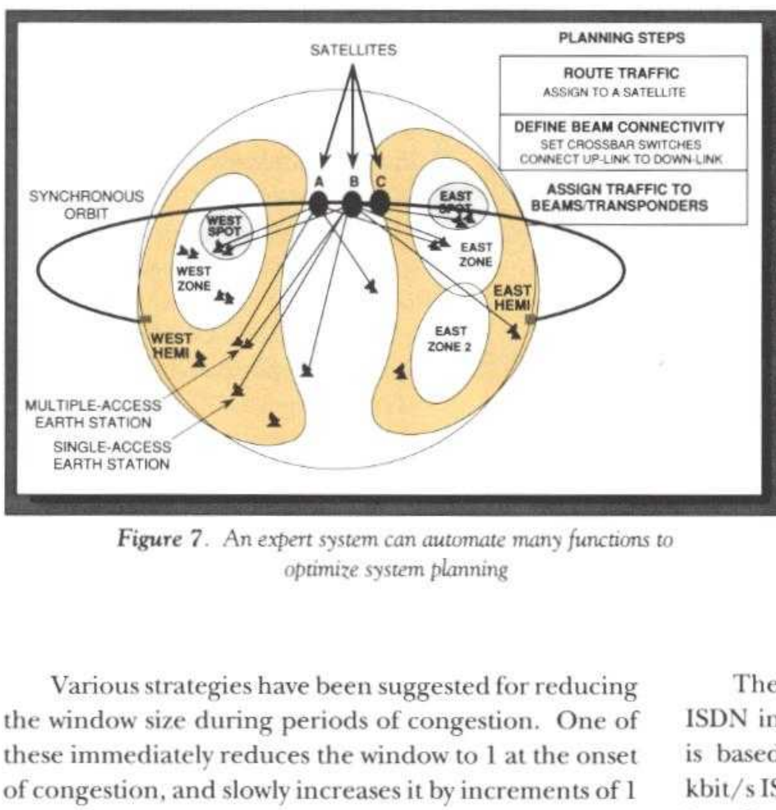


Figure 7. An expert system can automate many functions to optimize system planning

Various strategies have been suggested for reducing the window size during periods of congestion. One of these immediately reduces the window to 1 at the onset of congestion, and slowly increases it by increments of 1 until the maximum size is reached when congestion has abated. Because this method can result in inefficient utilization of satellite links, COMSAT has proposed another method which reduces the window size by a multiplicative factor at the onset of congestion.

A software model that simulates a frame relay network has been developed to test the relative performance of various window reduction schemes. This model is built on discrete event simulation using the Simscript simulation language and a shell based on a message-passing paradigm developed in NTD. The model includes terminal nodes that implement link access protocol on D-channel (LAPD+), and switching nodes that perform the frame relaying function. Simulations have shown that the multiplicative reduction scheme provides better overall performance for both satellite- and terrestrial-based networks. Figure 8 shows the satellite performance in a network in terms of delay vs offered load for the two dynamic window reduction schemes and for a network without dynamic window reduction.

ISDN Earth Station Interfaces

NTD is currently exploring the use of ISDN switching at IBS earth stations. The INTELSAT IBS system supports the transmission of digital carriers for business networks. Inclusion of this interface capability at an IBS earth station has two major advantages. First, it provides direct user access to international private networks that offer ISDN services, and second, it allows more efficient use of both satellite circuits and terrestrial access circuits. The switching capability allows traffic from different users which is destined for the same earth station to be aggregated onto a single satellite link. Likewise, it allows the user to aggregate traffic for different destinations onto a single terrestrial access to his earth station.

The architecture of a satellite system employing the ISDN interface is shown in Figure 9. This architecture 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 the signaling channels from the incoming terrestrial links, commands the appropriate switching of the cross-connect switch, and formats the appropriate outgoing signaling message. On the terrestrial access, the NIP implements the

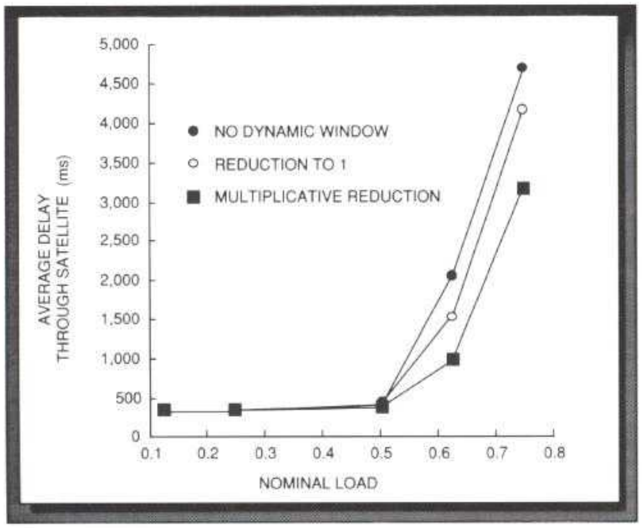


***Figure 8**. Software simulation supports a multiplicative reduction approach for window sizing*

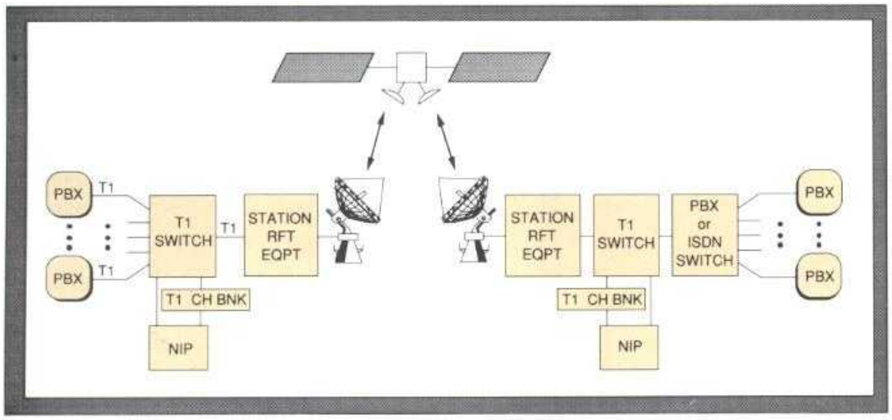


***Figure 9**. A satellite system employing the COMSAT-developed ISDN earth station interface*

primary rate (23B+D) ISDN user network interface protocols standardized by the International Telegraphy and Telephony Consultative Committee (CCITT), including Q.921 for the link layer and Q.931 for the network layer. On the satellite links, a protocol based on Common Channel Signaling System 7 has been developed to carry signaling information between earth stations. In addition, call control procedures have been developed to dynamically switch the digital cross-connect, allocate capacity on the satellite links, and perform management functions.

During 1989, potential earth station ISDN interface architectures were identified and the development of a test bed system was begun. This test bed facility includes a digital cross-connect switch that supports up to 16 T1 carriers, a network interface processor, and an ISDN private branch exchange (PBX). Software to implement the ISDN interface protocols (Q.921 and Q.931) has been purchased and modified to run on the COMSAT-developed NIP under the proprietary COMSAT Multiprocessor Operating System (COSMOS). Call control procedures and the satellite signaling protocol are undergoing development. The first stages of systems integration have demonstrated the compatibility of the interface protocol implementations of the ISDN PBX, the NIP, and the protocol analyzer used for network testing. During 1990, development of call control procedures and the satellite signaling protocol will continue. Integration of the entire system will demonstrate the ability to establish switched end-to-end connections via a satellite delay simulator.

Data Transmission Protocols

The International Standards Organization (ISO) has developed an international standard reference model of the open system 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, COMSAT and the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) have conducted a joint program to examine, implement, and test the performance of high-level data communications protocols over satellite links, and to study different aspects of OSI networks. The investigation first analyzes the relevant protocols and then identifies the parameters and procedures that affect efficient operation of the protocols over satellite links for different ranges of transmission speeds and BERs. Next, the protocols and any necessary modifications are implemented and tested in the laboratory. Finally, a joint satellite experiment is conducted with NIST, and the results are presented to national and international standards organizations for appropriate modification of the protocols.

Experiments completed from 1985 through 1988 by NTD concerned the TP-4, connectionless network protocol (CLNP), session protocol, message handling system (X.400), and File Transfer, Access, and Management (FTAM) protocols. All relevant modifications to TP-4 are being incorporated into an enhancement project in the standards committees.

Detailed experiments on FTAM were completed in 1988. Supported by the experimental results, specific modifications to FTAM protocols have been presented to various subcommittees (ANSI X3T5.5 and ISO/IEC JTC1/SC21/WG5). The concept has been accepted, and is shown in Figure 10. Procedures for normal file transfer are shown in Figure 10a. Six steps are involved in receiving a file, while five are involved in sending a file. A normal grouping sequence file transfer (Figure 10b) requires four steps for receiving a file and three for sending a file. For enhanced grouping sequences (Figure 10c), there are two steps for both receiving and sending a file. The major goal of this enhancement is to reduce the number of confirmation steps required for file transfer. Propagation delay imposed by satellite links is the main consideration, and when the file size is relatively small, each confirmation step saved will significantly improve the overall throughput.

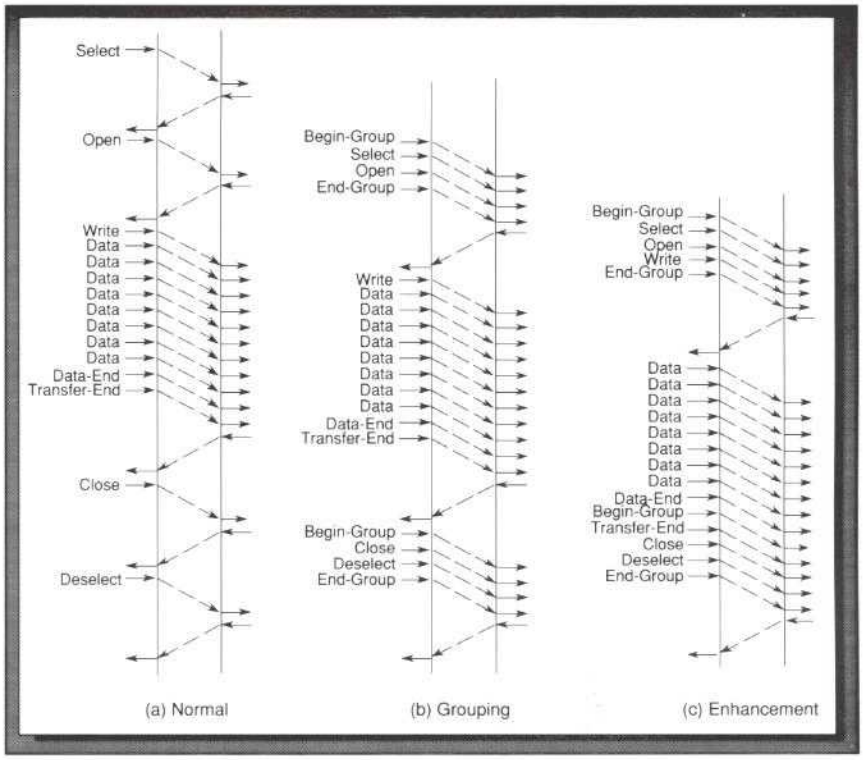


Figure 10. Modified file transfer procedures can significantly improve satellite link throughput

During 1989, OSI network management protocol was also investigated. COMSAT developed an experimental network management system based on a common management information service element (CMISE), which is above the remote operation service element (ROSE), the association control service element (ACSE), and other OSI layers. This package can be used to manage OSI protocols on different hosts that are connected on a local area network and through satellite links. Currently, it runs on Sun workstations and can specifically manage OSI software product, session, and transport protocols. The managed objects of various layers were also examined. There were two aspects of this investigation: management of local parameters to gain better communications efficiency over satellite links, and management of the objects.

Quality of Service for International Packet Switching Links

Since 1987, NTD has been conducting a series of experiments to determine the quality of service (QOS) parameters for satellite-based international packet switching links. The parameters under consideration, as defined by CCITT Recommendation X.135, are as follows:

- call setup and call clearing delays
- data packet transfer delay
- throughput capacity.

In 1989, NTD conducted an experiment to verify the values of the QOS parameters for an international packet switching link. Other participants in this experiment were Teleglobe, Kokusai Denshin Denwa Company, Ltd. (KDD), and INTELSAT. The international packet switching link consisted of the GlobeData-P packet network operated by Teleglobe, the Venus-P packet network operated by KDD, and a 9,600-bit/s satellite circuit on the INTELSAT 174° Pacific Ocean Region (POR) satellite for interconnecting the two packet networks. The source and destination networks were emulated via X.75 protocol simulators. The real-time clocks on the two protocol simulators were periodically synchronized by software on a Macintosh PC, using dial-up modems. Clock synchronization was required in order to accurately measure data packet transfer and call clearing delays, which are specified as one-way delays. Figure 11 shows the configuration used for the experiment.

In addition to X.135-specified measurements, the impact of various protocol parameters on performance was also studied. Figure 12 is a plot of the impact of the packet layer window size on the attainable user throughput. Experimental results successfully demonstrated that the QOS parameter values for satellite-based international packet switching links are well within the X.135 specifications. The experiment also demonstrated that the selection of optimal protocol parameter values is critical for obtaining good performance.

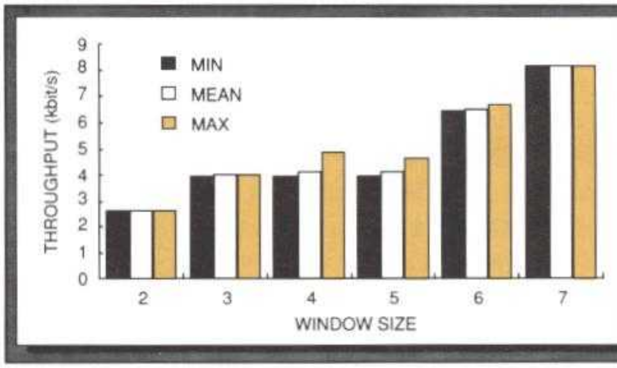


***Figure 12**. QOS parameters for satellite-based packet switching are well within CCITT-specified limits*

Nonlinear Optical Integrated Circuits

In the pursuit of advanced communications satellite systems, COMSAT Laboratories has considerable interest in developing lightweight, low-power, compact, high-efficiency components using innovative concepts and technology. Due to recent advances in optical components and integration technology, the use of on-board optical components to achieve these objectives seems promising. Integrated optical (IO) devices and circuits for on-board processing in satellites have potential applications for distribution, switching, and control of large-bandwidth, high-speed/microwave signals (e.g., beam-forming and steering in large phased-array antennas, and switching or routing of signals in broadband switch matrixes). This is likely to significantly improve satellite competitiveness.

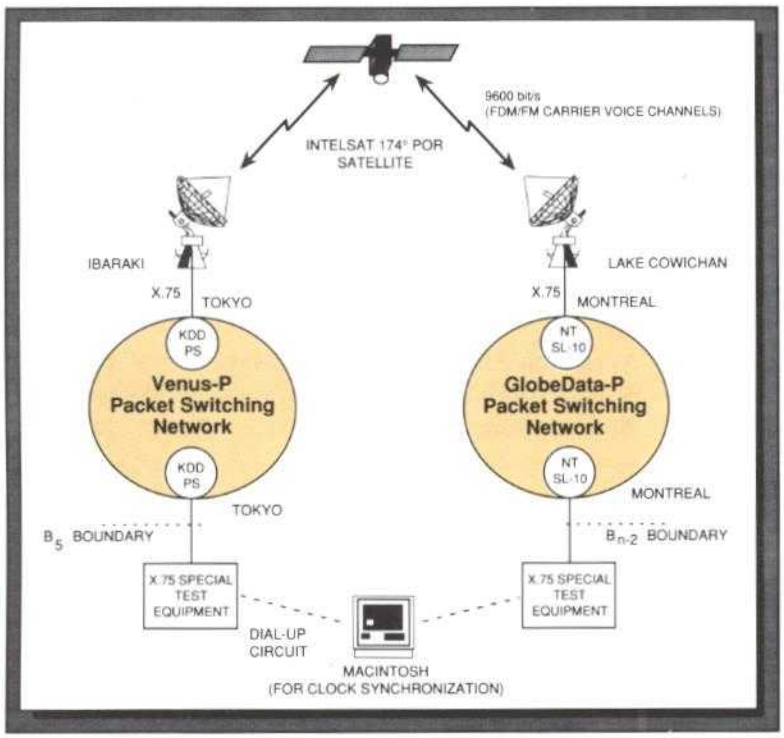


***Figure 11**. An international quality-of-service experiment*

A promising class of electro-optic materials is represented by nonlinear optical (NLO) organic polymer materials. Organic polymers can be formed into thin films, making them very useful in IO technology and leading to the monolithic integration of active and passive components (such as optical waveguides, light sources, detectors, modulators, switches, couplers, and electronics) on a single wafer. Organic polymer-based IO device and circuit technology is being developed under this project.

