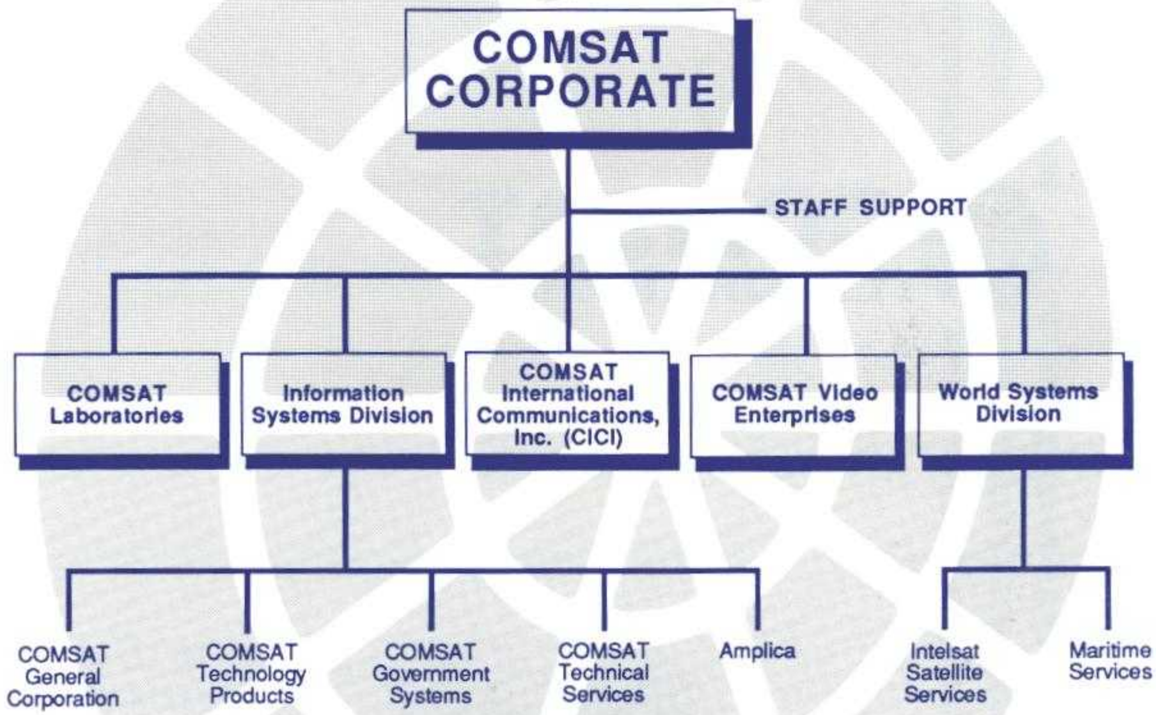
COMSAT LABORATORIES

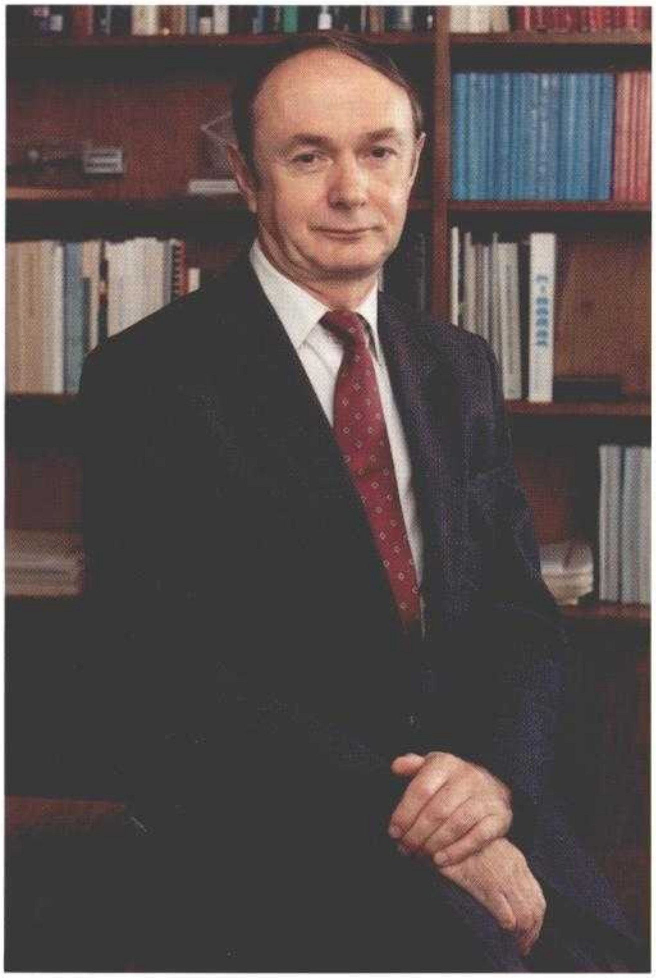
Annual Report 1987

COMSAT LABORATORIES

Annual Report 1987



COMMUNICATIONS SATELLITE CORPORATION
Organization 1987



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 Maritime 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 ratepayer) is made available to the public through a catalog that announces the availability of published papers and reports.

During 1987 COMSAT Laboratories had an operating budget somewhat in excess of $40 million, of which 60 percent came from Corporate sources and the balance from outside. Approximately 30 percent of the Corporate funding (20 percent of the total) supported an applied research program with the goal of creating new technology which has the potential for improving communications systems over the long term. A further 40 percent of the Corporate funding paid for development projects undertaken by the Laboratories for elements of the Corporation on a contract-like basis, which had 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 calendar year 1983 we have published an Annual Report summarizing the results of our research and development program. This report, the fifth in the series, summarizes all the R&D work undertaken with Corporate support during 1987.

John V. Evans
August 1988

COMSAT Corporation was created in 1963 following 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 114 member countries, and the organization presently provides service to 170 nations.

Until 1979, COMSAT also acted as technical manager of INTELSAT. In this role COMSAT encountered many technical problems, and COMSAT Laboratories was formed in 1967 to help meet these challenges. 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 350 and occupies buildings which afford nearly 400,000 square feet of space. These facilities are located on a 210-acre tract along Route I-270 north of Gaithersburg, Maryland.

In 1973, COMSAT formed the COMSAT General Corporation with the expectation of branching into domestic satellite communications. In 1975, in partnership with IBM and Aetna Casualty Co., the Satellite Business Systems Corporation was formed. In 1979, as a result of successful demonstrations using the MARISAT system of maritime mobile satellite communications, COMSAT and the State Department joined with other nations to form INMARSAT, for which COMSAT again serves as U.S. Signatory and representative.

In 1987, COMSAT was reorganized into five operating divisions. The *World Systems Division* (WSD) consisted of the units handling the INTELSAT and INMARSAT businesses (Intelsat Satellite Services and Maritime Services, respectively). *COMSAT International Communications, Inc.* (CICI), which operated the large gateway earth stations (until their sale to AT&T at the end of 1987) and provided overseas private business communications via smaller earth stations became, for the first time, a separate division, as did *COMSAT Video Enterprises*, which distributes video services to hotels within the U.S. COMSAT General Corporation, the manufacturing businesses, and the consulting engineering activity were grouped into a newly formed *Information Systems Division*. The last separate unit was *COMSAT Laboratories*, which now reported centrally. These changes were made in anticipation of the planned merger with the CONTEL Corporation. The failure of that merger later in the year led to the decision to sell off CICI and the manufacturing businesses, which in turn has reduced the Corporation's need for a large central Laboratory. As a result, the size of the Laboratories is presently being trimmed, to reach about 300 by the end of 1988.

In 1987, the largest portion of the work at COMSAT Laboratories was performed for the regulated activity of international satellite communications, either directly for COMSAT or indirectly for INTELSAT. Additional work was performed for CICI and COMSAT's manufacturing arms, COMSAT Technology Products and Amplica. 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 1987 the Laboratories remained organized into six technical divisions: Applied Technologies, Communications Techniques, Microelectronics, Microwave Technology, Network Technology, and System Development. Of these, the first five divisions participated 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 are held proprietary.

The balance of the Laboratories' support came from projects performed for and directed by various corporate elements, INTELSAT, INMARSAT, or 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 (R&D) activities in 1987. 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.

The Microwave Technology Division (MTD) of COMSAT Laboratories carries out research, development, and support functions in a number of technical areas of importance to the Corporation, including the development of technologies for an advanced communications satellite concept with many pencil beams and on-board processing. Specifically, a phased-array satellite antenna, including monolithic microwave integrated circuits (MMICs), is being developed. In addition, significant progress has been made toward the realization of a 64-element and K_u-band phased-array proof-of-concept antenna. A multicoupled cavity filter using four electrical modes in one cavity has been demonstrated, and an engineering model of a 120-Mbit/s QPSK demodulator for satellite on-board processing has been completed and has met all applicable INTELSAT performance requirements. Work has continued on MIC and waveguide filters, satellite monitoring and in-orbit testing, new earth station antennas and feeds, and microwave propagation studies. Additional support included antenna modifications at the Southbury and Santa Paula earth stations, and antenna measurements at the Washington, D.C., Intelsat Business Services (IBS) station.

COMSAT JURISDICTIONAL R&D

Multimode Microwave Filters

Research on multimode waveguide cavity filters continued in 1987. Both air and dielectrically loaded cylindrical multicavity filters were designed and tested. A number of triple-mode, 6-pole air dielectric filters, including one which uses only TE modes, were designed and built. Test results at 12 GHz showed excellent agreement with theoretical models with unloaded Qs ranging from 9,000 to 17,500. All of these filters provide spurious-free, out-of-band responses suitable for spacecraft input and output multiplexer designs. Figure 1 is a photograph of the filter and Figure 2 shows the frequency response.

A 10-pole air dielectric filter using a mixed quadruple-mode degenerate pair of cavities and a dual-mode cavity was designed and tested. This filter meets the typical communications satellite transponder input multiplexer channel specification, and reduces the weight and volume by a ratio of 5:3 compared to conventional designs. Unloaded Qs of 11,500 were measured, and the frequency response is shown in Figure 3. Figure 4 is a photograph of the filter.

Propagation Studies

COMSAT Laboratories performs radiowave propagation studies applicable to satellite communications. A variety of slant-path propagation impairment models have been developed over the years, and methods for impairment mitigation such as up-link power control, site diversity, and depolarization compensation have been studied. In 1987, collection of several types of data was continued, and computer programs for some of the models were upgraded.

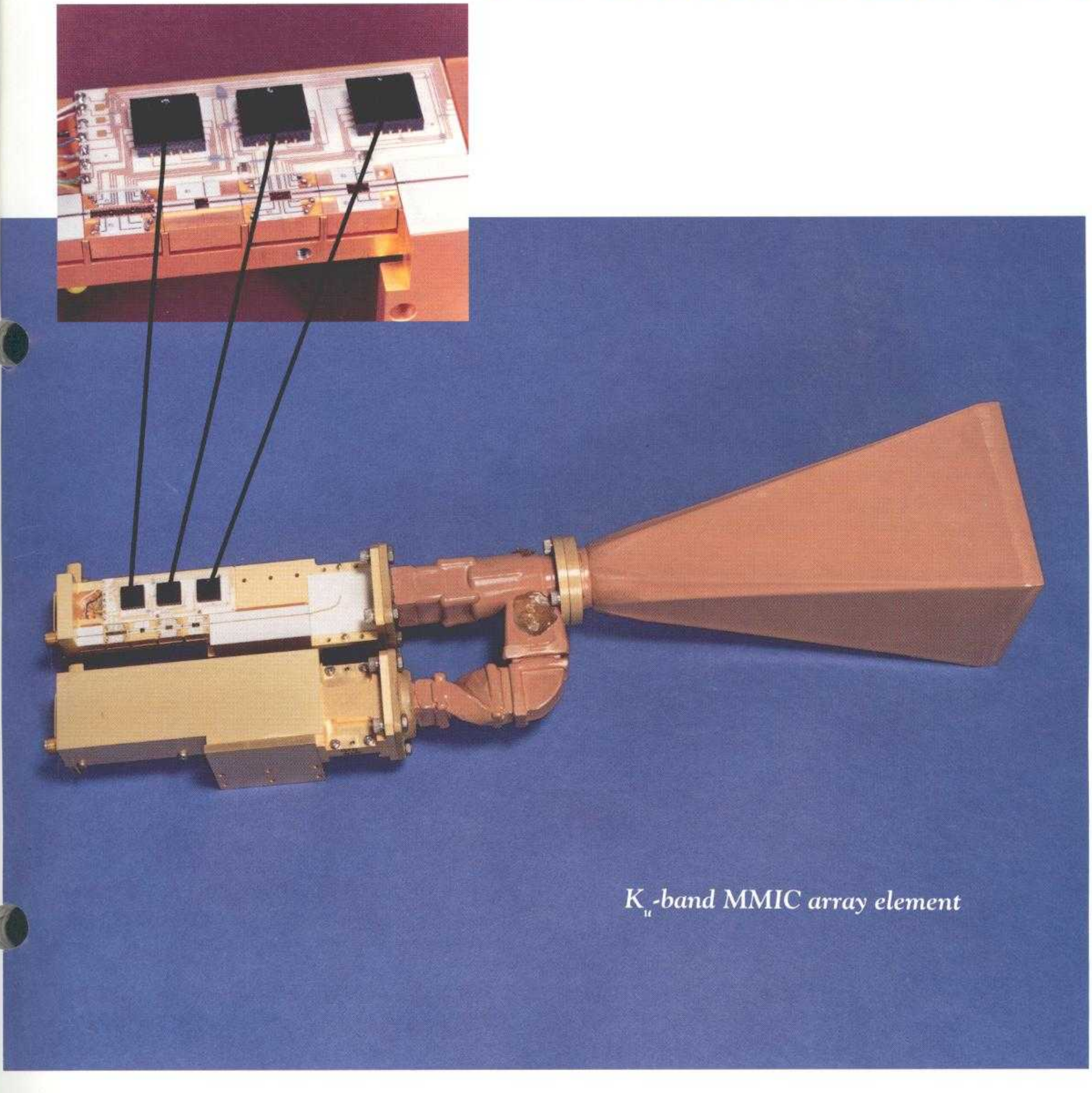
Modeling efforts included the implementation of a simple, empirically based prediction technique for tropospheric scintillations for communications system applications. In addition, the latest improvements to the CCIR Study Group 5 models for gaseous attenuation and slant-path depolarization were incorporated into the available software packages.

Antenna Diagnosis Using Microwave Holographic Techniques

The microwave holographic antenna measurement capability on the rooftop antenna range was substantially improved during 1987. Antenna pointing accuracy was increased to 0.015° with improvements to the pedestal control unit and the mounting of new tachometers. The associated software was substantially upgraded to take into account phase tilt due to parallax errors, to incorporate rules for maximum angle intervals which limit the resolution, and to provide several facilities for manipulation and improved display of the data.

Figure 5 is a far-field amplitude contour plot of a prime focus antenna. The blockage from the three-feed support spars is shown in the contour plot. The far-field contour and its aperture plane fields transform can both be used for antenna diagnosis.

MICROWAVE TECHNOLOGY



K_u-band MMIC array element

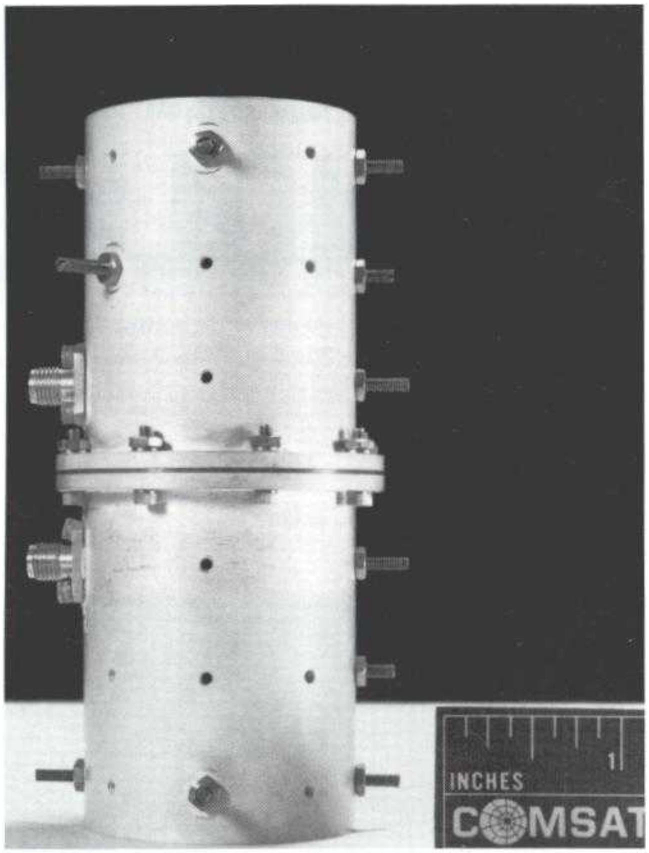


Figure 1. Photo of triple-mode, six-pole, air dielectric filter

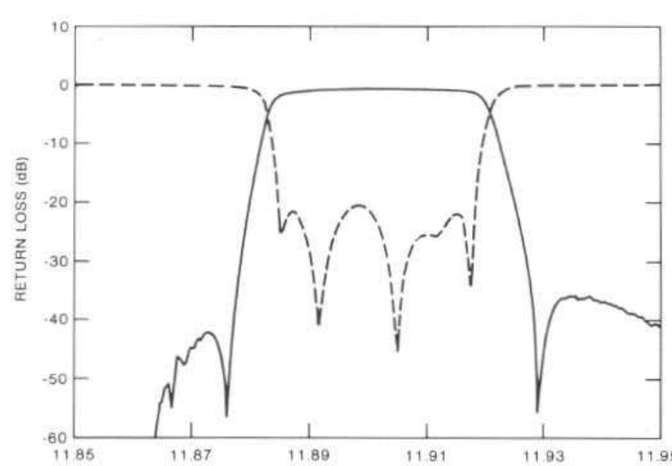


Figure 2. Frequency response of filter in Figure 1

4-GHz SSPA Development

The development of solid-state power amplifiers (SSPAs) for INTELSAT Satellite Services at 4 GHz continued in 1987, with emphasis on extending the single-stage amplifier techniques to multistage amplifiers that simultaneously offer high efficiency, low intermodulation distortion, and low mass achieved by miniaturization. Fabrication cost and reliability were major factors.

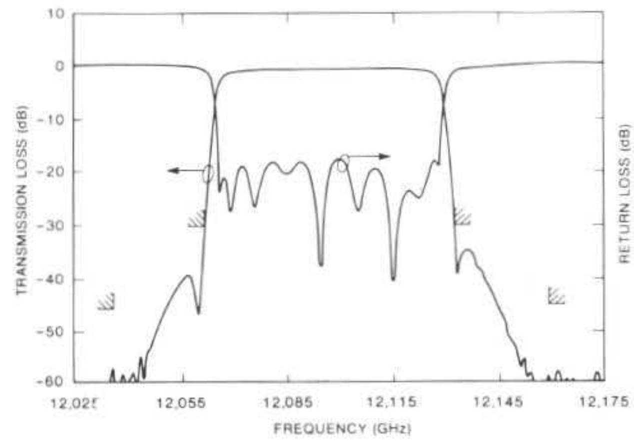


Figure 3. Frequency response of 10-pole filter

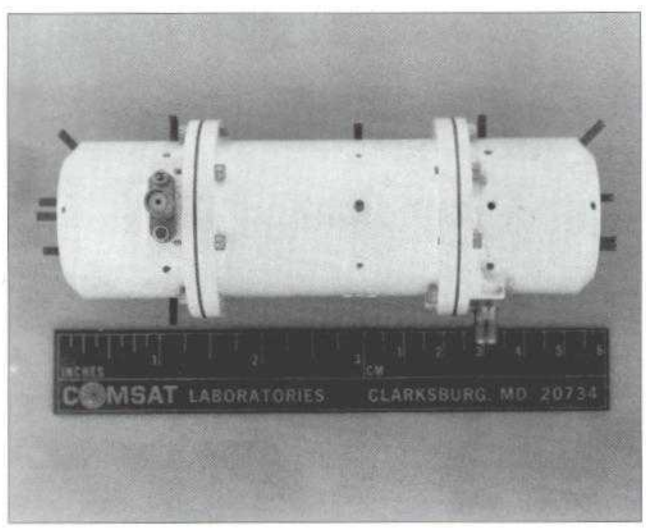


Figure 4. Photo of 10-pole filter

The three-stage, 2-W miniaturized amplifier shown in Figure 6 was developed and tested, and 15 units were built to demonstrate ease of assembly. The individual 1-W amplifiers used in the output stage achieved 65-percent DC-to-RF efficiency by operating the device in a class AB mode, the highest reported efficiency above S-band. The overall three-stage amplifier also achieved excellent (over 50-percent) DC-to-RF efficiency over the 3.7- to 4.2-GHz band. Figure 7 shows typical performance of the amplifier when tuned for maximum efficiency, and also when tuned for broadband frequency flatness. Due to the miniature microwave active circuit (MMAC) construction, the amplifier size is very small (37 cm^3) and the weight is low (less than 90 g). The new design and assembly techniques will also enhance reliability, and amplifiers of this type will be applicable to any new satellite using C-band transmitters.

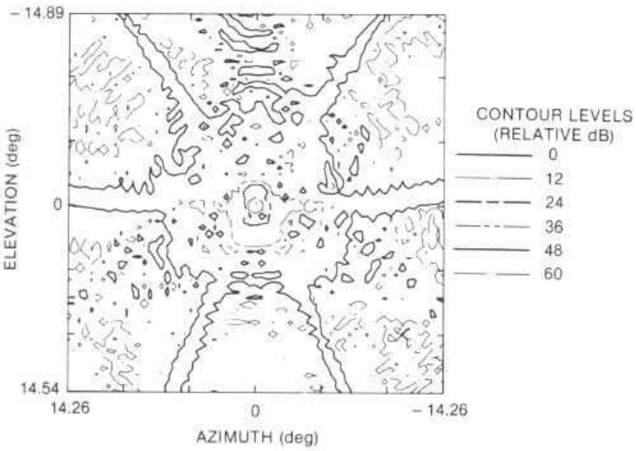


Figure 5. *Far-field amplitude contour plot of prime focus antenna*

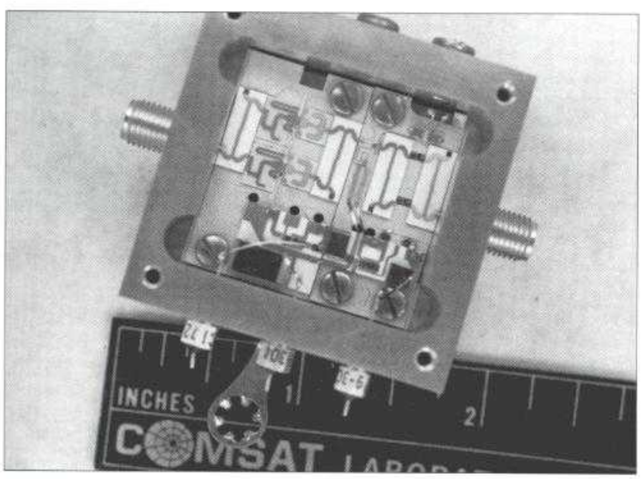


Figure 6. *Three-stage, 2-W miniaturized amplifier*

11-GHz SSPA Development

11-GHz amplifier development is targeted at an MMIC implementation of a 2-W multistage amplifier operating in class AB, which will be integrated into the transmit modules of the array antenna described below. In addition to the conventional requirements for a satellite transmitter, small size, unit-to-unit tracking, and ease of fabrication in large numbers are of major concern for this application, and must be designed into the equipment from conception.

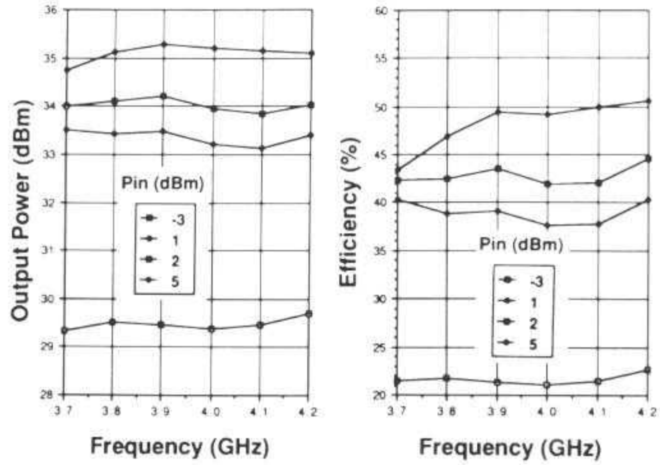


Figure 7. *Performance of 3-stage amplifier in Figure 6*

Individual stages for a hybrid version of a four-stage, 2-W amplifier were developed in 1987 (Figure 8). This design can easily be modified to an all-MMIC version once the processing technology provides sufficient yield. The device development necessary to realize an MMIC version of the output stage is more difficult. For proper operation, these devices (field-effect transistors [FETs]) must operate in a class AB mode with sufficient gain, power output, and efficiency. So far these goals have not been achieved simultaneously at 11 GHz, and the amplifier design will be completed when the device technology is ready.

Power switching circuits for these 11-GHz amplifiers were also developed. These circuits must turn the amplifier on and off very rapidly in order to conserve satellite prime power. For instance, in a hopping beam antenna, DC power is consumed by the amplifier only when useful information is transmitted. A hybrid version of this circuit was built and successfully tested; the MMIC version to be integrated with the 11-GHz MMIC power amplifier has been designed and the layout has been prepared. It will be fabricated together with the 11-GHz MMIC amplifier.

Multibeam Phased-Array Antenna

Two K_u-band multifeed arrays are currently under development: a 64-element array with 0.1-W transmit power per element; and a 16-element array with a 2-W power amplifier driving each element. Each horn of the first array is fed by a module containing a digitally

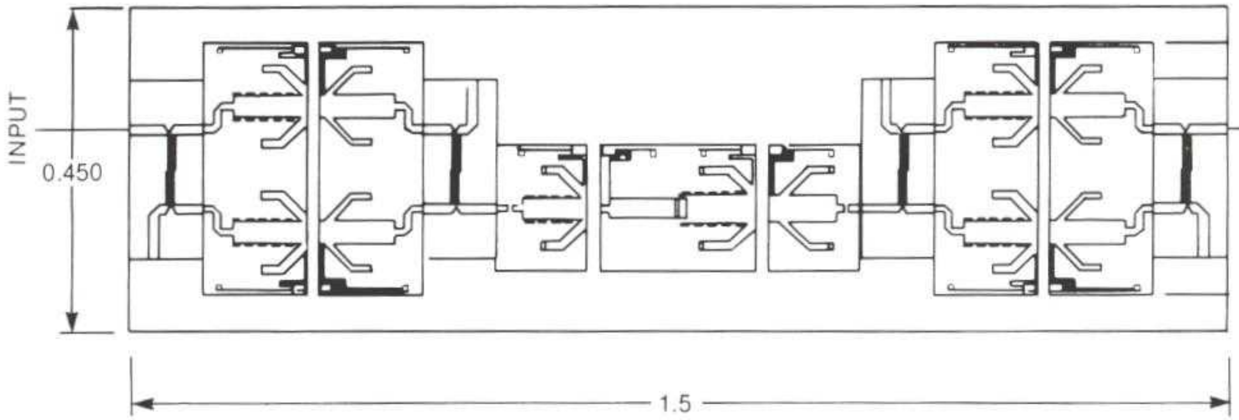


Figure 8. Individual stages for a hybrid version of a four-stage, 2-W amplifier

controlled phase shifter and attenuator and driver and buffer amplifiers, all in MMIC form, plus the necessary digital control circuitry and the power supply. In addition to all elements of the low-power array, the high-power array is also intended to contain 11-GHz power amplifiers. These arrays are intended as a testbed for future multibeam antennas (with or without a reflector system) generating shaped, hopping, and scanned beams.

Assembly and testing of the 64 horns with power dividers completed during 1987, and the design of the individual modules and the fabrication of the MMIC active circuits was continued. Out of four MMIC circuits (buffer amplifier, driver amplifier, digitally controlled attenuator, and phase shifter), three were successful in the first iteration. A substantial number of circuits were assembled on carriers and tested and are awaiting integration into the modules. Only the phase shifter was not successful in the first iteration. It appears that proximity effects and/or spurious coupling between the elements of these highly compact circuits are not yet modeled with sufficient accuracy to permit precise phase shift to be achieved. Work is in progress to improve the modeling, and proper performance has been achieved in some circuits. Fabrication of the phase shifters will be completed in 1988. Figures 9 and 10 provide photographs and performance curves of the buffer amplifier and the driver amplifier.

A module, complete except for the phase shifter, has been assembled and successfully tested. Figure 11 is a photograph and Figure 12 shows its performance.

The conceptual design of the high-power array went through several iterations in 1987 to make it serve various traffic situations more efficiently. Several candidate architectures and layouts were studied. A prime criterion for selection is flexibility for various applications such as beam shaping, beam scanning, or beam hopping. In particular, the integration of the control aspects of the array (digital control of the power amplifier, phase shifter, and attenuator), in conjunction with microwave switch matrices, is critical for routing of the traffic on board the satellite.

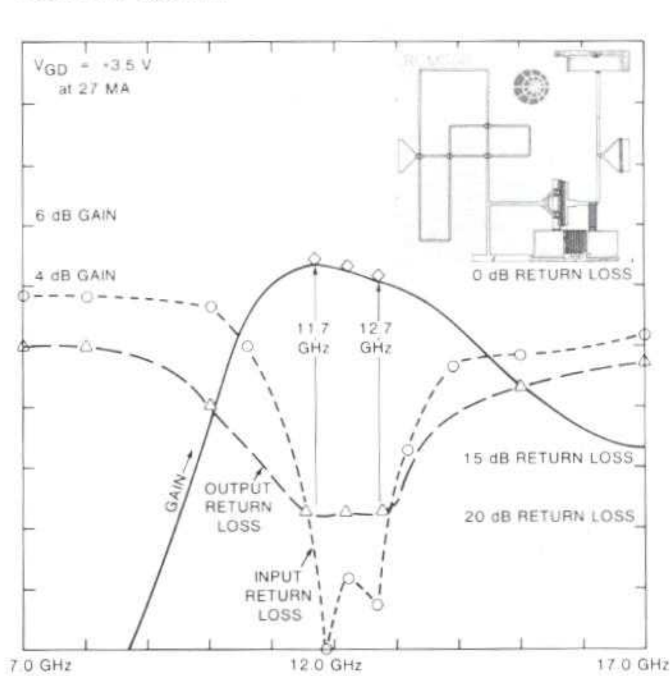


Figure 9. Buffer amplifier and measured performance

A confocal parabolic reflector system was developed to serve as a testbed for array antennas that require optical magnification. Testing of the dual reflector system was completed and good correlation between measured and computer-predicted performance was obtained. Figure 13 shows the reflector system and Figure 14 provides a sample pattern. A computer program to design optimized shaped reflectors is still under development.

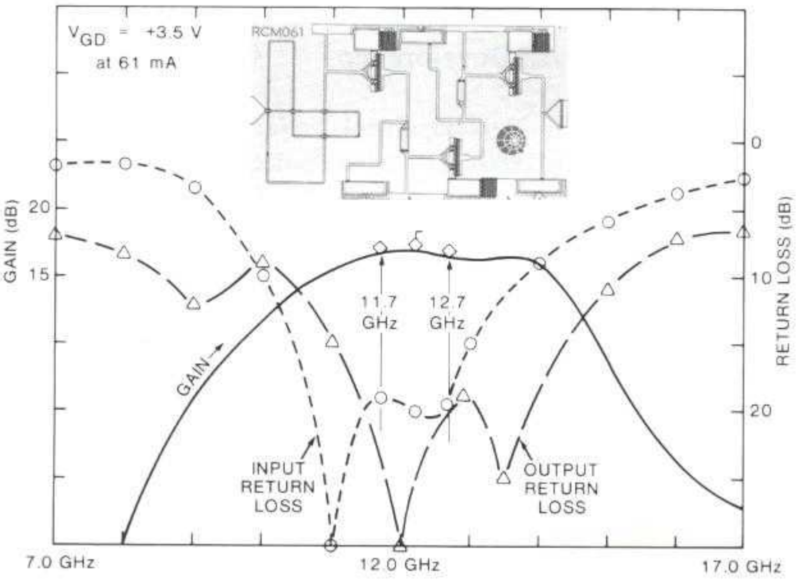


Figure 10. Driver amplifier and measured performance

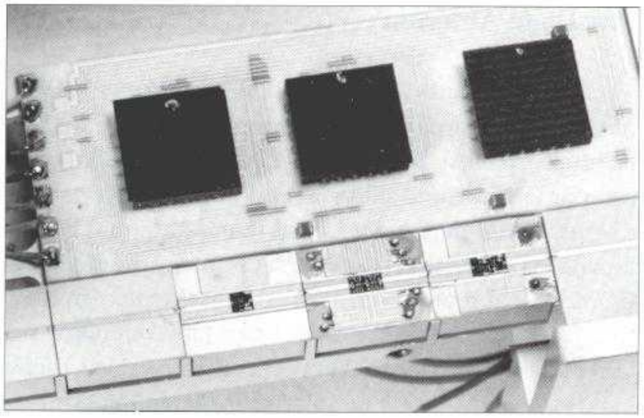


Figure 11. Completed module

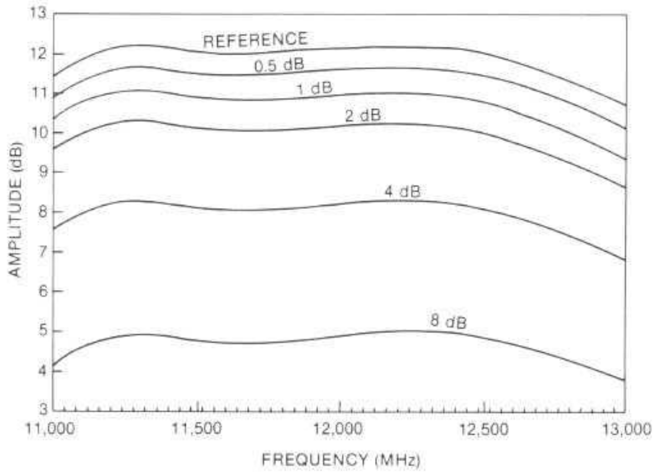


Figure 12. Performance of completed module

On-Board Demodulation and Remodulation

Measurements on the 120-Mbit/s CQPSK C-band modem were made to quantify the effects of frequency drift and phase characteristics of the voltage controlled oscillator (VCO) on modem performance. Oscillator drift of less than ±30 kHz over the required temperature range will maintain good modem performance. An improved VCO at 3.95 GHz, stabilized by a series feedback dielectric resonator, was designed, assembled, and tested. Temperature testing of the VCO is proceeding.

Development continued on a highly reliable, miniature four-by-four microwave switch matrix (MSM) operating from 3.5 to 6.5 GHz. All component development was completed, and the housing, the MMIC switches, and all other hardware has been fabricated. The housing has been designed for ease of assembly, and will be 2 x 2 x 0.5 in. and weigh 75 g. Assembly of the switch modules and the 4 x 4 MSM is still in progress. Figure 15 shows a partially assembled matrix.

Propagation Measurements in Africa

During the past two years, COMSAT Laboratories cooperated with INTELSAT, the U.S. Telecommunications Training Institute, the National Telecommunications and Information Administration, the U.S. Agency for International Development, the U.S. Information Agency, and the governments of Cameroon, Kenya, and Nigeria to conduct radiometric sky noise measurements at K_u-band in Africa. Radiometers were installed in 1987 at three sites in the respective countries. COMSAT provided on-site technical expertise and assisted with the inspection of the installed equipment and the initiation of data collection. A number of spare and replacement parts and components also were provided. Data collection was expected to continue into 1988.

4/6-GHz Compact Diplexer

Development of a 4/6-GHz compact CP diplexer was completed in 1987. The objective of this program was to develop a compact, lightweight, and low-cost diplexer meeting INTELSAT 1.06:1 voltage axial ratio specifications. This diplexer may be used as part of a feed system for large Cassegrain antennas, but would be particularly suitable for installation in smaller, 4.5- to 7-m-diameter, front-feed reflector antennas. All performance objectives were achieved. Figure 16 shows typical transmit and receive band axial ratio performance, and Figure 17 is a photograph of the completed prototype unit.

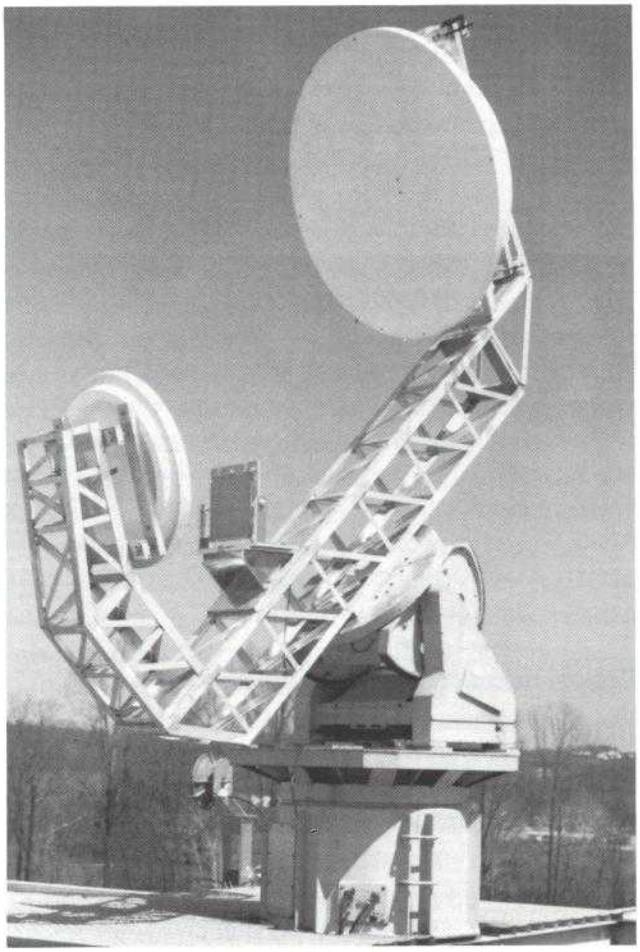


Figure 13. Reflector system

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

Development of a feed system which allows simultaneous operation over the 4/6- and 11/14-GHz bands for INTELSAT earth station antennas continued. The 4/6-GHz portion of this feed has been realized with an existing diplexer design. The 11/14-GHz portion has been the focus of intense work, in particular to realize 11- and 14-GHz circular waveguide couplers with near unity coupling values over the entire bandwidth and high mode purity. Coupling structures with excellent mode purity have been achieved, and work is continuing to reduce the coupling losses.

K_u-Band Up-Link Power Control Development

The K_u-band up-link power control system developed in 1986 was tested in a variety of weather conditions during winter (snow, rain, sleet, and ice on the antenna) and summer (thunderstorms). The purpose of the system is to provide a constant flux density at the satellite receive antenna, irrespective of propagation losses. Two methods were tested: monitoring of a down-link beacon; and monitoring of sky noise at a frequency adjacent to the up-link band, with the former proving more effective. Figure 18 shows an event with heavy rain. In general, the system compensated within ±1 dB for fade depth up to 7 to 10 dB. This proves that the technique can be very useful for large and small K_u-band earth stations.

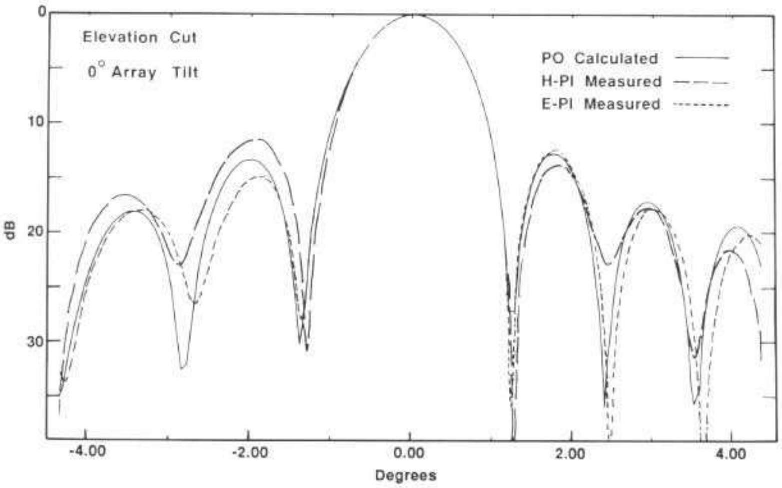
COMSAT PROPRIETARY R&D

Flat Plate Antenna

COMSAT and Matsushita Electric Works (MEW) have a joint development agreement to develop and produce low-cost, lightweight, high-efficiency flat plate array antennas for satellite reception. The first product, a series of circularly polarized K_u-band antennas for the Japanese DBS system based on technology developed at COMSAT Laboratories, reached the marketplace in 1987. COMSAT has developed both linear and circularly polarized arrays with over 60-percent efficiency over 1-GHz bandwidth, and excellent polarization isolation. During 1987, a dual-polarized K_u-band version with polarization isolation greater than 25 dB and efficiency greater than 65 percent over the 11.7- to 12.5-GHz band was developed and successfully tested in several sizes.

Computer-Assisted Microwave Measurement Techniques

During the past several years, COMSAT Laboratories has been engaged in the design, assembly, and delivery of complete in-orbit test (IOT) systems to a variety of customers. These systems are used to measure the communications portion of a satellite, and are controlled by very sophisticated software that embodies over 20 years of COMSAT measurement expertise. Recently, the trend toward multiuser systems with remote terminals required a new operating system. The implementation of a computer operating system (MPCP II) that provides a "platform" for the development of user-



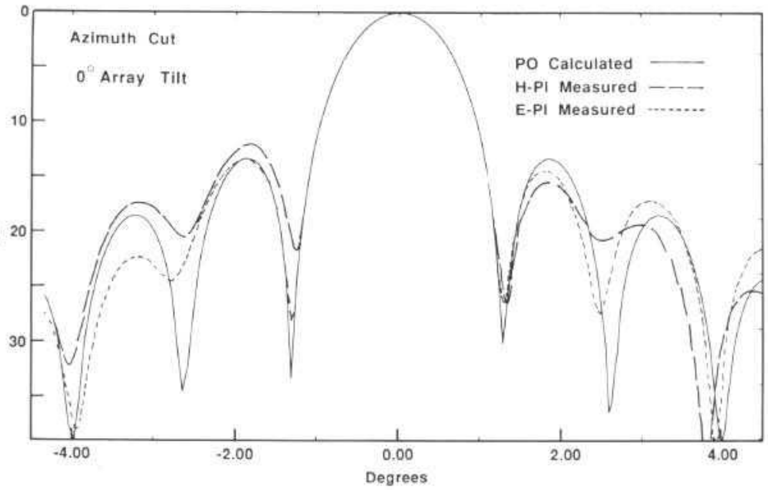


Figure 14. Sample pattern of reflector system

friendly, efficient software to control microwave instrumentation was started in 1987, and is based on an old system that was used in several in-orbit test projects. Unlike the old system, which was for a single terminal, the new MPCP II will be a multiuser system (several workstations) working over a computer network. The new system is based on UNIX™, and utilizes the industry standard X-window interface.

17-GHz Power Amplifier

A two-stage, 1/2-W MMIC power amplifier was designed for the 17-GHz radar band. The overall size of the amplifier chip is 100 x 60 mil on a 3-mil-thick GaAs substrate. The circuit is designed to provide optimum performance over the 16.5- to 18.5-GHz frequency band. The predicted large signal gain is about 5.3 dB, and measured results show a small signal gain of 6 to 7 dB over the 16- to 20-GHz frequency range. The circuit has an oscillation around 4 GHz which must be stabilized, and also a poor input return loss which may be improved by further tuning.

MMAC Lumped-Element Combiners

A new, lumped-element MMAC power divider has been developed that incorporates a lattice structure of four capacitors and four inductors. The power from a single input is split equally between two outputs with a 180° phase difference. The circuits can be designed for arbitrary load impedances, and therefore may be useful in a variety of situations. An additional advantage is provided by the 180° phase difference at the outputs. This provides push-pull operation by a pair of power FETs connected at the output. The effective impedance level at the input and output of the FET is therefore increased, and the impedance-transforming requirements of the combiner circuit are made less severe. Divider circuits were designed and fabricated for 10, 25, and 50Ω loads for these purposes. The typical chip size is 43 x 46 mils.

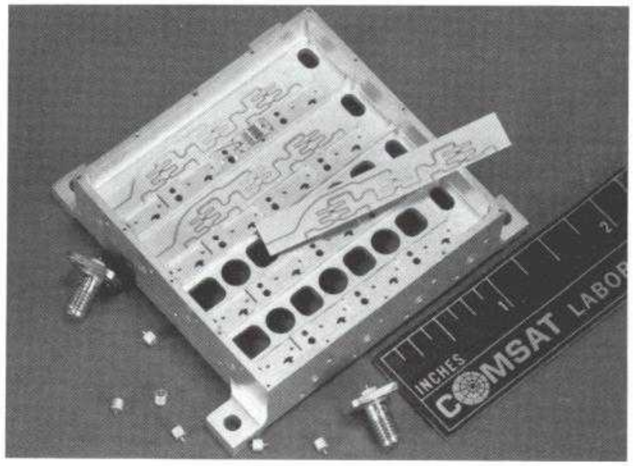


Figure 15. Partially assembled microwave switch matrix

A four-way combiner amplifier has also been the basic divider circuit topology as a building block. This circuit incorporates four 1/2-W power FETs. Initial test results show a small signal gain of 5 to 8 dB, depending on bias, centered at 9.6 GHz. This is in good agreement with the designed band center of 10 GHz. The entire combiner circuit is essentially a partially matched "super FET." This circuit will eventually be used with additional input/output matching networks to optimize amplifier performance.

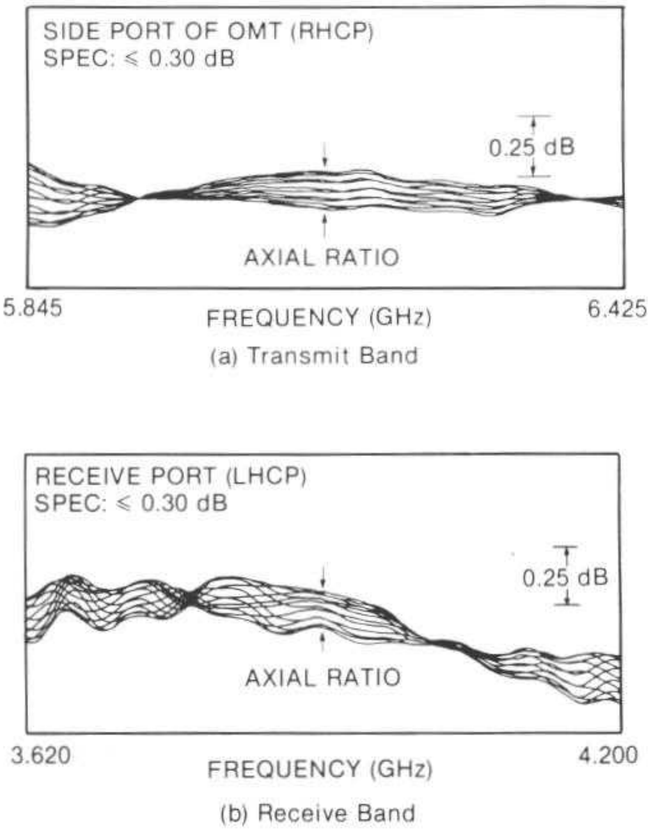


Figure 16. Typical transmit and receive band axial ratio

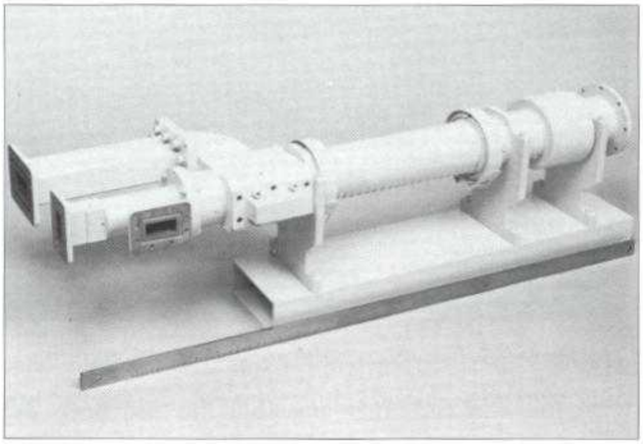


Figure 17. Completed prototype unit

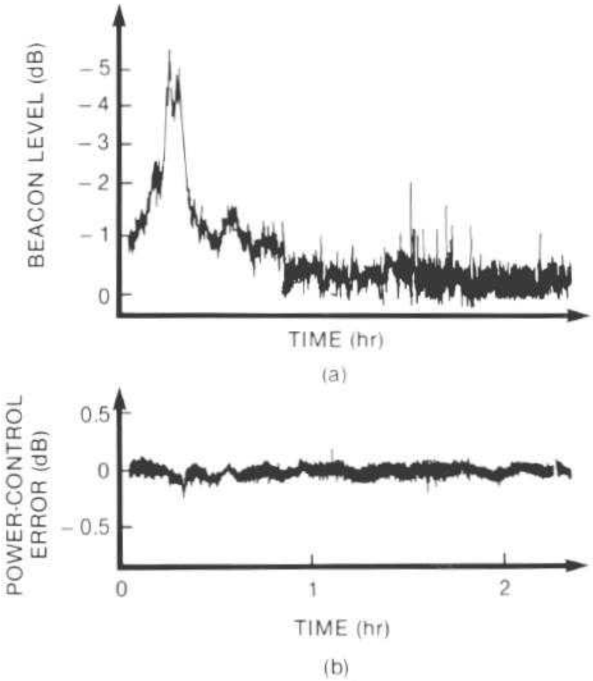


Figure 18. Event with heavy rain

Miscellaneous

Activities were begun in 1987 to evaluate the application of new, high-temperature superconducting materials to satellite communications hardware. It is believed that one of the first potential applications will be in the microwave filter area, in particular for output multiplexers where low loss is exceedingly important. A single resonant 12-GHz cavity was designed to measure unloaded Q factors down to liquid nitrogen temperatures. Monitoring temperatures inside and outside the cavity showed that a sample of the superconducting material can be cooled to 79K, and that the technique is very sensitive.

COMSAT SUPPORT

Southbury INMARSAT Antenna Modification

Two antennas at COMSAT's Southbury INMARSAT shore station were retrofitted during 1987 to allow operation with the INMARSAT II satellite, which has new and extended frequency bands. The polarizer of one antenna was modified, new low-noise amplifiers were installed, and a complete set of acceptance tests were conducted. Both antennas are now compliant with INMARSAT II specifications.

INTELSAT CONTRACTS

G/T Measurement Techniques

A two-phase study of gain and G/T measurement techniques for the smaller INTELSAT 4/6- and 11/14-GHz earth station antennas was completed. A moon ephemeris computer program for antenna pointing was developed and various methods of measurement using the moon, the sun, radio stars, and satellite beacons as flux sources were compared.

Investigation of Site Diversity Modeling

Under contract INTEL-508, COMSAT investigated site diversity as a method for improving the availability of satellite communications systems at K_u-band frequencies and above. Several site diversity models were evaluated against a data bank previously compiled by COMSAT Laboratories for INTELSAT. These models included a joint INTELSAT/COMSAT model previously developed from meteorological considerations, a new model obtained within the INTEL-508 effort by empirical optimizations in conjunction with site diversity simulations, and an empirical model from the literature. Both empirical models performed well and are easy to implement. The new INTELSAT/COMSAT model replicates observed diversity gain behavior with respect to individual input parameters, thus providing a powerful tool for model development and evaluation.

In addition, INTELSAT's propagation database was updated for a set of new earth station locations.

Compact Feed Development

Work on contract INTEL-480 to develop flight-qualified, lightweight feed elements was initiated. The goal of the program is to use printed circuit radiator technology to develop lightweight, high-polarization-purity feed elements that may replace the waveguide horns, OMTs, and polarizers presently being used in satellite antennas. To date, two types of patch radiators have been designed, and a four-element array (equivalent to a 1.5l horn) was built and exhibited an on-axis axial ratio from 3.6 to 4.2 GHz of less than 0.25 dB.

FIELD SUPPORT

INTELSAT VI SS-TDMA Subsystem Evaluation

Equipment evaluation and testing of the INTELSAT VI SS-TDMA subsystem, consisting of a microwave switch matrix, a distribution control unit, and a high-stability timing source, was completed in 1987. Unit-level tests were performed to check specification compliance, and a number of static and dynamic tests were performed on the integrated subsystem. Figure 19 is a photograph of the hardware undergoing tests. Telemetry and command functions were simulated by special hardware and software developed at COMSAT Laboratories.

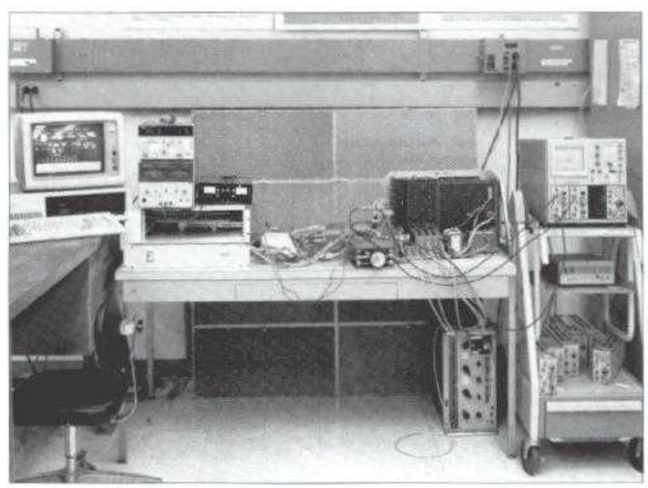


Figure 19. *Hardware undergoing test*

The Microelectronics Division (MED) supports the Corporation's need for state-of-the-art microelectronics components for use in advancing satellite communications systems and other aerospace applications, and promoting COMSAT's other competitive businesses. Research and development are performed on discrete components, as well as on microwave integrated circuits (MICs) and monolithic MICs (MMICs). The general goals of these efforts are to improve the performance of electronic components, enhance their operating frequencies (or speeds), and ensure long and reliable product life. MED capabilities encompass all aspects of this technology, from device modeling and circuit design to materials preparation, device fabrication, DC and RF characterization, and reliability assessment.

COMSAT JURISDICTIONAL R&D

Materials

The MED prepares active semiconductor material, primarily gallium arsenide (GaAs), for components fabrication by modifying wafers purchased from commercial vendors. Two processes, epitaxial growth and ion implantation, are performed routinely. Within the limits of the particular process, good control can be maintained on the characteristics of materials prepared by these two methods. As the requirements for higher frequency operation and lower noise figures become difficult to meet using GaAs, it will be necessary to develop new materials which possess properties, such as higher carrier mobility, that permit further advancement.

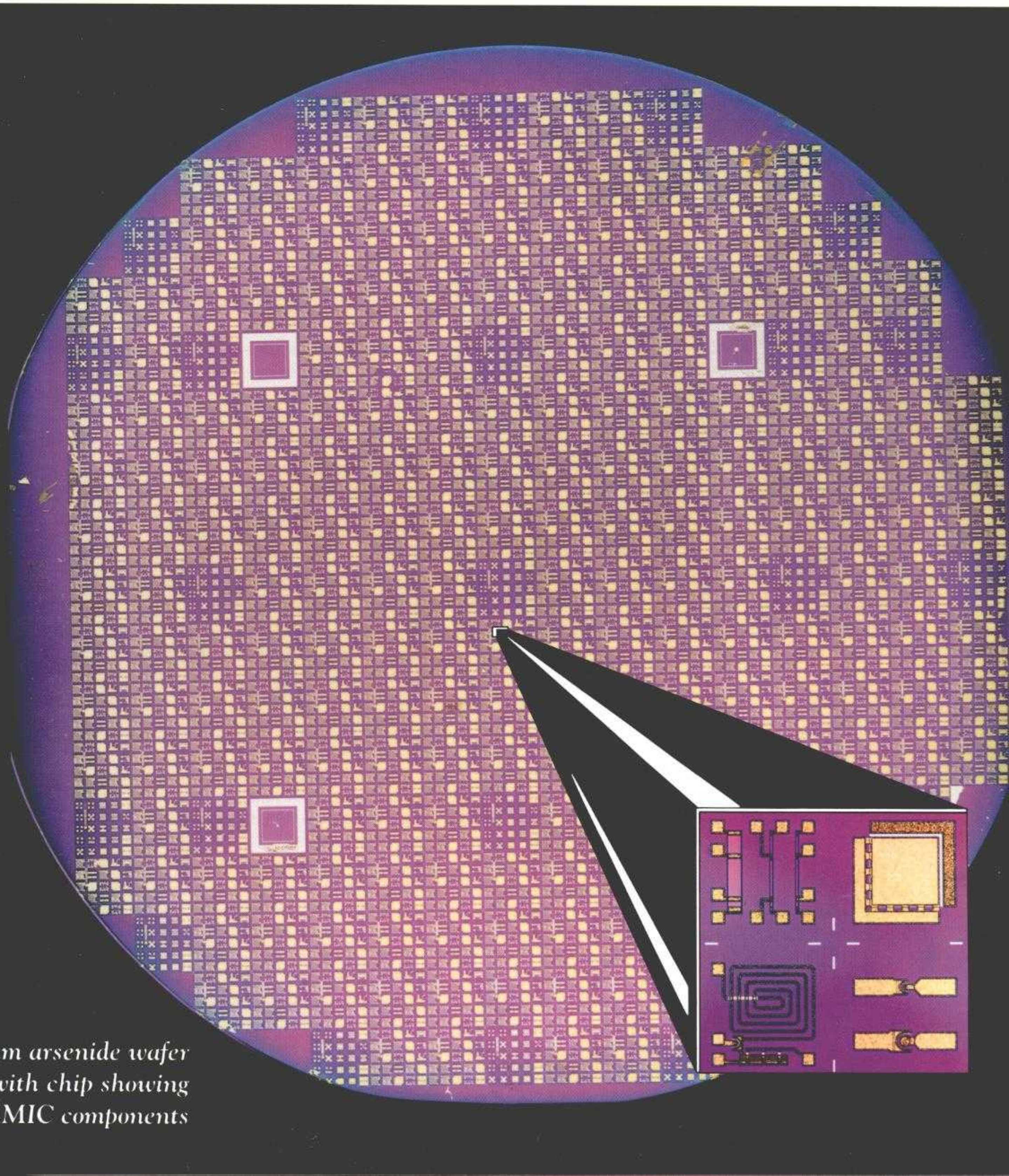
COMSAT recently installed a molecular beam epitaxy (MBE) system for growing layers of active materials that cannot be produced by other, more conventional methods. Because MBE growth takes place very slowly and at very low pressures, more precise definition of material interfaces is possible and the growth of unusual compounds is facilitated. A field-effect transistor (FET) structure with a p-doped buffer layer and monolayer abruptness at the active layer/buffer layer interface has been prepared from GaAs. These two features lead to improved confinement of carriers to the active region and better performance at higher frequencies (>30 GHz).

MBE methods are superior for growing heterostructures; GaAs/GaAlAs has been prepared and used for studying the transport properties of two-dimensional electron gases. Figure 1 is a schematic representation of such a heterostructure. The advantage of this structure over the conventional FET structure is the higher carrier mobility that exists in the lightly doped GaAs layer. Hall mobilities and sheet-carrier densities as a function of temperature and spacer layer thickness are shown in Figure 2. Other capabilities of MBE growth methods are being pursued and will be described below.

Device Fabrication

The next generation of advanced-power, low-noise, metal semiconductor FETs (MESFETs) for MIC or MMIC applications at frequencies above 40 GHz will require further development of materials and fabrication technologies. One very promising device structure to emerge in the past few years, called the modulation-doped FET (MODFET) or high electron mobility transistor (HEMT), incorporates heterojunctions (i.e., AlGaAs/GaAs and/or AlGaAs/InGaAs/GaAs) into the device growth structure. Such structures allow the device physicist greater flexibility in altering the carrier transport dynamics, which in turn directly influences device performance. This "band gap" engineering is used empirically to produce devices that have much shorter switching times, higher maximum frequency of operation, and lower noise figures than conventional MESFETs with comparable device geometries.

MICROELECTRONICS



Gallium arsenide wafer with chip showing MMIC components

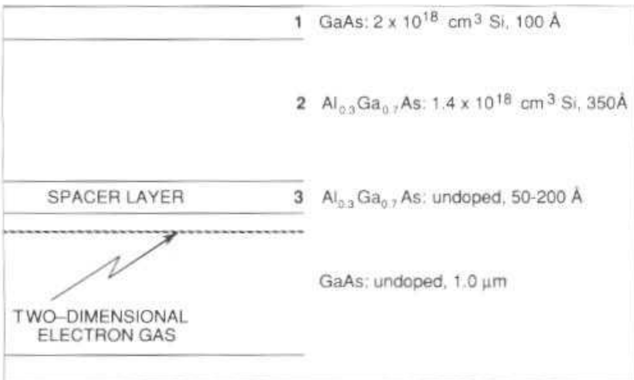


Figure 1. Schematic of a high-electron-mobility layer structure

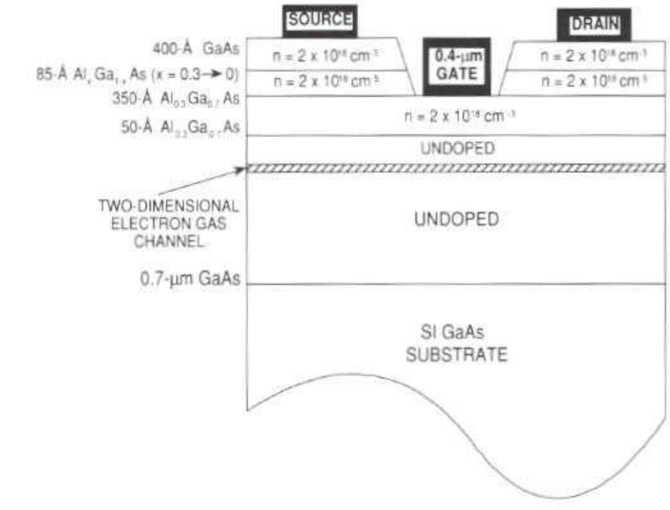


Figure 3. Cross-section of a MODFET

Because of the performance advantages of MODFET devices and their implications for advanced communications systems, the MED has begun developing the technologies necessary to synthesize these advanced components. The more critical technologies currently under development use MBE to grow the device structure, and electron-beam (e-beam) lithography to define the submicron gate regions. The refinement of both MBE and e-beam lithography is crucial to the success of this program. Recently, the MED completed fabrication of its first in-house MODFETs. Figure 3 is a cross-sectional representation of an MBE-grown MODFET; Figure 4 shows the results of preliminary measurements of current (I_{DS}) and gain (G_M) as a function of gate bias. These devices show superior linearity, with nearly flat transconductance over a wide range of gate biases.