COMSAT Laboratories has designed an IO planar waveguide (Figure 13), selected the device material, and defined the fabrication processes, including the electric field poling arrangement, as shown in Figure 14. The design and analysis steps require solution of the lightwave propagation constants

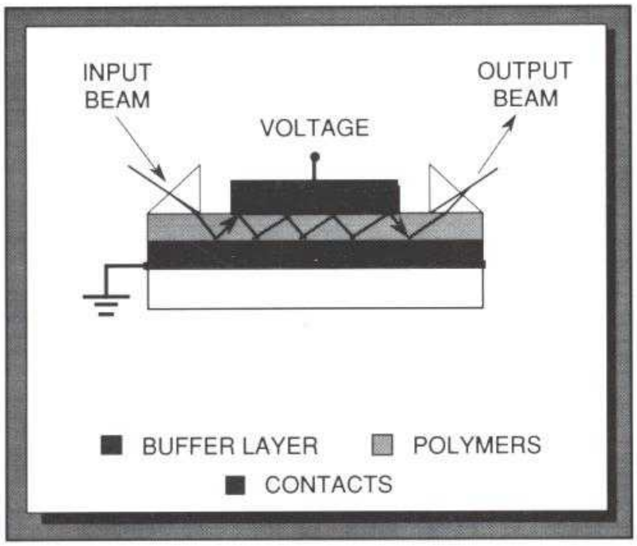


Figure 13. COMSAT-designed organic optical planar waveguide with input/output prism couplers

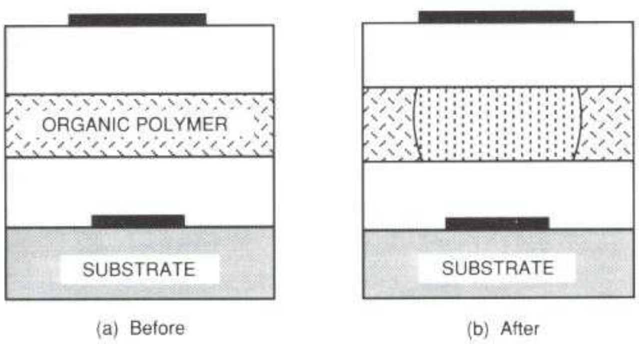


Figure 14. Electro-optic organic polymer waveguide device structures before and after electrically induced poling/waveguide formation

for a three-layer (actually five layers, including the superstrate and substrate) boundary value problem. The required thicknesses of the core and cladding layers are determined from the condition of single or multimode propagation in the waveguide for a given set of refractive index data, index profile, and wavelength. Several three-layer NLO polymer IO waveguide stacks were fabricated on Ti-Au-coated silicon wafers by spin-coating and UV curing/baking, following established procedures. UV radiation wavelength and exposure time, as well as acceptable environmental conditions, are critical for successful film growth. Processing in a clean room with controlled humidity has produced useful films.

The planar waveguides were inspected microscopically for processing-related surface damage, film defects, and other conditions, before complete optical characterization (e.g., refractive index and thickness profile, optical mode excitation, and loss). The refractive index of the core and cladding layers ranged between 1.490 and 1.545. Two types of core-cladding combinations were tried to test the fabrication and optical guided-wave parameters. Prism coupling was used to excite light into the planar waveguides, after which multimode propagation was observed in waveguides with thicker cores. Scattering loss was small in waveguides that had smooth surfaces. The typical propagation measured loss was approximately 3 dB/cm.

ANSI/CCITT/ISO Standards Activities

The COMSAT activity in the telecommunications standards development forum is designed to establish equal footing of the satellite medium with that of unadvanced terrestrial fiber systems in order to maintain the highest level of global network connectivity and availability.

During 1989, NTD continued its activities in several national and international standards bodies, including CCITT Study Groups XI and XVIII, ISO subcommittees, and various American National Standards Institute (ANSI) groups.

NTD is active in committee T1S1 covering services, architectures, and signaling, which includes the ISDN and Signaling System 7. The two main areas of interest to COMSAT in committee T1S1 during 1989 were the development of protocols for frame relay and for broadband ISDN (B-ISDN).

COMSAT has submitted a series of contributions on a window-reduction scheme for the frame relaying protocol, advocating a multiplicative reduction rather than the proposed reduction to one, which is harmful for satellites. As a result, the reduction-to-one scheme has not been approved, and the debate has now shifted to the precise value of the multiplicative factor. COMSAT was also successful in having the timer value for T200 of LAPD+ specified as 1.5 s, which is crucial for operation over a satellite link. In addition, COMSAT found a bug in LAPD+ and submitted a contribution expounding on the protocol error and suggesting a possible solution.

Regarding B-ISDN, COMSAT removed the bias toward fiber in the B-ISDN baseline document. Also, the stringent specification of an asynchronous transfer mode (ATM) cell loss ratio of 1×10^{-10} would have put an undue burden on satellites to provide a bit error rate (BER) on the order of 1×10^{-11}. COMSAT succeeded in forestalling such a development.

For data communications via satellite, COMSAT is involved in a number of U.S. standards committees (ANSI X3S3.3, X3T5.4, and X3T5.5) and international standards committees (ISO/IEC JTC1/SC6/WG4, ISO/IEC JTC1/SC21/WGs 4, 5, 6). COMSAT's major interest is to ensure that higher layer protocols are satellite-friendly. To that end, COMSAT actively participates in these committees to ensure that current standards operate satisfactorily over satellite links, and to shape future standards that are satellite-compatible. Two major accomplishments in this regard involved the Transport Protocol, Class 4 (TP-4) and the FTAM, which are two of the key higher-layer protocols.

Selective acknowledgment enhancement to TP-4 was presented to ISO/IEC JTC1/SC6/WG4 in May 1987, in a group with other enhancements. The official New Work Item letter ballot was issued in January 1988. COMSAT's proposal was approved by ANSI X3S3.3 and X3S3 and forwarded as a U.S. contribution to the ISO/IEC JTC1/SC6/WG4 meeting in May 1989. COMSAT hosted an international ad hoc meeting of ISO/IEC JTC1/SC6/WG4 Transport Enhancement in October 1989, during which the selective acknowledgment scheme was clearly incorporated into the editor's draft. This major enhancement to the international standard for accommodating satellite communications is now close to being achieved.

The extended grouping sequence enhancement to the FTAM was presented to ANSI X3T5.5 in January 1989. A few cycles of technical refinement were accomplished in meetings of ANSI X3T5.5 in April 1989 and the ISO/IEC JTC1/SC21/WG5 FTAM group in May 1989. Finally, the group agreed to propose a New Work Item for this enhancement with a broad view that includes other possible enhancements. This is the first step toward achieving COMSAT's goal.

COMSAT NONJURISDICTIONAL

Integrated LAN/WAN Systems and Network Management.

A project was begun in 1989 to address the problem of designing and managing multivendor, multiprotocol, multimedia, and multiservice local area networks/wide area networks (LANs/WANs). Today's networks typically consist of LANs within a campus or building, interconnected by WANs. Each network contains a multitude of equipment from multiple vendors which use a variety of protocols for communication. This project addresses the requirements for interconnecting the various equipment so that different user equipment can communicate. The problem of managing all the equipment in this diverse network is also examined. Most vendor management systems address only a single protocol or a single vendor family of equipment, and most do not have software interfaces to other management systems.

An architecture has been created that implements the above interconnections using commercial off-the-shelf equipment and a single shared backbone WAN system. Based on this architecture, a test bed (as shown in Figure 15) was designed and implemented which represents a prototypical customer network. The test bed consists of three campus networks (all located at COMSAT Laboratories), each containing a number of different LANs, such as Ethernet, token ring, localtalk, and fiber-distributed data interface (FDDI); a number of different devices such as PCs, PS/2s, Sun workstations, Macintoshes, and IBM mainframes and terminals; and a number of interconnection devices such as bridges, routers, gateways, X.25 packet switches, and X.25 packet assemblers/disassemblers (PADs).

The architecture allows comprehensive network management across multiple vendors and protocols. It takes a hierarchical approach to network management in which individual network control centers (NCCs) can manage regional or campus networks or a single vendor product line or protocol, and management control centers (MCCs) can manage the entire network through the individual NCCs. The architecture also allows an MCC to directly manage the entire network without NCCs, or an NCC to manage a regional multiprotocol network.

The management system addresses all major management areas: configuration management, fault management, performance management, and accounting management. The configuration management function allows operators to define/observe the topology of the network on a set of graphical screens and to define/observe operating parameter values for the various devices in the network. The fault management function allows an operator to observe the status of the network

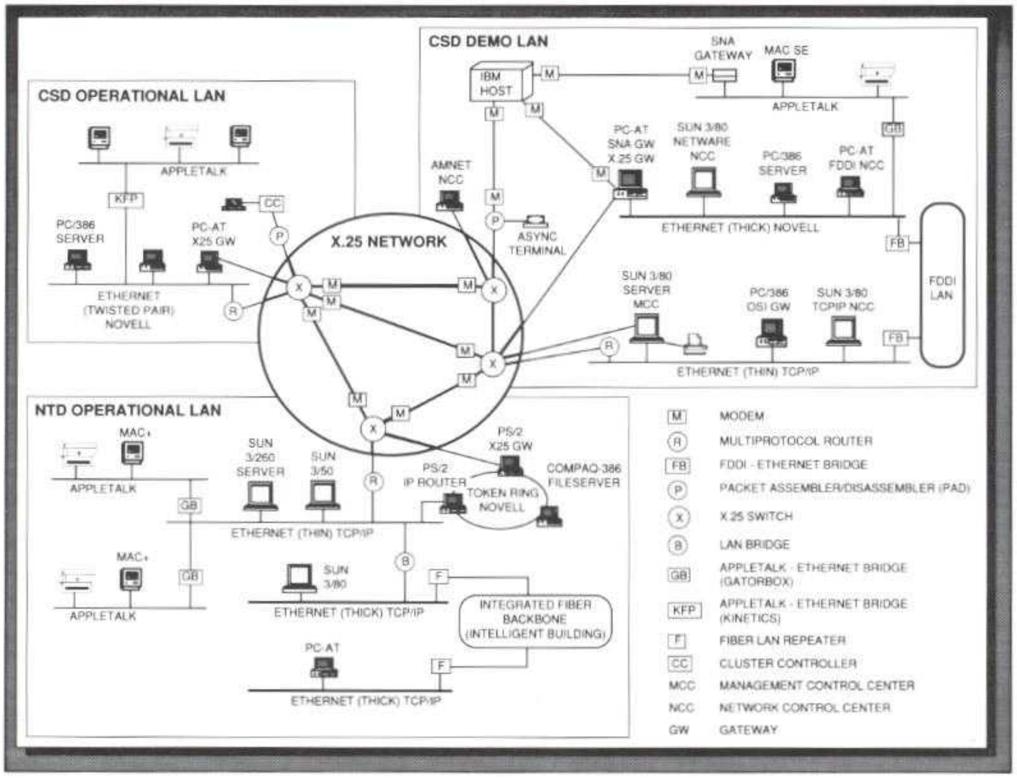


Figure 15. *Test bed implemented to study the interconnection and management of diverse LANs*

components in various degrees of detail. Alarms are collected by the system from various devices and displayed on the operator screens, as well as logged for later report generation. For devices that do not report alarms, the system periodically polls the devices to determine their status. The performance management function allows the operator to observe, in real time, various counters and statistics defined by the devices. Statistics can also be collected in the background, in which case the data are saved in the database and reports can be generated to analyze system performance, as well as to identify trends. Figure 16 shows a typical user interface screen.

The system is based on Sun workstations with high-resolution color bitmap displays and uses the Ingres relational database as the repository for all management-related information. The system uses X Window and the Motif tool kit to create an extremely powerful and friendly user interface. The management system initially supports X.25 packet switches, X.25 PADs, transmission control protocol/internet protocol (TCP/IP)-based workstations and routers, and Novell Netware-based PCs and routers.

High-Performance LAN/WAN Interface Processor

The rapid growth of communications technology is dramatically changing the networking environment. LANs such as Ethernet (10 Mbit/s) are expected to be replaced by much higher speed LANs like FDDI, which operate at 100 Mbit/s. WANs are also rapidly evolving from medium-speed T1 (1.544-Mbit/s) links to T3 (45-Mbit/s) links. A similar trend in processor technology with the advent of microprocessors such as the INTEL 80486 and MC68040 is enabling user workstations to take advantage of the large available bandwidth. These trends, coupled with bandwidth-intensive applications, will be extremely demanding on the switching capabilities of internetworking devices like routers and bridges. The switching requirement for supporting these high-speed networks is in excess of 30,000 packet/s, and current internetworking implementations are incapable of providing this performance.

NTD has embarked on a research program to develop an internetworking processor capable of meeting these switching requirements. Figure 17 is an example of a future internetworking environment which makes extensive use of a high-performance processor. The key to obtaining this performance is the incorporation of reduced instruction set computer (RISC) architecture based microprocessors in the design. RISC-based microprocessors possess several features that make them extremely attractive for communications processing applications. These features include reduction of the clocks required per instruction, a streamlined instruction set, separate buses for data and instructions, multiple pipelines, and optimizing compilers.

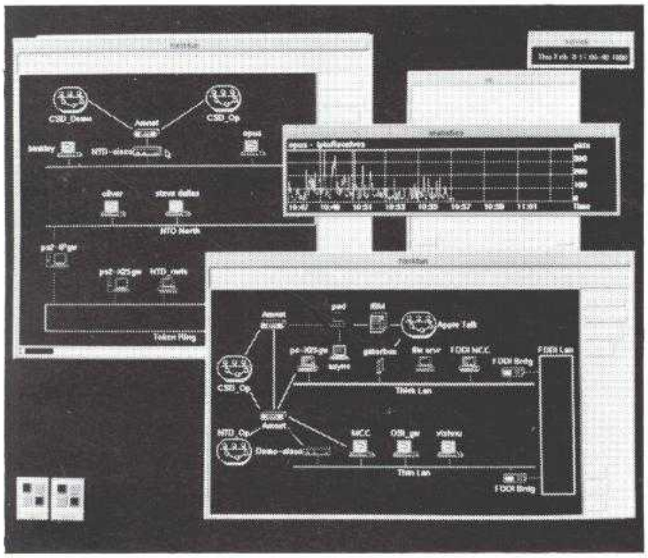


Figure 16. Typical user interface screen for NTD's comprehensive LAN/WAN management system

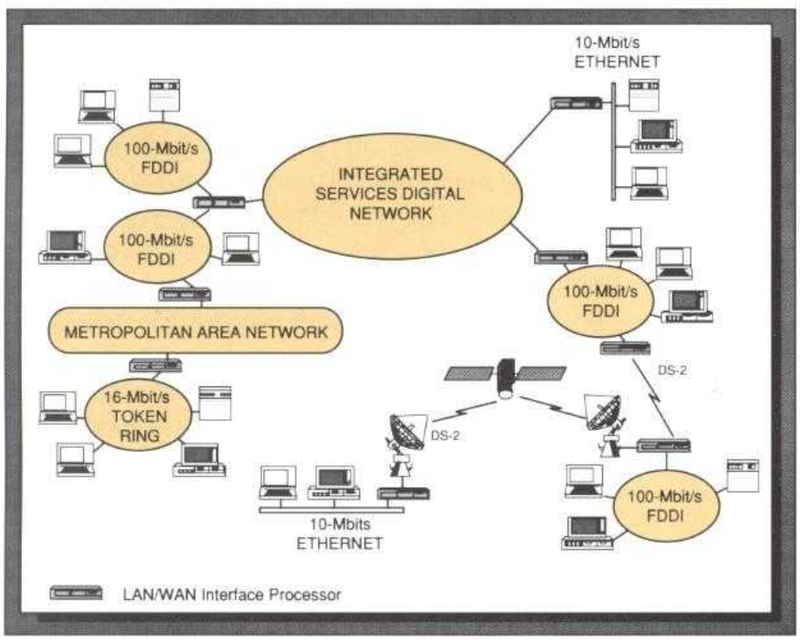


Figure 17. Future internetworking environment

After carefully evaluating available RISC processors, the MC88000 chip set from Motorola was chosen as the platform for the LAN/WAN interface processor. This chip set consists of the MC88100 processor and two MC88200 cache memory management systems for data and instruction storage. During 1989, the proprietary real-time operating COSMOS was ported to the MC88000-based VME board. Preliminary estimates indicate that a switching performance between 30,000 and 50,000 packet/s is feasible using this hardware platform. The hardware architecture for the LAN/WAN processor is shown in Figure 19. Software was also developed for media access control (MAC) layer bridging and for U.S. Department of Defense (DoD) IP routing. A prototype unit that incorporates the Ethernet and FDDI interfaces will be developed by the end of 1990.

Expert Systems in Network Management

The operation of large communications networks has traditionally required the services of skilled human experts to investigate and solve complex problems that affect the functioning of the network. NTD has been investigating the applicability of expert systems technology to network management.

Among the most widely used network communications protocols today are those that comprise the TCP/IP suite originally developed for the DoD. NTD has developed a system architecture for an expert system to manage TCP/IP networks. In this model, a knowledge-based system is used in conjunction with an existing network management system to aid in diagnosing faults and performance degradation of networks. Information such as status, and statistics from network entities accessible through the Simple Network Management. Protocol (SNMP) is used as the primary basis for inferencing mechanisms.