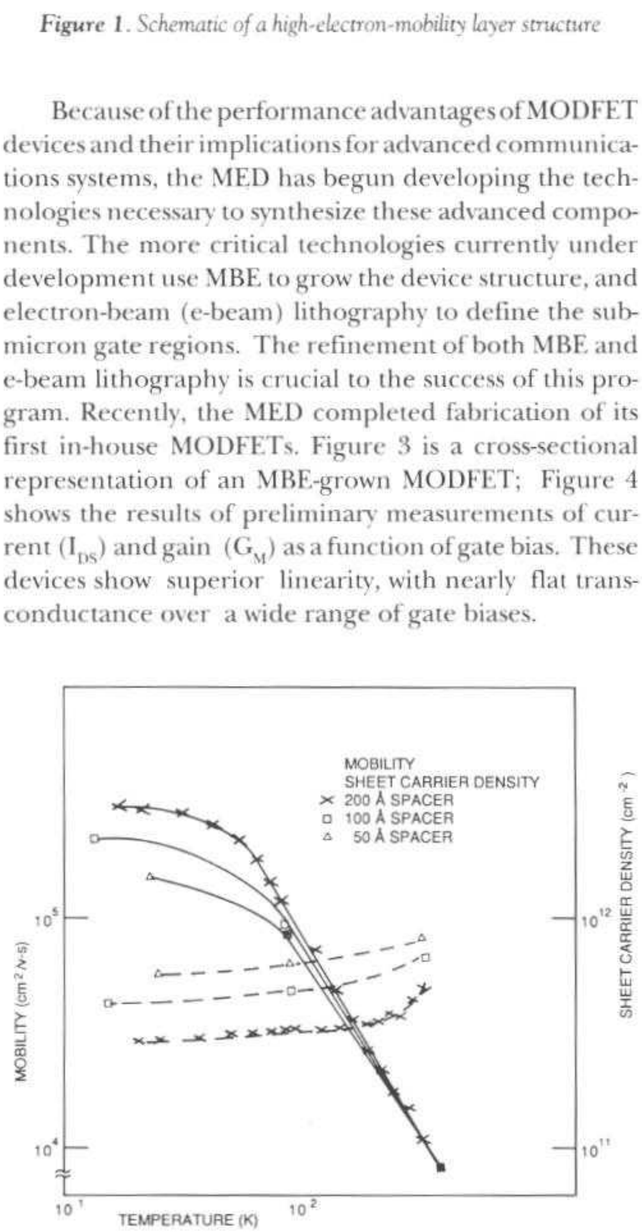


Figure 2. Hall mobility and sheet-carrier density vs temperature

Research was also performed on the fabrication of reproducible quarter-micron gates. Patterning methods in polymethyl methacrylate (PMMA) have been developed and are routinely used in the fabrication of GaAs FETs and MMICs. Placement of the gate electrode with respect to the source is critical in determining the performance of a GaAs FET. Techniques have been developed for controlling gate placement in a process where two e-beam writing steps are required for gate recess and gate metalization. Figure 5 is a scanning electron micrograph of a completed gate in a recess, illustrating the excellent capability of the e-beam system to direct gate placement. In this case, the gate was intended to be exactly centered in the recess. These same techniques can be used to fabricate MODFETs.

Another advance for the MED was the development of a method for measuring finished metal gate lengths directly on the wafer. The e-beam is used to rapidly measure large numbers of gate lengths on the wafer and obtain statistical data on their uniformity. These data may also be displayed graphically to help in understanding the ability of the e-beam system to correct itself during calibration, and to apply these corrections during gate writing.

Analytical Techniques

The life of the communications package on board a satellite is determined by the life of its shortest lived

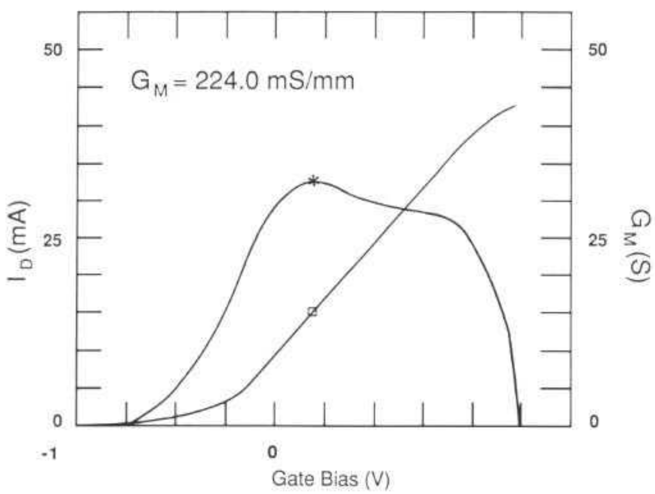


***Figure 4**. Measured current and gain vs gate bias*

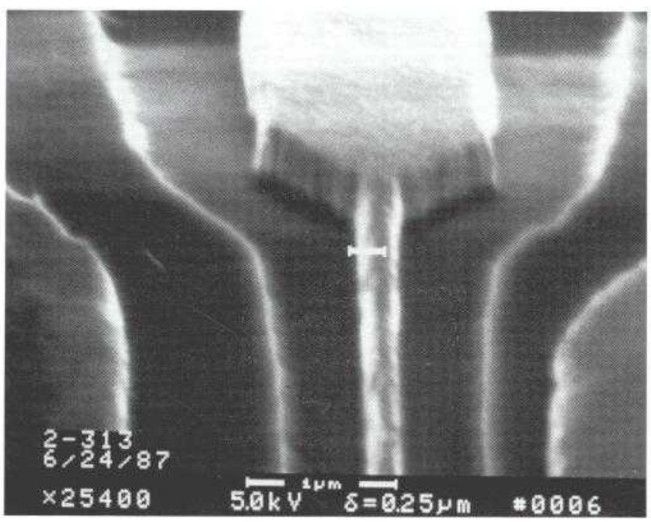


***Figure 5**. Scanning electron micrograph of an e-beam-written gate*

components. One of the most critical components is the traveling wave tube (TWT), more specifically the TWT cathode. Cathode degradation is manifested by a gradual decrease in electron emission intensity, and failure occurs when the emission falls below some predetermined value; failure can also occur catastrophically.

The MED has studied a "good" barium/strontium oxide-coated, nickel-based cathode to understand cathode composition and to devise methods for extending cathode life. This study revealed that the electron-exchange mechanism that provides the electrons for emission occurs from many point sources, rather than uniformly over the entire surface. Figure 6 shows the surface of the base material after the oxide has been chemically removed. It is apparent from point analysis that the distribution of zirconium is irregular across the surface, while elements suspected of being cathode "poisons" (carbon and sulfur) are concentrated in grain boundaries. The depth profile of elements at the oxide/base interface, determined by Auger spectroscopy, is depicted in Figure 7. Surface roughness was accentuated by argon sputtering during the Auger mapping, and it was found that the harder segments were rich in zirconium, which was used as the activator in this cathode. Failed cathodes are being examined and compared in order to understand failure mechanisms.

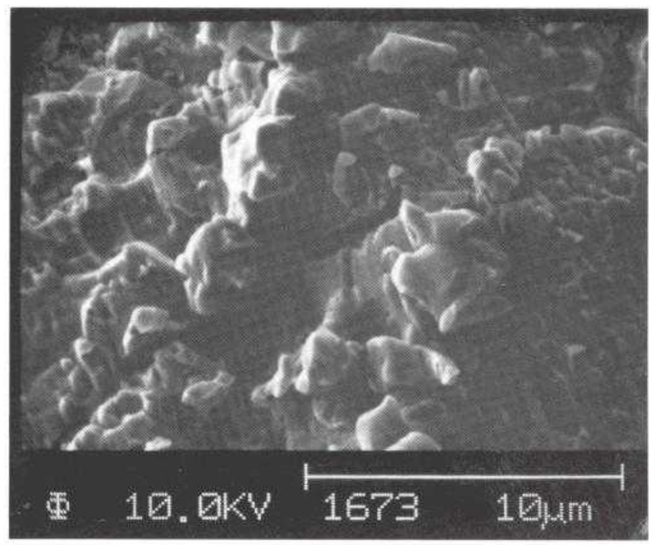


***Figure 6**. TWT cathode surface*

The long-term failure of GaAs-based devices and integrated circuits is often caused by degradation of the ohmic contacts required in active devices such as MESFETs and HEMTs. Increased contact resistance may be brought on by aging due to thermal and electrical stress, and is particularly noticeable in FETs exhibiting high power dissipation. A materials analysis was undertaken to study the reliability-dependent characteristics of alloyed ohmic contacts on GaAs. The compositional and morphological characteristics of a high-temperature, furnace-alloyed ohmic contact (conventional method) were compared to those of a rapid thermal-alloyed (RTA) contact also alloyed at high temperature, but for a much shorter time. The contacts were formed by vacuum deposition of separate layers of Au, Ge, Ni, Ag, and Au, respectively.

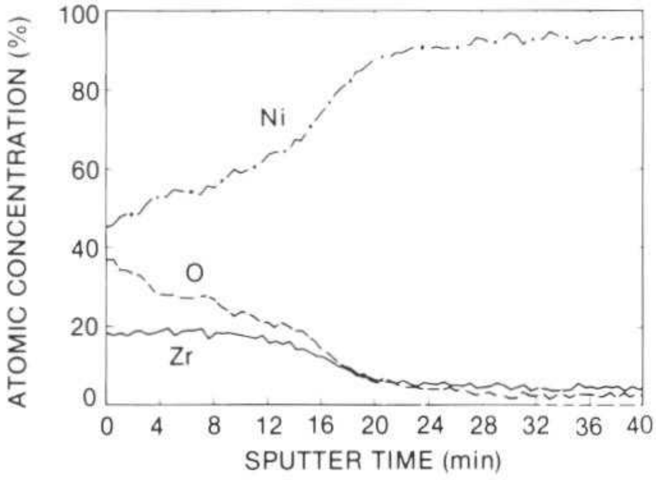


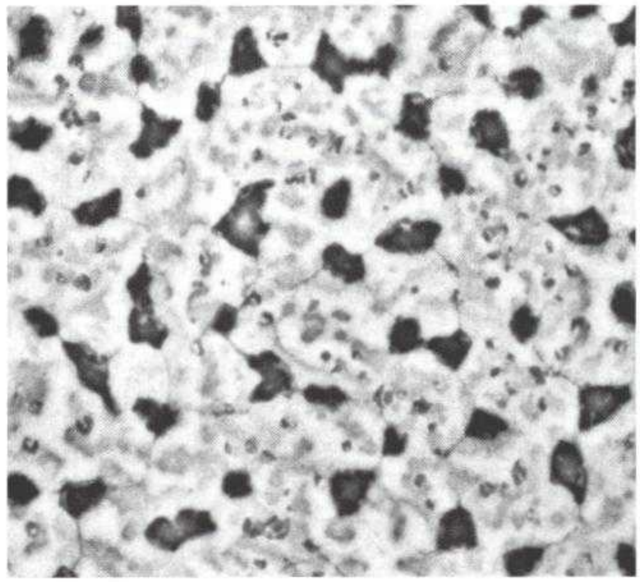
Figure 7. *Depth profile through a grain of zirconia*

The studies were performed using an innovative method to expose the undersides of the contacts by selectively removing all the GaAs, thus presenting a "GaAs-eye-view" of the contact. To analyze this interfacial surface, a combination of high-resolution Auger spectroscopy, secondary-electron, and backscattered-electron image analysis was employed. As shown in Figure 8a, the footprint of the furnace-alloyed contact is characterized by the segregation of relatively large (1-μm) Ge-Ni-rich grains dispersed in a sea of gold. The gold-rich phase has penetrated most deeply into the GaAs, as much as 2,000 to 3,000 Å.

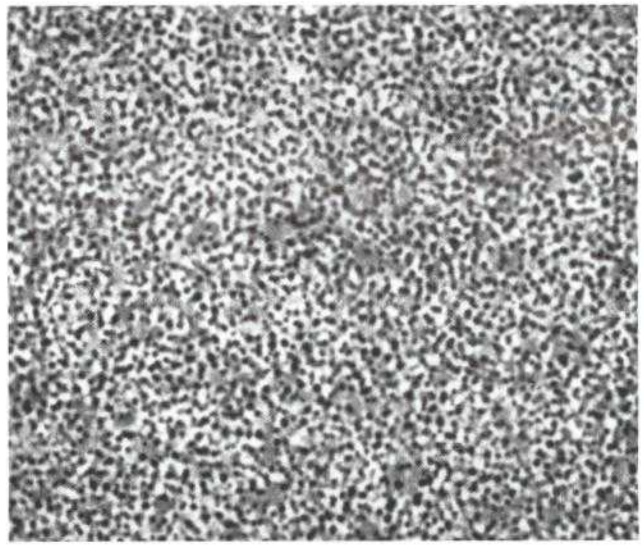
In sharp contrast to the furnace-alloyed contact, the RTA contacts show a more homogeneous alloy depth, without the gross irregularities associated with the preferred penetration of any one phase into the GaAs (Figure 8b). In RTA contacts, the Ge-Ni-rich grains are rarely more than 1,500 Å across, but occupy a larger portion of the contact area. These contacts exhibit more uniform alloy depth; no spiking of the gold into the semiconductor; less initial lateral diffusion of metals; and a lower probability of diffusion-induced, deep-level traps in the vicinity of the contacts, which are morphological and chemical characteristics that are especially desirable for fabricating high-reliability HEMTs and pseudomorphic devices. Finally, because the RTA contacts have smoother edges, they provide better patterns for alignment during the e-beam writing of FET gates.

Advanced Devices and Circuits

The results of materials and fabrication technology research were applied in fabricating new and improved semiconductor devices and circuits (e.g., MMICs). Several examples of these components are described below.



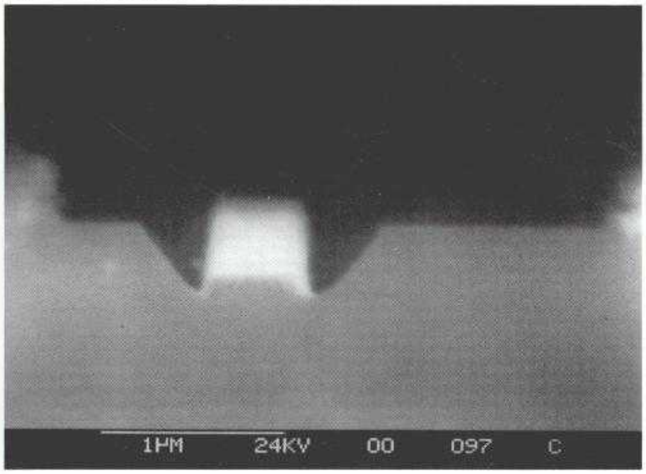
a) *Conventional: furnace alloy contact*



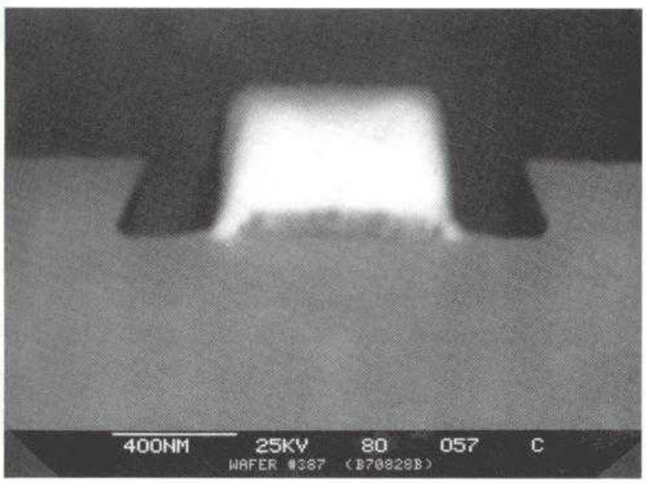
b) *Improved: rapid thermal alloy contact*

Figure 8. *Backscattered electron micrograph of the undersides of two alloyed ohmic contacts after removal of GaAs*

For transmitter applications it is desirable to use components which exhibit very high efficiency, particularly in phased-array antennas. To realize a goal of 40-percent power-added efficiency at 11 GHz, the avalanche breakdown voltage of the COMSAT power FET had to be significantly increased. This was achieved by reconfiguring the gate recess (the groove in the GaAs material where the metallic gate-control electrode lies). Figure 9a shows a cross section of a COMSAT power FET which had a breakdown of 11 V. A similar cross section, after the gate recess was reconfigured, is shown in Figure 9b for an FET with a 20-V breakdown.



a) 11-V breakdown



b) 20-V breakdown

Figure 9. *Scanning electron micrograph of a COMSAT power FET*

The maximum DC voltage that may be applied to existing FET devices is 10 V, because of the occurrence of avalanche at higher voltages. Using a novel device/circuit configuration, multiple FETs can be DC-biased in series. With this approach, power FETs and X-band MMIC amplifiers that require bias voltages close to that of a satellite bus (e.g., 32 V) have been designed and fabricated. These devices will allow elimination of the electronic power conditioner, or its replacement with a simple voltage regulator, thus improving the overall DC-to-RF efficiency of satellite transponders and reducing the mass. Figure 10 shows the layout and frequency response of one cell of one of the X-band, high-voltage monolithic amplifiers currently being fabricated.

MMICs have been developed for use in a wide spectrum of frequency bands and for applications such as power amplifiers and low-noise amplifiers (LNAs). An MMIC version of an LNA for direct replacement of an existing hybrid MIC amplifier is under development in the 14- to 14.5-GHz fixed satellite band. Single-stage and two-stage LNAs were designed and fabricated. A first design iteration of a single-stage LNA provided a noise figure of 2.2 dB and an associated gain of 8 dB. Figure 11 depicts a two-stage LNA chip which, when cascaded with a second chip, provided a 2.6-dB noise figure and over 32 dB of associated gain.

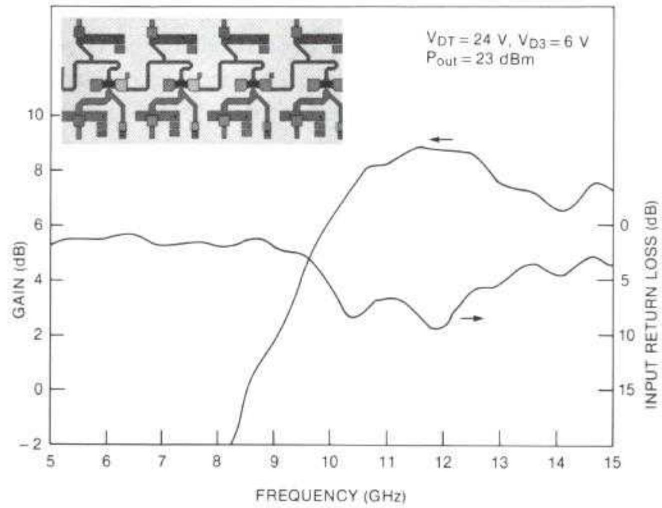


Figure 10. *X-band high-voltage FET showing frequency response of one cell*

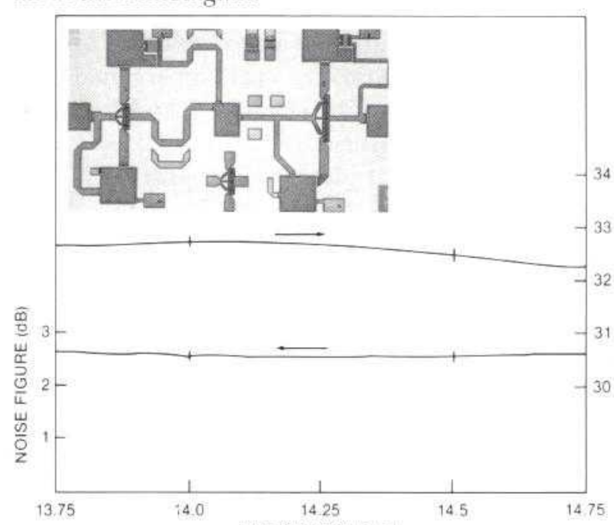


Figure 11. *Two-stage LNA at 14 GHz*

At higher frequencies, improvements in K-band (20-GHz) and K_a-band (28-GHz) monolithic power amplifiers have been achieved. The K-band amplifiers developed at COMSAT have demonstrated a state-of-the-art power added efficiency of 27 percent with 513-mW output power. A multistage amplifier exhibited linear gain exceeding 23 dB, with an output power of more than 2 W at 20 GHz. At 28 GHz, 20-percent power-added efficiency has been achieved with an MMIC amplifier providing 0.5-W output power. Figure 12 shows a balanced K_a-band power amplifier in a waveguide assembly. The gain of this amplifier is over 6 dB in a 1.8-GHz bandwidth with an output power of 1 W.

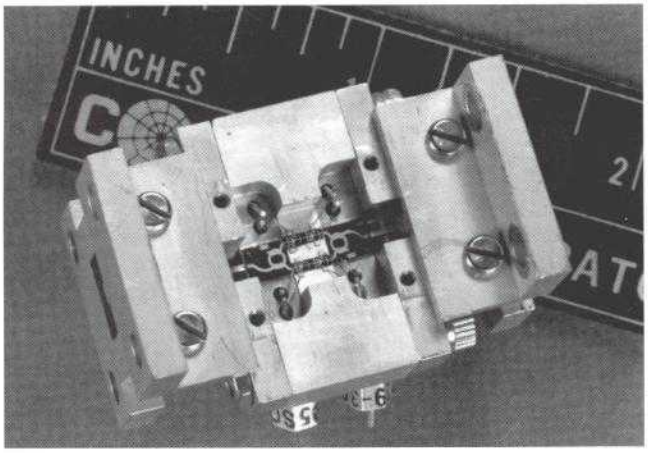


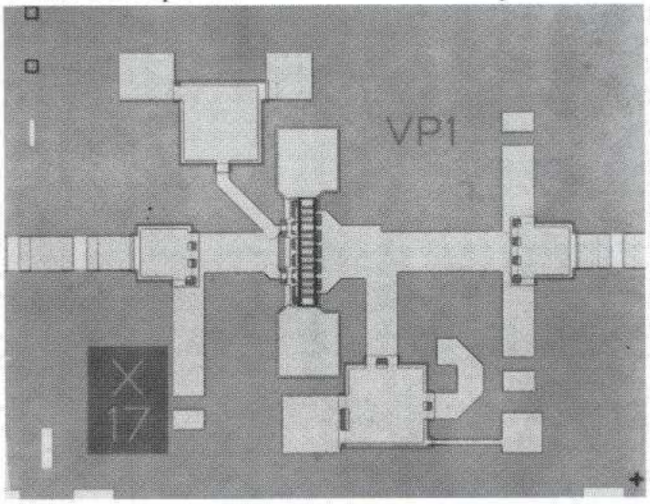
***Figure 12**. K_a-band power amplifier*

Monolithic GaAs V-band power amplifiers and LNAs (50 to 75 GHz) have been developed. A single-stage MMIC LNA has achieved a 6.4-dB noise figure and 3.5-dB gain at 59 GHz. A cascaded multistage amplifier exhibited a 9.5-dB minimum noise figure and 26-dB gain from 56 to 60 GHz. Figure 13 is a photograph of a power MMIC which has demonstrated small-signal gain of 4 dB from 50 to 56 GHz, output power of 95 mW, and 11-percent power-added efficiency.

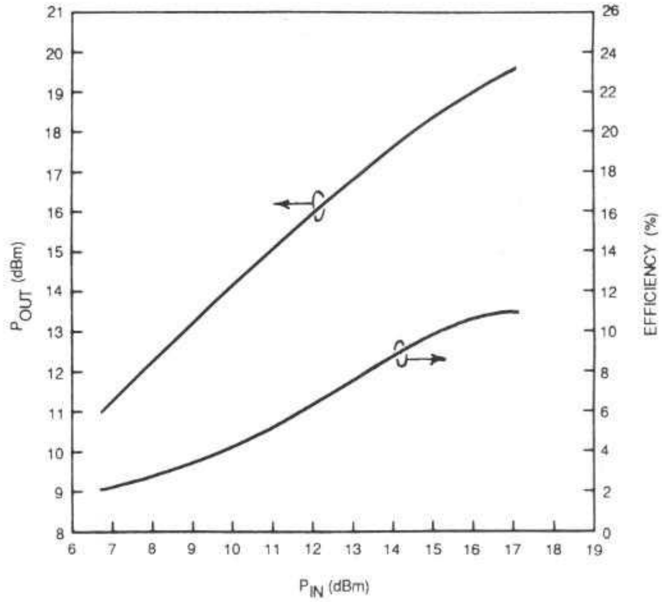
Circuit Characterization

In cooperation with the University of Maryland, COMSAT demonstrated a novel technique for characterizing millimeter-wave MMICs by using picosecond optical sampling. The broadband signals at the input and output of a 28-GHz MMIC power amplifier are sampled using photoconductive switches. The spectral response of the MMIC is analyzed by fast Fourier transform and compared with the continuous-wave characteristics. Good agreement has been obtained between the measured results from this technique and conventional RF measurements. Figure 14 shows the switch/MMIC assembly. This optical technique may be extended to perform noncontact, on-wafer MMIC evaluations.

Device and MMIC characterization capability has been established for various frequency bands up to 60 GHz using noise figure and power measurement equipment available at COMSAT Laboratories. The passive circuit components, such as microstrip-to-waveguide transitions and divider/combiner circuits, necessary to test MMIC amplifiers and combine several of them to obtain useful power, have also been developed.



***a)** MMIC chip 30 mil x 40 mil (0.75 x 1.0 mm)*



***b)** Output power and power-added efficiency vs input power*

***Figure 13**. Power MMIC*

Device Reliability

Consistency in the quality and reliability of MED-fabricated GaAs MMICs has been ensured by implementation of a product assurance and wafer qualification test plan. Consistent and documented fabrication, test, and inspection procedures are followed, and sample devices from each wafer in the program are thoroughly evaluated by scanning electron microscopy and electrical testing, both before and after stringent thermal and electrical stress tests. These tests ensure that acceptable wafers meet high standards of workmanship, performance, and reliability.

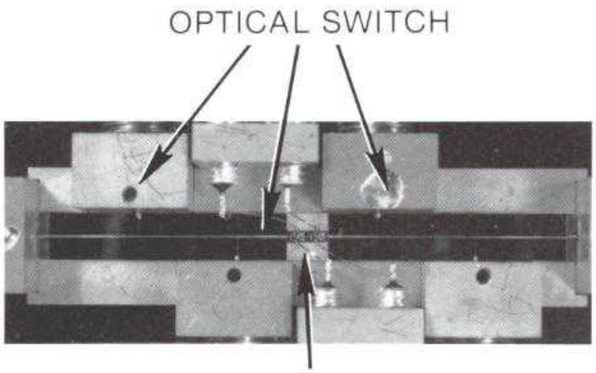


Figure 14. Optical switch/MMIC assembly

Even though a semiconductor device or circuit is shown to be reliable from a thermal/mechanical viewpoint, its reliability must be demonstrated in a radiation environment if it is to be useful for satellite applications. The MED has been studying radiation effects on silicon devices for over 15 years, and recently began considering GaAs components because of their anticipated use in spacecraft. One focus of this work has been the examination of the effects of radiation on the operating speed of devices and circuits.

COMSAT Laboratories has developed a radiation-hardened oxide for silicon that has an interface trap density which exhibits unusually small dependence on radiation. Because trap density plays a significant role in operating speed, the new process could be of particular value for the fabrication of high-speed switching circuits. GaAs is not affected by radiation in the same manner as silicon; however, it too loses high-frequency capability with increased radiation exposure. Figure 15 shows the effects of radiation on the electron mobility in GaAs FETs that were irradiated by two different sources. The considerable difference in apparent damage emphasizes the need for proper specification of the radiation environment and test conditions.

COMSAT PROPRIETARY R&D

Modeling

Accurate modeling of FETs is essential to successful monolithic circuit design. Toward that end, both the MESFET and MODFET devices have been modeled. Computer programs based on device physics and microwave circuit theory have been developed to assist microwave designers in predicting device and MMIC performance. These programs are also used to perform parametric studies as device and material parameters are changed, prior to expensive and time-consuming fabrication processing. Figure 16 presents a comparison between predicted and measured FET DC and RF parameters. Continuing efforts are focused on combining these software programs into a user-friendly expert system, with an FET cell library that can be readily accessed for MMIC design by the engineer who is not expert in device design.

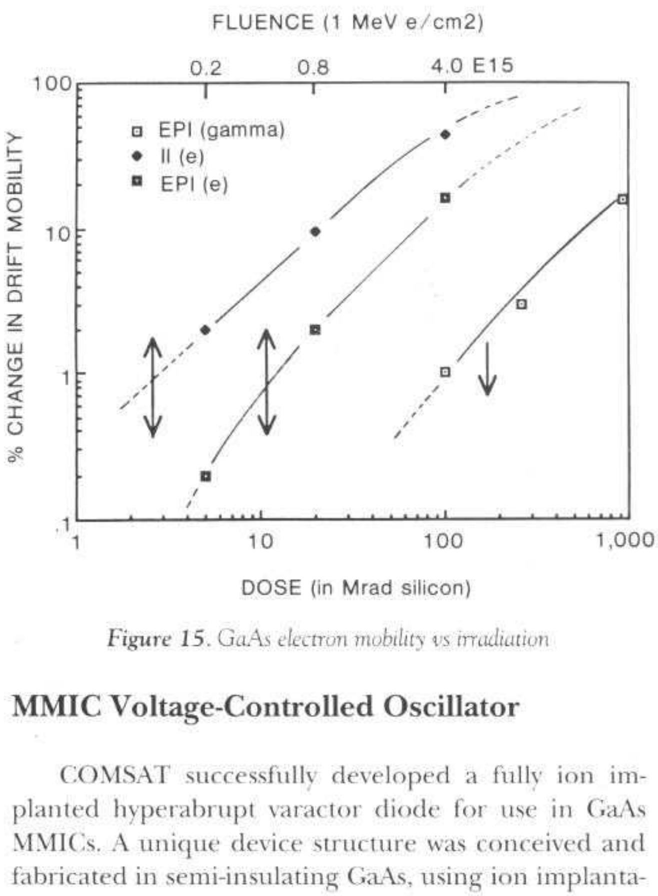
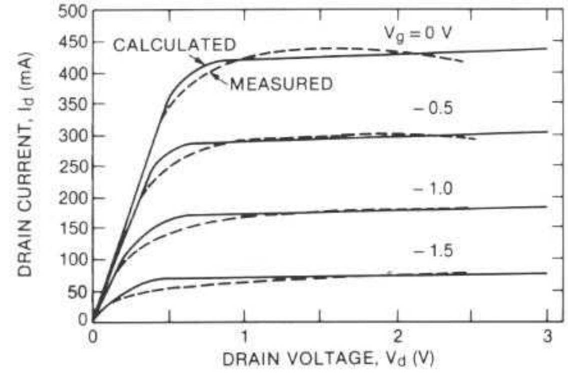


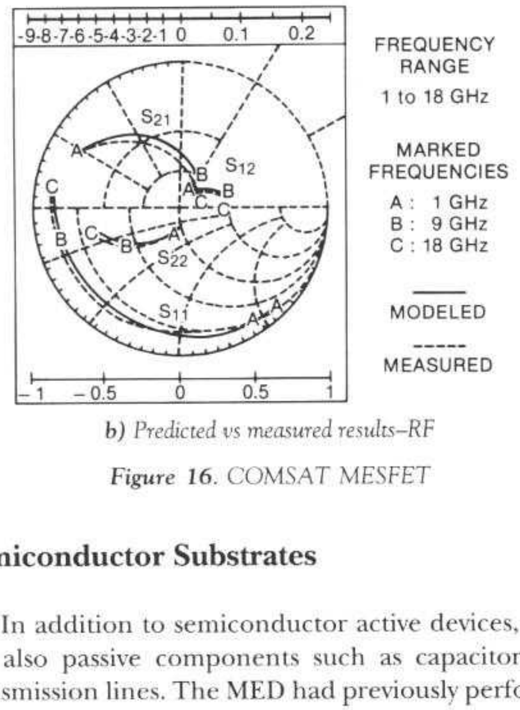
Figure 15. GaAs electron mobility vs irradiation

MMIC Voltage-Controlled Oscillator

COMSAT successfully developed a fully ion implanted hyperabrupt varactor diode for use in GaAs MMICs. A unique device structure was conceived and fabricated in semi-insulating GaAs, using ion implantation doping to produce conducting layers with electrical properties tailored for high-performance operation. Figure 17 depicts a cross section of the varactor diode showing the several implanted regions. Selective ion implantation techniques were used to fabricate the planar device shown. One of the implant steps is the hyperabrupt capacitor impurity profile, which controls the capacitance-voltage behavior of the diode. The relationship between capacitance and voltage depends on the energy and dose of the implant, and these may be varied to satisfy the specific circuit requirement. The figure also shows ohmic contacts to n^+ layers and a Schottky barrier over the hyperabrupt capacitor implant. Voltage applied to the Schottky barrier depletes charge in the doped region below it, resulting in a controlled decrease in capacitance with increasing voltage. A considerable change in capacitance with voltage is desirable for many circuit applications. The ion implanted carrier profile in COMSAT's device produced a capacitance ratio greater than 10:1 over the useful voltage range.



a) Predicted vs measured results–DC



b) Predicted vs measured results–RF

Figure 16. COMSAT MESFET

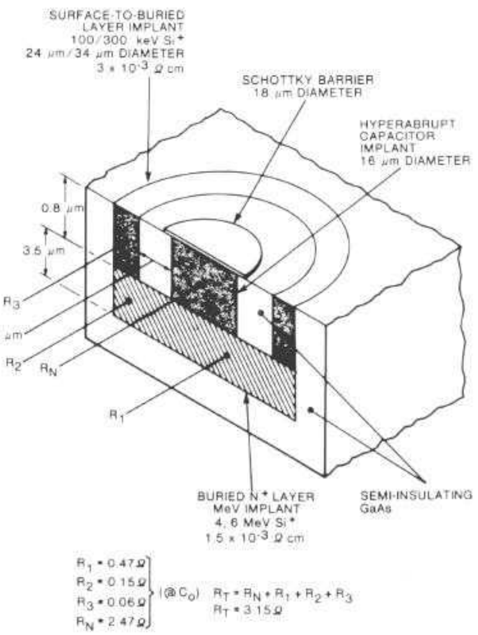


Figure 17. *Cross section of a varactor diode*

Semiconductor Substrates

In addition to semiconductor active devices, there are also passive components such as capacitors and transmission lines. The MED had previously performed studies on the fabrication yield of capacitors on alumina substrates. This work was extended to the use of silicon substrates. Nearly 15,000 capacitors were made in 1987 using 2,000 Å of silicon nitride as the dielectric in value ranges from 6 to 60 pF. Typical yields (breakdown voltage >50 V) were 94 percent for the large size to 97 percent for the small size.

Microstrip transmission lines on silicon and GaAs substrates were characterized as a function of temperature, and the results were compared to those for transmission lines on conventional substrate materials such as alumina. This study is important, since monolithic circuits usually consist of transmission lines defined over semiconductor substrates such as silicon or GaAs. Measured results indicated that the RF loss of transmission lines on silicon at room temperature is comparable to that on alumina. Additionally, the RF loss increased as the temperature rose above 125°C. This is believed to be caused by electrons being excited from the valence band to the conduction band by the elevated temperature. This effect was not observed in alumina, which is an insulator, nor in GaAs, which has a larger band gap than silicon, making it more difficult to excite the electrons to a higher band level. These results are summarized in Figure 18, which compares the RF attentuation vs temperature characteristics of different substrate materials.

CORPORATE SUPPORT

Analytical help was provided to COMSAT General to rectify a problem at the master antenna used for national distribution in the NBC TV satellite network. Troublesome transmitter outages were traced to viscid, blue-green deposits in the waveguides, which COMSAT Laboratories' chemists identified as copper hydroxy nitrate complexes created by high moisture and ionizing RF energy in the waveguides. A relatively inexpensive repair procedure was recommended to remove the deposits and add adequate moisture control to the waveguide, thus returning the transmitter to service after minimum downtime.

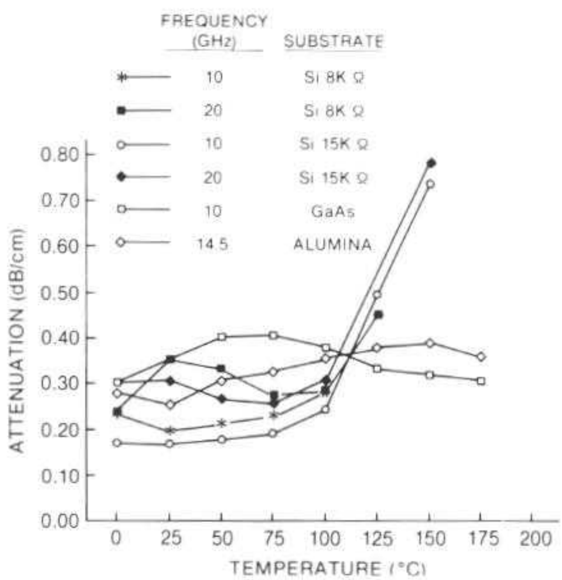


Figure 18. *RF attenuation as a function of substrate*

Technical assistance also was provided to COMSAT International Communications, Inc. (CICI) for operation and maintenance of the Roaring Creek, West Virginia, earth station.

INTELSAT

Studies continued in 1987 on the Ni/H_2 battery-plate blistering problem. A failure mechanism was identified that relates the reduced tensile strength of the nickel plaque to embrittlement and high carbon concentrations at fracture surfaces. Changes were recommended in the plate fabrication process to reduce embrittlement and stress.

At the request of the Applied Technologies Division, components of the INTELSAT V momentum wheel bearing were analyzed for evidence of abnormal wear following an accelerated life test simulating operation with a depleted lubricant supply. The study showed the expected burnishing marks on the retainer but no significant wear on the races, indicating that there is a desirable safety margin in the design.

OTHER

Chemical and microstructural analyses of Ni/H_2 and Ni/Cd battery plates were continued on a contractual basis in 1987 to support several spacecraft programs, including Skynet, Eutelsat II, INMARSAT, and Olympus. In addition to the specialized technique devised in the MED to analyze positive battery plate compositions by using backscattered electron microscopy, a new method was developed to etch and stain negative plates in order to determine the cadmium hydroxide distribution.

Under a subcontract from the University of Maryland, the MED fabricated GaAs photoconductive switches with sufficiently rapid response time to act as optical mixer diodes, with an intermediate frequency (IF) in the range of 1 to 10 GHz. The university tested these switches with a multimode ultraviolet laser, which had an output that contained a number of discrete ultraviolet frequencies separated by 250 MHz. The resulting IF signal contains multiples of 250 MHz, up to approximately 5 GHz. It is not yet known whether this signal is limited by the number of laser frequencies or by the mixer response. The IF output-to-noise ratio was reported to be at least 70 dB.

Results of COMSAT's research on ion implanted varactor diodes in GaAs are being implemented in programs with Hughes Aircraft Co. and the Naval Research Laboratory. Both programs employ the device structure shown in Figure 17, which also shows implantation parameters, device geometry, and implanted layer resistances derived from device modeling. Figure 19 depicts device performance at 10 GHz using these specifications. It also shows capacitance, series resistance, and Q, all with respect to applied voltage.

The Hughes Aircraft Co. program is in the final phase of fabricating both hyperabrupt varactor diodes and small-signal FETs on the same GaAs wafer. Again, the varactor diode of Figure 17 is being fabricated in this program. The maskset contains varactor diodes, FETs, large-value capacitors, and resistors, all of which are required in order to completely characterize individual components for an MMIC VCO design.

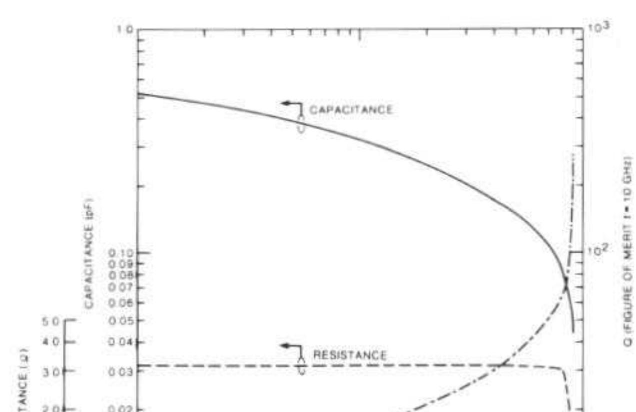


Figure 19. *Varactor diode performance at 10 GHz*

The Applied Technologies Division (ATD) provides a broad range of research and development capabilities covering disciplines such as controls; dynamics and propulsion; telemetry, tracking, and command; traveling-wave tubes (TWTs); and high-voltage power supplies, as well as structures, mechanisms, thermal control, power systems, energy conversion and storage, reliability and quality assurance, and environmental and qualification testing. The division conducts studies directed toward extending satellite lifetime and reliability, as well as supporting development programs in other divisions such as the development of multibeam antennas under the INTELSAT Satellite Services (ISS) development program. The ATD continues to provide engineering support under contract to INTELSAT and other spacecraft programs, including INMARSAT II in support of COMSAT Technical Services. Significant activities in 1987 included the development of an architecture for the high-speed controller used in the multibeam phased-array antenna, support of the multiple satellite system program (MSSP) under contract to the U.S. Air Force Rome Air Development Center, and completion of an accelerated life test on an INTELSAT VI slipring assembly that required redesign.

COMSAT JURISDICTIONAL R&D

Analytical Techniques

The Analytical Techniques jurisdictional research task was created in 1987 to improve the overall software capabilities of the ATD. The goals of this effort were to develop new and improved analytical techniques relevant to the ATD's technical disciplines, enhance existing programs, convert existing programs to the VAX operating system, enhance the local area network (LAN), and expand and maintain the software library.

Several new industry-standard computer programs were added to the ATD's software library in 1987, including CADKEY, for three-dimensional computer-aided design; CTRL-C, for control system design and analysis; ACSL, for simulation of dynamic systems; ADORE, for real-time simulation bearing analysis; SSPTA, for shuttle cargo bay thermal analysis; QARMS, a reliability and statistical analysis package; BAT and LAST, for nickel-hydrogen battery analysis; and ITPLOT and TRASYS, which are graphics and translators to SSPTA and PATRAN. NBOD2, a program for spacecraft deployment and attitude dynamics, was modified to handle latchup loads. The ATD library now contains more than 90 program packages.

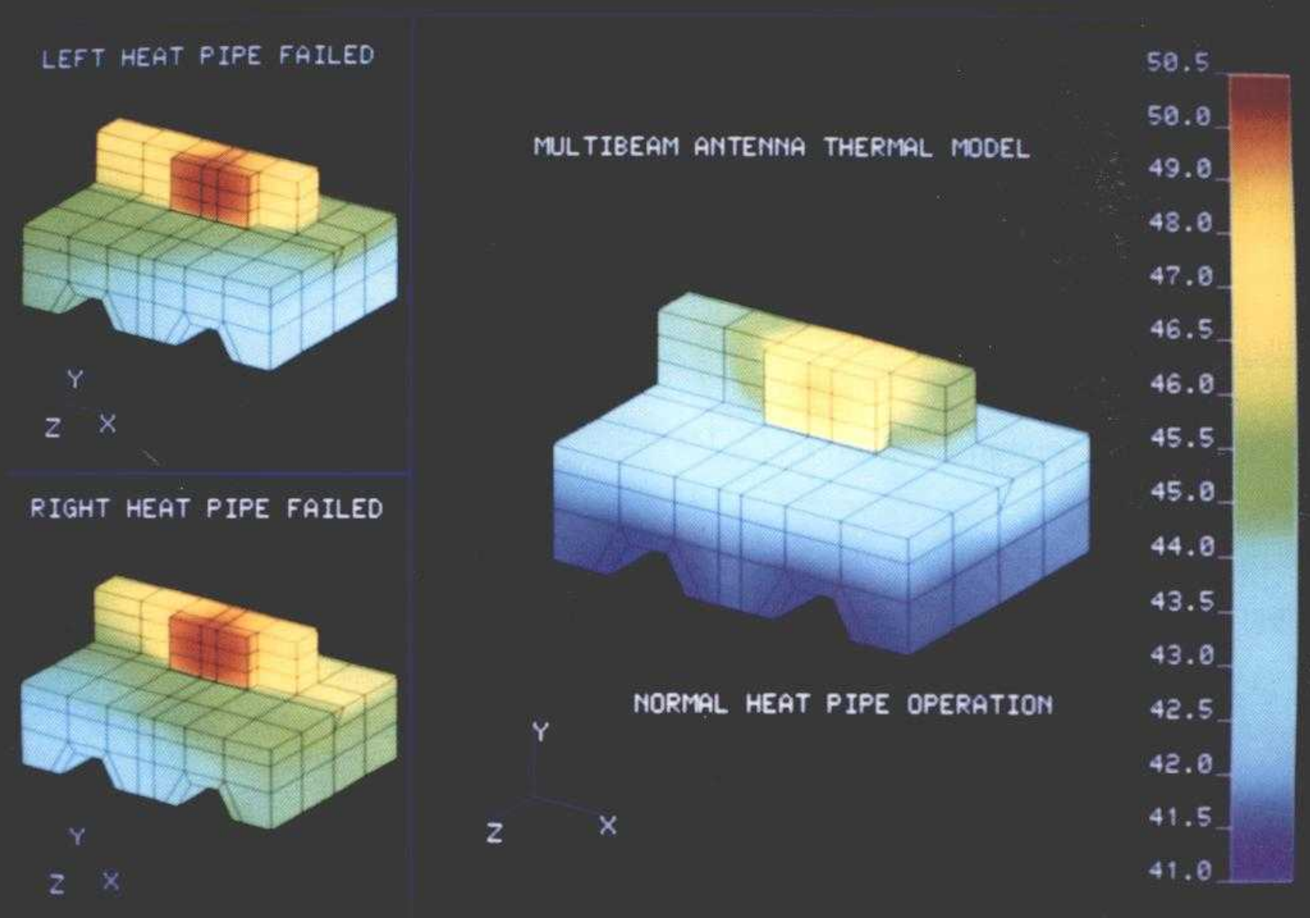
Additionally, more graphics software and hardware were made available, and the integration of programs has increased efficiency and reduced labor-intensive processes.

Power Conditioners for SSPAs

Customized DC power supplies have been designed, constructed, and delivered by the ATD in support of the 2-W, 4-GHz SSPA jurisdictional development by the Microwave Technology Division (MTD). In support of the 11-GHz, high-power solid-state power amplifiers (SSPAs) for the high-power phased-array antenna, an extended version of the design has been assembled at the brassboard level. A power conditioner has also been built and delivered for the 64-element, low-power phased array.

The high-power stages in the array will be capable of being switched on upon demand, in order to use the SSPAs most efficiently. This involves applying the DC power supply voltages to the power transistors in a switched mode, with very fast (less than 50 ns, with a predicted value of about 10 ns) ON/OFF transitions. To achieve this speed, a switching circuit has been designed which will use a high-current metal semiconductor field-effect transistor (MESFET) to control the voltage supplied to the drain electrodes of the SSPA output transistors. A monolithic microwave integrated circuit (MMIC) realization of this circuit has been designed on a 60- x 70-mil chip, as illustrated in Figure 1. The switching circuit will be integrated with the SSPA in MMIC form for each element of the antenna array.

APPLIED TECHNOLOGIES



Multibeam antenna amplifier thermal analysis

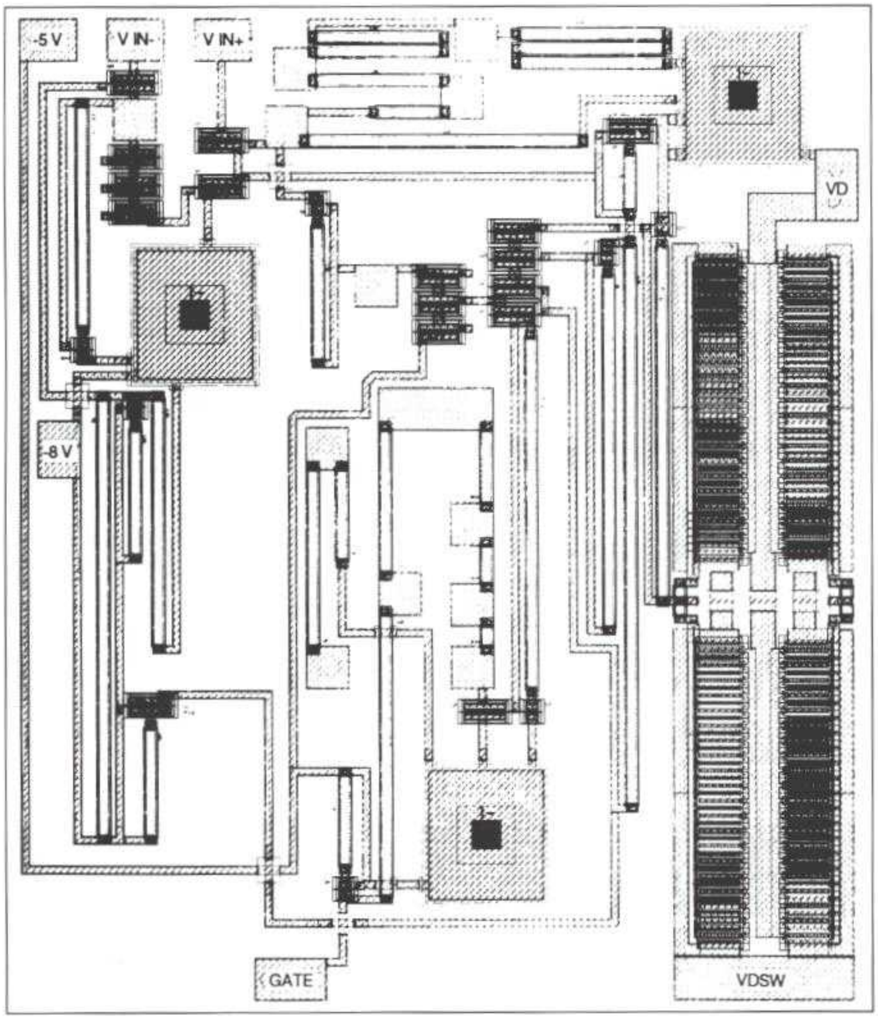


Figure 1. MMIC realization of circuit using high-current MESFET to control voltage

Multibeam Phased-Array Antenna

A system study of the high-power array conceptual design was supported with candidate architectures for the digital controller. Technological and architectural issues were considered in relation to the total requirements of large beam-scanning, hopping, or shaping antenna arrays. A prime selection criterion was flexibility over the wide range of satellite applications. The distributed hierarchical architecture was retained from the previous design, including the local controller modules (LCMs), the data distribution and timing unit (DDTU), and executive levels. A microcontroller was used in place of custom gate arrays in the LCM, which includes the MMIC driver circuit. This architecture is sufficiently flexible to also be suitable for the microwave switch matrix being developed for on-board demodulation/remodulation. Hardware designs for the three-level controller of the high-power array were completed and breadboarded. Prototype software designs were also completed.

Ten prototype MMIC driver circuits for the 64-element, low-power array were fabricated by a vendor and tested at COMSAT Laboratories, and some were integrated into the MMIC active circuits. RF-digital control tests performed on the subassembly were satisfactory, and, on the basis of these results, production of the remaining driver circuits was initiated and nearly completed in 1987.

The power supply for the low-power array was designed, assembled, and tested. The power supply for the high-power array was designed, and a breadboard version was constructed. The harness interconnecting the MMIC active circuits, the digital controller, and the power supply for the low-power array was designed and constructed.

Mechanical and thermal design of the low-power array was completed during 1987. Although the array has very little dissipation, provision has been made to incorporate high-power amplifiers and attendant cooling into it. The selected design will mount the SSPA directly to a heat pipe, which carries the dissipated heat to a remote thermal radiator for rejection into space. The design is such that any element may be removed without disassembling the entire feed system.

During 1987, several conceptual designs were developed for the high-power, 64-element array that satisfy the changing RF requirements. These requirements necessitated the use of high-transport heat pipes (monogroove) to remove the amplifier heat to a remote array. The latest concept for the high-power array consists of a beam-forming matrix unit and an amplifier/horn unit.

Advanced Satellite Thermal Control

Technological requirements for the thermal control subsystem of a satellite incorporating a multibeam phased-array antenna have been assessed, and a preliminary conceptual design evaluation has been completed.

A multibeam array communications payload contains a large, high-density heat source, which is located away from the prime satellite heat rejection surfaces. The concepts of heat removal from the densely packed array elements, the transport of this heat from the multibeam antenna (MBA) to the satellite radiators, and the area/weight-efficient rejection of this heat to space have been evaluated during this project. High heat transport capacity pipes have been identified and are an integral part of the proposed MBA design. The latest two-phase heat transport technology (under development for the space station) has been investigated to determine its potential use on the MBA spacecraft bus. Spacecraft radiator designs have been weight/area optimized to include east/west and deployable radiators. A conceptual MBA satellite thermal design, shown in Figure 2, has been developed to provide a reference for identifying problem areas, determining performance requirements, and comparing other satellite designs.

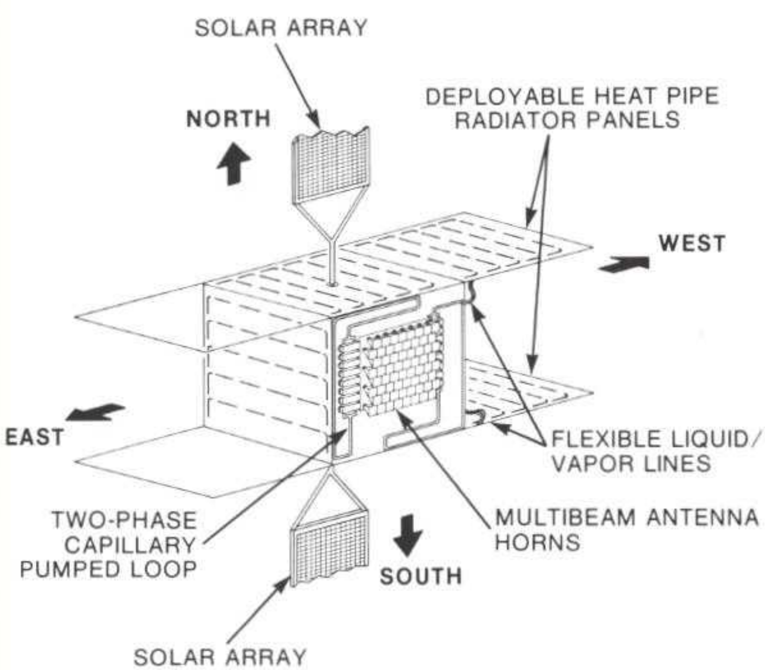


Figure 2. *Conceptual MBA satellite thermal design*

Accelerated Bearing Life Test

Experience gained at COMSAT Laboratories during the investigation of ball bearing dynamics, cage instability, and various bearing tests, including long-term life tests, has shown the need for a detailed study of minimally lubricated bearings in their end-of-life condition. Research and testing during the Momentum Wheel Bearing Cage Instability Project had initially linked cage instability with minimal lubricant quantities. To further define the bearings' characteristics as they approach the end of their useful life, COMSAT Laboratories undertook the Accelerated INTELSAT V Bearing Life Test.

The specific objective of this project was to estimate INTELSAT V momentum wheel bearing life by testing bearings in their end-of-life lubricant condition. A further objective was to determine the observable symptoms, if any, of impending bearing failure. Tests were performed in a vacuum to maximize lubricant bleed-out, and thus accelerate bearing wear rates.

During 1987, three separate INTELSAT V-type bearings and cages were run to failure in tests where lubricant condition was the primary variable. Failure was manifested by high torque and excessive wear caused by lubricant exhaustion. It was shown that the phenolic cage has an essential function in lubricant flow equilibrium within the bearing. Several indices of bearing health were identified, including bearing torque and temperature, as well as spectral characteristics and elastohydrodynamic lubricant film condition within the bearing. Some of these indices can be monitored in orbit to anticipate impending bearing failure.

TWT Linearization

Due to both the differential phase and gain nonlinearity of traveling-wave tubes, the power level at which they may be operated with multicarrier or amplitude-varying input signals is limited according to the degree of acceptable output signal intermodulation or distortion. Various schemes have been proposed for operating a TWT at a higher mean power level, relative to its saturation level, while keeping multisignal intermodulation below some preassigned level. Several schemes that use RF envelope preemphasis have been tested, each presenting some disadvantages in implementation.

A method that has proven to be advantageous is to impose a relatively small modulation of the TWT voltages in synchronism with changes in the amplitude of the RF drive signal, using the variation of overall TWT gain and phase-shift with voltage to correct for the nonlinear performance changes in drive level. Extensive measurements on a 16-W, 4-GHz space TWT (such as that on

INTELSAT VI) showed that if both the anode and helix voltages can be suitably modulated in synchronism with variations in the RF drive signal envelope, strictly linear operation should be possible for peak values up to TWT saturation. Unfortunately, the peak anode modulating voltage required would be greater than 200 V, and this appears to be impractical (especially since high video frequencies would be required).

However, TWT intermodulation at more than 2-dB input backoff is mostly due to phase nonlinearity, and it was found that a significant reduction in two-signal intermodulation components could be achieved with a maximum of 15-V peak-to-peak synchronous voltage modulation applied to the TWT helix alone. The instantaneous swing would be proportional to the instantaneous RF drive power level. For a given carrier-to-third-order intermodulation (C/I) level of 18 to 20 dB, this scheme would allow a given TWT to be operated at 1.5 to 2 dB higher useful output power (see Figure 3).

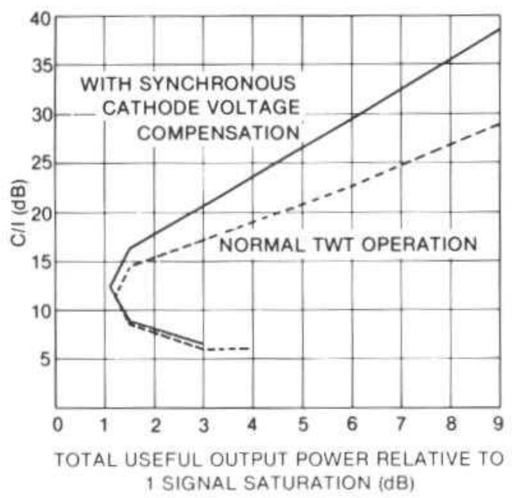


***Figure* 3.** *Total useful* P_o *relative to 1 signal saturation (dB)*

Although design of a broadband (0- to 30-MHz) amplifier capable of providing the required helix voltage modulation was not practical within the project, the principle was tested at spot frequencies (with two equal RF carriers separated by the given frequency difference) from 100 kHz to 100 MHz. The linearizing effect was substantially independent of this frequency difference, and the effective impedance of the TWT helix over this frequency range resulted in less modulating voltage being required at the higher frequencies. The technique was shown to be feasible, but would probably require a TWT designed to accommodate the scheme, in order to be economically practical.

Expert System Applications

The purpose of this project is to determine the best approaches for lowering the cost of satellite operations and minimizing the risk to in-orbit assets and service. The project focuses on the use of knowledge-based (or expert) systems to overcome problems which may occur during either normal or abnormal operation of spacecraft subsystems such as attitude control, electric power, thermal control, propulsion, and orbit determination and control.

The following accomplishments were achieved during the past year:

- a survey of expert system software and hardware options was conducted,
- candidate expert system architectures appropriate for the INTELSAT environment were generated, and a baseline architecture for further development was selected, and
- the first prototype expert system that diagnoses the failure of the pitch control loop of a wheel-stabilized spacecraft due to one of several possible causes was developed and demonstrated.

This system processed the dynamic telemetry which was generated by a real-time attitude control system simulator available at COMSAT Laboratories. Because the simulator includes extensive models of credible failure modes, it is a useful tool for developing and validating attitude control expert systems.

Satellite Life Extension Studies

The possibility of greatly extending the life (up to 30 years) of INTELSAT spacecraft encouraged the study of bus subsystem durability and performance. The INTELSAT V attitude control system operation with a "COMSAT Maneuver" tilt was simulated. Ground and spacecraft antenna pointing for an inclined orbit was studied and the degradation of solar array power output due to space radiation and random string failures was estimated. The effects of life extension on thermal control and propulsion system capability were also considered. The greatest effort was expended on improving the prediction of battery performance. Battery analysis was supplemented by testing that will continue into 1988.

Follow-On Satellite Design Evaluation

The Design Evaluation project was intended to evaluate candidate spacecraft buses for their potential application to the INTELSAT follow-on spacecraft, and to determine the compatibility between specific follow-on satellite payload concepts and candidate spacecraft buses. The project was divided into two tasks: compiling a database on existing buses, and conducting payload compatibility evaluations.

In 1987, COMSAT Laboratories updated and revalidated the communications satellite spacecraft bus database generated in 1986 under ISS Engineering Support. The database includes satellite bus characteristics and capabilities for 19 commercially available communications satellites. Items such as mass, power, lifetime, and launch vehicle compatibility are included.

A menu-driven software package for the IBM PC was developed to manage the database. This software presents the data for each spacecraft bus. These "off the shelf" satellite buses are being evaluated to determine their application to future INTELSAT spacecraft. The software calculates the tradeoff between communications subsystem power and electrical subsystem mass for each spacecraft bus, in order to evaluate payload compatibility. A graphical output of the mass/power tradeoff is also available.

COMSAT NONJURISDICTIONAL R&D

COMSTAR/SBS Batteries

The COMSTAR/SBS Batteries task continues the life testing of COMSTAR-type and SBS Ni/Cd batteries, simulating real-time battery operation in orbit. Test results provide a database for predicting in-orbit performance and lifetime expectancy on board COMSTAR and SBS satellites. A computer model is being developed to improve these predictions. The COMSTAR-type battery life test has completed 25 real-time eclipse seasons, while the SBS batteries test has completed 15 seasons.

The battery life prediction model combines a multiple linear regression approach (to fit data on past battery voltage performance) and a statistical expression which predicts the wearout or failure rate of the battery cells. The resulting performance predictions provide an additional confidence level for operating these satellites up to and beyond their contractual lifetimes.

COMSTAR/SBS TWT Performance

The useful life of satellites in orbit may be increased by 5 to 10 years by employing the COMSAT Maneuver in the operation of communications spacecraft, provided the communications payload is also operable for this period. The COMSTAR D2 and D4 (C-band) spacecraft will be maintained in this mode, and COMSAT has acquired ownership of the SBS spacecraft SBS1 and SBS2 (K_u-band) with the same intention.

In-orbit performance data compiled since the launch of both the COMSTAR and SBS spacecraft have been monitored at the Laboratories, and during 1987 projections were made of the expected remaining traveling wave tube amplifier (TWTA) life, based on the total available data for each spacecraft. In the case of COMSTAR, this knowledge was augmented by measurements on C-band TWTAs on life-test at the Labs. In the two COMSTAR spacecraft, over 85 percent of the channels will provide useful performance well beyond the 7-year design life. Each SBS spacecraft could maintain the original 10 channels for several more years, but the number of channels will be cut to match traffic and conserve operating life.

COMSAT SUPPORT

Technical and Engineering Support

The ATD provided technical and engineering support to a number of COMSAT business units during 1987, including ISS, Maritime Services (MS), and COMSAT Technical Services (CTS), as well as COMSAT Technology Products and Amplica.

Efforts for both ISS and MS involved technical studies and reviews related to COMSAT's Signatory position on the INTELSAT and INMARSAT technical committees. Direct support was provided to Maritime Services by conducting an independent assessment of the stability booms added to the INMARSAT II spacecraft.

The ATD supported CTS' efforts to market the direct broadcast satellites (DBS), including engineering design analyses of Satellite 6 modifications, and support for the final acceptance of the spacecraft prior to the termination of the program. The division also acted as consultant to the INMARSAT II and ITALSAT contracts being managed by CTS. These efforts involved support of the TWTA mechanism, thermal design, and other spacecraft subsystems.

DBS TWTA Life Testing

The TWTA model 1262H, originally designed for the COMSAT DBS, comprises the 230-W, K_u-band TWT manufactured by AEG-Telefunken with the power supply designed and integrated by Hughes Electron Dynamics Division (HEDD).

The life test and thermal cycling of the QTM-1 and QTM-2 TWTAs in thermal vacuum continued during 1987, after formal qualification test procedures were completed. Both have now operated for some 12,000 hours and undergone over 1,300 on/off switchings, with temperature cycling designed to simulate conditions in an orbiting spacecraft. This approximates over 10 years of in-orbit cycling due to natural spacecraft eclipsing, and as yet no measurable change in TWTA characteristics has resulted. Occasional switchoffs were recorded during the first six months of operation (1985-1986) due to the unexpected outgassing of the high-voltage wire leads. However, no damage or deterioration of the TWTAs occurred, and subsequently there have been only occasional isolated switchoffs when the thermal vacuum chambers have been opened to the atmosphere for experimental activities.