A set of problems and diagnostic tests symptomatic of TCP/IP networks was identified. Of special interest were conditions with relatively obscure warning signs which, if left unattended, could lead to a catastrophic loss of network facilities. The structure of the knowledge base was designed using KEE on a Symbolics 3640 machine. A set of rules relating to the detection of problems in the TCP/IP domain was defined. In general, the system hypothesizes that a problem exists by observing changes in the values of certain key parameters. If the system observes evidence confirming this hypothesis, in the form of changes in other parameters, it strengthens or confirms the hypothesis and generates an appropriate warning message.

In order to test the system, additional test rules were defined and diagnosis rules were tested using locally simulated problem conditions that required a response from the expert system. This work will be pursued further by testing the expert system against simulated faults in a TCP/IP network, integrating it with an existing network management system, and extending it to the management of other protocol domains.

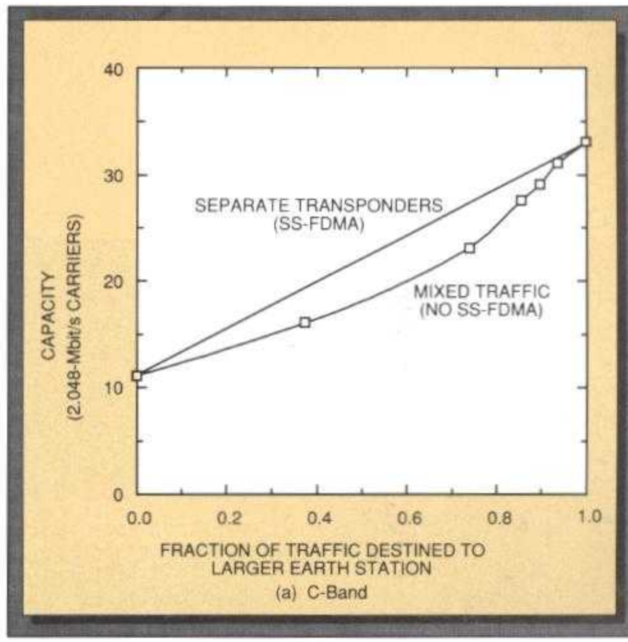
INTELSAT

Satellite-Switched FDMA Capacity Improvement Analysis

This study for INTELSAT analyzed the potential increase in satellite transponder capacity achievable through the use of satellite-switched FDMA (SS-FDMA) transponders. The increased capacity results chiefly from reduced intermodulation interference effects. This is accomplished by using the SS-FDMA switching capability to separate low-power carriers destined for high gain-to-noise temperature ratio (G/T) ground stations from high-power carriers destined for low-G/T ground stations. This separation of low- and high-power carriers prevents the intermodulation products of the high-power carriers from interfering with the low-power carriers. The resulting performance improvement increases the number of carriers that can be accommodated by a transponder.

The Satellite Transmission Impairments Program (STRIP) 6 software was used to estimate the capacity of transponders with uniform carriers and transponders that support carriers with different power levels (mixed traffic). Capacity was estimated in terms of the number of 2.048-Mbit/s IDR carriers supported by a 70-MHz transponder. The satellite and earth station characteristics assumed were those of an INTELSAT V spacecraft and various INTELSAT Ku-band and C-band standard earth stations. Due to data storage requirements, STRIP6 can accommodate only a limited number of carriers. In order to generate meaningful results, it was necessary to develop a number of smaller cases in which transponder power and bandwidth were proportionately reduced. These cases were carefully chosen so that the results could reasonably be scaled to represent full transponders.

C-band mixed traffic cases employ Standard-F3 and F1 earth stations. The results show that these cases have reduced transponder capacity relative to cases where uniform carriers are employed. The capacity increase resulting from the use of separate transponders was found to be greatest when an equal number of the two types of carriers was employed. A maximum capacity increase of approximately 25 percent is estimated for C-band transponders (Figure 18a). Similar results for Ku-band cases indicate that improvements of up to 40 percent may be achieved when VSAT terminals are employed in mixed traffic cases (Figure 18b).



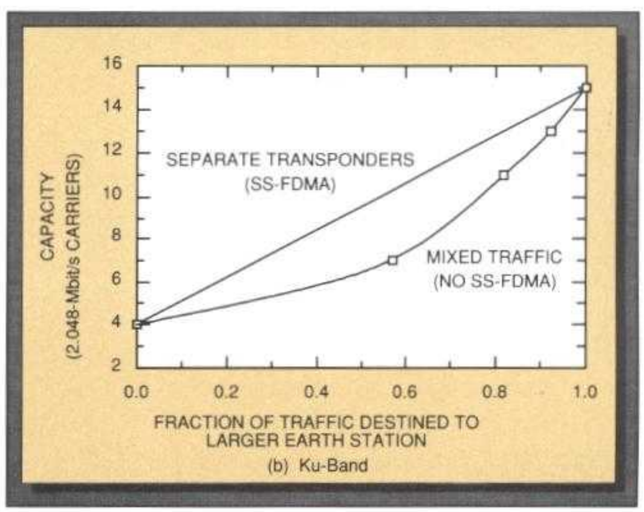


Figure 18. *SS-FDMA capacity improvement achieved using SS-FDMA*

The System Development Division (SDD) performs software research and development. Development activities include designing and implementing real-time systems, developing modeling and simulation tools, and developing software tools that will improve the overall software development process within COMSAT. Communications network monitoring and control systems and measurement systems are examples of typical real-time development applications. Modeling and simulation tools are used to evaluate communications systems and subsystems and include programs that predict transmission impairments and plan the deployment of satellite resources. Research tasks explore and define new software technologies and techniques such as computer-aided software engineering tools, project management tools, user interface systems, languages, operating systems, computing platforms, and development methodologies.

COMSAT JURISDICTIONAL R&D

General Antenna Program

The General Antenna Program (GAP) was initially developed in 1973 as a general-purpose tool to analyze reflecting antenna systems. Over the years, modifications and extensions have been incorporated into GAP to ensure its continuing usefulness to antenna design engineers. In 1989, an effort was initiated to restructure the program to meet the requirements of current software engineering standards. This effort, which will continue into 1990, will reduce future maintenance costs for the program and facilitate the incorporation of new program features.

Rain Analysis Program

During 1989, the Rain Analysis Program (RAIN) was developed to estimate the impairments caused by rain to a signal transmitted over a satellite communications link. These impairments, which include excess rain attenuation, down-link degradation, and cross-polarization discrimination, occur on a path between an earth station and a geostationary satellite. RAIN is based on the earlier Propagation Analysis Program (PAP-2) and incorporates a number of improvements.

RAIN uses the Rice-Holmberg rain-rate model to compute rain impairment statistics for various percentages of time during a year. Inputs entered into the program include earth station and satellite locations, up- and down-link frequencies, and mean annual rainfall parameters of the earth station. The output consists of two tables of rain impairment figures: one for the up-link and one for the down-link. These tables detail the cumulative, annual percentage of time that a given impairment level is expected to be exceeded at the specified location. RAIN is machine-independent and can be ported to any computer that has a FORTRAN-77 compiler. It currently runs on the IBM 3083 computer under the CMS operating system, the IBM/PC under DOS, and the HP-840A and APOLLO workstation, both of which operate under UNIX. RAIN has been thoroughly tested, and a software reference manual and user's manual are available.

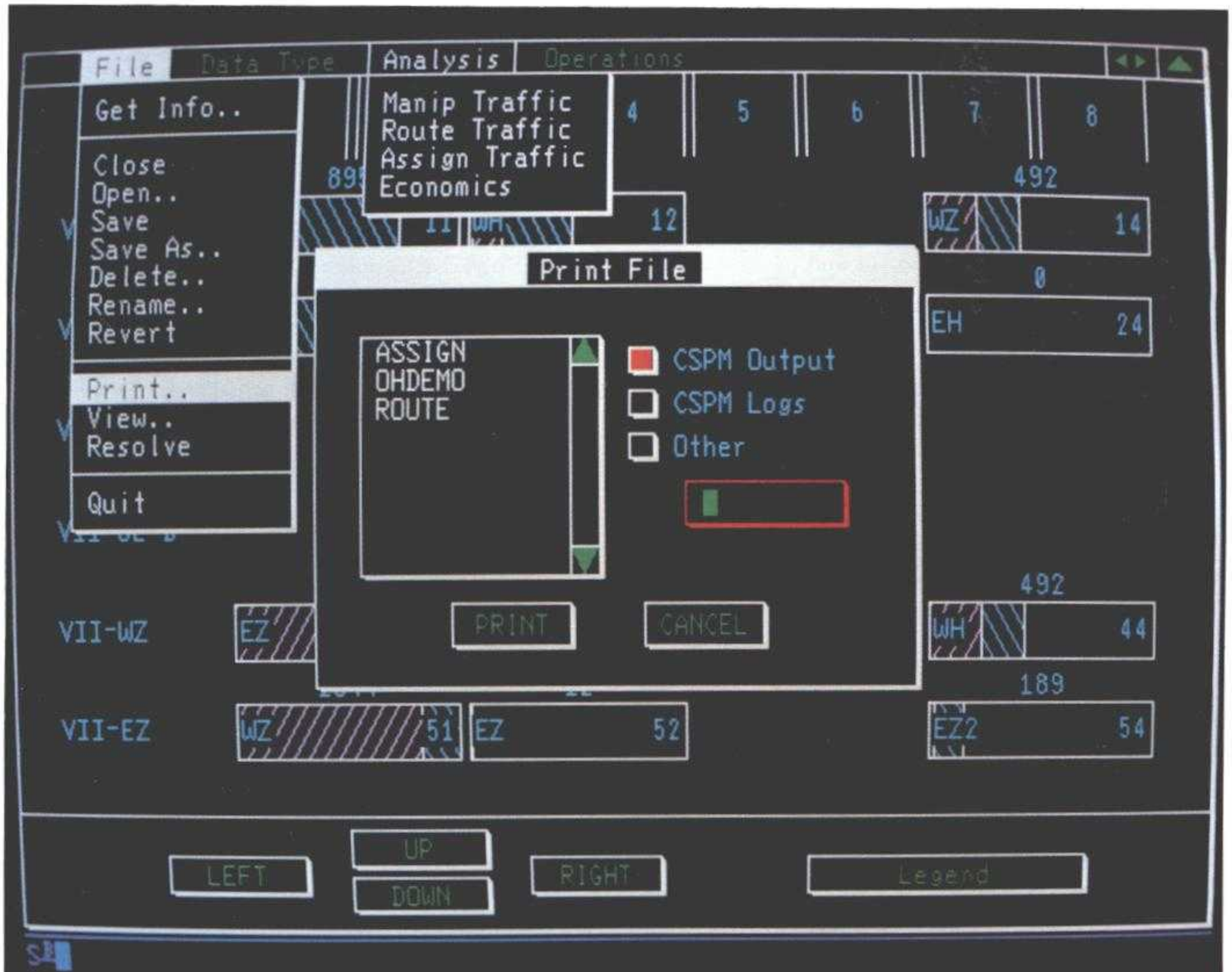
COMSAT NONJURISDICTIONAL R&D

User Interface Management System

A User Interface Management System (UIMS), initiated in 1989, is being developed as a two-year proprietary research task. The purpose of this task is to implement a development system that will be used by programmers to create sophisticated, interactive user interfaces for future software applications. The task was motivated by the need for improved user interface consistency across software applications and for improved programmer productivity during system development.

During 1989, currently available user interface environments and development tools were surveyed to assess the general direction of the software industry. Early in

SYSTEM DEVELOPMENT



the year, the X-Window System developed at the Massachusetts Institute of Technology (MIT) was selected as the base user interface. This windowing software provides significant capabilities for an off-the-shelf product, although it is not an easy system to use. UIMS will be built on top of the X-Window System and will simplify the task of the application developer.

Another off-the-shelf product, MOTIF, will also be part of the UIMS. MOTIF is a set of predefined objects, known as "widgets," that are based on the X-Window System and provide user interface functionality. UIMS will use these widgets to assist the application developer in building user interfaces for interactive applications. This set of widgets will be expanded to meet the special requirements common to many COMSAT applications. An example of a screen generated using MOTIF widgets is shown in Figure 1.

The other major components of the UIMS will be developed in-house. These components will be used to automate many steps in the application development process while hiding the details of the X-Window System. These components include tool kits, automation tools, prototypes, application templates, user interface guidelines, and other software libraries.

During 1990, the expertise gained in the X-Window System, MOTIF, and workstation technology will be applied to implement the toolkits and prototype tools and apply these tools to the implementation of one or more prototype systems.

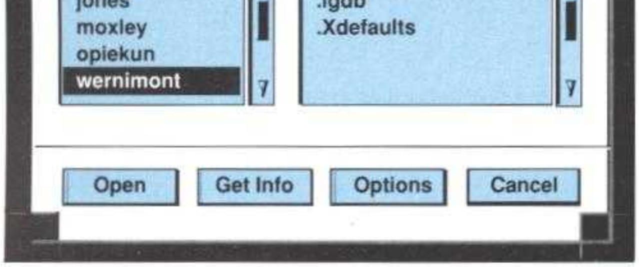


Figure 1. *MOTIF widgets will assist the developer in building user interfaces for interactive applications*

Ada Software Development Environment

The objectives of the Ada Software Development Environment task in 1989 were twofold: to improve COMSAT's expertise in developing Ada software and to implement several Ada programs using the Ada Programming Support Environment (APSE) established in 1988. The APSE includes a VAX 3500 computer and the DEC Ada compiler. The ultimate objective of this work is to make COMSAT competitive in the fast-growing market for Department of Defense (DoD) government and non-government Ada systems.

Ada is a modern computer language designated by DoD as the official language for all future software DoD projects. It supports the basic software engineering principles of abstraction and information hiding and is a strongly "typed" language (i.e., variable types must be defined unambiguously) that has strict cross-checking of interfaces. Further, Ada is a highly portable language that provides a software development environment independent of the computer or the operating system. Thus, software developed in Ada tends to be error free and reusable, which significantly increases software productivity while decreasing maintenance costs. Because of these benefits, Ada is becoming the language of choice in both commercial and governmental environments.

During 1989, all planned objectives of this task were accomplished. Eight additional COMSAT Systems Division (CSD) and Laboratories programmers were trained in Ada. Object oriented design (OOD) methodology was selected for use in future Ada software development projects, and Ada coding standards were defined. The APSE was used to verify the portability of Ada code and the feasibility of writing hybrid Ada and C language programs.

A generic real-time alarm handling program usable in a typical network monitor and control system was coded in the C language for the ACTS/MCS project. An Ada version of this alarm handler was coded and compiled on the Janus Ada compiler using an IBM PC that ran the MS/DOS operating system. This 600-line program was ported to the VAX 3500 computer (the APSE computer), where it was recompiled with the DEC Ada compiler and made operational under the VAX/VMS operating system. This process demonstrated the portability of Ada software on different computers, compilers, and operating systems. Finally, the low-level input/output modules of the Ada alarm handler were replaced with the corresponding input/output modules written in C from the ACTS/MCS software libraries. The resulting hybrid Ada/C program then successfully replaced the C alarm handler in the ACTS/MCS operation. This experiment proved that COMSAT's investment in C software can be protected using hybrid Ada/C programs.

COMSAT SUPPORT

Communications System Planning Model

The Communications System Planning Model (CSPM), begun in 1987, is an interactive computer program that facilitates planning of a satellite communications system. The need for CSPM stems from the large amount of data involved in the planning process and the desire to examine many system alternatives.

The first version of CSPM was completed in 1988. During 1989, the interactive user interface was enhanced significantly, and numerous features were added to give the user more control over the analysis algorithms performed. In addition, new output charts and diagrams can now be produced. The most significant addition to the user interface capabilities is the scrolling list box. The list box, an example of which is shown in Figure 2, can be added to any dialog and allows a user to browse through and select items from an available list. This feature has been integrated into many functions of CSPM because it reduces the required amount of input as well as the number of possible user errors.

CSPM's traffic routing algorithm divides the system-wide traffic between satellites in an ocean region to create traffic matrices for individual satellites. Traffic routing has been enhanced by enabling the system planner to control the order in which the satellites were considered during the process. In addition, communications services can now be routed individually, and intermediate results displayed. New output includes on a bar chart that graphically depicts the distribution of traffic among the satellites, as shown in Figure 3.