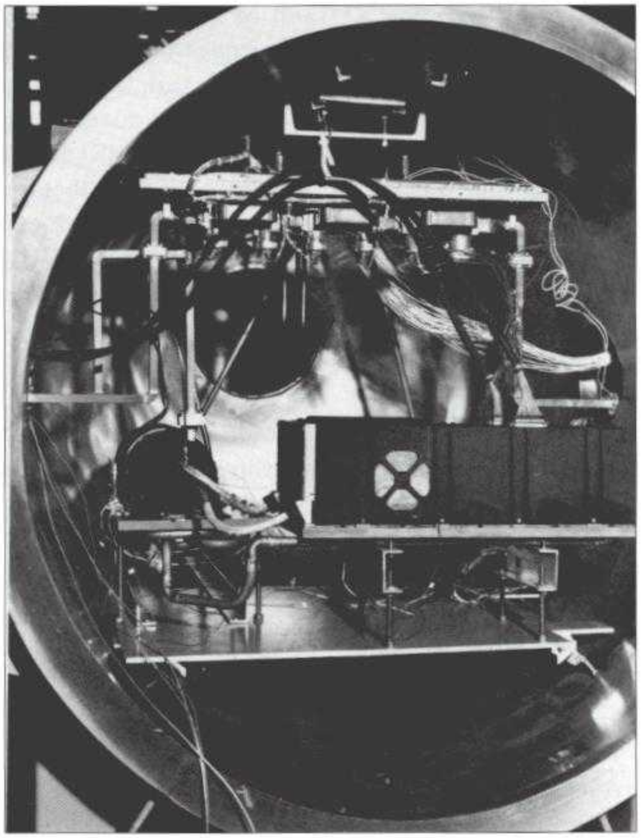


Figure 4. Waveguide switch/QTM-2 TWTA life test

Extensive measurements were made on QTM-1 to show that the TWTAs could be operated at lower RF power output (180 W), with virtually unreduced efficiency; that the nonlinear intermodulation performance met certain customer requirements; and that there were no significant adverse TWT/power supply interactions during multisignal operation. This work proved that the TWTAs were capable of meeting the requirements of the proposed NOTELSAT (Nordic Telecommunications) system.

A band of six space-type waveguide switches was added to the life-test of QTM-2 in early 1987. These switches are important elements in the spacecraft's output waveguide circuitry. The switches have been operated for 5,000 hours while passing an effective 400 W of K_u-band power, with frequent operation of the path switching function, and with no measurable change in RF transmission properties (see Figure 4).

INTELSAT LABORATORY ENGINEERING ASSISTANCE CONTRACT

INTELSAT V Battery Investigations

Begun in 1979, life tests of the INTELSAT V batteries, simulating real-time battery operation in orbit, continued during 1987. The Ni/Cd battery has completed 16 eclipse seasons, and the first Ni/H_2 battery has completed 12. A second Ni/H_2 battery which includes cell design changes to the first battery was tested during 1987. Test results are providing a database for predicting in-orbit performance and life expectancy. Cells are periodically removed from test to assess degradation mechanisms.

The life test also provides a means to investigate in-orbit battery anomalies, and has proved invaluable in two such events. When a short circuit developed in one of the battery circuits of an INTELSAT V spacecraft, stable operating parameters were derived from experiments with the life test battery. In a second instance, a voltage loss during discharge had been observed in several cells of operational INTELSAT V satellites. When this same phenomenon was observed in the life test battery, the life test battery helped to experimentally identify the cause for the voltage loss as an electrolyte loss mechanism. A method for performance recovery was developed in 1987 and is presently undergoing evaluation.

Momentum Wheel Life Tests

The performance and life of INTELSAT V/V-A satellites depend on the performance of the momentum wheels. The long-term effects of speed and temperature cycling on the momentum wheel motor, electronics, and bearings were not fully defined prior to 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 EM wheel life test program has accumulated over 14 wheel-years of running time. One wheel acts as a control case by operating at ambient conditions at a nominal 3,500 rpm, while the other is speed and temperature cycled to simulate the worst-case in-orbit conditions. Performance data such as power consumption and reaction torque are collected monthly and added to the database. A spectral analysis of the torque signals is also performed each month and compared with beginning-of-life baseline spectra (see Figure 5).

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

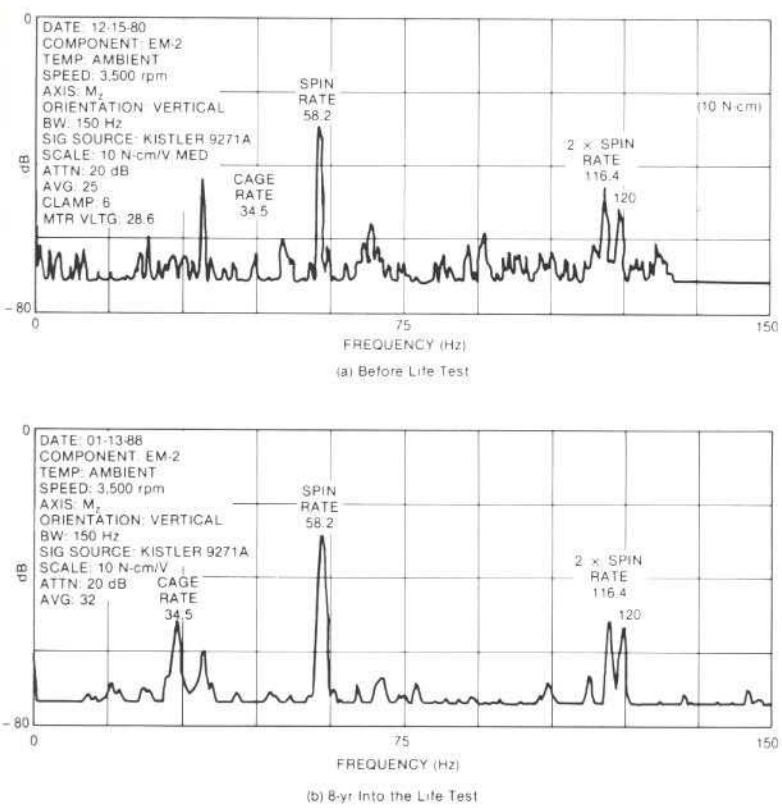


Figure 5. *EM wheel life test*

INTELSAT VI Battery Support

INTELSAT VI Ni/H_2 cells show capacity loss when stored for extended periods at room temperature in the open circuit discharged condition. A change implemented by Hughes Aircraft Company, activating the cells with a slightly excessive positive precharge instead of the conventional hydrogen precharge, did not solve the capacity loss problem. In support of the INTELSAT VI Program Office, the ATD performed a storage mode investigation which showed that capacity maintenance is satisfactory in the following storage conditions: (1) passive storage at 0°C in the open circuit discharged condition; (2) trickle charge; and (3) top charge at room temperature. Based on the results, the INTELSAT VI Program Office directed Hughes to store all flight batteries in a low-temperature chamber.

The INTELSAT VI Ni/H_2 battery life test (see Figure 6), simulating real-time battery operation in orbit, was begun in 1986 and has continued during 1987. The method of pre-charge (positive versus hydrogen) was the major variable under investigation. These batteries have completed three eclipse seasons and have shown excellent performance.

INTELSAT VI ECRA Life Test

The INTELSAT VI electrical contact ring assembly (ECRA) S/N 010 was tested at COMSAT Laboratories in 1987. HAC experienced an open circuit failure during their in-house test. COMSAT's test was aimed at determining if this is a typical failure mode of the power section of the ECRA.

The ECRA provides the spun/despun interface for transfer of electrical power and telemetry and command signals. This is accomplished through the use of sliprings, where brushes slide along a ring maintaining electrical contact. Two distinctly different types of slipring circuits exist within the ECRA: one for power, and one for telemetry. The power circuit of the INTELSAT VI ECRA tested at Hughes failed, exhibiting an open circuit. A loss of power to the communications payload would result if this occurred in orbit.

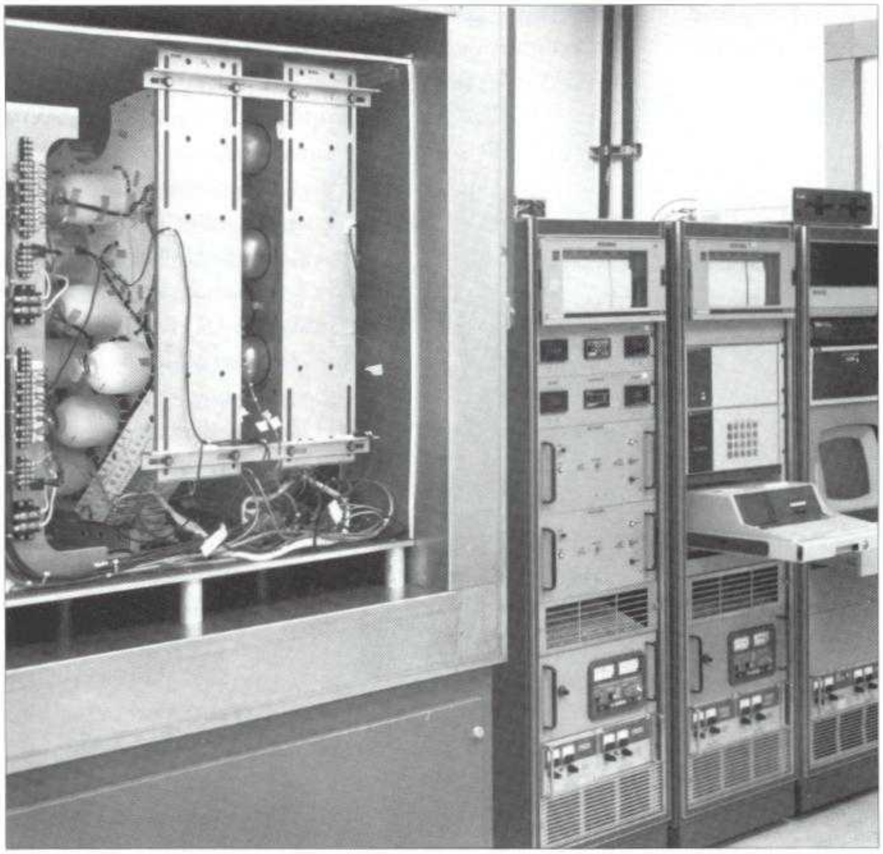


Figure 6. INTELSAT VI Ni/H$_2$ battery life test

A life test program was instituted at COMSAT to further understand this ECRA failure. The ECRA was put in a thermal vacuum chamber to simulate the space environment (see Figure 7). Instrumentation was implemented to monitor the brush motion as the ECRA accumulated running time. Monitoring brush motion verifies that the continuity is maintained between the brush and slipring.

The failure of the ECRA power section occurred in the same manner as seen previously at HAC—an open circuit between the brush and slipring. The instrumentation monitoring brush movement gradually began to indicate abnormal brush motion. The data indicated that the brush was no longer tracking the shaft. Subsequent to the anomalous data, the circuit containing that brush became noisy, eventually developing an open circuit. Following the test, the ECRA was disassembled and inspected, revealing that debris resulting from brush wear had accumulated in the unit.

Additional tests were conducted on the ECRA power section brushes. The results of all the tests indicated that the open circuit is caused by the brush sticking in its holder, losing contact with the slipring. This was caused by a combination of the lateral loads being applied to the brush and the accumulation of debris. The test results, along with additional testing at HAC, led to a redesign of the power brush section of the ECRA.

INTELSAT V Temperature Trends

INTELSAT V spacecraft are monitored to evaluate thermal performance and identify potential trends in component temperatures in support of the INTELSAT Satellite Operations Department. Seasonal estimates of the spacecraft radiator degradation in solar absorptance are used to predict end-of-life spacecraft temperatures. Forecasts of future operating environments based on these predictions permit better utilization of the in-orbit spacecraft.

INTELSAT Thermal Model Conversion

Analytical thermal models of the INTELSAT V and VI spacecraft are being acquired by INTELSAT, which will use them to assess the thermal consequences of in-orbit anomalies or unusual operation modes, independent of the spacecraft contractor. The ATD is converting these models to SINDA format (thermal analyzer program) for INTELSAT's use. During 1987, six Ford Aerospace and Communications Corporation (FACC)-developed INTELSAT V thermal models were converted to SINDA format. A translator was written to perform the conversion.

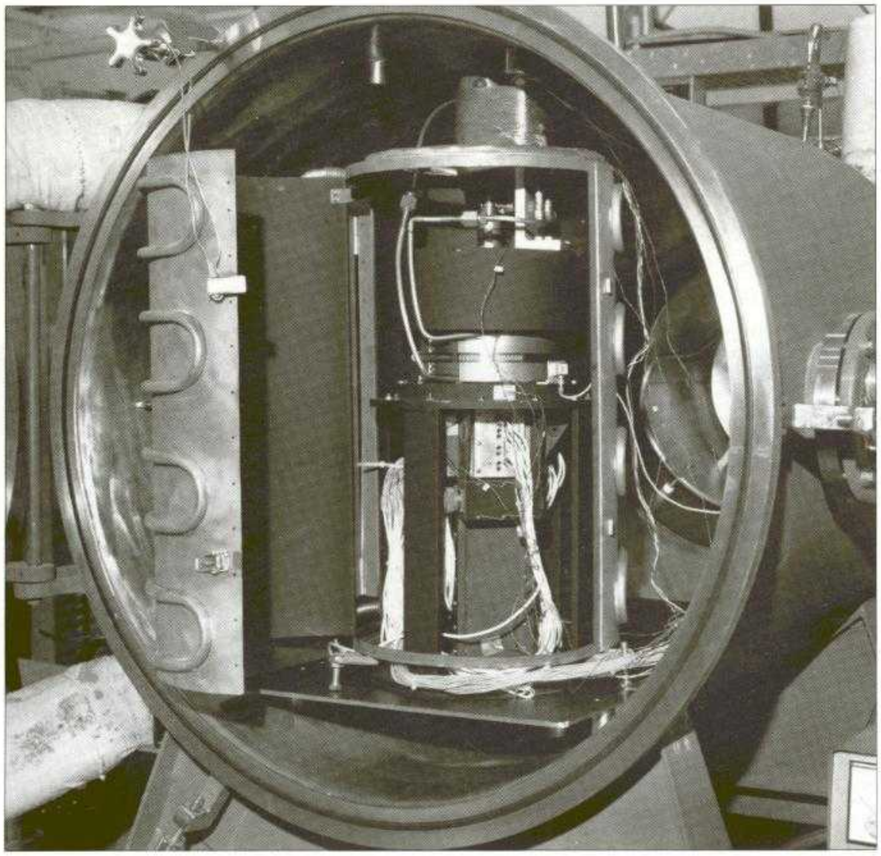


Figure 7. INTELSAT VI ERCA life test

Ariane Liftoff Analysis

An addendum to the INTELSAT V Flight Data Analysis Report was issued under INTELSAT R&D sponsorship during 1987. The new work presents results of an evaluation of the Ariane liftoff nonstationary random environment using a tunable analog resonant circuit to simulate potential spacecraft response. The addendum was forwarded to ARIANESPACE for comment after review by INTELSAT.

OTHER CONTRACTS

Multiple Satellite System Program

Under U.S. Air Force contract F30602-86-C-0063 the ATD studied aspects of the Multiple Satellite System Program (MSSP) for the U.S. Air Force Rome Air Development Center and the Defense Advanced Research Projects Agency (DARPA). The MSSP concept provides a highly survivable communications capability by using a large number of satellites, nominally 240, in low-earth orbit (740 km).

Each spacecraft has a ground link and an intersatellite link for half-duplex packet communications. The cost of building and launching the spacecraft must be affordable. The ATD performed cost studies and investigated launch and deployment concepts in search of the lowest cost solution. Expendable launch vehicle candidates, as well as the Space Shuttle, were evaluated. The studies related the space network cost and earth terminal cost to data rate throughput.

Environmental Test Laboratory

The ATD operates the Environmental Test Laboratory. Vibration, shock, temperature cycling, and thermal-vacuum test services have been provided for both ground and aerospace equipment under contract to several customers. During 1987, these customers included COMSAT Technology Products, Weinschel Engineering, and Schonstedt Instrument Company.

Battery-Powered Electric Propulsion: Ni/H_2 Cells

This activity, which began in 1980, was continued in 1987. The objectives were, and still are, to evaluate new design concepts and new components for Ni/H_2 cells. These cells are being evaluated in a test program simulating battery-powered electrical propulsion: two eclipse seasons per year, and daily cycling between eclipse seasons.

The original five cells have completed 7 years of test, or over 2,300 cycles. The most significant conclusion to date is that the best-performing cell is the one with two layers of zircar separator material. Two new cells which were added to evaluate dry powder sinter/aqueous impregnation process positive plates are showing capacities as high as that of the zircar separator cell, and have completed 300 cycles.

The Communications Techniques Division (CTD) pursues research and development activities and provides technical support in 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 cost competitiveness of satellite communications relative to other media. These advanced architectures and technologies depend , in turn, on widespread applications of digital signal processing techniques. Examples of such developments in 1987 include 4.8- and 32-kbit/s low-rate encoded voice, advanced on-board digital signal processing, and digital signal processor-based modem technology applied to the INMARSAT system. Other significant efforts in 1987 include: continued development of coded-phase modem systems, advanced TV processors, and transmission analysis software, and development of a variable-rate program audio codec; study of future communications satellite systems and techniques; investigation of advanced modulation and forward error correction (FEC) coding, adaptive arrays for improved performance ship earth stations, lower rate voice encoding, interference into communications satellite systems, and data transmission via channels using digital channel multiplication equipment (DCME); and demonstrations of the international satellite integrated services digital network (ISDN).

COMSAT JURISDICTIONAL R&D

Advanced On-Board Digital Processing

The long-term objective of this project, initiated in 1985, is to develop an engineering model of an integrated on-board flexible digital processing unit for use on a satellite for international commercial communications. This digital processing unit will perform demultiplexing/demodulation and associated filtering and control for a number of carriers occupying a bandwidth of 20 MHz (minimum) to 80 MHz (design goal) at C- or K_u-band. In addition to improving the link power efficiency, on-board processing and associated switching provide the needed interconnectivity in a multibeam system. The architecture used in this project is very flexible, allowing in-orbit frequency plan reconfiguration under ground command.

In 1986, a baseline system was defined and its performance evaluated by analysis and computer simulation. Some improvements and modifications in the overall architecture were made in 1987: the frequency resolution and the fast Fourier transform (FFT) size were changed to match the actual symbol rates and carrier spacings used in the INTELSAT system while processing a 20-MHz frequency band. The feasibility of operation at twice the clock rate originally chosen resulted in substantial hardware savings of paramount importance because of mass and power constraints imposed on flyable spacecraft processors.

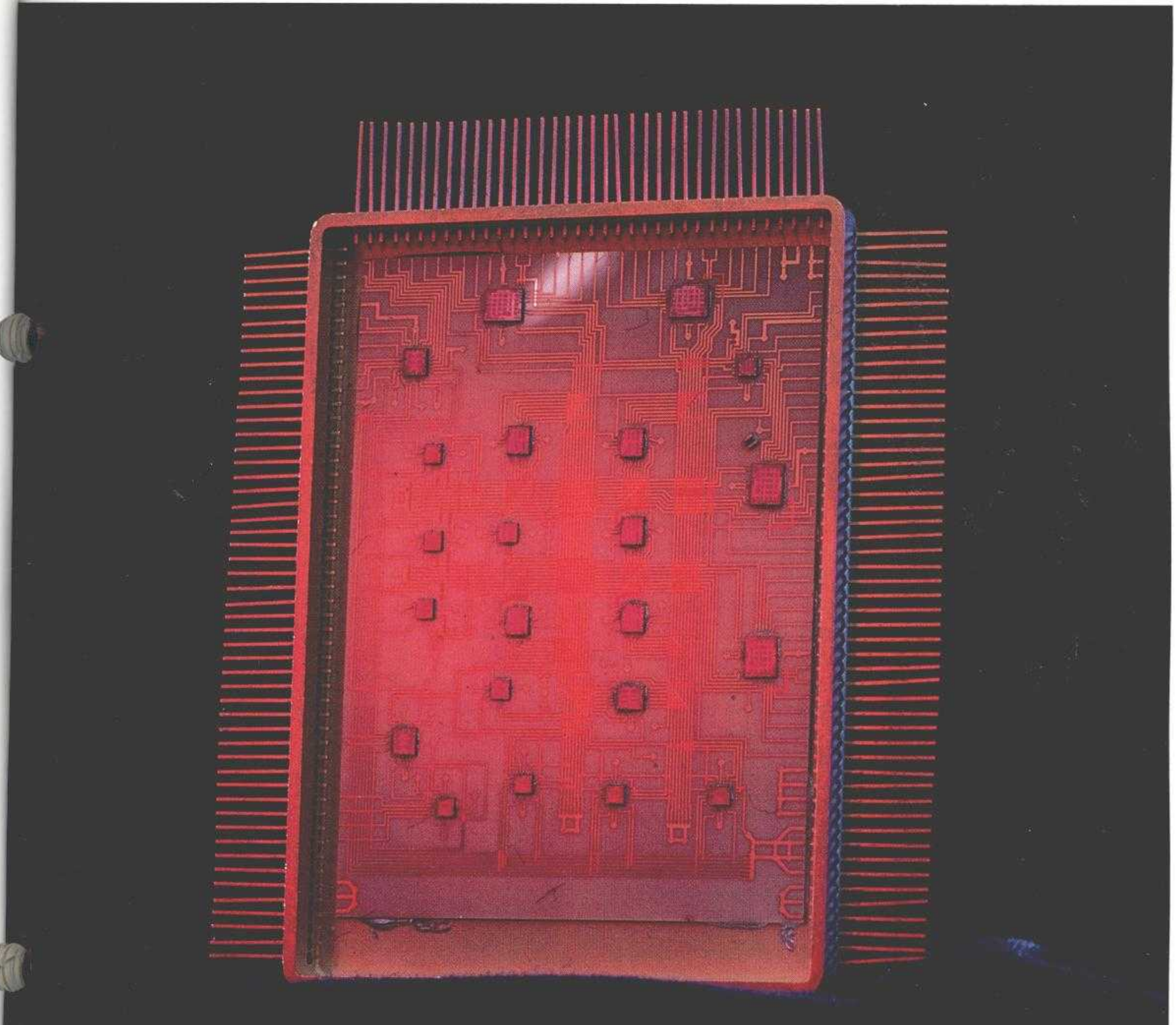
A method of sharing a single pipeline inverse FFT (IFFT) processor among the different carriers was conceived. By interleaving frequency samples of those carriers at the input to the IFFT processor and selectively bypassing butterfly operations, carriers of different bandwidths can be handled simultaneously in the shared processor.

A novel PROM-based implementation for the acquisition section of the shared digital demodulator significantly reduces the required hardware. Hardware design, construction, and testing of the different modules for a testbed of the demultiplexer/demodulator, shown in Figure 1, are currently underway.

140-Mbit/s Coded Octal-PSK Transmission System

The development and laboratory testing of the 140-Mbit/s coded octal phase-shift keying (COPSK) system was completed in 1987. This system was designed to allow satellite restoration of the TAT-8 cable, which requires transmission at 140 Mbit/s through 72-MHz of available satellite transponder bandwidth. Currently, the maximum information rate carried by such transponders is 120 Mbit/s (INTELSAT TDMA). To obtain the required BER performance, a jointly optimized modulation and coding approach was employed.

COMMUNICATIONS TECHNIQUES



Closeup of an add-compare-select (ACS) hybrid chip

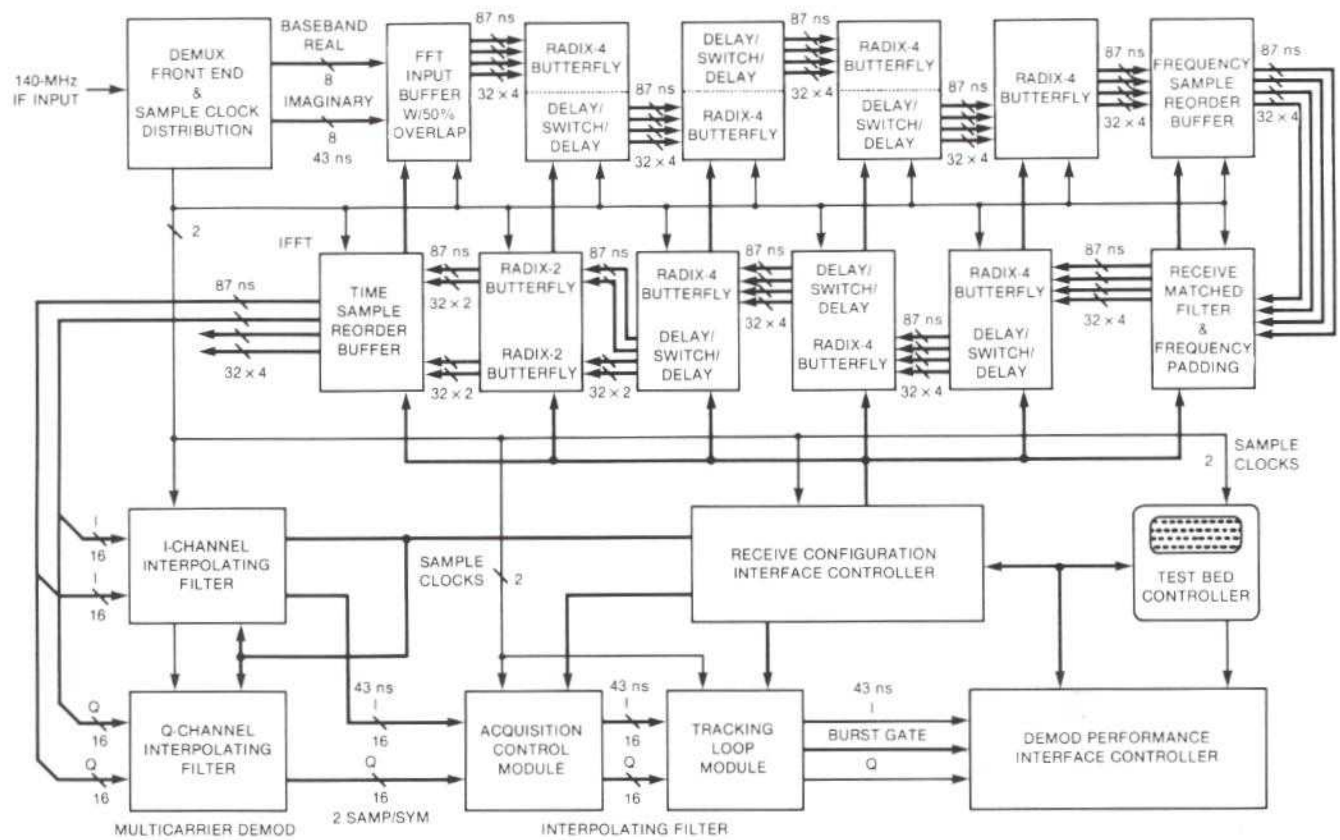


Figure 1. *Demultiplexer/demodulator testbed*

The system consists of an 8-PSK modem and a periodically time-varying, rate 7/9, 16-state Viterbi codec shown in Figure 2. The 8-PSK modem operates at a 60-Msymbol/s (or 180-Mbit/s) rate, with a spectral occupancy nearly identical to that of the current 120-Mbit/s TDMA system, and is therefore ideal for the 72-MHz transponder bandwidth. The rate 7/9 codec incorporates important advancements, such as the use of a periodically time-varying code to simplify high-speed add-compare-select operations, necessary for the Viterbi decoder; and novel design techniques in the normalization and traceback circuits which substantially reduce the codec circuit complexity.

COPSK system performance was measured in IF loopback and through the COMSAT satellite simulator at an earth station HPA input backoff of 10 dB and a TWTA input backoff of 2 dB. Results are plotted in Figure 3, which includes performance data from the 120-Mbit/s QPSK system using the INTELSAT V simulator. It can be seen that the COPSK system offers better performance over most of the operating range, while carrying about 17 percent more information. Field trials are planned for early 1988 to further characterize performance.

150-Mbit/s Coded Trellis Modulation

The purpose of this study is to develop combined modulation and coding methods for international satellite transmissions over 72-MHz transponders to serve wideband, integrated services digital networks (ISDNs) at about 150 Mbit/s. A set of high-rate multidimensional coded trellis modulation methods using M-ary PSK signal sets was investigated. The higher trellis dimension makes it possible to achieve larger coding gains and/or higher bandwidth efficiency. In particular, two powerful coded 8-PSK modulation schemes using Reed-Muller block codes were found. The first has an overall code rate of 63/96, an asymptotic coding gain of 5.95 dB compared to QPSK, and a 1.48-bit/s/Hz bandwidth efficiency. The second has an overall code rate of 79/96, an asymptotic coding gain of 3.92 dB compared to QPSK, and a 1.85-bit/s/Hz bandwidth efficiency.

Preambleless Burst-Mode Communications

The use of preambeless bursts to increase the communications efficiency of low-data-rate communications using BPSK and QPSK modulation formats was studied.

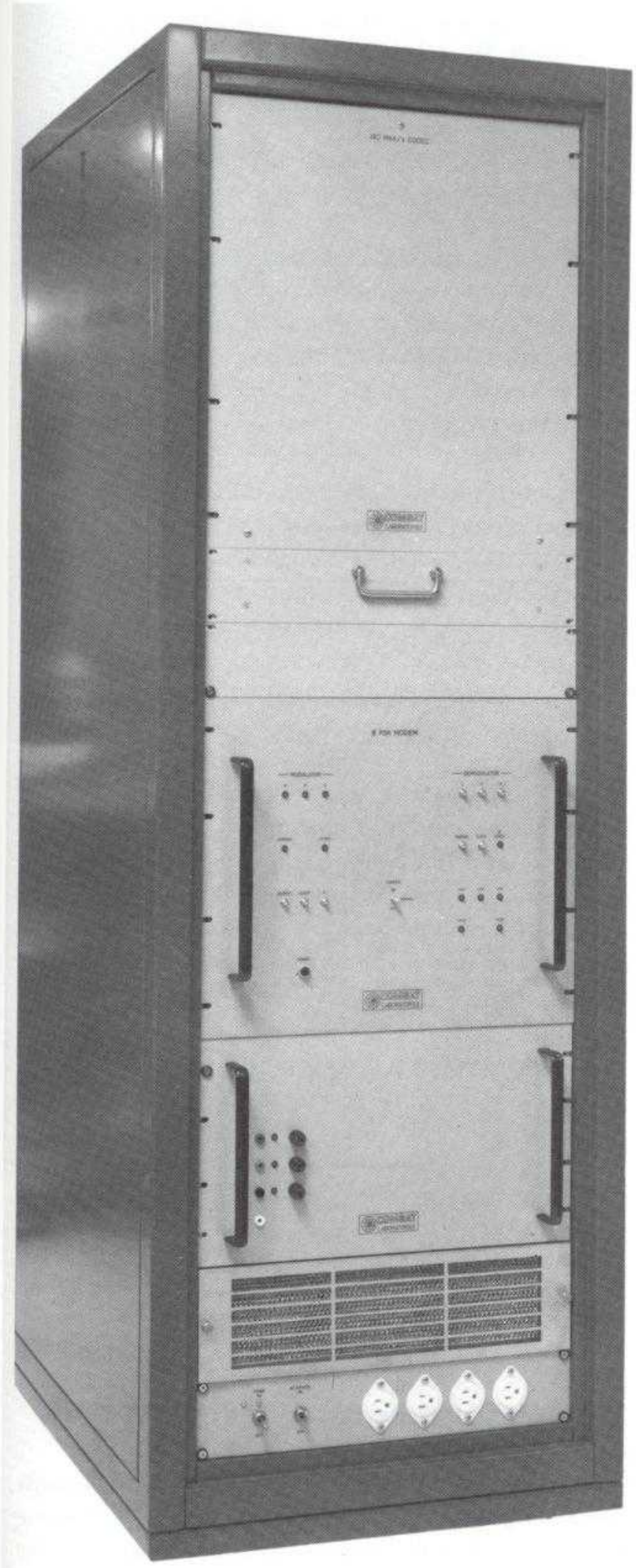


Figure 2. 140 Mbit/s coded octal-PSK transmission system

By sampling and storing the received signal and using parallel processing for coarse frequency acquisition followed by matched filtering and symbol and carrier synchronization, reliable demodulation can be achieved despite the large initial frequency uncertainty. For normal E_s/N_o values of 10 dB or more and burst lengths of 100 or more modulation symbols, the rms timing error was computed to be less than 2 percent of the symbol interval. The rms carrier phase error was computed to be less than 4°. Therefore, for BPSK and QPSK, detection performance over an additive white Gaussian noise (AWGN) channel is expected to be within a few tenths of a dB from ideal coherent detection.

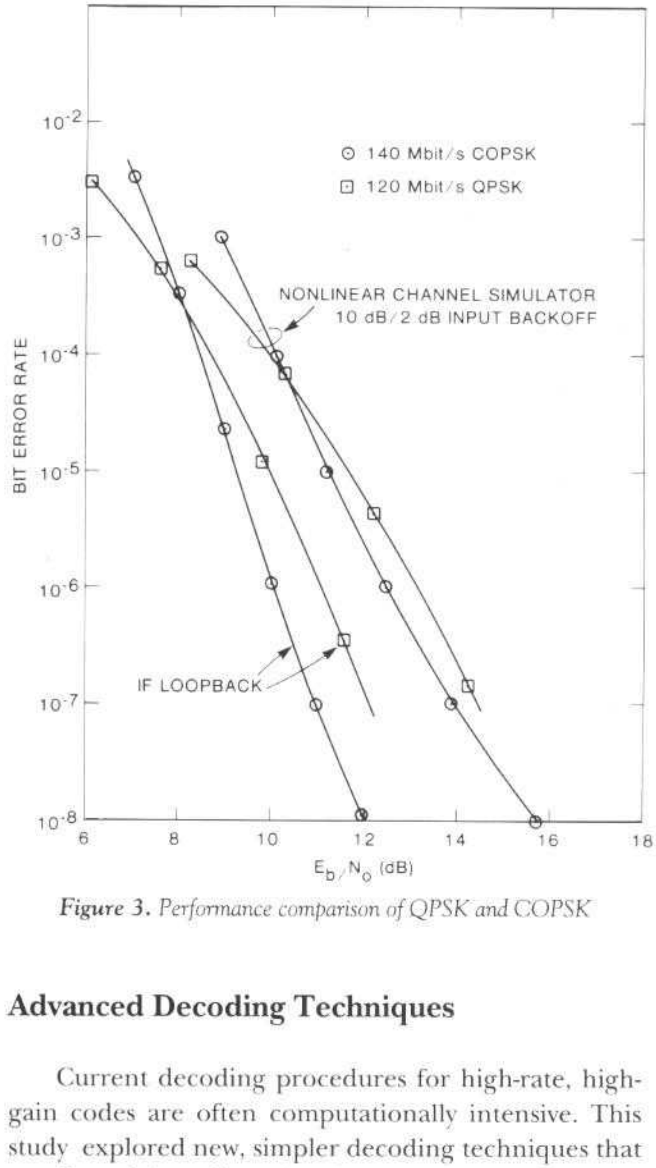


***Figure 3.** Performance comparison of QPSK and COPSK*

Advanced Decoding Techniques

Current decoding procedures for high-rate, high-gain codes are often computationally intensive. This study explored new, simpler decoding techniques that would result in coding gains almost as high as those of the more complex methods available. An efficient soft-decision decoding technique for a large class of block codes was developed. This is known as closest coset decoding because it is based on the well-known concept of coset decoding, which involves repeating the decoding algorithm for each coset of a subcode of the given code. However, closest coset decoding consists of first finding the coset which is closest to the received block of channel symbols and then applying the decoding algorithm, only once, to that closest coset. This achieves the same asymptotic coding gain as a maximum-likelihood decoder, but with substantially less computational effort, resulting in significantly reduced hardware implementation complexity.

Other work involved combining several commercial decoder chips to obtain higher coding gain and/or higher speed. A scheme based on signal-space, convolutionally coded QPSK achieved an incremental coding gain of 0.5 dB at a BER of 10^{-6}.

Octal-PSK Adaptive Equalizer

An adaptive equalizer was developed for an 8-PSK modem with an information transmission rate of 180 Mbit/s. Such a modem, described above, had been developed as part of the COPSK system. Without the companion rate 7/9 FEC codec, 8-PSK is significantly more sensitive to link distortions than QPSK; adaptive equalization may be used to maintain proper equalization.

The equalizer operates on the analog baseband signals with equalization accomplished at IF by a three-tap transversal equalizer (Figure 4). The baseband signals are digitized, and processed using high-speed digital techniques. The equalizer tap weights are derived from ordinary data, and thus no special test sequences are required. The technique is similar to that employed for a QPSK adaptive equalizer, described in the *COMSAT Laboratories 1986 Annual Report.*

Performance with and without the adaptive equalizer has been measured for IF loopback with a variety of amplitude and group delay distortions added. Figure 5 illustrates the degradation in BER resulting from the addition of an 8-ns linear group delay distortion as well as the improved equalized performance. For the 140-Mbit/s COPSK system application, the uncoded BER for the PSK modem is about 10^{-3}. Thus, the adaptive equalizer improvement is about 1 to 1.5 dB.

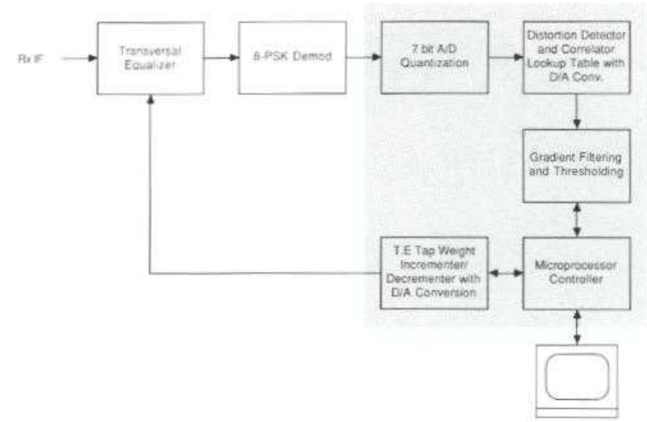


Figure 4. *8-PSK adaptive equalizer configuration*

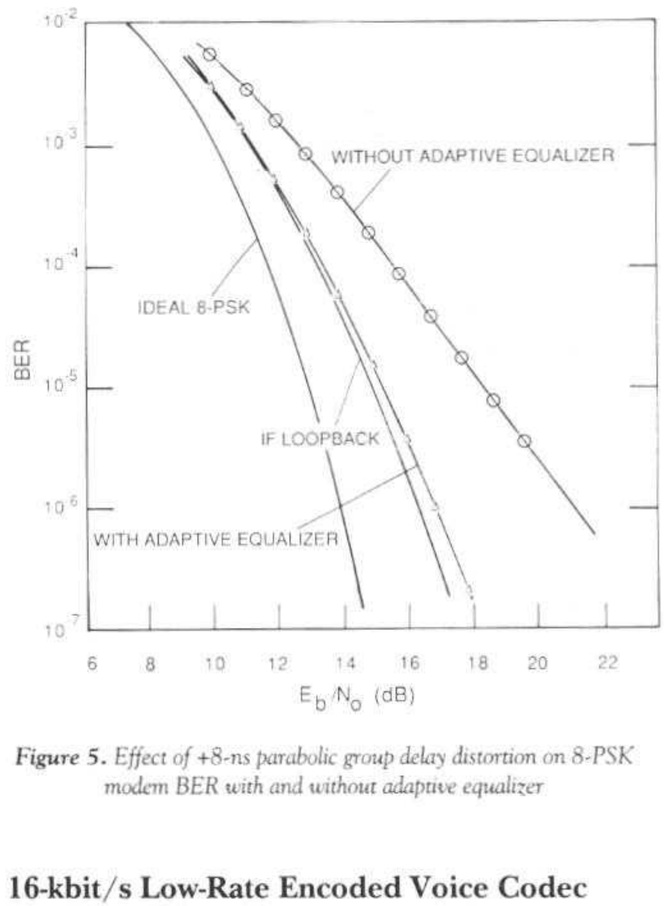


Figure 5. *Effect of +8-ns parabolic group delay distortion on 8-PSK modem BER with and without adaptive equalizer*

16-kbit/s Low-Rate Encoded Voice Codec

Initiated in 1985, the development of toll-quality speech codecs at 16 kbit/s continued in 1987. During 1986, adaptive predictive coding (APC) techniques were investigated using non-real-time computer simulations of selected algorithms. APC performance was evaluated using a simulation program to process several sentences of male and female speech, with quality judged superior to that achieved with waveform coding approaches.

During 1987, efforts focused on real-time realization of the APC codec. Codec parameters and quantizer were improved so that the performance is closer to toll-quality. A realization based on the Analog Devices ADSP100 Digital Signal Processor (DSP) was initiated. A single ADSP100 can realize a full duplex codec, with considerable computation time remaining for experimentation to further optimize the codec. By late 1987, the codec software was developed and the target hardware system was designed and built; debugging the hardware/software combination in the real-time environment has begun.

After completion, it will be further optimized for speech, and its performance assessed by subjective quality measurements. Codec performance with voiceband data will also be studied, and the codec algorithm will be modified to improve performance.

Variable Rate Program Audio Codec

A flexible digital codec for encoding sound program audio signals ranging from 5-kHz to 15-kHz bandwidths in 2.5-kHz increments at output bit rates of N x 64 kbit/s ($1 \leq N \leq 4$) was designed and built, providing a single unit solution to a variety of non-standard applications often encountered in operational situations. Table 1 gives output bit rates as a function of audio bandwidth.

Table 1. *Output bit rate vs sound program audio bandwidth*

Audio Bandwidth (kHz)	Output Bit Rate (kbit/s)
5.0	64
7.5	128
10.0	128
12.5	192
15.0	256

An adpative differential PCM (ADPCM) encoding algorithm similar to CCITT Rec. G.721 was implemented using DSPs. Depending on the manually selected audio bandwidth, an appropriate sampling rate and ADPCM quantizer are automatically chosen for the lowest N x 64-kbit/s output bit rate necessary to meet the performance requirements of the CCITT (Red Book) J series sound program recommendations. Synchronization bits are included within the N x 64-kbit/s, and automatic muting is provided to eliminate loud noise bursts when synchronization is lost. The unit uses oversampling to ease filter performance requirements, 16-bit analog-to-digital and digital-to-analog converters, and new VLSI filters.

More work is needed. Representative performance measurements made using the encoder combined with a portion of the decoder yielded the performance curves of signal-to-noise and distortion ratio (SINAD) as a function of signal level for a 1-kHz tone for bandwidths from 5 to 12.5 kHz shown in Figure 6.

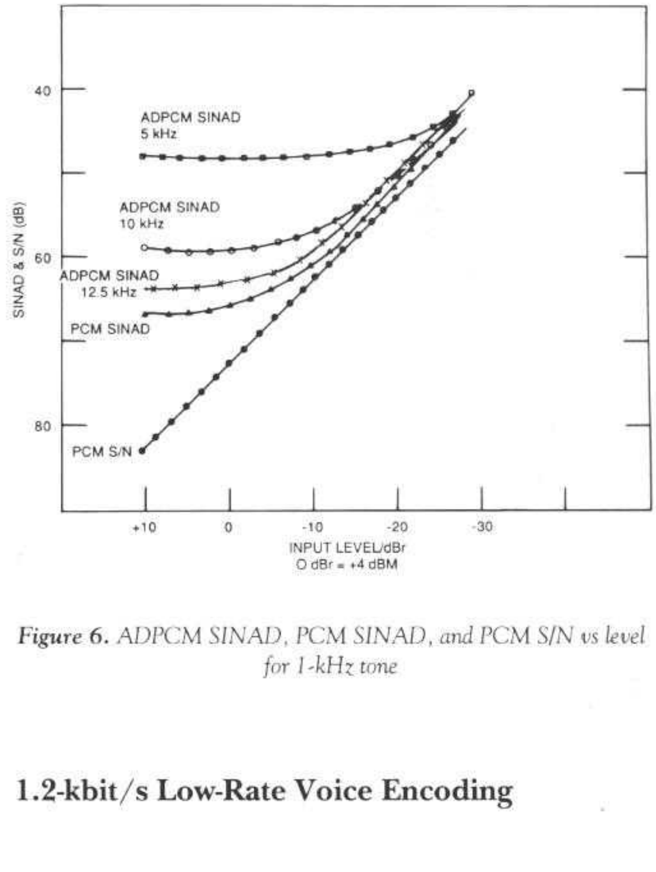


Figure 6. *ADPCM SINAD, PCM SINAD, and PCM S/N vs level for 1-kHz tone*

1.2-kbit/s Low-Rate Voice Encoding

In 1987, COMSAT Laboratories initiated a new research effort in low-bit-rate speech coding, focusing on novel 1.2-kbit/s methods, employing techniques such as waveform vector quantization and nonlinear model deconvolution to achieve communications quality voice for mobile systems in routine and emergency situations. The goal is a reduction of more than 50 to 1 in bit rate requirements for a single voice channel from 64-kbit/s PCM, to allow communications with substantially lower cost earth station equipment.

9.6-kbit/s Data Transmission Over a 64-kbit/s PCM Channel

Digital data, transmitted via telephone circuit connections using voiceband data modems, are used to modulate a carrier, with the resulting spectrum confined to the usable 3.2 kHz of the 4-kHz telephone bandwidth. The bit error performance of such modems is primarily influenced by analog impairments such as delay distortion, 2nd- and 3rd-order harmonic distortion, and signal-to-noise ratio. When the voiceband data modem output signal is carried via a 64-kbit/s PCM transmission channel, a new impairment, bit errors in the PCM channel may be introduced which can significantly impact the voiceband data BER performance by producing bursts of errors in the data. For modems carrying 9.6-kbit/s voiceband data, this error multiplication effect may be as high as 10 to 15, depending on the weight of the bit in the PCM sample affected by the error.

A method to improve BER performance of voiceband data over PCM channels has been developed and tested over the past 3 years. This involves intercepting the 64-kbit/s PCM channel, truncating the 8-bit PCM encoded sample to 7 bits, and introducing forward error correction (FEC) using the truncated bit position to carry the FEC parity bits. The FEC-protected signal is still a 64-kbit/s bit stream.

Figure 7 shows the effects of truncating the PCM-encoded samples to 7 and then to 6 bits. The degradation in the BER vs signal-to-distortion performance curve is about 0.5 dB when the least significant bit (LSB) is truncated. This is acceptable, but eliminating 2 bits is not.

A weighted FEC code corrects double errors for the most significant bits (MSBs) of the PCM encoded samples and single errors for the middle bits. No protection is provided to the LSBs, since errors here do not result in voiceband data bit errors. Figure 8 shows the results of laboratory measurements with and without FEC. Curve 1 shows the predicted performance for a V.29 modem operating at 9.6 kbit/s based on measurements made of 9.6-kbit/s error burst length as a function of which bit in the PCM sample was in error. Curves 2 and 3 show 9.6-kbit/s voiceband data modem performance without FEC and with FEC, respectively. At a PCM channel BER of 10^{-5}, the 9.6-kbit/s voiceband data BER was improved from 1.5×10^{-4} to 2×10^{-9} through the use of the weighted FEC. Measurements using a V.33 modem operating at 14.4 kbit/s, yield curves 4 and 5, showing that the approach is also applicable at this higher voiceband data rate.

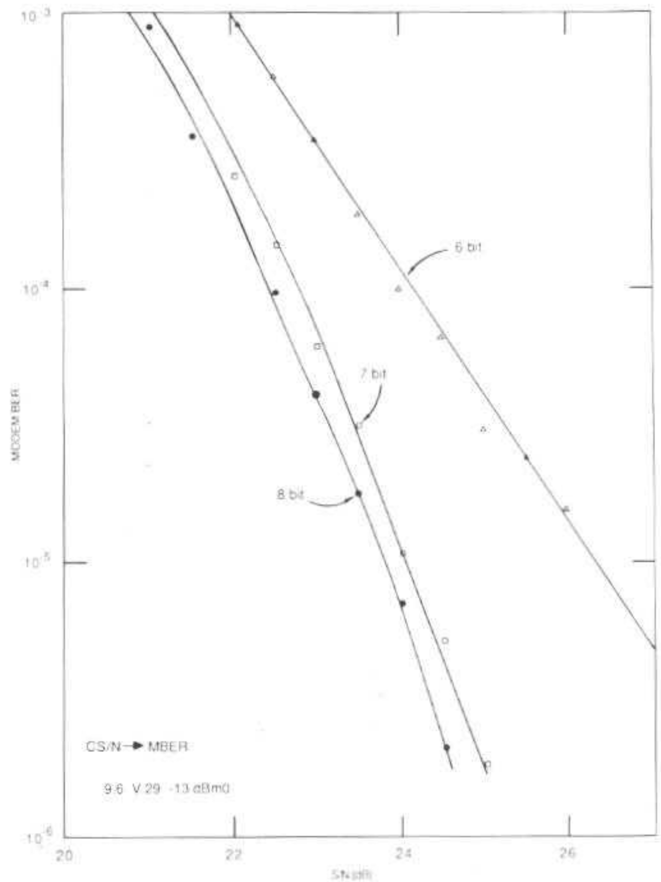


Figure 7. Effects of PCM truncation on V.29 modem performance

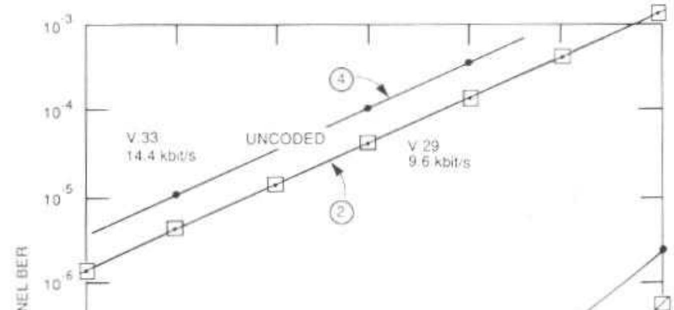


Figure 8. 9.6-kbit/s V.29 and 14.4-kbit/s V.33 modem performance

Data Transmission via Channels Using DCME

When the CCITT approved the 32-kbit/s ADPCM algorithm, Recommendation G.721, acceptable transmission performance for voiceband data at rates greater than 4,800 bit/s was not guaranteed. As work on standardizing digital circuit multiplication equipment (DCME) gained momentum, Study Group (SG) XVIII of the CCITT decided that DCME should be transparent to 9.6-kbit/s voiceband data, and established an ad hoc group to select such an algorithm for use in DCME.

COMSAT Laboratories, as the host test laboratory, contributed to this selection effort by evaluating the voiceband data performance of several algorithms including:

- A 40-kbit/s ADPCM algorithm based on CCITT Rec G.721 for use only on data, proposed by France (CNET),
- A 32-kbit/s ADPCM algorithm, optimized for data, involving down-sampling from 8.0 to 6.4 kHz and encoding using a 5 bit/sample quantizer, proposed by Israel (ECI),
- A 32-kbit/s ADPCM algorithm for speech and data proposed by Japan (OKI/KDD),
- A 40-kbit/s ADPCM algorithm optimized for data, proposed by Japan (OKI/KDD).

Evaluation included the use of voiceband data modems operating at bit rates from 4,800 to 18,000 bits/s over one, two, and three links in tandem with the block error rate (BLER) measured as a function of S/N and channel BER. Figure 9 shows the baseline performance for the data modems used in the evaluation, and the representative performance of a typical modem for each of the algorithms is shown in Figure 10.

Subjective Evaluation of Speech in the Presence of Long Delay

CCITT Recommendation G.114 gives an upper limit of 400 ms for the mean one-way propagation time (MOPT) for telephone connections, as determined from extensive subjective evaluations conducted prior to 1964 using analog echo suppressors. Since 1964, digital echo suppressors, which perform significantly better, have been developed, and a significant improvement has been provided by the use of echo cancellers. With the growth of digital processing, where delays of 60 to 100 ms may occur in lower bit rate speech codecs (<16 kbit/s), and the possible future application of intersatellite links, propagation times in excess of 400 ms may occur in the public switched telephone network (PSTN).

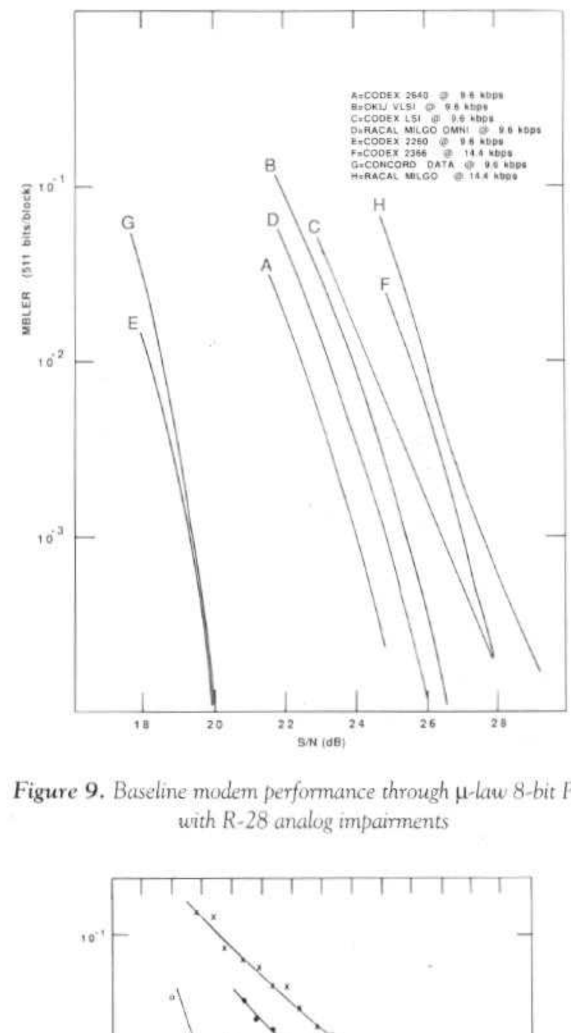


Figure 9. *Baseline modem performance through μ-law 8-bit PCM with R-28 analog impairments*

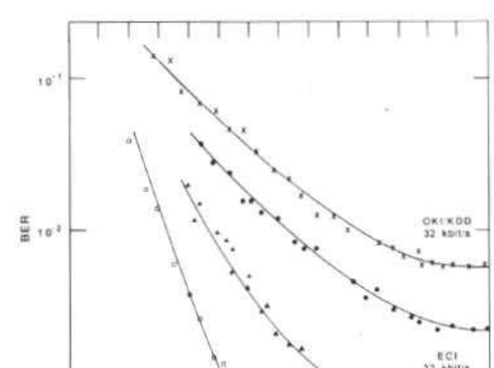


Figure 10. *V.29 modem operating at 9.6 kbit/s through two asynchronous ADPCM coders and analog impairments*

To review the MOPT limit of 400 ms, a customer call-back evaluation was conducted between locations in New Jersey and Tennessee using five different circuit conditions:

- terrestrial reference with 45 ms MOPT
- satellite circuit with 300 ms MOPT
- terrestrial circuit with 300 ms MOPT
- satellite circuit with 500 ms MOPT
- terrestrial circuit with 500 ms MOPT

Between 100 and 120 completed interviews were obtained for each circuit condition. During the call-back interview the customers were requested to give their opinion of the quality of the connection as excellent, good, fair, poor, or bad. A mean opinion score (MOS) was determined by assigning a weight of 4 to excellent, 3 to good, etc., and computing the mean for each circuit condition. In addition, interviewed customers were asked if they had any difficulty talking or hearing and a percentage difficulty measure was obtained.

The evaluation results, summarized in Table 2, showed no significant differences between the satellite and terrestrial connection for the same delay, which permitted pooling of these results into single MOPT categories of 300 and 500 ms. There were no significant differences observed in the MOS between any of the MOPT circuit conditions. For the percent difficulty measure the difference between the 45-ms and 300-ms circuit conditions was not significant, while the difference between the 300-ms and 500-ms conditions was significant at the 0.05 level.

Table 2. *Subjective evaluation tests*

MOPT	MOS ± 95 PERCENT CONF INTERVAL	PERCENT DIFFERENCE
45 ms	3.28 ±0.14	6.9
300 ms	3.25 ±0.08	7.6
500 ms	3.21 ±0.09	15.8

The results of this evaluation were reported to CCITT Study Group XII, where they have been accepted as a basis for a proposed revision to Rec. G.114 to increase the MOPT upper limit from 400 to 450 ms.

Modified-PAL TV Processor

Test results of the modified NTSC investigation, described in the COMSAT Laboratories 1984 and 1985 Annual Reports, indicated that significant improvement was achieved in the objective S/N measurement when compared to that of an NTSC video link operating to the CCIR standard, and an impressive improvement in the subjective video performance when operated at a low carrier- to-noise ratio (C/N). The purpose of development of modified PAL video transmission is to realize similar performance improvements for the PAL signals, also widely carried by the INTELSAT system.

A modified PAL TV processor was developed in 1987. Two units were constructed and integrated into the two existing modified NTSC units. The units can detect whether the signal format is PAL or NTSC and automatically switch to the appropriate processor.

Due to some peculiarities of the PAL format, compromises were made in the modified PAL format, resulting in a data transmission capacity of only 1 Mbits/s, compared to 1.9 Mbits/s in the modified-NTSC processor. However, this capacity is still sufficient to support up to four channels of high-quality digital audio, or a mixture of audio and data. These data are time multiplexed with the video signal. A rate 1/2 convolutional code may be selected to provide additional noise margin in the digital audio channels for operation at low C/N values, if desired.

Preliminary test results indicate that the modified-PAL receiver is much more robust at low C/N values than the normal PAL receiver, and about the same S/N improvements are achieved as for modified NTSC.

3-D Comb Filter for NTSC-Compatible HDTV

High-definition television (HDTV), provides twice the horizontal and vertical resolution of the current NTSC format (with a more pleasing 16:9 wide-aspect ratio) and has gained considerable momentum in the television and motion picture industries in recent years. In the U.S., 99 percent of the households currently receive signals broadcast in NTSC format by about 1,300 TV stations. Introduction of HDTV incompatible with the NTSC format would have significant impact on these existing investments.

The difficulties in designing a compatible HDTV transmission technique involve the separation of chrominance and luminance signals from the composite signal at the receiver, and the removal of luminance-to-chrominance crosstalk around the color subcarrier frequencies in the transmitted signal. For the NTSC format, the crosstalk is generally of minor significance because the color subcarrier is located at the high end of the luminance band. For HDTV, however, the effect is considerably worse, as the subcarrier is located in the middle of the luminance band due to the wider luminance bandwidth required to provide increased horizontal resolution.

A system with a motion adaptive three-dimensional (3-D) comb filter combined with precombing at the transmit end was conceived to resolve these difficulties. Human vision is less sensitive to the high spatial resolution of moving objects, and no temporal resolution is needed for stationary objects. Detecting motion on a pixel-by-pixel basis permits use of a two-dimensional spatial comb filter for moving objects, while a temporal comb filter is used for stationary objects. Combined with precombing in the motion mode, which removes that part of the luminance spectrum interfering with the chrominance subcarrier, a subjectively high-quality, high-resolution signal can be recovered. Figure 11 illustrates the concept of the 3-D comb filter.

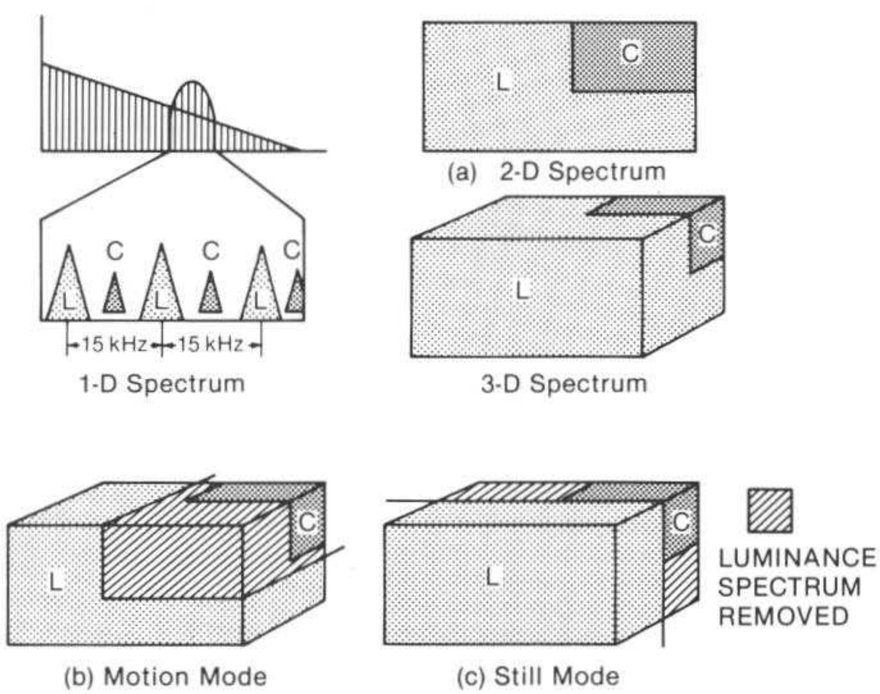


Figure 11. Concept of 3-D comb filter

This motion-adaptive 3-D comb filter has been simulated with an NTSC test signal using the COMSAT Image Processing Facility. The resultant signal was indistinguishable from that transmitted directly in component form. Further investigation of this approach using an HDTV signal will continue in 1988.

Adaptive Array for Improved G/T Ship Earth Station

A study was performed to develop a preliminary design for a ship earth station (SES) which can provide communications quality voice service, the cost of which will be between one-third to one-fourth that of an SES now used for voice communications. The receiving antenna uses a vertical linear array having four fixed low-gain elements. For transmission, a separate, low-gain antenna is used. All antenna elements are quadrifilar helices.

The G/T and e.i.r.p. values selected are -18 dBi/K, and 18 dBW, respectively, for this SES, which can support an information data rate of 2,400 bit/s, permitting the transmission of communications-quality voice using LPC vocoders. Performance/cost comparisons were made before a design was selected in which the outputs of the receive array's antenna elements, feed LNAs, and phase shifters were combined at RF. The phase shifters are controlled by digitally processing the receiver output to maximize the S/N ratio in a multipath environment.

A key feature of the design approach is the implementation of the digital array control. Figure 12 shows the basic array architecture, and Figure 13 shows the functions of the array controller, which is designed to be implemented on a digital signal processing chip. Manufacturing cost reductions are realized by using digital processing techniques to operate the array in a self-calibrating mode, thereby allowing its RF components to be manufactured and assembled with less precision than is required for other array-control or beam-forming techniques.

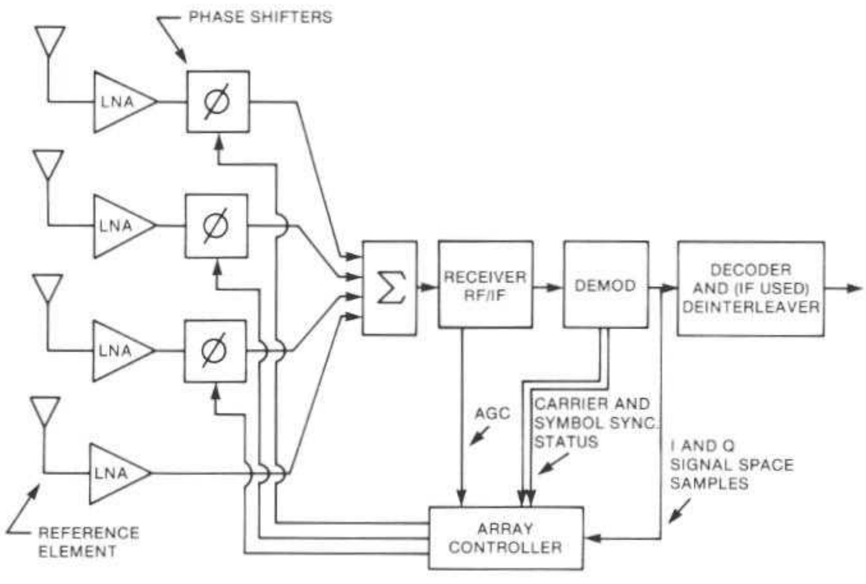


Figure 12. Basic architecture of active receive array

COMSAT NONJURISDICTIONAL R&D

Mobile and Portable Terminal Technology

The purpose of this project is to develop technologies for low-cost maritime mobile, aeronautical mobile, land mobile, and portable satellite terminal applications. Because of bandwidth and power limitations in the current maritime mobile system, studies were conducted on the development of a 4.8-kbit/s communications quality vocoder and on the transmission of the 4.8-kbit/s signal over a 5-kHz fading channel.