CSPM's traffic assignment algorithm assigns a satellite's traffic to specific transponders, resulting in a transponder loading plan. This algorithm has been enhanced to allow a system planner to assign one service at a time or remove a service from the generated transponder loading plan. During any phase in the assignment process, the planner can generate a report or a

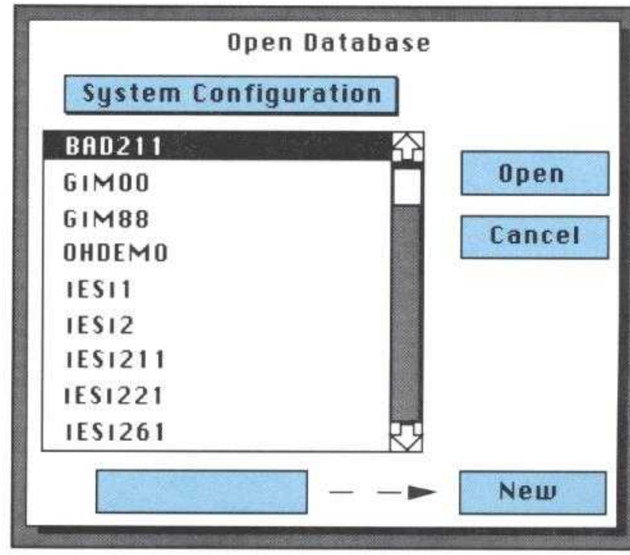


Figure 2. The CSPM scrolling list box allows a user to browse through and select items from a list

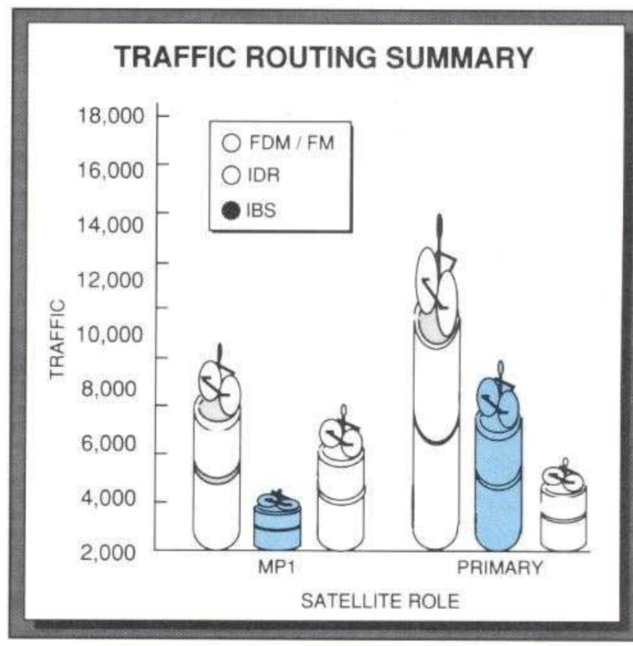


Figure 3. CSPM produces a bar chart that highlights traffic distribution in an easily understood manner

transponder loading plan diagram, such as that shown in Figure 4. From this diagram, the system planner can view the loading of a satellite's transponders. If the planner selects a transponder, the details of the services and transmission groups loaded on that transponder appear in a dialog box. After viewing the results, the planner can return to the traffic assignment algorithm and adjust parameters as necessary.

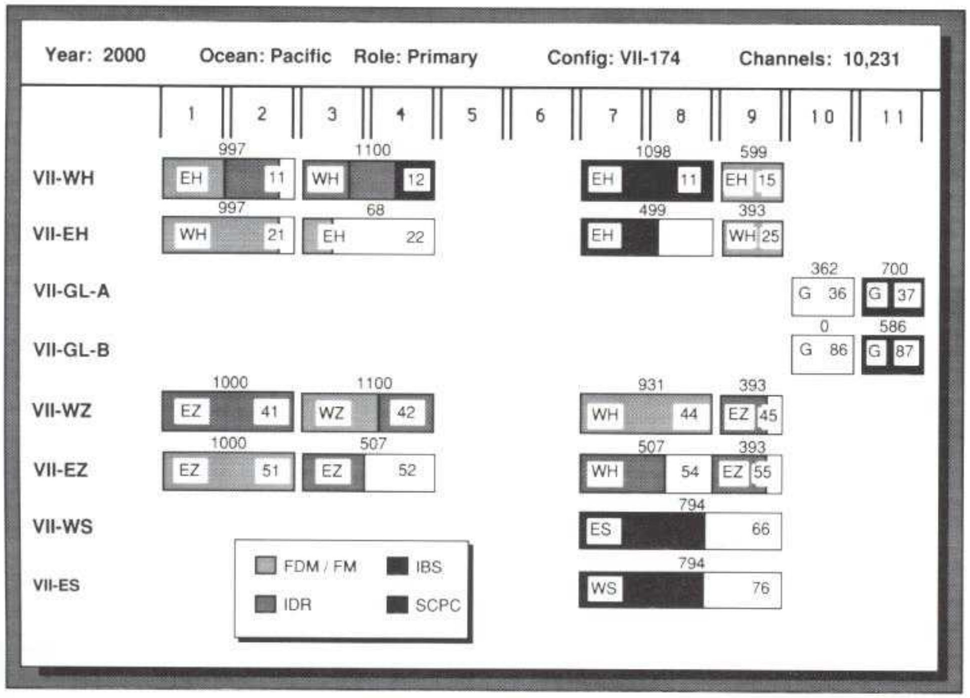


Figure 4. CSPM transponder loading plan diagram, which enables the system planner to view the loading of the satellite's transponders

from mathematical models for circular, elliptical, or shaped beams, from specified coverage outlines or sampled values of the far-field radiation pattern. During 1989, ACP was modified to produce contours of constant e.i.r.p. and G/T. In addition, the mathematical models used to produce circular and elliptical beams were improved to include antennas that use tapered parabolic aperture distributions.

One of the most important extensions to ACP in 1989 was the addition of a satellite availability analysis program. The availability of an earth-satellite link in the presence of rain is defined as the percent of time, averaged over a year, that the link impairments due to rain do not exceed the clear-sky margin. Given a description of a satellite and its antenna gain pattern, the effects of rain attenuation and degradation on link availability can be determined and graphically displayed in the form of contours of equal availability. These availability contours (see Figure 5) highlight the area on the earth's surface for which a satellite is available for a given percentage of time averaged over a year.

A further extension to ACP is the ability to compute beta factors for earth-satellite links. The up-link or down-link beta factor for an earth station with respect to a particular satellite antenna pattern is the difference between the gain measured at the earth station and the gain at the beam edge. In 1989, the INTELSAT V prelaunch antenna gain files were obtained from INTELSAT and converted to a format compatible with ACP. Using the new beta factors capability in conjunction with the newly obtained INTELSAT data, ACP can now generate beta factors for any of the INTELSAT V, VA, and VA IBS satellites.

Other work on ACP during 1989 was oriented toward producing higher quality plots by extending the range of user control over the features that define the world map. Some of the new map features include

The output of the economic analysis algorithm has been expanded to include bar charts for each of the existing output reports. In addition, the numerous parameters used in the economic analysis can now be saved by a user to a specified database file.

Other enhancements include additional links to the Intelsat Satellite Services (ISS) Database Management Facility (IDBMF), a quicker menu system, a multiple-record deletion facility, true field-editing capabilities, and easier screen movement capabilities. The second version of CSPM was completed at the end of 1989. A user's manual and programmer's manual for the new version were also completed.

ISS Software Support

The Antenna Coverage Program (ACP) generates satellite "footprints," or antenna beam patterns, on a world map. Significant enhancements and modifications during 1989 have made ACP a versatile tool for modeling and analysis of antenna coverage patterns.

ACP was originally designed to generate and display antenna beam patterns of normalized gain and flux density on a world map. Beam contours were generated

***Figure** 5. The ACP availability contours graphically display the effects of rain attenuation and degradation*

footnotes, automatic and user-defined beam labels, and highlighted beam contours.

The complete set of ACP documentation, including a theoretical manual, a programmer's manual, and a user's manual, was revised in 1989 to reflect these modifications and extensions.

Other software support activities during 1989 included the production of a new INTELSAT Satellite Antenna Beam Coverage Notebook. This notebook contains maps that show up-link and down-link antenna beam coverage regions for each of the current and planned satellites in the INTELSAT system. The coverage maps (as shown in Figure 6) were produced at COMSAT Laboratories using the ACP. Several enhancements were made to ACP to generate this notebook.

SDD also developed and conducted a series of training classes for the ISS staff in the use of the following software tools: IDBMF, ACP, CSPM, COIN, RAIN, STRIP6, LINK, and CIA5. The classes combined lectures with hands-on training. As part of the training, each student received a bound copy of the training materials as well as personal instruction during the hands-on sessions. SDD collected feedback from the participants on the effectiveness of each instructor and on the clarity of the class materials through the use of course evaluations. These evaluations will enable future classes to meet the needs of the students as well as provide the best possible training.

On-Board VSAT Hub Study

Under the sponsorship of ISS Business Development, SDD studied the idea of adding limited baseband processing and control functions (an on-board hub) to one transponder on a later INTELSAT VII spacecraft. The on-board hub would allow INTELSAT to offer an innovative and affordable thin-route telephone and data service. The initial focus was on thin-route service for the Pacific islands, but the idea is applicable in other areas of the world as well.

For the study, thin-route service was defined as one or two telephone or data circuits per earth station, expandable to perhaps four or eight circuits, and provided to customers at locations not presently served by either cable or satellite. For such a service, minimum earth station capital cost, and hence minimum size, is essential. However, to keep space segment charges affordable, this must be achieved without inordinately using spacecraft resources to compensate for the small size. An on-board hub addresses this issue by achieving maximum transmission efficiency, which allows the use of low-cost, mass-produced VSAT (very small aperture terminal)

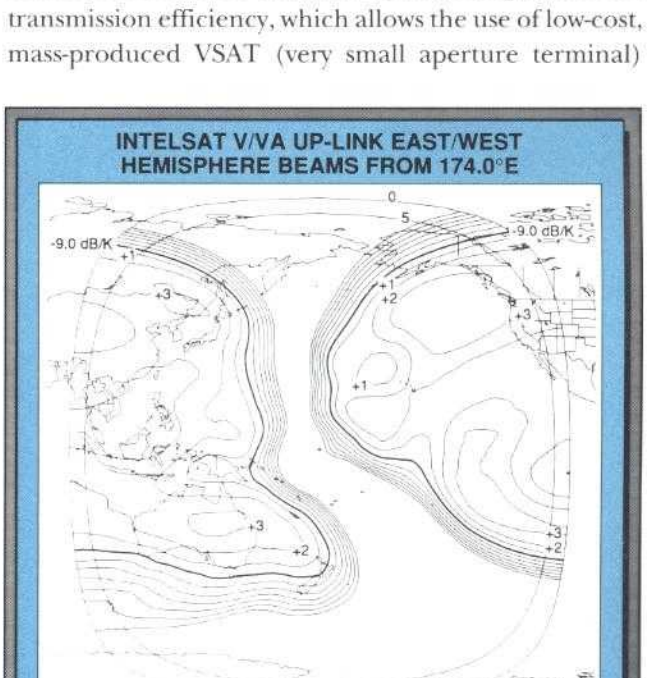


***Figure 6.** The INTELSAT Satellite Antenna Beam Coverage Notebook contains ACP coverage maps such as this one*

earth stations to be used, without requiring excessive spacecraft power or bandwidth. VSATs are available now from a number of vendors in several nations at prices of approximately U.S. $10,000. It is widely predicted that these costs will drop to U.S. $5,000 or so within 5 to 10 years, comparing favorably with the cost of HF radio equipment.

Currently, VSATs are kept small without inordinate use of satellite resources by linking them only to a large hub earth station, as shown in Figure 7. This works well for centralized business data networks; however, any transmissions between VSATs must be relayed through the hub earth station, resulting in a double delay of 520 ms.

The on-board hub shown in Figure 8 can provide full-mesh connectivity between VSAT earth stations with only one 260-ms user-to-user delay, allowing user-attractive telephony or efficient interactive data transfer protocols. Its location on the spacecraft at the natural center of the system allows for efficient and reliable demand-assigned multiple access and system control. Finally, putting the hub on the satellite avoids any problems

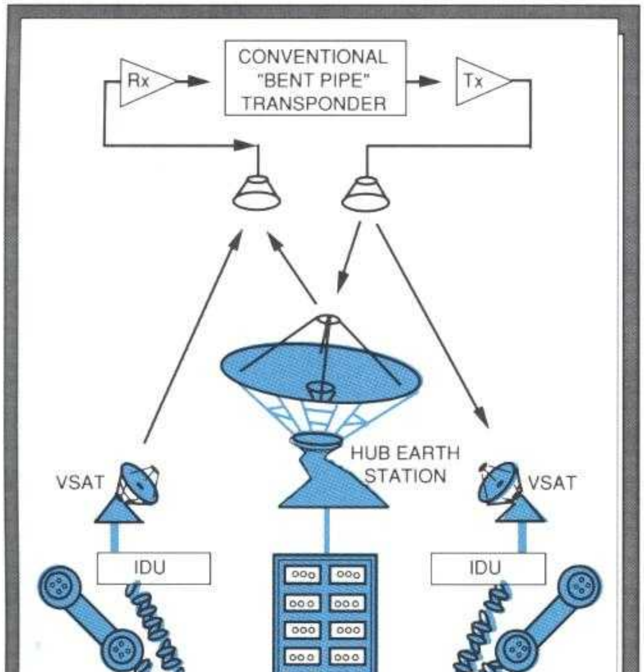


Figure 7. *VSAT with conventional hub*

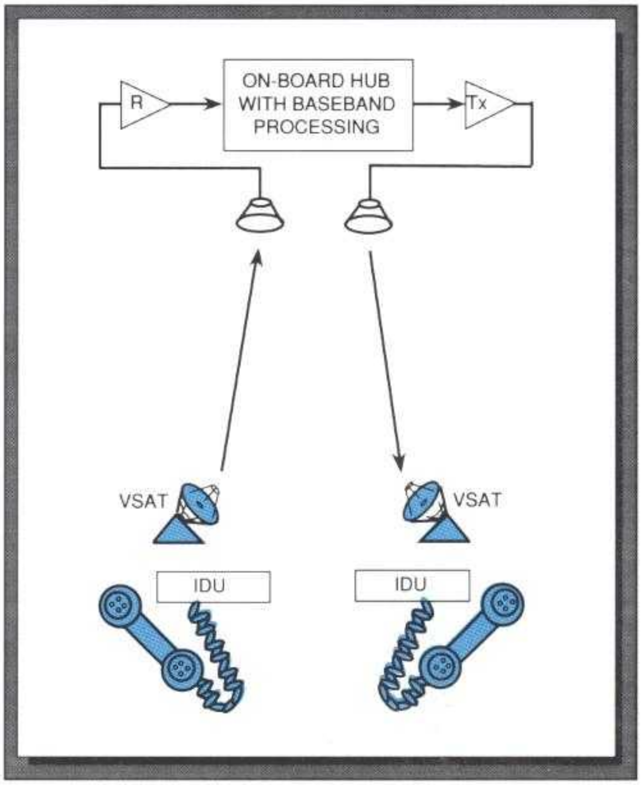


Figure 8. *VSAT with on-board hub*

associated with selecting a location for a large, ground-based hub and ensuring its near 100-percent availability.

The study showed that a capacity of hundreds of half-circuits per on-board hub transponder is feasible, using VSATs with antenna diameters of 1.8 to 3 meters at C-band or 1.2 to 2.4 meters at Ku-band. The required earth-station transmitter (HPA) power is only a few watts per circuit, which is approximately 20 to 40 times lower than that required for full-mesh connectivity with VSATs and a conventional transponder, even at maximum gain. The small earth stations can meet applicable International Radio Consultative Committee (CCIR) and INTELSAT Earth Station Standard (IESS) off-axis sidelobe requirements, and can operate with no significant interference to or from other spacecraft 3° away in orbit at C-band or 2° away at Ku-band. Demand-assigned multiple access (DAMA) control can be implemented by the on-board hub with simple procedures and few control messages. Detailed issues remain to be explored in 1990; however, no reason was found to doubt the technical feasibility of putting a hub on later INTELSAT VII spacecraft.

IDR Link Error Analysis Program

The INTELSAT intermediate data rate (IDR) Link Error Analysis Program (LEAP) was initiated in 1989 to formulate and analyze statistics of burst errors collected from a circuit operating over the INTELSAT IDR system. LEAP accepts as input an encoded binary file that contains a complete record of errors encountered on a link; the file is generated by the IDR Error Analyzer, which was developed by CSD. The encoded data are collected continuously in order to characterize the link under a variety of conditions, including rain impairments and interference, which can cause significant fluctuations in the bit error rate (BER). LEAP is a cooperative effort with the Communications Technology Division of COMSAT Laboratories, which was responsible for data capture and encoding and evaluation of the statistical results.

LEAP examines the errors on a data link and generates statistics used to predict the impact of the errors on perceived link quality. The statistics include overall BER, relative frequency of the length of error events and error-free intervals, and average number of errors within the range of error-event lengths. The results of the analysis are displayed as a table in a user output file and as a bar chart using histograms. LEAP was developed on an IBM/PC using C language for the analysis and Harvard Graphics for the display of histograms.

In 1990, additional analyses with the resulting graphic representation will be studied, and program documentation will be finalized.

Sun Outage Computation Program

The Sun Outage Program (SUNOUT) was developed to predict the effects of outages caused by sun interference in a satellite communications system. The program estimates the time of peak sun interference over the satellite link and the duration of the transit period, and it then computes the level of degradation in these periods.