Four techniques were investigated for use in a 4.8-kbit/s communications quality vocoder: the vector quantization, spectrum-pair, spectral deviation, and multipulse excitation coding. The first two techniques apply to vocal tract filter parameter coding, while the latter two apply to excitation signal coding. The use of an excitation signal in addition to filter parameter coding is essential for obtaining natural quality speech. Simulation software was developed, and a speech database which contains data from five male speakers and five female speakers, each speaking nine carefully selected sentences, was generated for optimization and evaluation of speech coding schemes. Subjective listening tests are currently underway to fine-tune the system design parameters of each technique and how to best combine them.

For 4.8-kbit/s voice transmission, a partially coherent technique using channel memory over several symbols was investigated, and showed a gain of 0.8 dB over differential QPSK at a BER of 10^{-3}. This technique is particularly useful for mobile communications where coherent detection is adversely affected by the relatively large fading bandwidth-to-symbol rate ratio.

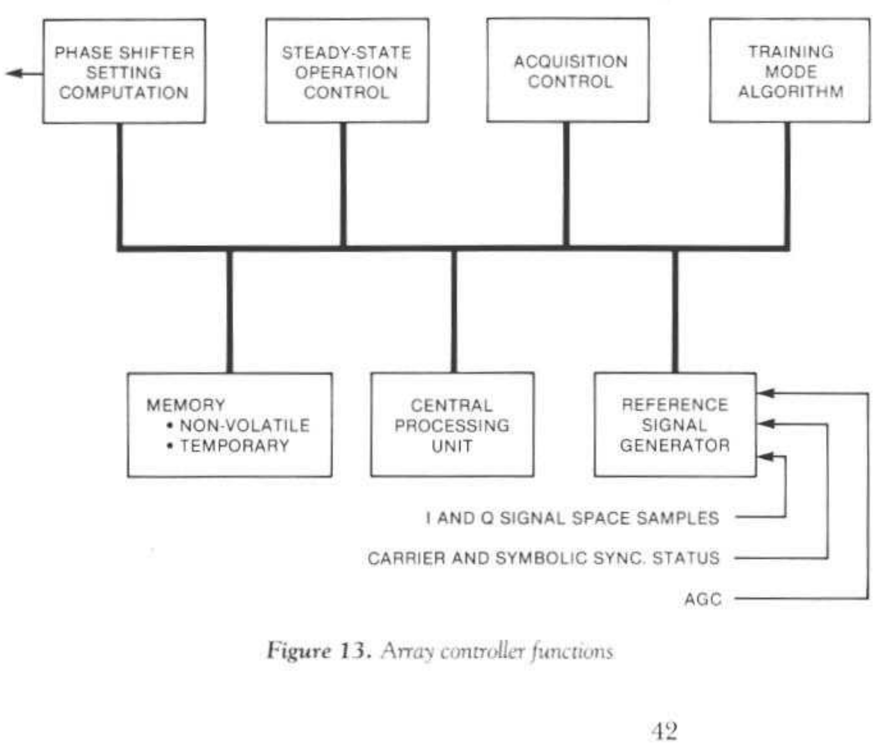


Figure 13. Array controller functions

Sequential Decoding

Practical implementation of high complexity convolutional codes has been limited by the decoding algorithm. The Viterbi algorithm is widely used over noisy satellite channels, but algorithm complexity grows exponentially with the code constraint length, k, leading to a limitation of $k < 9$. In 1987 COMSAT initiated a study of sequential decoding algorithms for decoding much more powerful and longer convolutional codes, to provide additional link margin for small earth terminals.

Sequential decoding is a type of systematic tree search, the complexity of which is virtually independent of the code's constraint length. Two different algorithms have been widely reported: the Fano algorithm, and the stack algorithm. The Fano algorithm has been successfully implemented in several commercial products but its computational speed requirements grow exponentially as the channel error rate approaches a certain threshold. As a result, performance is degraded at low signal-to-noise ratios. The stack algorithm exhibits a much lower demand for increased speed as the threshold is approached, but at the expense of a large stack memory.

Memory technology has advanced to the point where an inexpensive, compact, sequential stack decoder should be possible. Consequently, the stack algorithm was studied and extensively simulated by computer. Techniques to reduce memory requirements and permit parallel implementations were developed. Results of the simulations, shown in Figure 14, compare performance of commercial Viterbi decoders of constraint length k = 7 to a simulated, stack sequential decoder of constraint length k = 31. At a BER of 10^{-6}, the sequential decoder provides more than 1 dB additional coding gain than the Viterbi decoder. The computation rate of the sequential decoder is nearly constant E_b/N_o above 3.2 dB.

This stack sequential decoder may be successfully implemented at bit rates in the 2-Mbit/s range using conventional TTL logic and about 10 standard 32K x 8 RAM memory chips. Speed and performance enhancements are under investigation.

COMSAT SUPPORT

Future International Communications Satellite System Study

A detailed investigation was performed to identify candidate architectures for future satellite systems that could provide projected INTELSAT services at costs competitive with fiber optic transoceanic cables, examining cost sensitivities for each architecture by optimizing parameters to minimize the circuit cost. Spacecraft technologies that require accelerated development to implement these architectures by the mid to late 1990s have been identified. Other issues addressed include design and cost of the earth stations, optimum (minimum cost) transmission methods, launch vehicle options, satellite lifetime considerations, and satellite deployment and sparing philosophy.

Five satellite architectures, covering a broad range of satellite technologies, compared to one another and to future transoceanic fiber optic cables are listed below in ascending order of the level of spacecraft development required:

- Concept 1: INTELSAT VI (baseline architecture)
- Concept 2: Simple low-technology satellite
- Concept 3: U.S. to Europe trunking satellite
- Concept 4: Fixed multibeam satellite
- Concept 5: Hopping multibeam satellite with on-board processing.

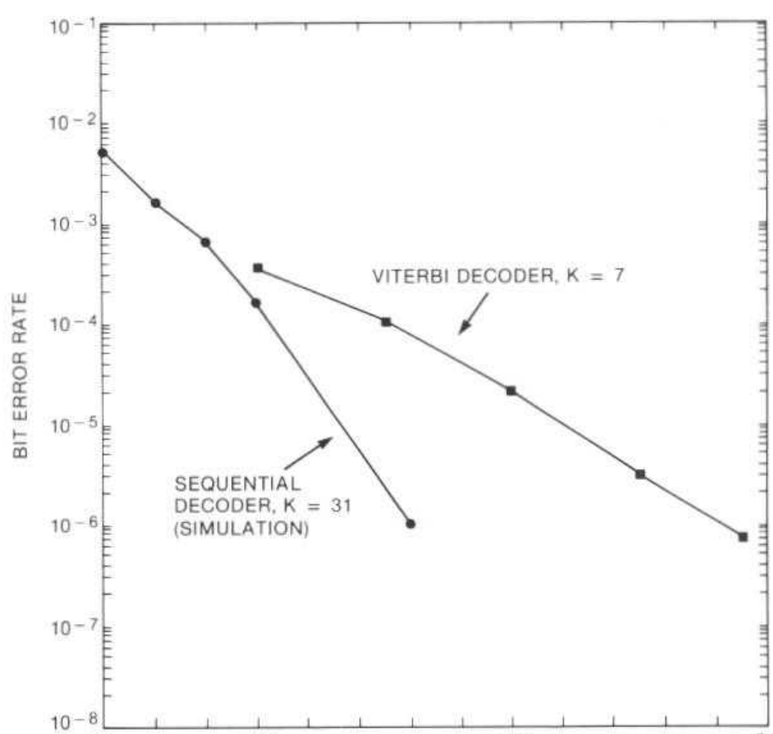


Figure 14. *Comparison of BER performance between a simulated sequential decoder and a commercial Viterbi decoder*

The investigation shows that the architectures of concepts 2 through 5 can lead to significant cost reductions relative to existing INTELSAT satellites. Concept 2 (simple low-technology satellite) employs twofold frequency reuse at C-band, which provides 31.0 dBW of e.i.r.p. through the use of four mechanically steerable quarter global beams, and fourfold reuse at K_u-band through the use of four 3° x 2° steerable spot beams. Due to its simplicity and relatively low in-orbit cost ($121M, based on a buy of five satellites), it can reduce end-to-end circuit cost by about 20 percent at C-band and up to about 35 percent at K_u-band compared to the INTELSAT VI, including earth station costs.

Concept 3, the U.S. to Europe trunking satellite architecture, also provides very cost-effective service because of its relatively simple design and resulting low in-orbit cost of $95M (based on a buy of five satellites) with reductions in the end-to-end circuit costs of up to approximately 40 percent at C-band and 25 percent at K_u-band compared to the INTELSAT VI satellite when earth station costs are included. A major drawback is that this concept leads to use of two satellite designs in the Atlantic Ocean Region (AOR) with undesirable cost and operational implications. Concept 4, the fixed multibeam satellite, employs thirteen 3° down-link beams at C-band to provide high e.i.r.p. with relatively low on-board RF power (4 W/72 MHz), yielding savings in the end-to-end per circuit cost of up to about 45 percent at C-band. Concept 5, the hopping-multibeam satellite with on-board processing, shown in Figure 15, incorporates 120 1° K_u-band hopping spot beams which deliver 46.0 dBW of e.i.r.p. requiring 4 W/72 MHz on-board RF power. It provides very cost-effective service, especially at K_u-band where the high e.i.r.p. permits the efficient use of small (3.5- to 5.0-m) low-cost earth stations, and achieves total AOR coverage. For low K_u-band earth station traffic loads, this architecture provides reduction to about 55 percent in end-to-end per-circuit costs relative to the

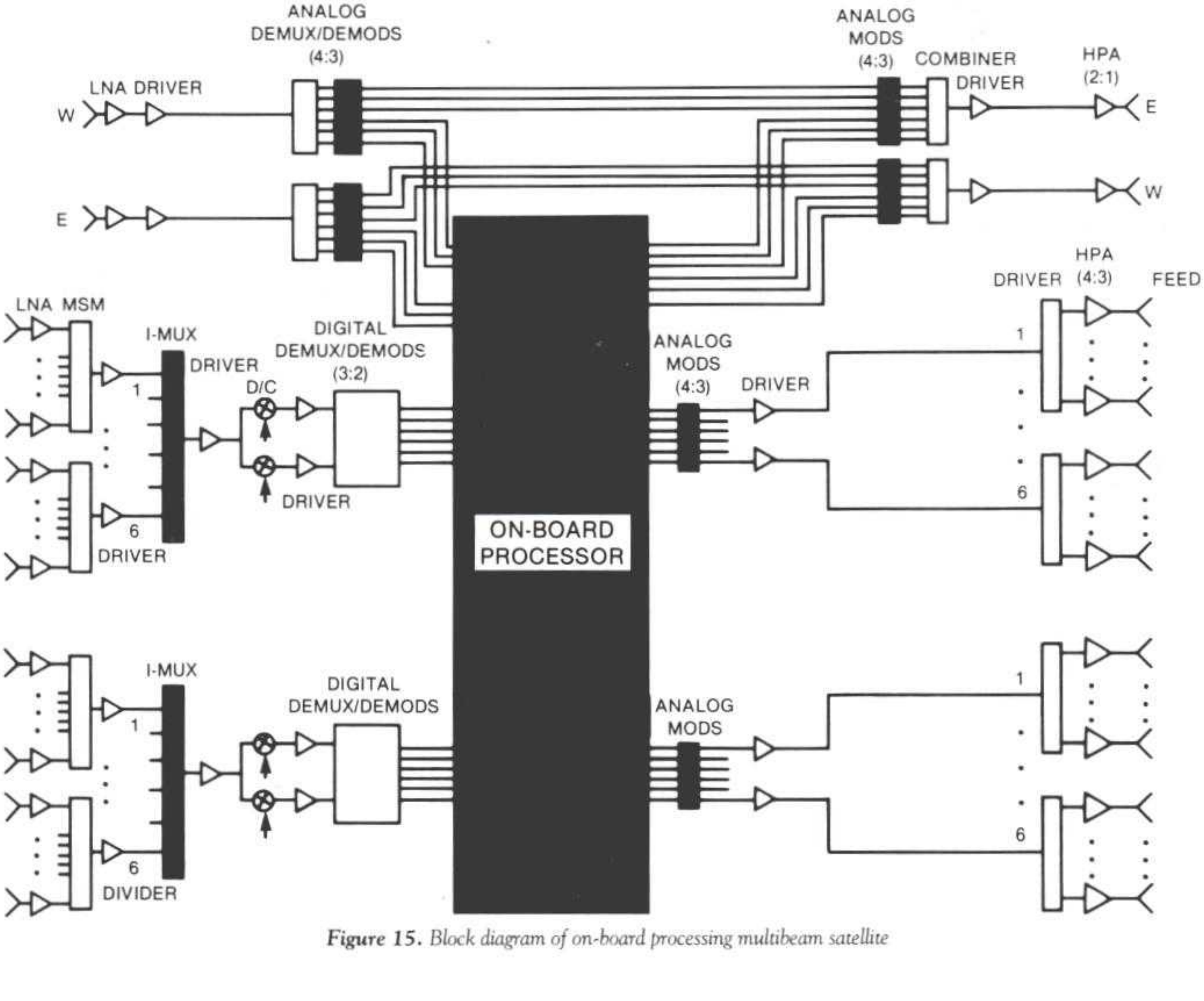


Figure 15. Block diagram of on-board processing multibeam satellite

INTELSAT VI (see Figure 16). Reduction in terrestrial tail costs, which is particularly applicable to lower traffic earth stations, will tend to make the advanced satellite system even more competitive with the TAT-9 cable.

When used in combination with optimum earth station designs incorporating the digital transmission and coding technique best suited to the specific service and traffic load of each earth station in the network, the technology of all five satellite concepts can be cost competitive with the technology of the TAT-8 cable. The study also shows that the technology of concepts 4 at C-band and 5 at K_u-band can provide service that is cost competitive with the technology of the advanced fiber optic TAT-9 cable. It is expected that an optimum satellite design would incorporate the fixed multibeam antenna of concept 4 at C-band and the hopping multibeam configuration with on-board processing of concept 5 at K_u-band.

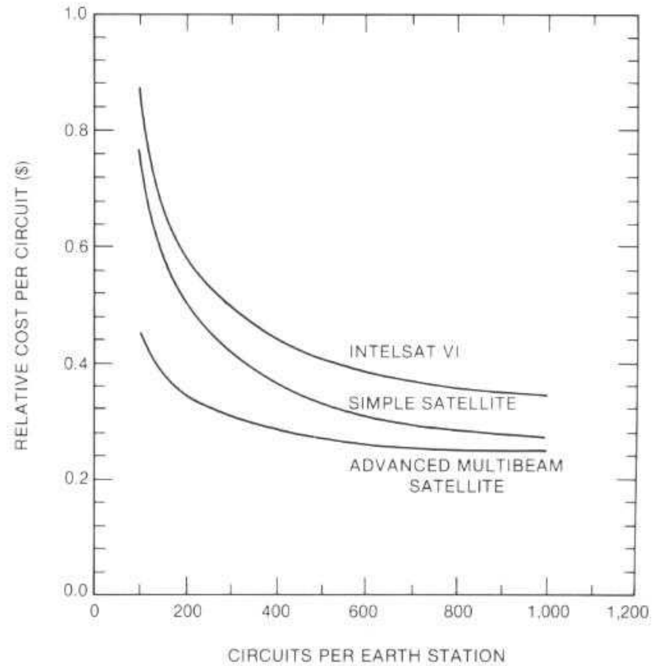


Figure 16. Total annualized relative link cost per circuit

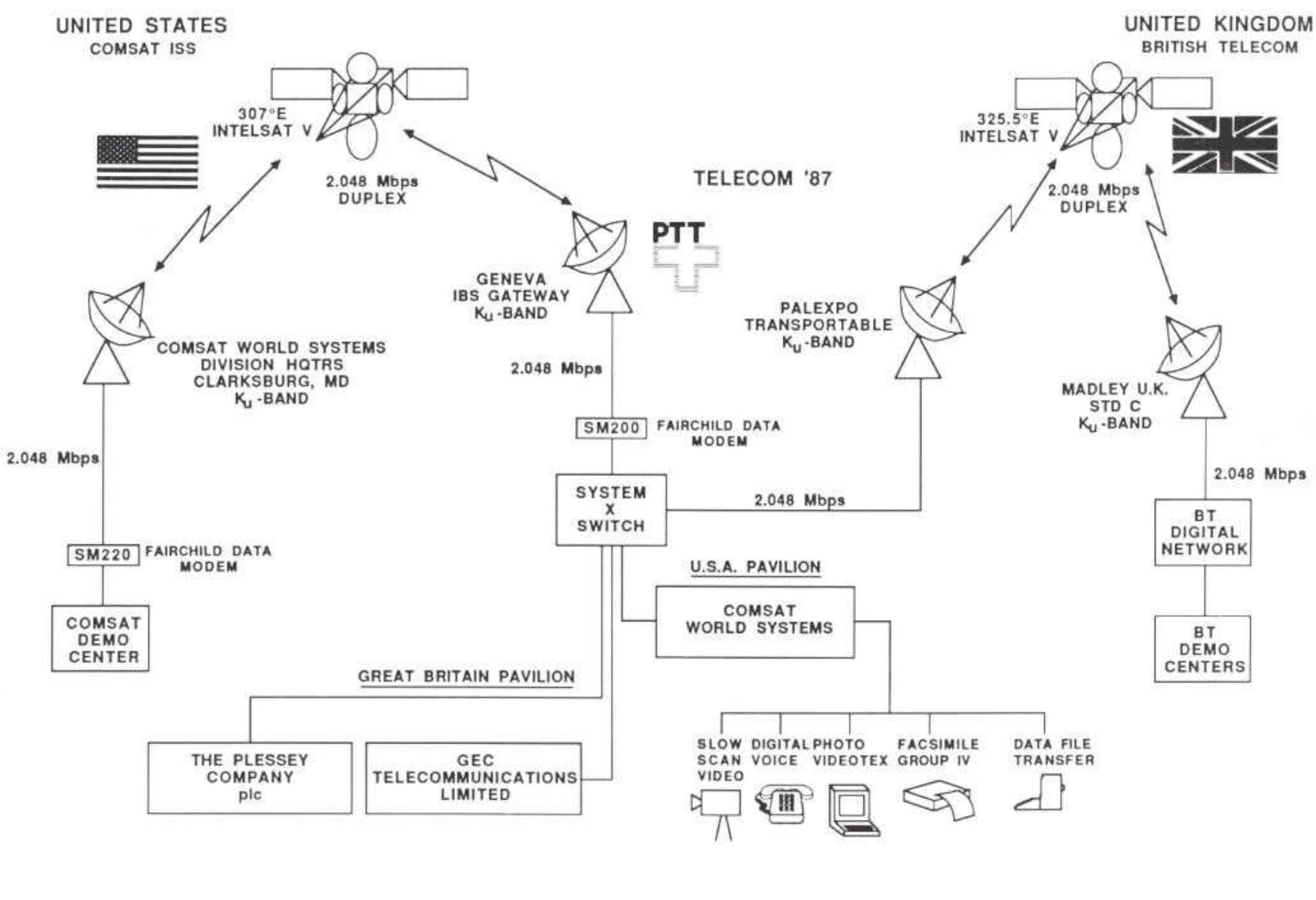


Figure 17. International satellite services digital network (ISDN) configuration

International Satellite ISDN Demonstrations

The CTD supported the World Systems Division (WSD) in ISDN demonstrations via international satellite from the International Communications Association (ICA) Convention in New Orleans, Louisiana, and from TELECOM '87 in Geneva, Switzerland. The first public demonstration of intercontinental ISDN via satellite occurred at the ICA Convention in May 1987, using a transportable earth station to the COMSAT WSD exhibit on the floor of the ICA Convention via an INTELSAT V spacecraft at 307°E longitude (cross-strapped with C-band to the U.S. and K_u-Band to Great Britain) to a British TELECOM in London via the London Teleport.

For TELECOM '87, COMSAT Laboratories served as one node of an ISDN centered in Geneva, Switzerland, via the INTELSAT V spacecraft at 307°E longitude using a 5-m INTELSAT Standard E1 earth station located on the roof of COMSAT Laboratories, and the Geneva E3 earth station owned and operated by the Swiss PTT. Figure 17 is a diagram of the system used.

A variety of digital applications operating at 64 kbit/s were demonstrated during both exhibitions. The interconnections between earth stations were made with a 2.048-Mbit/s link employing rate 1/2 FEC. Capabilities demonstrated included full color photovideotex, which provided high-resolution color material with graphic information displayed on a computer terminal; slow-scan video, which could be used for desktop teleconferencing; Group 4 facsimile, which provided high-speed, high-resolution document transmission; digital telephony; and personal computer file transfer.

Interference in Communications Satellite Systems

Interference between satellite systems limits the number of satellites that should be placed in the geostationary orbit. Maximum usage of the geostationary orbit requires coordination activities using the most realistic assessment available of inter- and intra-system interference. It is often most difficult to coordinate between low-power, single-channel-per-carrier (SCPC) signals and high-powered carriers such as FM television. Relaxing interference criteria as much as possible facilitates such coordination, which is important due to crowded conditions on certain portions of the geostationary orbit. Work reported during 1987 showed that the criterion

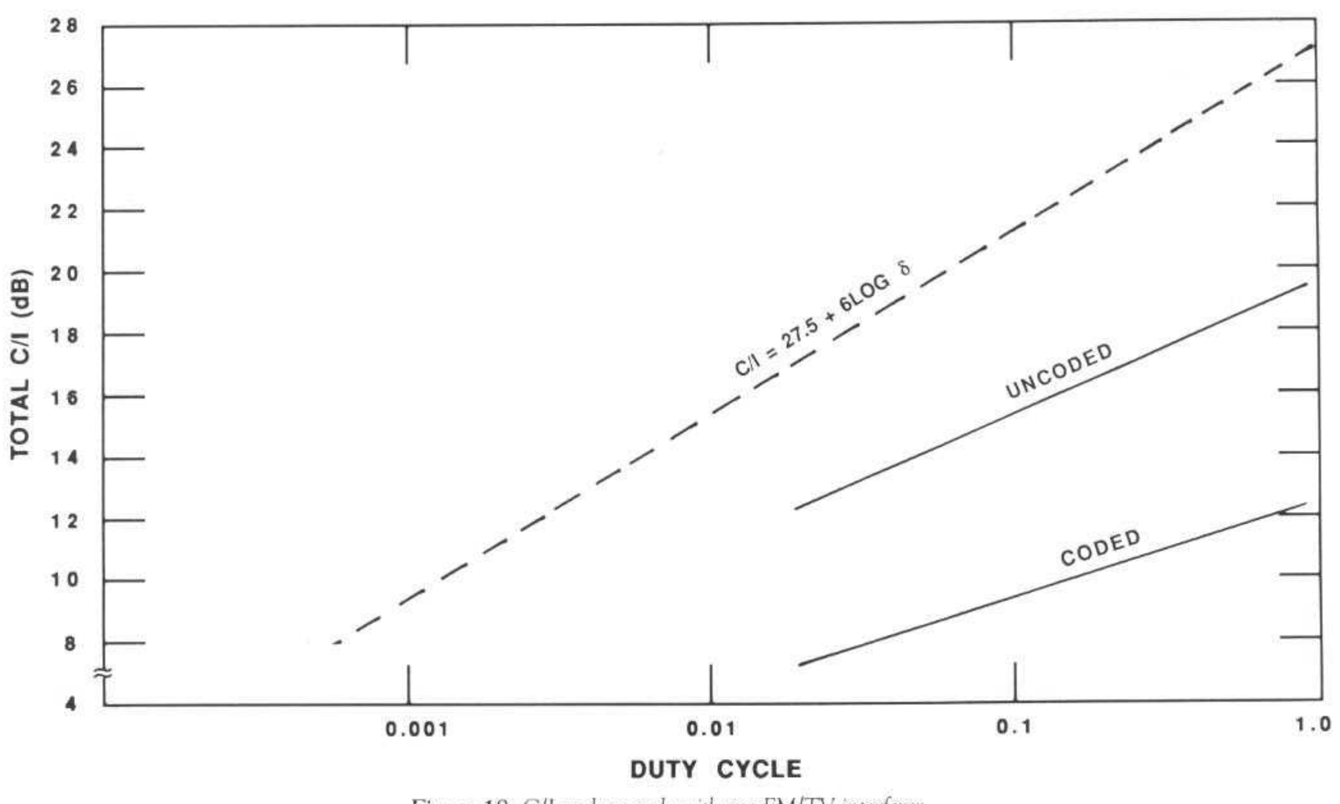


Figure 18. C/I vs duty cycle with one FM/TV interferer

for 64-kbit/s SCPC/PSK carriers operating at relatively high carrier-to-noise ratios (C/N) could be eased without causing excessive interference degradation.

The results of this year's experiment exploring the possibility that the criterion for SCPC/PSK carriers employing FEC and operating at relatively low C/N could also be eased are summarized in Figure 18. This figure shows the total carrier-to-interference ratio (C/I) necessary to degrade performance of the desired carrier to a BER of 1×10^{-6} as a function of duty cycle (w) (defined as the ratio of the occupied bandwidth of the desired signal to the occupied bandwidth of the interferer). The C/I was determined experimentally by varying the interference until the performance of the desired carrier, operating at a C/N 1 dB better than required for a BER of 1×10^{6}, was degraded to a BER of 1×10^{-6}. The figure shows the current interference criterion of $C/I = 27.5 + 6 \log (W)$, and the experimental results with and without FEC. It is quite apparent that some relaxation of this criterion is possible.

INTELSAT SUPPORT

Time-Multiplexed Analog TV

Their broadcast capability makes satellites the appropriate media for international and domestic distribution of television signals, as demonstrated by the steady growth in television traffic over the INTELSAT system. To achieve more cost-effective use of the space segment for television transmission, and thereby promote further traffic growth, COMSAT is under contract to INTELSAT to develop advanced techniques for analog television transmission for occasional use over INTELSAT global beam transponders.

During the first phase of this effort, completed in 1987, candidate transmission schemes were evaluated. Computer simulations were performed to assess the impact on signal quality of more promising schemes including inter-field and intra-field Time-Multiplexed Analog Television (TMATV), initially reported in the *COMSAT Laboratories 1985 Annual Report,* allowing the transmission of three television signals per transponder. Since the bandwidth reduction processing algorithms of the TMATV technique operate on component signals, the resultant signal is free from the artifacts observed with three operations on composite signals.

It was clear that inter-field processing provides slightly better bandwidth compression because adjacent lines between two fields usually have more correlation than adjacent lines in the same field. But the ease of standards conversion, the potential for further bandwidth reduction through temporal processing, and the hardware simplicity, led to the recommendation of the intra-field TMATV scheme for INTELSAT applications.

The TMATV method uses horizontal and vertical blanking intervals to transmit digitized program audio. The recommended scheme can accommodate up to six channels of high-fidelity, high-quality 15-kHz-sound program channels to accompany the three television channels, as well as a data transmission capability.

The hardware for processing one TV channel is currently being implemented. Additional channels may be added in the future. Prototype system hardware, including a video encoder and decoder and audio transmit and receive buffers for the transmission of three high-quality television signals over a single 40-MHz satellite transponder, is being developed and implemented. The objective is to transmit television signals in a TDM signal format, allowing three television channels to be multiplexed and transmitted from the same location.

In addition to TDM operation, this system can be designed to transmit television signals in TDMA signal format, allowing point to multipoint applications by the addition of a simple TDMA controller or three television channels to be transmitted from three transmit stations at three different geographical locations. The last will require these three television channels to be multiplexed at the satellite transponder with proper transmit timing monitoring and control to prevent them from colliding. Although the present system hardware will not perform TDMA operations, it has been designed to be upgradable by adding extra TDMA buffers and TDMA controllers.

The successful implementation of this system hardware will increase the utilization efficiency of satellite transponders by 50 percent, thus reducing the space segment cost for TV transmission by up to 33 percent.

Upgrade of Outage Margin and Time Program

The Outage Margin and Time (OUTMAT) computer program is used by INTELSAT to estimate the effects of rain impairments on carriers. These impairments include the effects of attenuation on the up-link earth station, and the combined effects of attenuation and noise temperature increase on the down-link (down-link degradation) and rain depolarization effects on interfering up-link earth stations and on the carrier's down-link earth station in the presence of co-channel cross polarized interference.

The previous OUTMAT program was capable of computing such effects only for FDM/FM carriers. With the help of the System Development Division, the upgraded version has been completely restructured to add new carrier types, including digital, TV, SCPC/FM, and companded signal-sideband carriers. To minimize input requirements, the program reads INTELSAT databases that describe the specific satellite system and frequency plans being analyzed.

Both the original and enhanced versions of OUTMAT use the Propagation Analysis Package (PAP), developed previously by the Microwave Technology Division, to compute rain impairment effects for specific earth stations as a function of percent time.

OTHER

NASA Advanced Modem/Codec Technology Development

To advance the state-of-the-art of bandwidth- and power-efficient digital transmission via satellite, NASA awarded one contract for earth station (down-link) applications to COMSAT and another for satellite (up-link) applications to TRW to develop proof-of-concept demodulators and FEC decoders to operate at an information rate of 200 Mbit/s. For the up-link, 16-quadrature amplitude modulation (QAM) and a rate 3/4 convolutional code especially designed for the modulation were selected. For the down-link, 8-phase-shift-keyed (OPSK) modulation and a time-varying 8/9 convolutional code specially designed for the modulation were

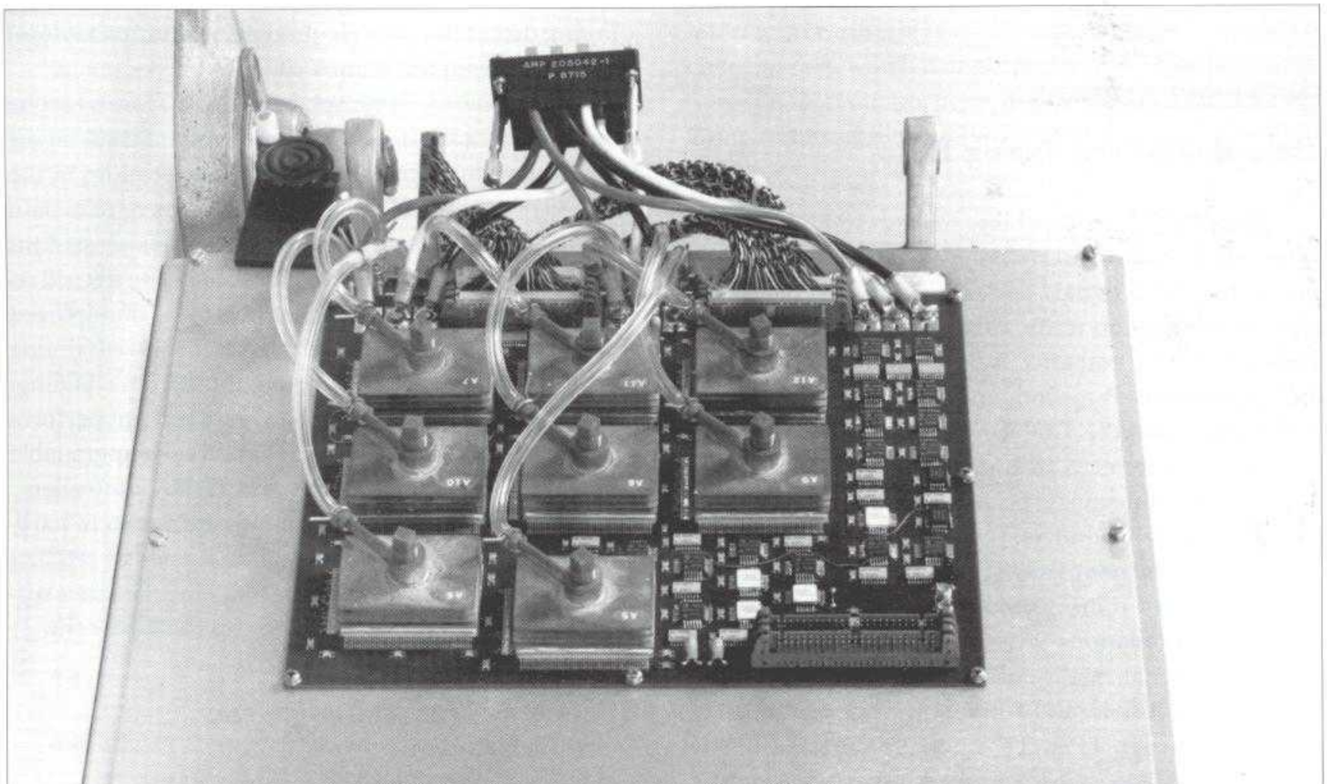


Figure 19. *ACS board for down-link decoder*

chosen. In both cases, a bandwidth efficiency of more than 2 bit/s/Hz is achieved. COMSAT is responsible for the initial system concept design and the development of the FEC codec for both contracts.