Inputs to SUNOUT include the earth station and satellite locations, the low-noise amplifier noise temperature, the antenna diameter, the antenna noise temperature, the feed loss, the earth station receiving frequency, and the ambient temperature. Program output consists of the noise temperature of the sun, the system noise temperature, and the figure of merit of the receiving earth station during the days around the vernal and autumnal equinoxes. SUNOUT runs on the IBM mainframe under the CMS operating system and on the IBM/PC under the DOS operating system.

During 1989, the IBM/PC version of SUNOUT was implemented, and the program documentation was prepared.

Satellite Command Assistance Monitoring System

The Satellite Command Assistance and Monitoring Program (SATCAM) was developed in 1989 to demonstrate the feasibility of using expert systems to aid spacecraft operators in performing complicated spacecraft control operations. An expert system is a computer program that attempts to encapsulate human knowledge in the form of rules. The rules for an expert system can be written to effectively parallel the human expert's train of thought. Consequently, these rules can be used to simulate the method that a human expert might use to first determine that a problem exists and to then determine the cause of the problem.

SATCAM helps the spacecraft controller execute a north/south stationkeeping maneuver. During this maneuver, a sequence of commands is sent to the spacecraft to control appropriate on-board equipment and to fire the spacecraft thrusters that will move the spacecraft in a north/south direction. The following factors are crucial to the successful execution of this maneuver and are addressed by the SATCAM program:

- the spacecraft command sequence must be correct
- the correct sensors must be powered on and correctly configured
- once the thrusters begin firing, the spacecraft must be monitored to determine if the spacecraft remains stable.

SATCAM runs on an IBM PS/2 personal computer and uses the expert system shell NEXPERT and the user interface product EASE+. SATCAM requires two primary inputs: a proposed command list and a satellite telemetry stream. The command list is a sequence of commands that the user proposes to send to the satellite, entered through the EASE+ user interface into a database. The telemetry stream originates from the Satellite Technology Division's direct broadcast satellite simulator and enters SATCAM through an RS-232 port. The telemetry stream contains information that describes the satellite's current attitude (such as pitch angle, sensor values, and equipment states).

SATCAM provides several user options. The first option is to determine if invalid equipment is included in the command list and if analog values set by the commands exceed recommended thresholds. The second option is to verify that the spacecraft is ready for the north/south stationkeeping maneuver to begin, i.e., that the minimum equipment configuration exists and that the proper equipment is powered on. If SATCAM determines that the spacecraft is not ready to execute the maneuver, icons representing the offending equipment will be displayed in red and the user can choose to display messages that describe the problem. Finally, the user can select an option to monitor the spacecraft. At this point, SATCAM will plot four different telemetry variables with respect to real time.

A requirements document and detailed design document were completed in 1989, along with a document that describes an approach to expert system design.

INMARSAT Resource Modeling and Analysis Program

During 1989, SDD developed a software program to estimate satellite power and bandwidth requirements from a set of communications traffic projections. The INMARSAT Resource Modeling and Analysis Program (IRMA) was written in Microsoft Excel on the Macintosh computer. Inputs to IRMA include traffic forecasts and parameters such as required service grades, data rates, geographical traffic distributions, efficiency ratios, traffic conversion factors, and traffic growth rates. From these inputs, IRMA computes the satellite e.i.r.p. and bandwidth requirements. IRMA generates output tables and charts (see Figure 9), which graphically demonstrate the effects of the forecasts and varying parameters on satellite power and bandwidth requirements.

INMARSAT Standard-B Network Control Center

In 1989, SDD supported CSD in winning and beginning work on a contract with INMARSAT for Standard-B/M network coordination stations (NCS). Standard-B is the digital ship-to-shore satellite

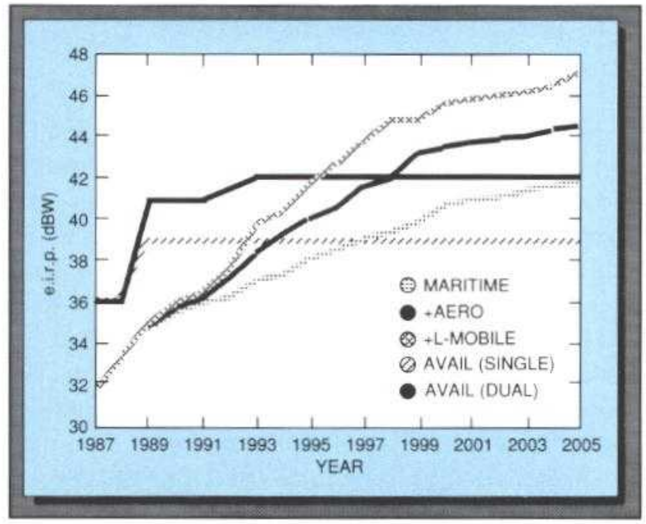


Figure 9. *IRMA generates tables and charts of satellite power and bandwidth requirements from a set of communications traffic*

communications system that INMARSAT is developing to eventually replace the existing analog Standard-A communications system. Standard-B will support voice and data calls, including distress calls and broadcasts. Standard-M is a simplified, voice-only version of Standard-B suitable for land mobile applications. Together, Standards B and M will serve a population of up to 500,000 mobile terminals.

The Standard-B/M NCS is the central computer and channel unit equipment that monitors and controls the network in each ocean region. Each of the three NCSs also communicate with INMARSAT's Operations Control Center (OCC) in London.

SDD is principally responsible for the operator interface software for the NCS and the OCC. Other contributions will include database management system (DBMS) utilities and specialized test support software. In 1989, SDD performed a structured analysis of requirements for the operator interfaces. During 1990, SDD will design, code, document, and begin testing the software system.

INTELSAT SUPPORT

Fixed TDMA Burst Time Plan Software

INTELSAT operates two time-division multiple access (TDMA) networks on satellites in the Atlantic Ocean Region and one TDMA network on a satellite in the Indian Ocean Region. Earth stations in these networks transmit communications traffic within preassigned time intervals as one or more high-rate streams of bits, referred to as bursts, using the entire bandwidth of a satellite transponder.

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

During 1989, SDD continued to maintain the BTPGEN software system and revise the software in response to INTELSAT's changing requirements. The orderwire assignment method was modified in response to problems encountered at a reference terminal, and the method for creating traffic return assignments was also revised.

At present, INTELSAT is investigating the feasibility of modifying current terrestrial interface modules for the TDMA terminals to allow transmission of asymmetric traffic links. If these modifications are made, COMSAT will modify the traffic assignment method in the software to comply with the new hardware capability.

Satellite-Switched TDMA Burst Time Plan Software

SDD is responsible for the development of the Satellite-Switched MTP/CTP (SS-MTP/SS-CTP) software system used with the INTELSAT Satellite-Switched TDMA (SS-TDMA) System. The SS-TDMA system will be employed on the newly launched INTELSAT VI satellite and will expand the coverage areas available to each earth station without requiring additional equipment at the station. It will also allow for much greater flexibility in traffic assignments through the satellite, since the beam connections can be dynamically reconfigured to respond to customer requests for transmission paths.

The equipment for the SS-TDMA system is currently being tested using output generated by the SS-MTP/SS-CTP software system. The first INTELSAT SS-TDMA system is scheduled for startup in the Atlantic Ocean Region in 1991.

In each INTELSAT SS-TDMA network, a community of transponders is synchronized to a common time period called the TDMA frame. During the frame, each accessing station transmits its traffic within preassigned time intervals as one or more bursts using the entire bandwidth of a satellite transponder. On the INTELSAT VI satellite, the beams on transmission channels 1–2 and 3–4 are dynamically switched. An INTELSAT SS-TDMA network comprises east and west reference stations with colocated diagnostic receiver equipment and system monitors, traffic stations, non-reference diagnostic receiver equipment, the INTELSAT Operations Center TDMA Facility (IOCTF), the Satellite Control Center, and the satellite.

In the SS-TDMA system, a TDMA frame is divided into a number of switch states. During each switch state, the on-board microwave switch matrix establishes switch connections to allow interconnections between up-beams and down-beams of a multibeam satellite. A particular earth station with a single up-beam coverage can then communicate cyclically (according to a controllable sequence over a TDMA frame period) with all of its destinations in various down-beams. The earth station communicates by placing its transmit bursts in time slots when the required beam connections are made by the microwave switch matrix. Figure 10 shows the basic concept of an SS-TDMA system.

For operation of the SS-TDMA network, a detailed satellite-switched burst time plan (SS-BTP) must be developed that provides the burst schedule as well as the switching sequence, maintaining transmission among stations within the various coverages without conflict. Requirements for control of the system must also be met. The SS-BTP is generated on the IBM mainframe computer at INTELSAT by combining a series of input traffic and network component specifications with the operational parameters and rules necessary for SS-TDMA equipment operation. After the SS-BTP is generated, this information is transferred to each reference or traffic station in the SS-TDMA network in the form of an MTP and a set of test and operational CTPs.

The MTP report is reviewed by the INTELSAT Signatory during network planning and contains all information necessary for the earth station to implement the time plan. The CTP is in an encoded format consistent

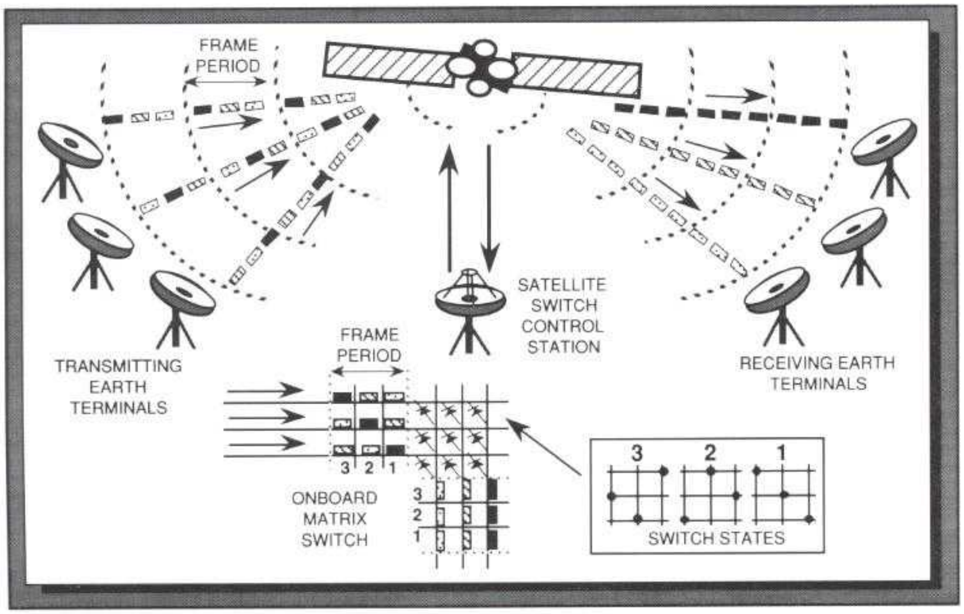


Figure 10. INTELSAT SS-TDMA Network

with ITA-2 transmission and contains a subset of the MTP information. The CTP is transmitted electronically to the terminal over the satellite and subsequently loaded into the terminal equipment. Time plans for the microwave switch matrix, diagnostic receiver equipment, and a diagnostic processor at the IOCTF are also used for equipment timing and control.

In 1988, SDD provided specifications for modifying the existing time plans in the INTELSAT TDMA system for use in the planned SS-TDMA system and proposed formats for a new series of time plans (TPs) to be used with the new equipment planned in the SS-TDMA system.

In 1989, SDD completed and delivered the SS-MTP/SS-CTP software system, which generates a set of coordinated MTPs, CTPs, and TPs for the physical elements of an SS-TDMA network from a database of burst schedule and control assignments. Figure 11 shows the design of the software system, which comprises two separate programs: one adding assignments to the database for the SS-TDMA network (SSMTPDATA) and one generating the coordinated set of time plans for each component of the network (SSGENTP).

This software system, which resides on the IBM MVS/TSO operating system, reads the database of SS-TDMA network assignments and adds network overhead assignments such as channel numbers and orderwires. It generates a coordinated set of MTPs and CTPs or TPs for each traffic and reference terminal, system monitor, and diagnostic receiver, as well as the satellite switch and the diagnostic processor at the INTELSAT Operations Center. The software system also provides an error-checking capability that monitors assignments against user errors. The MTPs are distributed by INTELSAT to all earth stations in the SS-TDMA network, and the CTPs and TPs are used for timing and control of the equipment. Figure 12 shows a typical

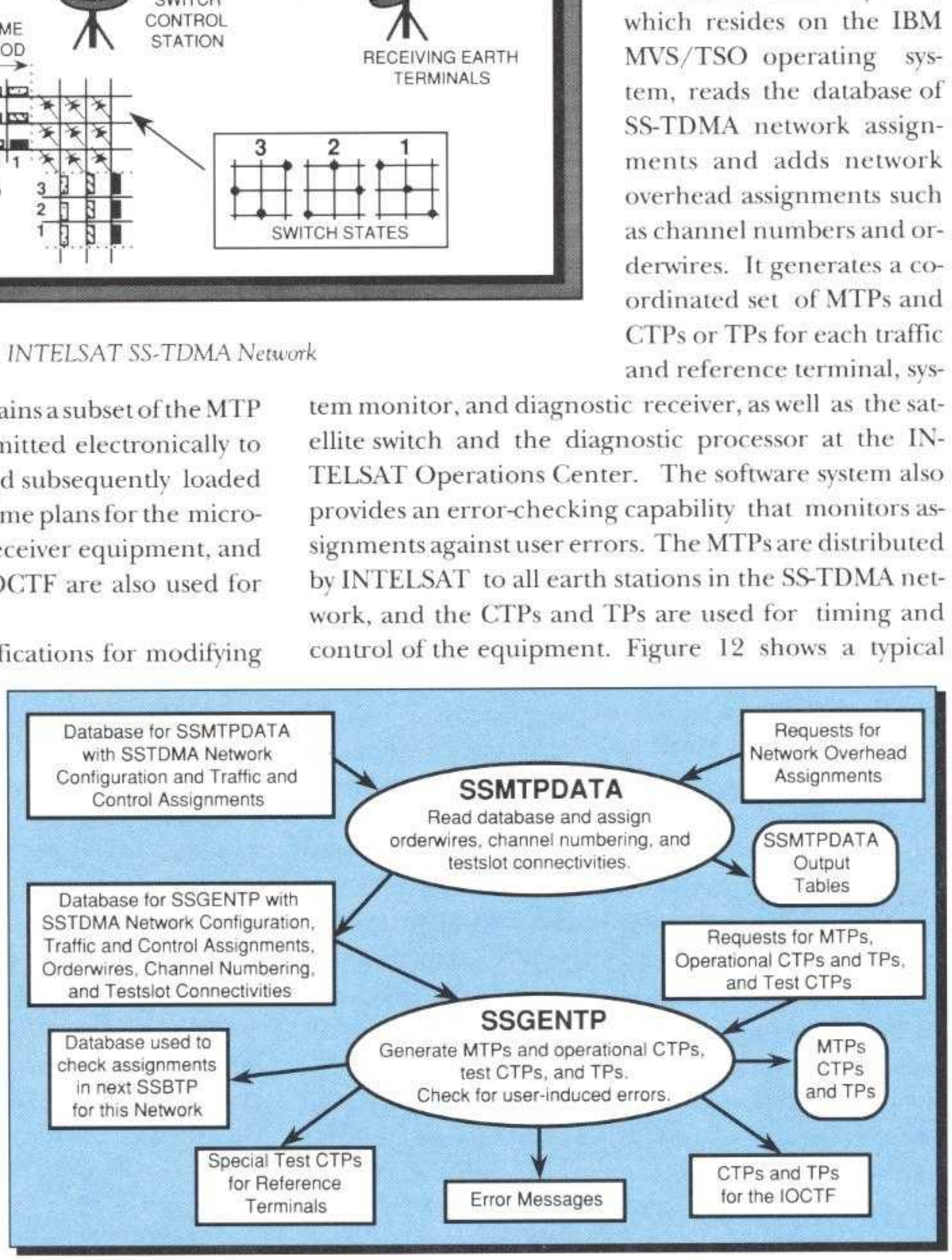


Figure 11. SS-MTP/SS-CTP software components

RECEIVE BURST INFORMATION

BURST (NO.)	RECEIVE TRANSPONDER	FREQUENCY	START OF BURST
22	51 (NEZ)	3745 MHZ	70361 SYM

BURST POSITION	LENGTH	FEC	SATELLITE CHANNELS
70560 SYM	4600 SYM	ON	59

TRANSMIT NAME / TERMINAL

KEN / 79

RECEIVE ORDERWIRES (ORIGINATOR / RETURN BURST / OW#)

P1 KEN (31 - P2)
P2 –
C1 KEN (31 - C2)
C2 –
C3 –
C4 –
C5 –
C6 –
C7 –
C8 –

SUB-BURST	TYPE	START (SYM)	LENGTH (SYM)	INTERNATIONAL CHANNELS VOICE	NB	TOTAL
1	DSI	81	3776	93	13	106

SATELLITE CHANNELS DSI	DNI	SUPV	TX DCME	DSI ALARM CHANNEL	RECEIVE DCME
0- 44	45- 57	58		193	

CONFIGURED CHANNELS AND (RETURN BURST / SUB-BURST)

77 V (BURST 31 SUB-BURST 1)
7 NB (BURST 31 SUB-BURST 1)

Figure 12. *Traffic burst page from an MPT*

page from an MTP, with information about a traffic burst received at the earth station. Documentation for the software system was written and is currently under review by INTELSAT.

During 1990, SDD will provide final documentation of the software system and a training class for INTELSAT personnel. In addition, SDD will continue to maintain the SS-MTP/SS-CTP software system and to respond to INTELSAT requests for modifications as various network configurations are tested and become operational.

Satellite Transmission Impairments Program

The Satellite Transmission Impairments Program (STRIP6) analyzes transmission impairments for all carriers in a frequency-reuse transmission channel of a geosynchronous satellite. The program computes the effects of up-link and down-link thermal noise, up-link and down-link intrasystem interference, and intermodulation distortion. It also computes the optimum transmitted power levels for each of the carriers.

The calculation of intermodulation distortion is the major contributor to computation time and memory requirements. As the number of carriers in the transmission channel increases, the time and memory required to compute transmission impairments increase exponentially.

In 1989, a new intermodulation analysis technique was incorporated into STRIP6 which has been shown to significantly reduce computation time for transponders having a large number of carriers while maintaining an acceptable level of accuracy. The algorithm was developed by the Communications Technology Division and incorporated into the STRIP6 program by SDD.

The Advanced Communications Technology Satellite (ACTS) program has been under development by the National Aeronautics and Space Administration (NASA) since 1984. Under direct contract to NASA's Lewis Research Center, COMSAT is responsible for developing the NASA Ground Station and the Master Control Station. This year saw the near-completion of the flight and ground segment hardware and software development, and the beginning of the flight and ground segment integration and test phases. Thus, the overall goal of developing basic technologies to ensure the continuing preeminence of the U.S. in the satellite communications industry is being realized. By combining its outstanding technical resources with a highly effective program management team, COMSAT Laboratories is demonstrating its ability to assemble and manage a large systems development and integration program.

ACTS PROGRAM MANAGEMENT OFFICE

Overall management of the ACTS program within COMSAT Laboratories, for both technical and business-related activities, is accomplished under the auspices of the Program Management Office (PMO). This office is staffed with personnel who have technical management expertise in each of the major work breakdown structure (WBS) elements, as well as with management and staff responsible for cost and schedule control/reporting activities. The PMO serves a dual role—providing internal matrix direction to all elements of COMSAT Laboratories engaged in work under the ACTS contract, and functioning as the principal liaison with NASA to address all planning, management, and performance reporting activities required by the contract.

All aspects of COMSAT's performance under the ACTS 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 their approval by NASA and implementation by COMSAT.

Each month, with the assistance of the Cost Account Manager responsible for a particular element of technical work in the program, the PMO assesses progress achieved against the work plan. Based on this information, cost and schedule variances from the plan are determined for each cost account, and corrective action is implemented or workaround plans are proposed as needed to bring performance back on target.

In those accounts where cost or schedule variances exceed a predetermined threshold, the PMO conducts a monthly formal internal review of the situation. It then reports to NASA, providing an assessment of the overall impact on the program and any corrective action necessary. A monthly program status review is also conducted by the PMO to keep the customer informed of all significant program and technical issues, together with the overall progress of each WBS element in the ACTS program.

As hardware and software development nears completion and the program moves into the system integration and test (I&T) phase, the PMO remains confident that these management techniques will result in successful conclusion of the ACTS NASA Ground Station (NGS) and Master Control Station (MCS) development programs.

SYSTEMS ENGINEERING

COMSAT's systems engineering role in the ACTS program includes responsibility for the engineering, analysis, integration, and testing associated with COMSAT's deliverable hardware and software. A second responsibility is to provide direct engineering and analytical support to NASA—a role that involves substantial technical interaction with NASA and with other ACTS program subcontractors. Both roles draw heavily on the Laboratories' technical resources and have led to significant engineering and analytical contributions.

A key milestone achieved during 1989 was the NGS/MCS Critical Design Review (CDR) held in November. This review essentially represented the end of the development phase and the start of the I&T phase of the COMSAT ACTS program. The CDR presentations and documentation focused on the system-level design of the NGS/MCS hardware and

ACTS

software. The objective was to show that all of the equipment under development will function together as a system to provide NASA with the required low-burst-rate (LBR) network control, ACTS payload command and telemetry processing, and experiment management functions.

One of the major milestones accomplished this year was the completion of the NGS/MCS Verification and Test Plan, which defines the strategy for bringing together the various elements of the COMSAT ACTS program and testing them as a fully operational system. The test plan defines each of the equipment deliveries to the systems I&T floor, defines the sequence and scope of tests to be performed, outlines requirements for test equipment, and details the layout of the I&T facility. The baseline test plan was delivered to NASA Lewis Research Center (LeRC) in conjunction with the NGS/MCS CDR in November.

Another major milestone was the completion and release of the LBR TDMA Network Control Performance Specification, which defines the architecture, control messages, and control procedures used in the ACTS LBR network. It also governs the behavior of the MCS and all LBR time-division multiple access (TDMA) terminals in the LBR network. The specification was originally drafted as a lower-level design specification for the COMSAT TDMA equipment. However, with the restructuring of the ACTS contract in 1988, the document was elevated to the status of an ACTS-wide system specification. During 1989, the specification was substantially modified to reflect this expanded role, and was subjected to a thorough review prior to delivery to NASA in conjunction with the NGS/MCS CDR. Systems Engineering continues to maintain this document through the ACTS LBR Working Group.

During 1989, all of the COMSAT-internal interface specifications were completed and delivered to NASA at the NGS/MCS CDR. These specifications detail the physical and logical requirements for each interface between the major NGS/MCS subsystems [RF Terminal (RFT), TDMA, and MCS] and are used by the subsystem development teams in implementing their respective equipment. By carefully documenting and controlling these interfaces, COMSAT expects to eliminate many of the interface problems that typically arise during the I&T phase of a large, multidisciplinary program. A total of 12 documents were produced, reviewed, and released. These included facilities requirements documents, which specify COMSAT's equipment facility needs (e.g., AC power, cooling, and floor space) for operation at the NASA LeRC facility.

Throughout 1989, Systems Engineering continued its support of the ACTS system interface working groups. These groups were chartered by NASA to develop and maintain the various interface control documents that govern the interfaces between COMSAT equipment and the equipment provided by the other ACTS contractors. The support included attendance at working group meetings, numerous telephone consultations, and processing of interface change requests.

Perhaps the most significant milestone achieved during 1989 was the successful integration of the MCS with the Communications Bus Simulator (CBS) and the Engineering Model-Communications Electronics Package (EM-CEP). The EM-CEP is a set of hardware that emulates the functions of the ACTS spacecraft payload. The CBS provides a baseband telemetry, tracking, and command (TT&C) interface to the EM-CEP and mimics the TT&C interfaces that the MCS will connect to at NASA LeRC. The CBS and EM-CEP were built by General Electric (GE) and provided to COMSAT as government-furnished equipment.

During December, the EM-CEP was installed in the COMSAT systems I&T facility by GE technicians, with assistance from COMSAT personnel. After several checkout tests of the EM-CEP, the communications link was established between the MCS and the CBS/EM-CEP. Informal checkout tests of the MCS command and telemetry processing software demonstrated flawless operation with the CBS/EM-CEP, thus retiring one of the major ACTS program risk elements. Formal acceptance testing is planned for early 1990. Figure 1 depicts COMSAT engineers using the CBS/EM-CEP for MCS software testing. Figure 2 shows the EM-CEP that will be used to emulate the performance and behavior of the ACTS spacecraft.

RF TERMINAL DEVELOPMENT

During 1989, substantial progress was made toward completion of the RFT portion of the NGS. COMSAT's Microwave Components Division was responsible for the major portion of this task, except in the areas of modems and traveling wave tubes, where the specialized skills of the Communications Technology Division (CTD) and the Satellite Technologies Division were utilized.

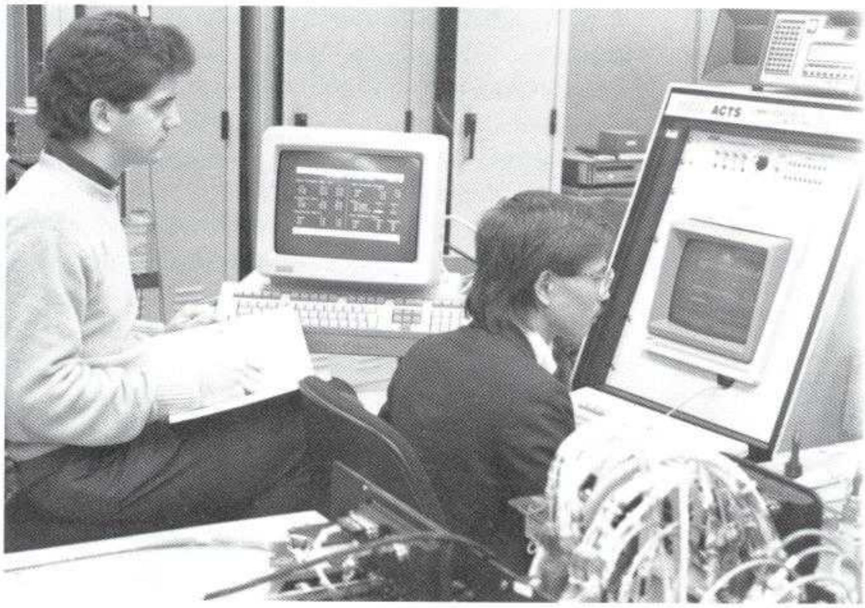


Figure 1. MCS software is used to test the communications bus simulator

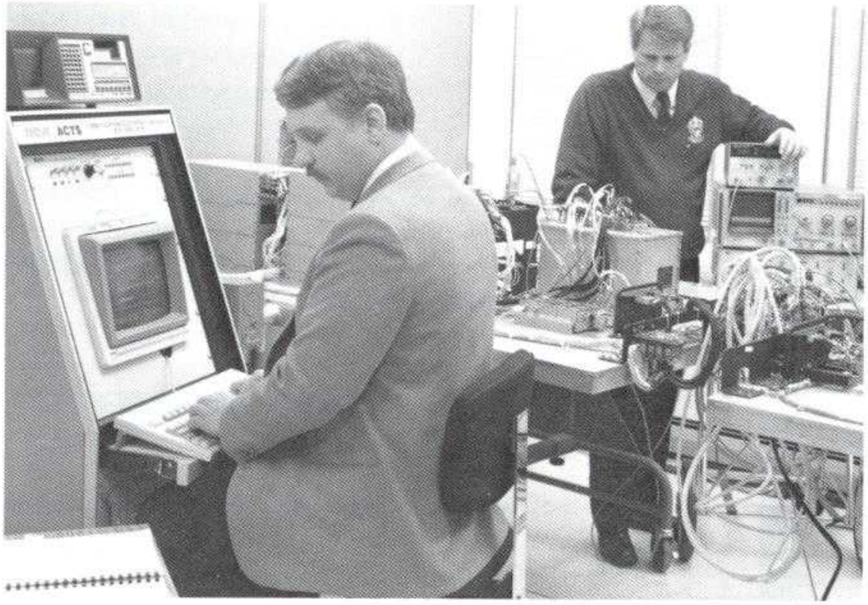


Figure 2. COMSAT I&T personnel operate EM-CEP to emulate the ACTS spacecraft

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

The major product of in-house activity in 1989 was the fabrication, assembly, and testing of most of the RFT hardware to be delivered by COMSAT. During the year, 20 complex subassemblies were integrated into eight equipment racks. At year's end, the eight racks were being incorporated into the ACTS system I&T facility, where the three major subsystems (MCS, TDMA, and RFT) will ultimately be integrated.

Figure 3 shows portions of the RFT equipment under test. In the center of the picture is the antenna frame, a structure which will stand below the central vertical axis of the antenna in the final installation at LeRC. The four waveguides from the antenna ports will be connected to RF transmit and receive interfaces in the antenna frame. The 27-GHz low-noise amplifier assembly can be seen against the left-hand side of the antenna frame, below the transmit diplexer switch assembly. The racks contain the up-converters and transmitter amplifiers (to the left) and the receive down-converters (to the right). Further to the left are the loopback equipment racks.

Figure 4 shows (at right) the beacon measurement system equipment, which measures the strength of three signals transmitted from the spacecraft. This information is used by the MCS to determine rain fade attenuation levels at two frequencies, and thus whether LBR signal coding is required to combat fading. Figure 4 also shows the utility racks containing experiment measurement and computer equipment.

The RFT will be controlled and monitored by the RFT supervisor and implemented on a Hewlett-Packard 9000/350C computer. The majority of the hardware for this function has been procured, and the software is now actively under development for a planned integration with the RFT hardware in 1990.

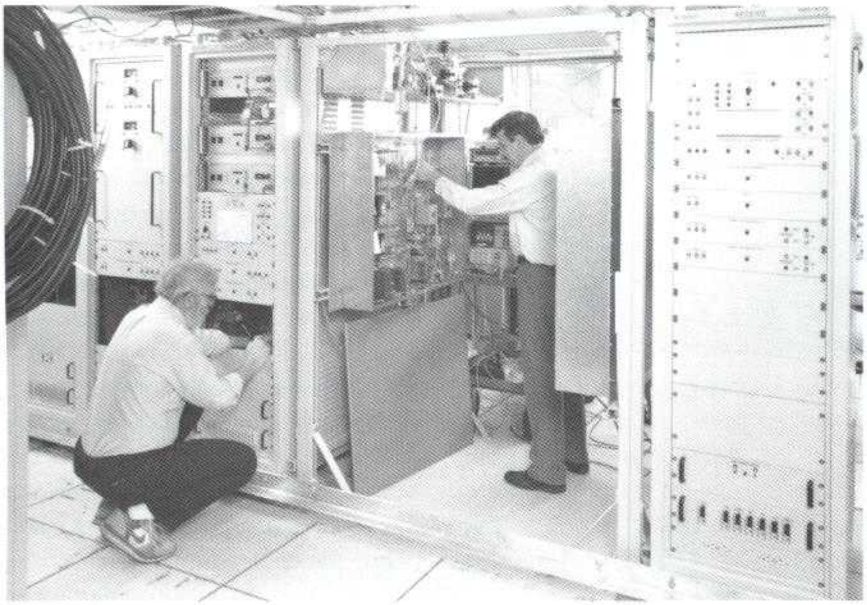


Figure 3. *RFT transmit and receive equipment*

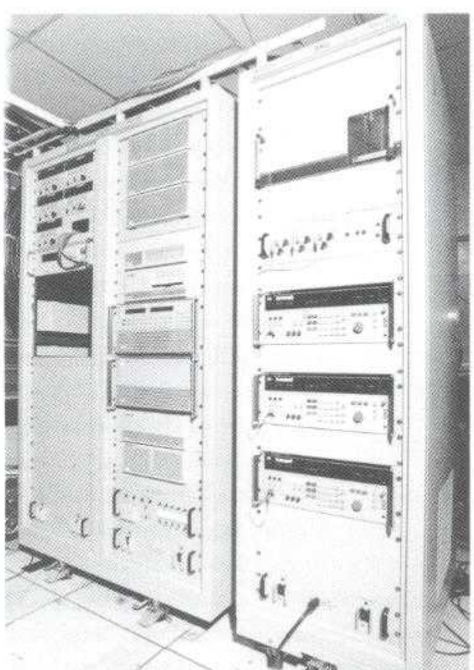


Figure 4. *RFT utility and beacon measurement subsystem measures spacecraft signal strength*

In parallel with the hardware development at COMSAT Laboratories, portions of the RFT are being developed outside of COMSAT. During this year, the final medium-power amplifier was delivered from Hughes Aircraft Company, completing a subcontract for three operational amplifiers and assorted spares. COMSAT has been monitoring the modem development work being performed by Motorola under a contract between Motorola and GE. Upon completion, the modems are to be provided as government-furnished equipment to COMSAT for integration into the RFT.

During 1989, specification and procurement documents were prepared for the 5-m antenna, which is to be installed in 1991 at LeRC to provide the link to the ACTS spacecraft. The procurement process led to the selection of Toronto Iron Works (TIW) as the vendor to develop, build, test, and install the antenna. The antenna will include a diplexer to separate the transmit and receive signals, with each signal being received on two polarizations. This diplexer will be developed, fabricated, and tested at COMSAT Laboratories and shipped to TIW for integration into its deliverable product.

TDMA TERMINAL DEVELOPMENT

COMSAT Laboratories has developed two TDMA terminals that will be integrated into the ACTS NGS: a 110-Mbit/s TDMA terminal serving as both the LBR reference terminal and a traffic terminal; and a 27.5-Mbit/s TDMA terminal serving as a stand-alone traffic terminal. The reference terminal acquires and synchronizes to the baseband processor (BBP)-generated TDMA frame in order to transfer the MCS control and status orderwire channels to the BBP and the LBR terminals. It also preprocesses these orderwire channels, which have a combined maximum rate of 1.476 Mbit/s. The reference terminal continuously compares BBP on-board clock drift to a local frequency standard, and periodically reports deviations to the MCS. The MCS then up-links frequency corrections to the BBP to maintain network clock stability.

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

The Network Technology Division (NTD) has primary responsibility for TDMA terminal development, from architectural concept through design and production and into subsystem acceptance testing. NTD will also provide support during systems integration and acceptance testing.

The forward error correction (FEC) decoder module was designed by CTD. It employs an LSI (large-scale integration) decoder circuit and provides some basic on-board self-testing features.

NTD has developed a TDMA design and documentation methodology that is structured in a six-level, top-down hierarchy. The highest levels include external interface specifications and major subsystem functional partitioning. Middle levels include analyses to derive the lowest-level functional elements in terms of hardware/software partitioning, and tradeoffs to map functional requirements into the physical implementation. The lowest levels include detailed electrical design of hardware using computer-aided engineering workstations, logical design and coding of embedded microprocessor software, and overall I&T of the terminals. This meticulous approach ensures that the design implementation fulfills all program requirements.

Figure 5 is a functional block diagram of the 110-Mbit/s TDMA terminal design. The 27.5-Mbit/s design is identical except for deletion of the transmit and receive MCS interfaces. The terminals are partitioned into two major subsystems: the terrestrial interface equipment (TIE) and a TDMA burst controller. The major functional elements of each are given below.

Terrestrial Interface Equipment

- ***T1 and 6.312-Mbit/s interfaces*** provide terrestrial line interface, plesiochronous buffering of channel data, and T1 supervisory signal processing.
- ***Transmit and receive bus controllers*** provide digital switching of channel data to/from the burst controller or the signaling-extraction/signaling-generation (SXU/SGU) hardware under call processor control.
- ***SXU/SGU*** provides DTMF (dual-tone multifrequency) selective signaling reception/transmission to or from experimenter channels for dynamic single-channel routing in the LBR network.
- ***Receive and transmit traffic buffer interfaces*** buffer channel data for high-speed transfer to/from the TDMA burst controller.
- ***Demand-assigned multiple access (DAMA) call processor*** processes supervisory and address signaling to/from experimenter channels, sends and receives orderwire messages to/from the MCS to acquire and release satellite capacity, dynamically routes channel data to/from the burst controller, and maintains call records for operator status display.

TDMA Burst Controllers

- ***Receive and transmit MCS interfaces*** provide high-speed transfer and preprocessing of orderwire channels to/from the MCS, the BBP, and the traffic terminal network.
- ***Receive and transmit traffic interfaces*** buffer channel data to/from the TIE and route channels into MCS-assigned satellite slots.
- ***DAMA (receive and transmit frame management)*** dynamically alters TDMA frame structure and traffic slot assignments in response to MCS orderwire commands, and performs synchronous burst time plan changes.
- ***Receive and transmit timing and control*** acquires and maintains synchronization to the BBP TDMA frame.
- ***Receive and transmit space segment interfaces*** multiplex/demultiplex channel data to/from the TDMA bursts at either the 110- or 27.5-Mbit/s serial rates, and provide FEC encoding/decoding at rate 1/2 and constraint length 5.

- *System executive* provides overall terminal monitoring and control, processes MCS monitor/control and LBR fade data links, and interfaces with the terminal operator for commands and status displays.

The terminal design presented in Figure 5 represents a carefully balanced selection of digital hardware and microprocessor software components. High-speed digital logic and carefully engineered digital interconnection backplanes ensure error-free and reliable performance, while the extensive use of programmed array logic hardware and microprocessor firmware ensures a design that can be easily adapted to the needs of NASA's experimental program, as well as to the operational requirements of future commercial terminals in the ACTS system.

Overall, the TDMA terminal design requires 42 unique hardware module designs and 77 firmware processes. During 1989, all hardware design, fabrication, and assembly was completed, including 235 circuit boards and seven racks of equipment. Figure 6 shows examples of several TDMA circuit board designs. Design verification testing was successfully completed on all hardware. A COMSAT-designed monolithic printed-circuit backplane based on the VME-Bus standard is the backbone of the TDMA subsystem hardware design. This backplane simultaneously passes transmit and receive data at rates up to 110 Mbit/s. Testing showed error-free performance.

Also during 1989, all firmware design and coding was completed. Over 43,800 lines of code were required. All firmware was integrated into functional firmware subsystems, and design verification testing was completed. The firmware employs an NTD-developed State Machine Generator utility program that has proven highly successful in creating C-language code from high-level state machine descriptions. All code for the ACTS TDMA microprocessors is designed to run in the COSMOS (an NTD-developed real-time executive program) operating environment.

The TDMA Subsystem CDR was held in August. COMSAT presented the detailed design of the TDMA and TIE, along with associated test plans, and demonstrated the hardware and software completed to date.

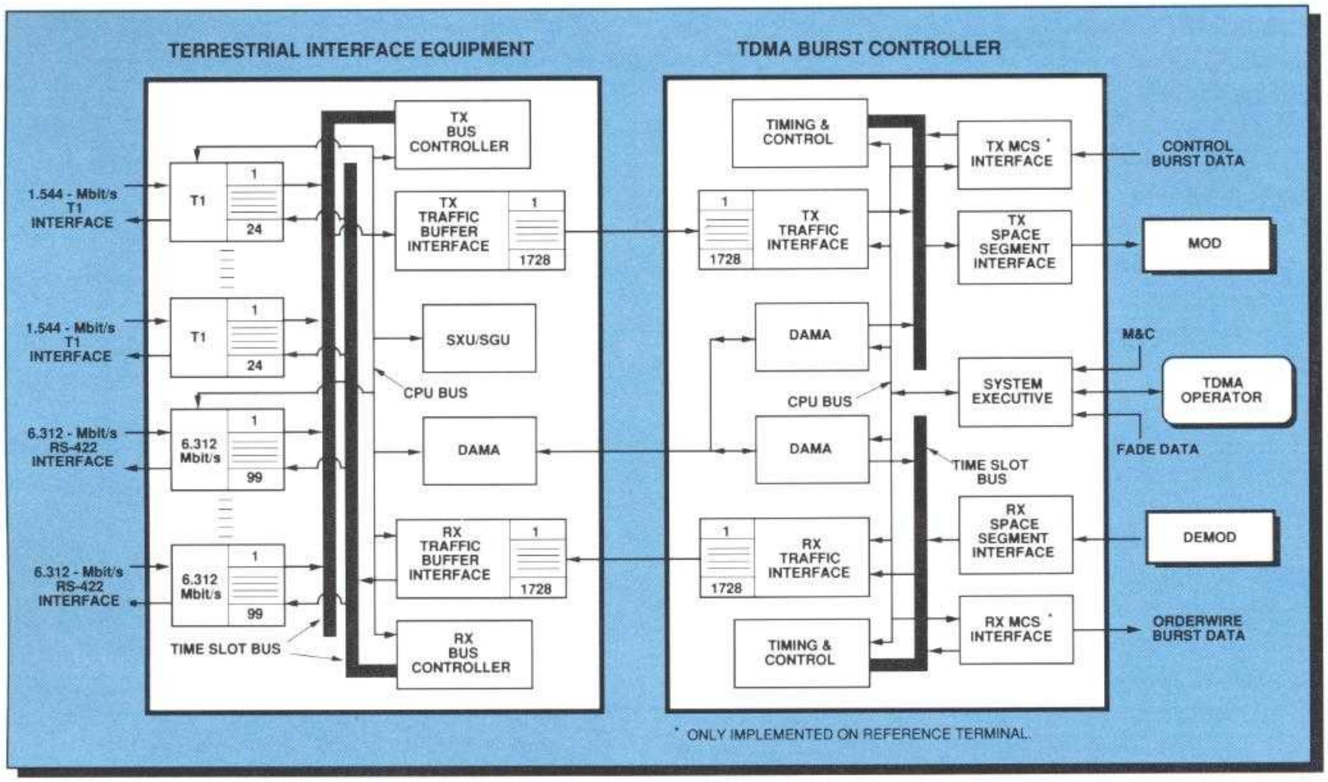


Figure 5. *COMSAT's 110-Mbit/s TDMA terminal functional architecture*

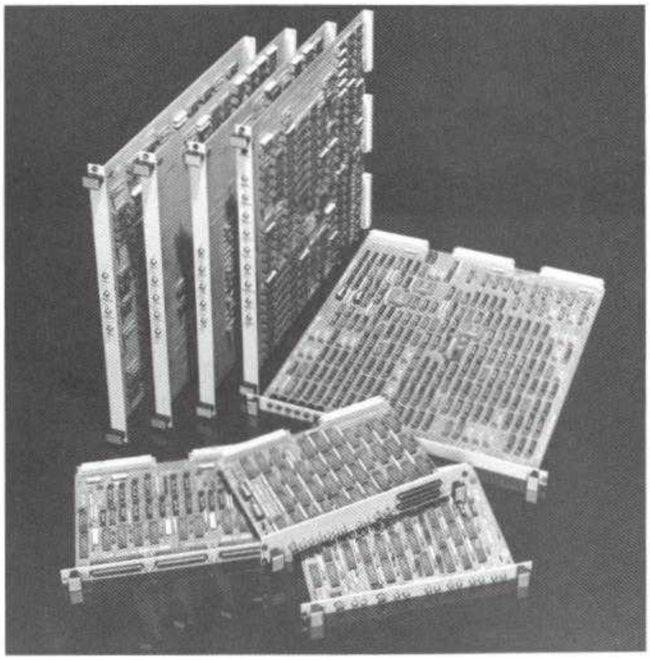


Figure 6. TDMA circuit boards

Hardware/firmware integration testing has been completed. Figure 7 shows five racks of equipment which comprise the 110-Mbit/s TDMA subsystem configured for final subsystem integration. From the left, the first two racks are the TIE, and the third rack contains the TDMA burst controllers, as well as the receive and transmit burst controllers for the 110-Mbit/s TDMA terminal. The fourth rack is the clock distribution subsystem, which contains the cesium frequency standard used to measure the accuracy of the spacecraft's on-board reference oscillator. It also contains synthesizers that generate signals used by both TDMA terminals and by the COMSAT-designed special test equipment. The last rack (far right) contains COMSAT-designed special test equipment that performs limited simulation of the MCS and the satellite BBP.

MCS DEVELOPMENT

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

During 1989, the MCS reached the point where 90 percent of the code was completed, and the major effort switched from design and coding to I&T.

The MCS Subsystem CDR held in May focused on the changes that had occurred since the MCS subsystem Preliminary Design Review. Areas where the design had changed or matured were presented, and the development, integration, and test status was reviewed. A detailed presentation of the DAMA algorithm was made. This algorithm has been designed and implemented to minimize call setup time, minimize the number of commands required for reconfiguring the network, maximize the use of the available BBP capacity, and minimize the processing load on the VAX 8600.

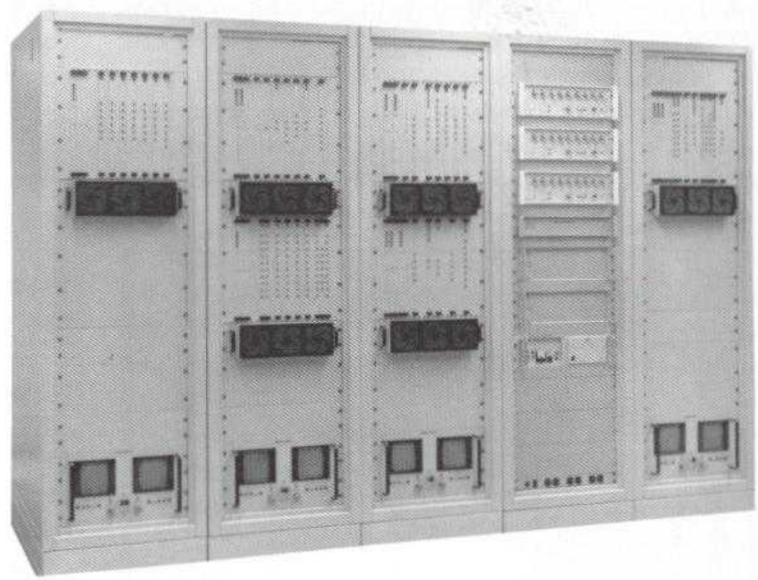


Figure 7. 110-Mbit/s TDMA subsystem and special test equipment configured for testing

A major part of the CDR consisted of a demonstration of the MCS software in a test environment. This demonstration was based on preliminary integration of the components of the LBR Network Control and the MCP (multibeam communications package) Telemetry and Control Subsystems of the MCS. The experiment configuration software was also demonstrated, including nearly all of the real-time MCS software and a major portion of the test support software. A nominal-size network of 12 LBR traffic terminals was simulated. All of the steps required to set up and run an LBR experiment were performed, including the following:

- definition of initial experiment parameters
- initialization of the MCP and BBP
- acquisition of the LBR reference terminal and traffic terminals
- traffic simulation
- shutdown of the network.

During operation, the MCS will be connected to GE-supplied TT&C equipment and to the LBR TDMA reference terminal equipment (RTE). The TT&C equipment will provide command and telemetry links between the MCP and the MCS. The MCS will use these links for sending commands to set the initial configuration of the MCP at the beginning of an experiment and to continually monitor the telemetry from the MCP for anomalies. Once the MCP/BBP has been initialized and the LBR reference terminal has been acquired, the MCS will use control circuits through the LBR reference terminal to communicate with the BBP and the LBR traffic terminals via inbound and outbound orderwires. This operational environment is illustrated in Figure 8.

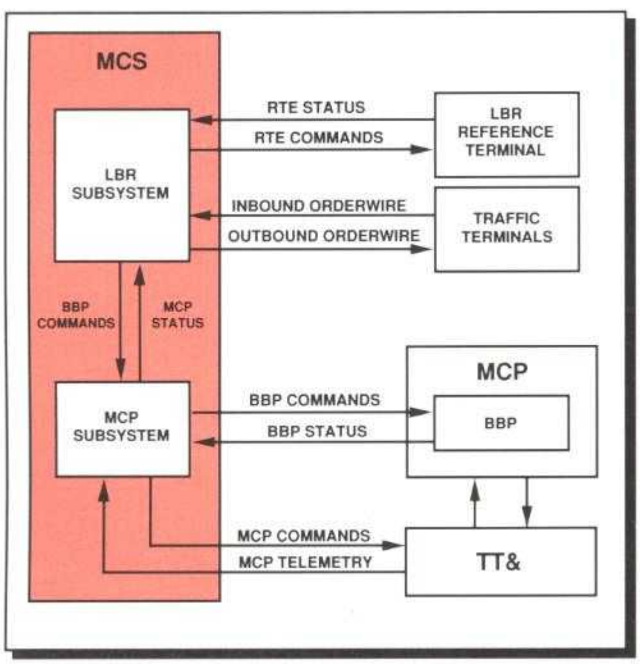


***Figure 8**. MCS operational environment*

For MCS subsystem testing, the test software provides the control and status portions of the network (not the traffic channels) and thus simulates the operation of the MCP/BBP, LBR reference terminal, and traffic terminals. This software test environment is depicted in Figure 9. The major elements of this environment are the orderwire simulator, BBP simulator, MCP TT&C receiver, and telemetry simulator. The orderwire simulator processes outbound orderwire messages and provides the proper response to the MCS. It also generates inbound orderwire messages to simulate capacity requests, fade requests, and terminal status. The BBP simulator processes BBP commands from the MCS and provides BBP status information back to the MCS. The MCP TT&C receiver processes TT&C link commands and sets the proper values for use by the telemetry simulator, which then generates telemetry data frames for the MCS. The test software provides the capability to create both normal and abnormal data, so that error conditions can also be tested. This software has been used extensively during testing of the MCS, and will continue to be used for future testing, including the acceptance tests.

During 1989, the design, coding, and component-level (program) testing was completed for the LBR network control, MCP telemetry and control, and experiment configuration subsystems. Design and coding were also completed for two components of the executive subsystem. Design of the NGS interface software was begun.

Subsystem I&T ("build" tests) of the MCS software also proceeded during 1989, with four builds completed and two more nearing completion at year's end. All of the MCP telemetry and control subsystem I&T activities have been completed. The final LBR network control build test will be completed in early 1990. One of the experiment configuration build tests was completed, and the other was nearing completion at year's end.

The first two MCS system-level build tests were completed. The MCS/CBS Interface build software was delivered to System Engineering for testing with the GE-supplied CBS. The second system build, MCS TT&C Operations, is awaiting regression tests which will be performed following completion of software updates that are necessary to incorporate recent changes to the spacecraft payload telemetry and command lists. This second build will be used in formal testing with the EM-CEP early in 1990.

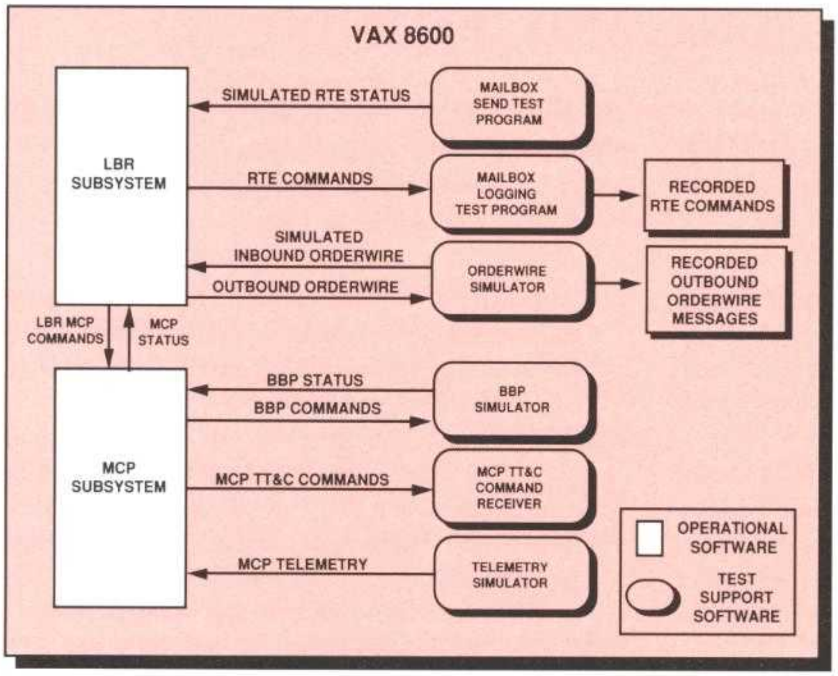


Figure 9. MCS simulated (test) environment

PERFORMANCE ASSURANCE

During 1989, the COMSAT Performance Assurance (PA) team continued to support the ACTS program in the areas of design reviews, component and subsystem procurement reviews, inspections, manufacturing engineering, production planning, configuration management, product assurance, and product safety.

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

COMSAT's PA program also encompasses software. The software PA personnel continued to maintain the configuration control database for all released software for the MCS, TDMA, and RFT. At year's end, the software libraries contained over 11,500 ASCII and binary files, including source files, test data files, and documentation files. Software PA personnel also established and maintained a reference library of specifications, drawings, analysis documents, and test data for ACTS Systems Engineering.

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

PUBLICATIONS AND PATENTS

The following is a list of 1989 publications and patents by authors at COMSAT Laboratories. Copies of the publications may be obtained by contacting the COMSAT authors at COMSAT Laboratories, 22300 Comsat Drive, Clarksburg, MD 20871-9475.

PUBLICATIONS

AGARWAL, A., and D. Kloper, "A Joint COMSAT/NIST Experiment on Connectionless-Mode Network Protocol," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 183–189.

ALLNUTT,** J. E., and D. V. Rogers, "Low-Fade-Margin Systems: Propagation Considerations and Implementation Approaches," 6th International Conference on Antennas and Propagation, University of Warwick, Coventry, U. K., April 1989, *IEE Conference Publication No. 301*, Part 2, pp. 6–9.

BONETTI, R. R., and A. E. Williams, "A Quadruple-Mode Contiguous-Band Multiplexer for Communications Satellites," 19th European Microwave Conference, London, September 1989, *Digest*, pp. 687–691.

BONETTI, R. R., and A. E. Williams, "A 6-Pole, Self-Equalized Triple-Mode Filter With a Single Cross-Coupling," 19th European Microwave Conference, London, September 1989, *Digest*, pp. 881–885.

CAMPANELLA, S. J., and J. H. Rieser, "Operating Aspects of New LRE/DSI DCME," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 803–811.

CHITRE, D. M., "Network Architectures for Satellite ISDN," 8th International Conference on Digital Satellite Communications, Guadeloupe (ICDSC8), FWI, April 1989, *Proc.*, pp. 721–727.

CHITRE, D. M., and R. Kohli, "Performance Modeling and Analysis of VSAT Networks," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 215–221.

DAS,* A. K., A. Mukhopadhyay,* A. Paul,* and D. K. Paul, "Optimum Fusion Splicing Condition of Optical Fibers," Conference on Fiber Optics Reliability: Benign and Adverse Environments III, Boston, MA, September 1988, *Proc. SPIE*, Vol. 1174, pp. 358–368, D. K. Paul and R. A. Greenwell, eds.

DIMOLITSAS, S., "An Adaptive IIR Filter Based on the Hurwitz Stability Properties and a Chebychev System Function Approximation," *Signal Processing*, Vol. 17, No. 1, May 1989, pp. 39–50.

DIMOLITSAS, S., "Objective Speech Distortion Measures and Their Relevance to Speech Quality Assessment," *Proc. IEE*, Part I: Communications, Speech and Vision, Vol. 136, No. 5, October 1989, pp. 317–324.

EARL, M., J. Dunlop, R. Beauchamp,* and J. Sindorf,* "Design and Development of an Aerospace CPV Ni/H_2 Battery," 24th Intersociety Energy Conversion Engineering Conference, Washington, DC, August 1989, *Proc.*, Vol. 3, Electrochemical Storage and Conversion, pp. 1395–1400.

EVANS, J. V., and C. E. Mahle, "Research Into Advanced Satellite Technology at COMSAT Laboratories," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 593–600.

GELLER, B., F. Assal, R. Gupta, and P. Cline, "A Technique for the Maintenance of FET Power Amplifier Efficiency Under Backoff," IEEE MTT-S International Microwave Symposium, Long Beach, CA, June 1989, *Digest*, pp. 949–952.

GOURLEY, S., S. Siddiqi, J. Potukuchi, F. Assal, R. Gupta, and R. Mott, "An Ultra-Broadband Linear Phase Shift Module for Phased-Array Applications," SBMO International Microwave Symposium, Brazil, July 1989, *Proc.*, pp. 53–58.

GREENWELL,* R. A., and D. K. Paul, eds., *Proc. SPIE*, Vol. 1174, Conference on Fiber Optics Reliability: Benign and Adverse Environments III, Boston, MA, September 1988.

HEGAZI, G., H-L. A. Hung, J. L. Singer, F. R. Phelleps, A. B. Cornfeld, T. Smith, J. F. Bass, H. E. Carlson, and H. C. Huang, "GaAs Molecular Beam Epitaxy Monolithic Power Amplifiers at U-Band," IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium, Long Beach, CA, June 1989, *Digest*, pp. 209–213.

* Non-COMSAT author.
**INTELSAT author.

HEMMATI, F., "Closest Coset Decoding of | u | u + v | Codes," *IEEE Transactions on Selected Areas in Communications*, Vol. 7, No. 6, pp. 982–988.

HULLEY, M., and J. Stevenson,** "Multiple-Stress Testing in the Screening of Space TWTAs," ESA/ESTEC International Workshop on Requirements for Space TWTAs in the 1990s, Noordwijk, The Netherlands, *Proc.*, pp. 295–302.

HUNG, H-L. A., T. T. Lee, P. Polak-Dingels,* E. Chauchard,* K. Webb,* C. H. Lee,* and H. C. Huang, "Characterization of GaAs Monolithic Integrated Circuits by Optical Techniques," SPIE Symposium on Optical Applications of Microwaves, *Proc.*, Vol. 1102, March 1989, pp. 98–106.

HUNG, H-L. A., P. Polak-Dingels,* K. J. Webb,* T. Smith, H. C. Huang, C. H. Lee,* "Millimeter-Wave Monolithic Integrated Circuit Characterization by a Picosecond Optoelectronic Technique," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 37, No. 8, August 1989, pp. 1223–1231.

LEE, Y. S., "Utility Analysis of Fiber Optic Networks in MILSATCOM Architecture," IEEE Military Communications Conference (MILCOM 89), Boston, MA, October 1989, *Conf. Rec.*, Vol. 1, pp. 251–257.

LUNSFORD, J.,* P. Roach,** T. Mizuike,* C. King, and P. Trusty, "Network Configuration and Control Selection in the INTELSAT Satellite Switched TDMA System," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 59–66.

METZE, G. M., A. Cornfeld, E. Carlson, G. Dahrooge, E. Chang, J. Singer, J. Bass, H-L. Hung, and T. Lee, "60-GHz Pseudomorphic-MODFET Low-Noise MMIC Amplifiers," *IEEE Electron Device Letters*, Vol. EDL-10, No. 4, April 1989, pp. 165–167.

METZE, G., A. Cornfeld, J. Singer, H. Carlson, E. Chang, T. Kirkendall, G. Dahrooge, J. Bass, H-L. Hung, and T. Lee, "Monolithic V-Band Pseudomorphic-MODFET Low-Noise Amplifiers," IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium, Long Beach, CA, June 1989, *Digest*, pp. 199–204.

NAKAMURA,* A. M., R. K. Gupta, F. T. Assal, J. N. Narayanan, and L. A. Argyle,* "Integration and Testing of the Satellite Switched TDMA (SS-TDMA) Subsystem for the INTELSAT-VI Spacecraft," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 49–57.

NEIBERT, M. T., "International Packet Switched Connection Performance Measurements," IEEE International Conference on Communications, Boston, MA, June 1989, *Conf. Rec.*, Vol. 1, pp. 3.6.1–3.6.3.

PALMER, L. C., "A Perspective on Satellite On-Board Processing," U. S. Army Communications Electronics Command Symposium on Space—Supporting the Soldier, Asbury Park, NJ, June 1989, *Proc.*, pp. III-48–III-53.

PALMER, L. C., and L. W. White, "An Evaluation of Two Error Detection Codes Used With a Particular Convolutional Coder/ML Decoder," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 241–248.

PETERSON, K. E., H-L. A. Hung, F. R. Phelleps, T. F. Noble, and H. C. Huang, "Monolithic High-Voltage Power Amplifiers," IEEE MTT-S International Microwave Symposium, Long Beach, CA, June 1989, *Digest*, pp. 945–948.

PONTANO, B. A., L. White, F. Faris, and D. K. Paul, "Cost-Effective Satellite Systems for International Communications," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 427–434.

RHODES, S. A., and S. I. Sayegh, "Digital On-Board Demodulator for Reception of an Up-Link Group of TDMA/QPSK Channels," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 845–852.

ROGERS, D. V., C. Zaks, and K. T. Lin, "Up-Link Power Control Experiments at 14/11 GHz," 6th International Conference on Antennas and Propagation, University of Warwick, Coventry, U. K., April 1989, *IEE Conference Publication No. 301*, Part 2, pp. 206–210.

SANDRIN, W. A., and L. N. Nguyen,** "Computing the Performance of Digital Satellite Links on a System-Wide Basis," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 747–754.

SEN, A., "INAM—An Expert System for Intelligent Network-Alarm Management," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 509–519.

---

* Non-COMSAT author.

**INTELSAT author.

SORBELLO, R. M., and A. I. Zaghloul, "Wideband, High-Efficiency, Circularly Polarized Slot Elements," IEEE International Symposium on Antennas and Propagation, San Jose, California, June 1989, *Proc.*, pp. 1473–1476.

TZENG, F., "Near-Toll-Quality Real-Time Speech Coding at 4.8 kbit/s for Mobile Satellite Communications," 8th International Conference on Digital Satellite Communications (ICDSC8), Guadeloupe, FWI, April 1989, *Proc.*, pp. 93–98.

TZENG, F., "Performance Improvement and Complexity Reduction for a High-Quality 4.8-kbps Speech Coder," (Abstract), IEEE Workshop on Speech Coding for Telecommunications, Vancouver, British Columbia, September 1989, *Program and Abstracts*, p. 5.

TZENG, F., "Analysis-by-Synthesis Linear Predictive Speech Coding at 2.4 kbit/s," IEEE Global Telecommunications Conference, Dallas, TX, November 1989, *Proc.*, pp. 34.4.1–34.4.5.

VAIDYANATHAN, H., "Effect of Design Variables on the Cycling Characteristics of Ni-H_2 Cells," 24th Intersociety Energy Conversion Engineering Conference, Washington, DC, August 1989, *Proc.*, pp. 1405–1409.

WEBB,* K. J., E. P. Chauchard,* P. Polak-Dingels,* C. H. Lee,* H-L. Hung, and T. Smith, "A Time-Domain Network Analyzer Which Uses Optoelectronic Techniques," IEEE MTT-S International Microwave Symposium, Long Beach, CA, June 1989, *Digest*, pp. 217–220.

ZAGHLOUL, A. I., J. R. Potukuchi, R. C. Mott, and R. T. Kroll, "Analysis and Measurement of Tolerances in MMIC Active Phased Arrays," 19th European Microwave Conference, London, September 1989, *Digest*, pp. 966–971.

PATENTS

The following patents were issued to employees (or former employees) of COMSAT Laboratories in 1989.

ASSAL, F. T., and A. I. Zaghloul, "Combined Global Spot Beam Configuration for Satellite Communications," U.S. Patent No. 4,868,886, issued September 19, 1989.

BECKER, N. D., A. Shenoy, and L-N. Lee, "Horizontal Synchronization, Clock Synchronization, DC Restoration, and Gain Control Scheme for Analog Television," U.S. Patent No. 4,829,377, issued May 9, 1989.

BHASKAR, B. U., "Pitch Learning Algorithm," U.S. Patent No. 4,809,334, issued February 28, 1989.

CHEN, C. H., "Broadband Circular Polarization Arrangement for Microstrip Antenna," U.S. Patent No. 4,866,451, issued September 12, 1989.

HEMMATI, F., and L-N. Lee, "Good Nonlinear Random Sequence Generator," U.S. Patent No. 4,852,023, issued July 25, 1989.

LEE, L-N., and N. D. Becker, "Subscription Control for Television Programming," U.S. Patent No. 4,797,918, issued January 10, 1989.

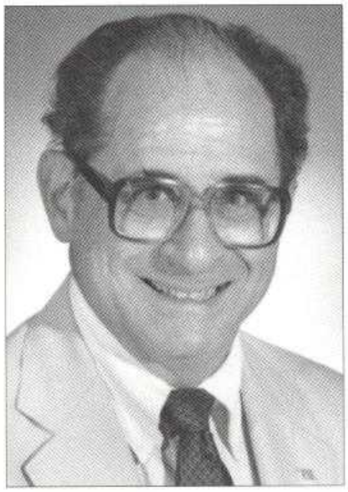
LEE, L-N., and N. D. Becker, "Stream Cipher With Feedback," U.S. Patent No. 4,815,130, issued March 21, 1989.

POKLEMBA, J. J., "Rate Synchronized Symbol Timing Recovery for Variable Rate Data Transmission Systems," U.S. Patent No. 4,849,998, issued July 18, 1989.

* Non-COMSAT author.

**INTELSAT author.

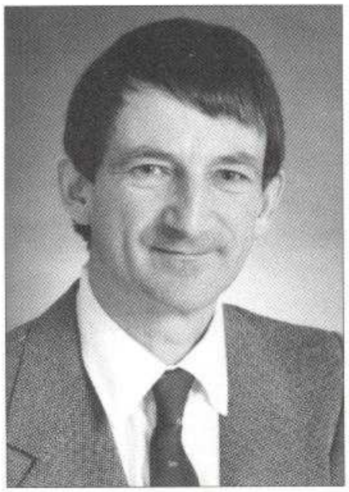
COMSAT Laboratories is pleased to acknowledge those of its scientists who were recognized in 1989 for their significant contributions to the field of satellite technology.



Dr. S. J. Campanella

IEEE AWARD

Dr. S. J. Campanella was named recipient of the 1990 Institute of Electrical and Electronics Engineers Award in International Communication "for the enhancement of international satellite communications through his contributions to signal processing, echo control, and multiple access systems." Dr. Campanella joined COMSAT in 1967 and has been actively involved in many aspects of communications technology at COMSAT, both as an engineer and manager. He is presently Chief Scientist at the Laboratories.



Dr. C. E. Mahle

IEEE FELLOW

Dr. C. E. Mahle was elevated to the rank of Fellow in IEEE in 1989. His promotion was made on the basis of his very significant contributions to satellite communications, including improved traveling wave tube technology and in-orbit testing of spacecraft payloads. Dr. Mahle joined the Laboratories in 1968 and held several positions before becoming Executive Director of the Satellite Technologies Division.

Dr. H. C. Huang was also raised to the level of Fellow in IEEE. His innovative work in space-qualified semiconductor applications to power amplifiers for satellites was cited as the basis of his nomination. Dr. Huang came to the Laboratories in 1983 and has been Executive Director of the Microelectronics Division since 1984.

Dr. H. C. Huang

Dr. D. V. Rogers was elected to full membership in the USNC/URSI Commission F, which focuses on research about propagation in non-ionized media. Dr. Rogers is Manager of the Propagation Studies Department of the Laboratories' Microwave Division. Dr. Rogers has been with COMSAT since 1977.