To minimize complexity for the up-link decoder and to maximize coding gain within practical implementation constraints for the down-link decoder(s), 8- and 16-state codes, respectively, were selected. To minimize the propagation delay in the most demanding operation for the ACS operation, 22 emitter-coupled logic (ECL) chips were bonded to ceramic substrates to form an ACS hybrid unit. One add-compare-select (ACS) metric computation unit is needed for each state in the decoder. Propagation delays were further reduced by using flat-pack surface mount packages instead of the common dual-in-line packages (DIPs) for other ECL-integrated circuits. Microwire technology, which allows signal routing in very restricted spaces, was chosen to facilitate interconnections between the hybrids and to increase wiring density. To further minimize the wire length between the 16 tightly interconnected ACS units for the down-link decoder, which must be operated at a minimum speed of 75 MHz (clock cycle), eight hybrids are mounted on each side of the microwire board. The special layout was made possible by using 45° signal routing and by taking advantage of the fact that only three of the four sides of each hybrid package have leads. Figure 19 is a photograph of one side of the ACS board for the down-link decoder.

Both the up-link and down-link decoders were constructed and partially tested during 1987. Performance testing of these decoders at the 200-Mbit/s information rate is scheduled for completion in the first quarter of 1988.

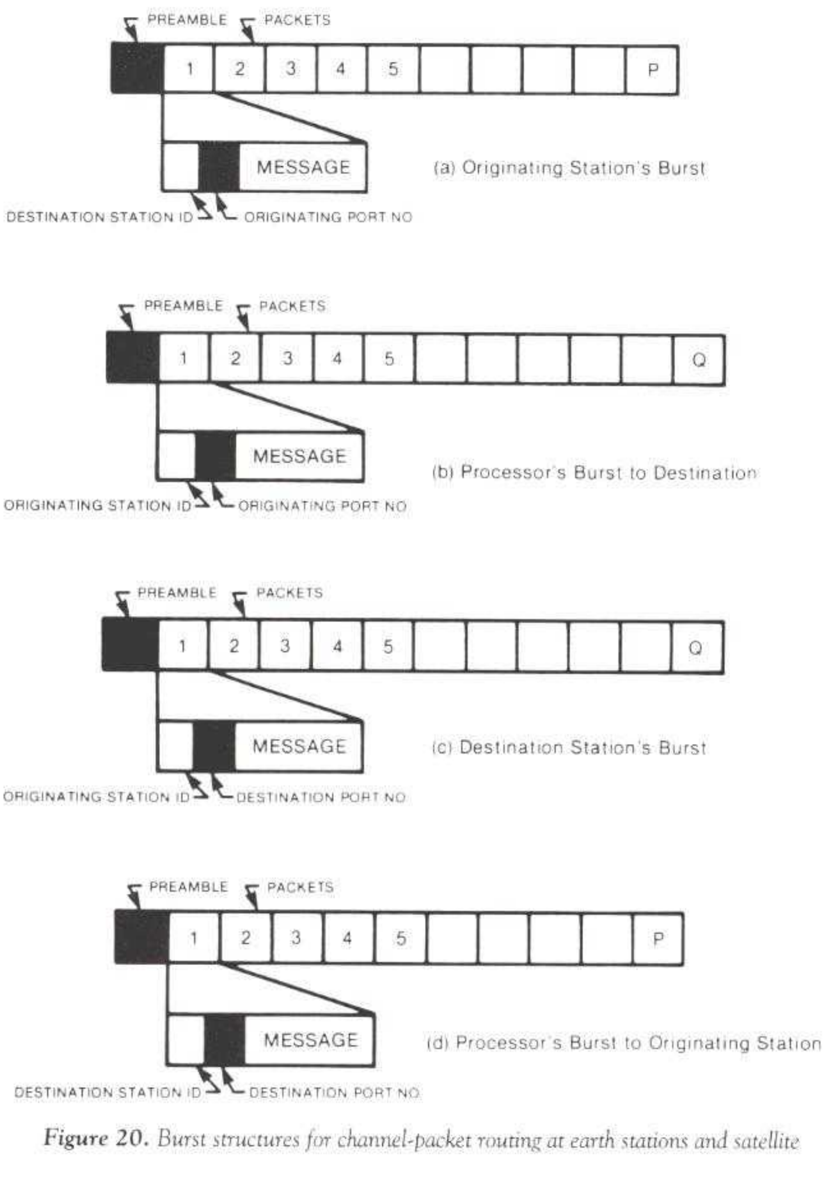


Figure 20. *Burst structures for channel-packet routing at earth stations and satellite*

NASA On-Board Processing Architecture Study

A recently completed study for NASA Lewis Research Center examined advanced on-board control methods for on-board processing satellites. The network control function is normally ground-based, as for NASA's Advanced Communications Technology Satellite (ACTS). Conventional circuit switching leads to a prohibitively complicated on-board control system. A fast-acting, packet-switching alternative for capacity assignment and channel routing was investigated resulting in the development of a completely autonomous concept which is highly efficient and flexible and yet relatively simple in design.

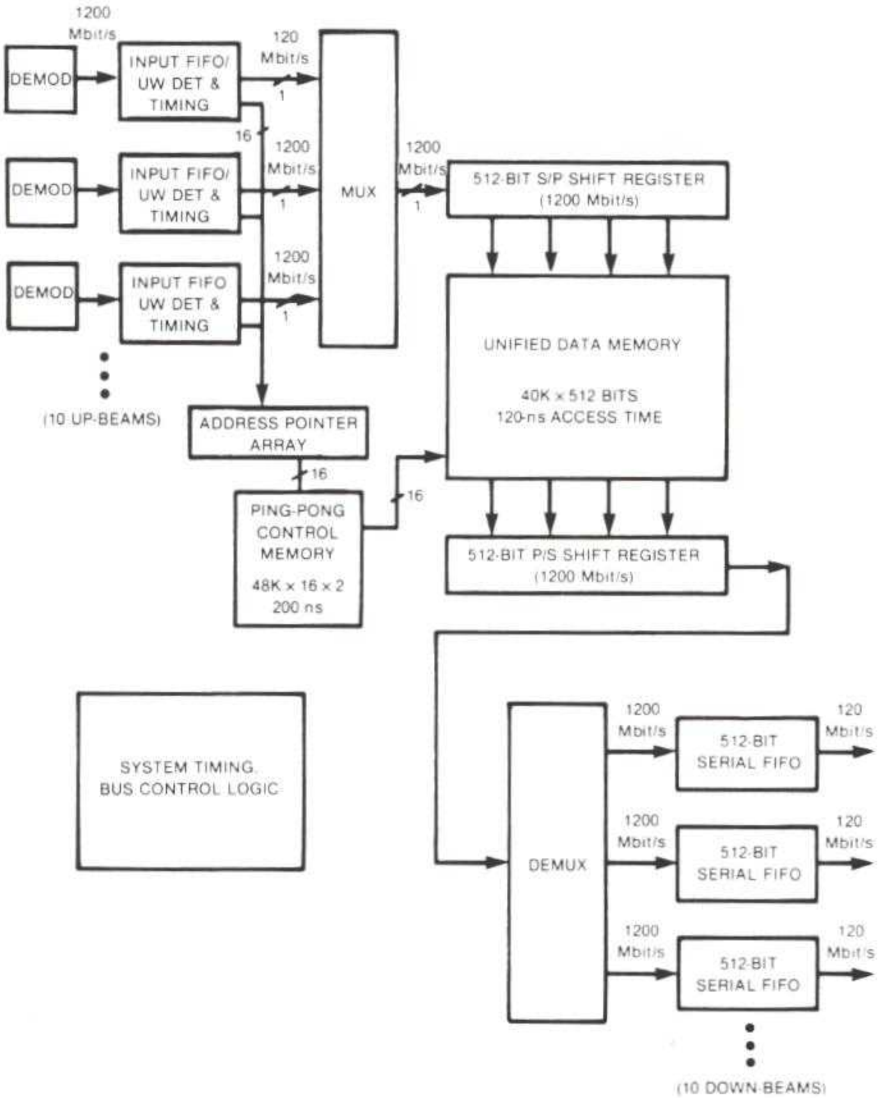


Figure 21. *Destination-directed packet switching system*

An additional benefit of the concept is voice and data activity compression and associated channel multiplication advantages. Channel capacity is used only when the message is actually present and is then returned to a pool for other network users. This can create a voice channel multiplication advantage of over 2:1 for a composite traffic load of as few as 30 channels. Significant activity compression occurs for data communication as well.

All on-board channel-packet switch control is obtained from a destination-addressed message sent as part of the burst preamble prior to the message data. This results in channel-packet routing on demand through the on-board switch. Since no other command link is needed to control routing, the satellite operates essentially autonomously, establishing routes between up- and down- beams and reassigning network capacity by generating burst time plans for the stations of the network.

Burst structures for channel-packet routing at the earth stations and satellite are shown in Figure 20. Each channel packet has a header that contains unique station identification numbers and port numbers.

For a system using the channel-packet method, the parameters below apply:

- 120-Mbit/s burst rate
- 2-bits-per-symbol modulation
- 32-kbit/s channel rate
- 256 station bursts in frame
- 8-symbol burst guard time
- 16-symbol beam dwell guard time
- 64-symbol burst preamble length
- average of 5 packets per destination
- 50 beam dwells per frame (in traffic field)
- 8- and 16-ms frame periods
- one reference burst per frame, per beam.

Taking into account all of the losses mentioned above, the resulting overall frame efficiency is 89.6 and 94.6 percent for frame periods of 8 and 16 ms, respectively.

The channel-packet switch can be implemented with only one memory using "in-place" design and operation. In-place operation refers to the process of storing the channel of an arriving channel packet in the location just vacated by the most recently departed channel packet. Figure 21 is a hardware block diagram of the destination-directed channel packet-switching system. The diagram assumes 10 upbeams and 10 downbeams with a capacity of 120 Mbit/s each, and a 16-ms frame period. The design reduces the amount of on-board memory by a factor of 4:1 compared to an equivalent time-space-time circuit switch.

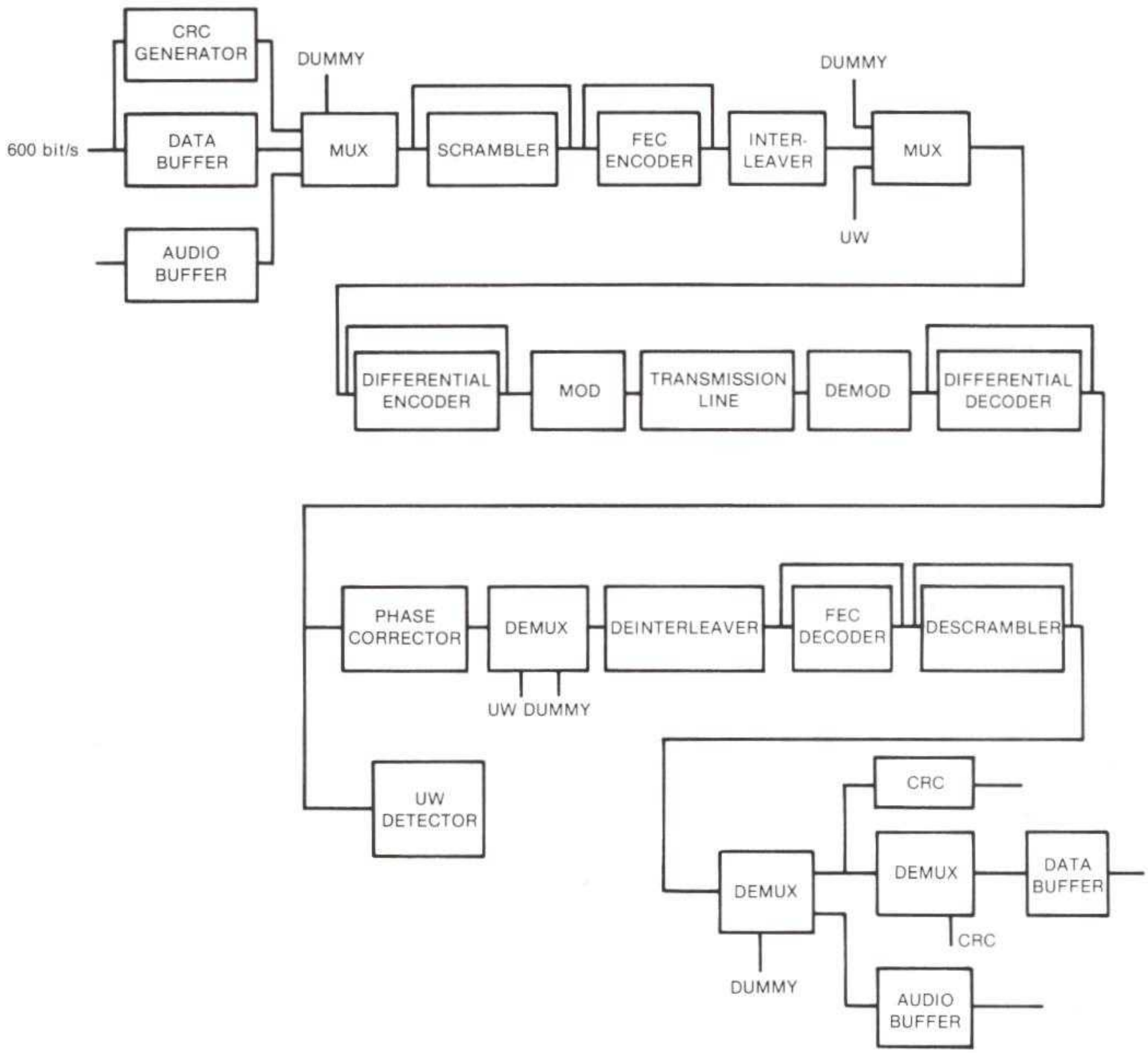


Figure 22. *Block diagram for the aeronautical mode of the INMARSAT Standard-B system*

INMARSAT Standard-B and Aeronautical Testbed

During 1987, additional work and testing were performed on the INMARSAT Standard-B Testbed Communications Subsystem under two amendments to INMARSAT contract INM-84/101: multipath and adjacent channel testing of the testbed in the Standard-B mode; and development of new hardware and software for operation of the testbed in the aeronautical mode to evaluate the transmission format design of the INMARSAT aeronautical channel. The aeronautical mode uses offset-QPSK modulation at a 21-kbit/s modulation data rate for continuous and voice-activated modes. A 9.6-kbit/s voice stream using adaptive predictive coding (APC) and a 480-bit/s signaling channel data stream are rate 1/2 encoded and multiplexed to form a 500-ms superframe.

The new hardware includes a 24- to 21-kbit/s programmable modem, which replaces the 24-kbit/s modem originally developed for the Standard-B mode. Microprocessor technology, (shown in Figure 22) is used to implement the functions for the aeronautical mode. At the transmit side, all functions except the modulator are implemented with a Zilog Super-8 microprocessor. At the receive side, special purpose digital hardware and a Texas Instruments (TI) TMS32010 DSP chip are used in conjunction with a Zilog Super-8 microprocessor. The synchronizers include the necessary voice and data interfaces, and a switchable differential encoder/decoder pair for offset QPSK. The demodulator has been implemented with two TI TMS32020 DSP chips. The demodulator software was modified to improve the energy detection, frequency estimation, and carrier and clock acquisition performance. The existing up/down-converters have also been modified with additional local oscillators to maintain the same channel frequencies for the Standard-B and aeronautical modes.

In the continuous mode, the offset QPSK BER performance of the new demodulator in 21.4-MHz IF loopback is very close to theory. When a maximum frequency offset of 1 kHz is introduced between the transmit and receive units, only 0.2-dB degradation in BER is observed.

The new demodulator configuration was also tested with INMARSAT-supplied Class-C amplifiers in an L-band loopback to evaluate the performance of offset QPSK modulation in a nonlinear channel with adjacent channel interference. Figure 23 shows the measured BER performance for both uncoded and rate 3/4 coded operation. The degradation from the baseline IF loopback for the nonlinear channel, at L-band is about 0.4 dB at a BER of 5×10^{-4} with no adjacent channel and about 0.8 dB with the main channel faded by 5 dB (C/A = -5 dB). The measured results agree well with those obtained by computer simulation.

The BER performance under multipath conditions for continuous offset QPSK modulation in the aeronautical mode at 21.4-MHz IF with the INMARSAT-supplied multipath simulator is shown in Figure 24. The BER performance for Rice factors of 10 and 12 dB and fading bandwidths of 80 and 150 Hz are close to theory.

The INMARSAT Standard-B Testbed Communications Subsystem, including the aeronautical mode, has passed the in-plant and final acceptance tests. The aeronautical mode hardware has been delivered to INMARSAT under the third amendment. COMSAT Laboratories is currently implementing a new microprocessor-based frame synchronizer for the Standard-B system, scheduled for delivery in mid-1988.

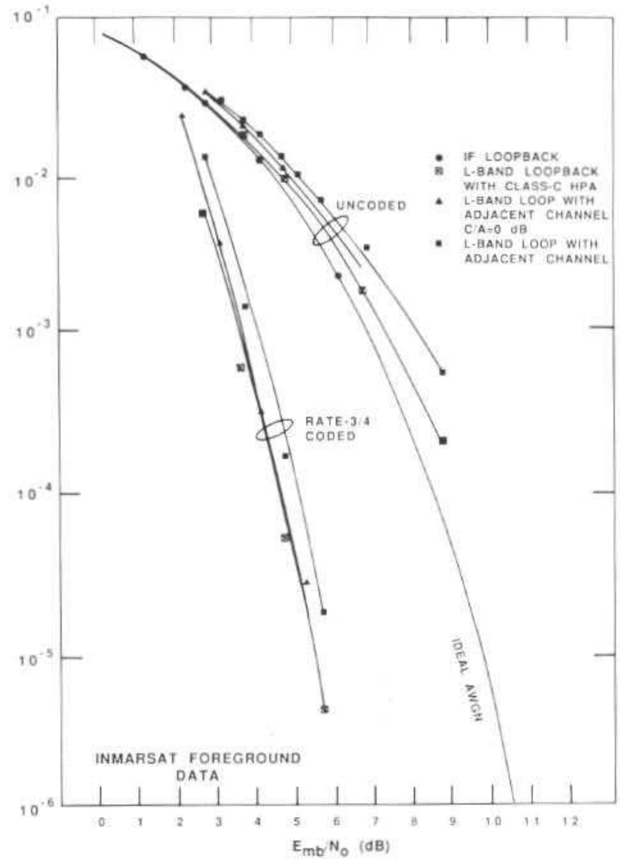


Figure 23. Measured BER performance for offset QPSK modulation in the Standard-B mode with Class-C HPA and adjacent channel interference

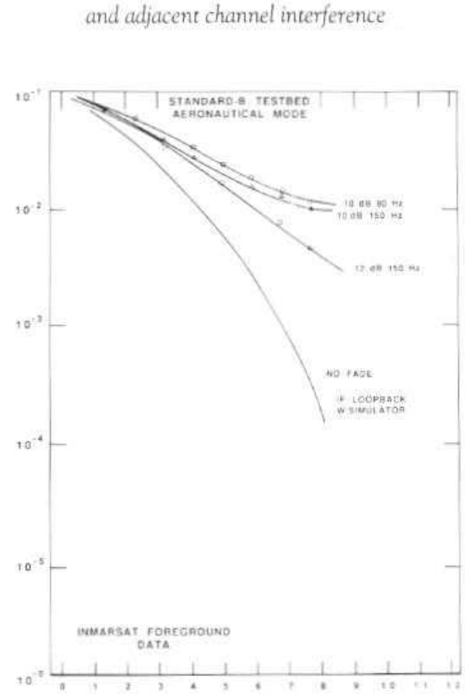


Figure 24. Measured BER performance for continuous offset QPSK modulation with the INMARSAT multipath channel simulator

Corporate K_u -Band Transponder Simulator

1987 saw the completion of the COMSAT Corporate K_u-Band Transponder Simulator enabling studies of satellite transmission systems over simulated K_u-Band, international, and domestic links. It provides a hardware transmission model of typical K_u-band spacecraft and is equipped with filters for simulation of INTELSAT VI-type K_u-band transponders. Figure 25 is a diagram of the international portion of the simulator. The domestic portion of the simulator is identical except for filter bandwidths. Each portion of the simulator consists of a receiver/frequency converter, transponder input filters, nonlinear amplifiers, and transponder output filters. The simulator uses TWTs with nonlinear characteristics that are nearly identical to actual spacecraft tubes. Proper frequency planning allows modeling of frequency reuse configurations. Up to six separate transponders are available for simultaneous experiments , and modular construction facilitates substitution and evaluation of effects of new transponder components on transmission.

Hardware simulation has long been employed by both COMSAT and INTELSAT in evaluating and optimizing the performance of satellite transmission systems. It complements computer or software simulation by providing an actual model of the communications system which can identify unforeseen implementation degradations. It further allows calibration of software simulations against a precisely controlled and readily available hardware system.

Hardware simulation can be used to identify and troubleshoot system anomalies off-line. It allows the investigation of the effects of channel nonlinearities and interference conditions in a precisely controlled manner. Finally, hardware simulation allows the assessment of system performance without interrupting revenue-producing activities.

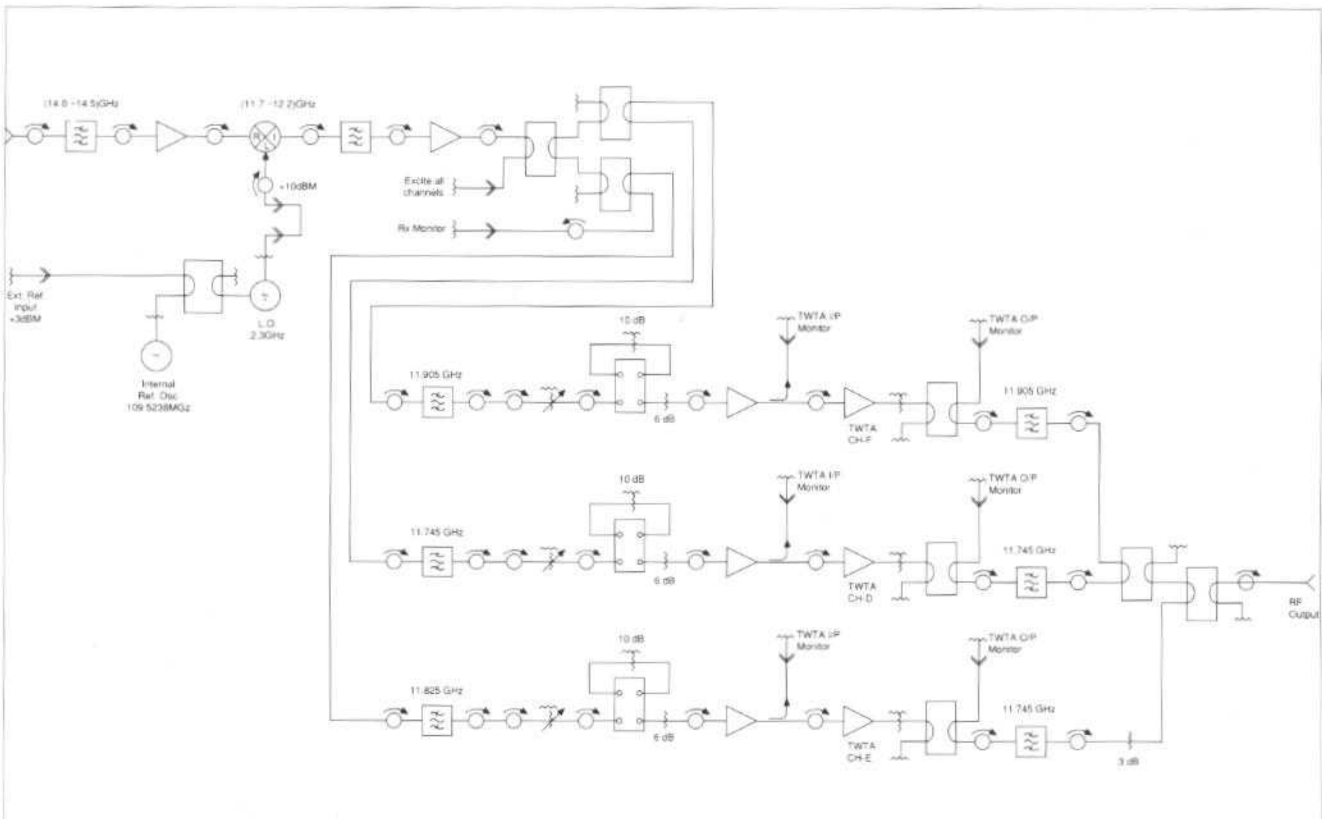


Figure 25. *International portion of the COMSAT Corporate K_u-band Transponder Simulator*

Developments in digital transmission and switching technology have led to innovative network designs that provide new services at reduced cost. As a result, networks are evolving at an ever-increasing pace. COMSAT's Network Technology Division (NTD) has focused on the rapidly developing area called "networking," from systems and architecture to software and hardware. By applying an integrated approach to simplify procedures and designs, the NTD ensures a manageable network design capable of continuing orderly growth and encouraging the incorporation of technological advances. While the NTD is primarily concerned with telecommunications networks, special emphasis is also placed on exploiting the advantages of satellites to provide new services at competitive cost. The NTD is responsible for research and development activities pertaining to communications network design, control, and management; protocol development; satellite multiple access; and fiber optic systems and devices. In addition, hardware and software developed by the NTD plays a crucial role in cost-effective network implementation. In all of these areas, the NTD provides support for the Corporation and its various lines of business.

COMSAT JURISDICTIONAL R&D

Joint COMSAT/NBS OSI Protocol Experiment

The International Standards Organization (ISO) has developed an International Standard Reference Model of Open System Interconnection (OSI), which provides a basis for the coordination of 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 Bureau of Standards (NBS) have been engaged in a joint program to examine, implement, and test the performance of high-level data communications protocols over satellite links. The investigation is carried out by first analyzing the relevant protocols and identifying the parameters and procedures that affect the efficient operation of the protocols over satellite links for different ranges of transmission speeds and bit error rates. Next, the protocols and any necessary modifications are implemented and tested in the laboratory. Finally, a joint satellite experiment is conducted with NBS, and the results are presented to national and international standards organizations for appropriate modification of the protocols.

Experiments completed in 1985 and 1986 by the NTD concerned transport protocol class 4 (TP-4) and the Internet Protocol (IP). All relevant modifications to TP-4 have been approved by various subcommittees and are being considered for approval in the next release of the TP-4 draft proposal.

The session layer protocol and the X.400 message handling system (MHS) protocols were investigated during 1987. The MHS provides users with a set of services that enable them to exchange messages with local or remote users by using a store-and-forward mechanism. Two major session service facilities were found to require modification for better performance over satellite links: the capability data exchange service, and the major synchronization point service. Specific modifications (affecting protocol operation minimally, but improving performance considerably) were designed, implemented, and tested.

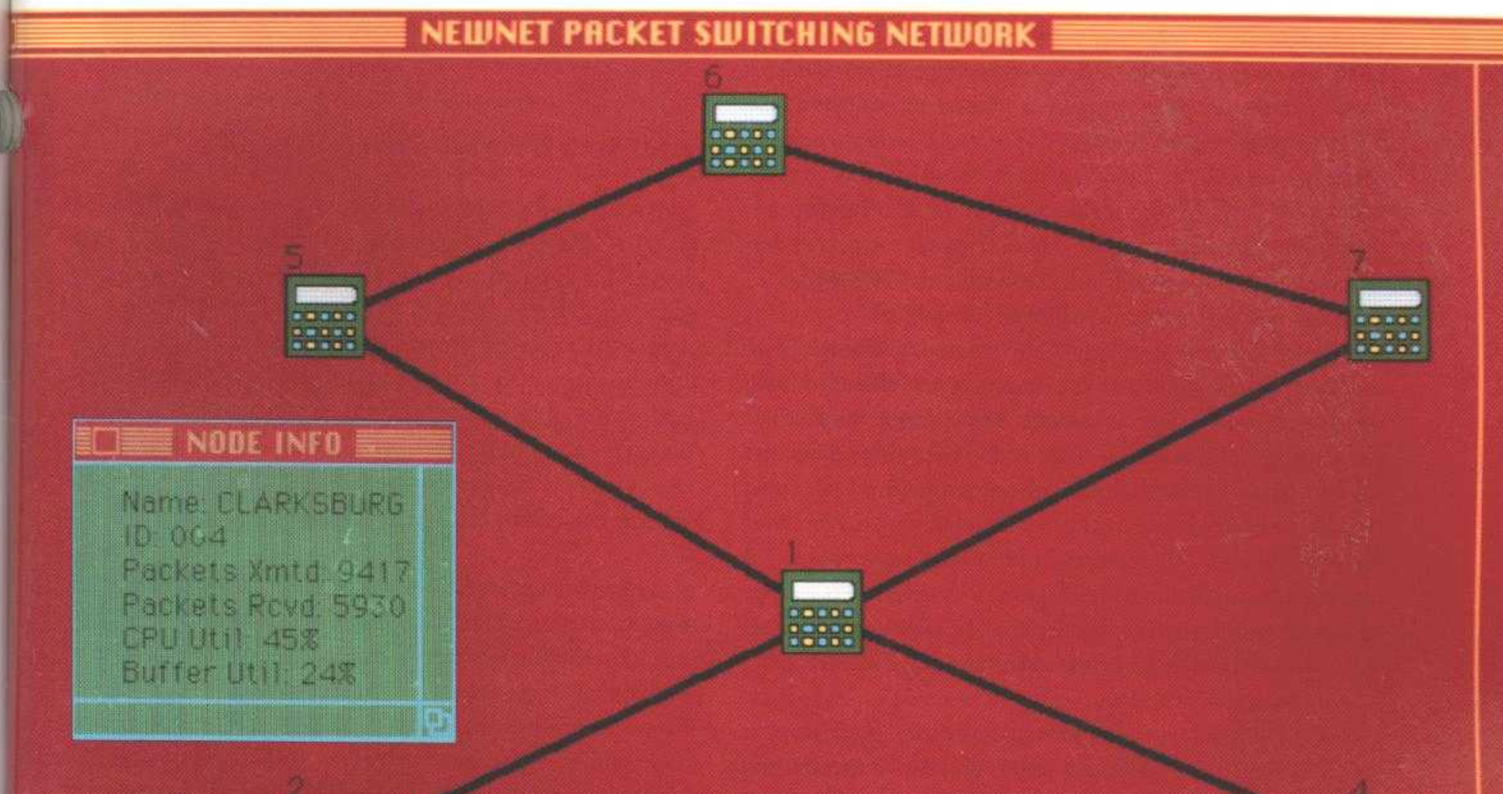
The backbone network of the MHS system is a collection of entities called message transfer agents (MTAs). Reliable transfer service element (RTSE) procedures are used to transfer messages between MTAs. The relevant protocols from the X.400 series were analyzed and implemented, and a number of parameters were identified that will have an impact on the performance of these protocols over satellite links.

A detailed set of experiments has been designed and tested in the laboratory for the session layer and X.400 series protocols. The satellite experiments will be carried out in early 1988.

CCITT and T1 Activities

The NTD has been an active participant in international and national standards organizations dealing with integrated services digital networks (ISDNs) and data communications issues. Members of the NTD have participated in Study Groups XI and XV III of the International Telegraph and Telephone Consultative Commit-

NETWORK TECHNOLOGY



Newnet packet-switching network

tee (CCITT) and in the subcommittees of the ANSI T1 Committee on Telecommunication.

These efforts have been directed toward ensuring that satellite systems are included in the development of national and international standards. Various timer values suitable for operation over satellite links were introduced by the NTD into various recommendations being developed in CCITT. For example, in Recommendation Q.716 dealing with the performance requirements of the signaling connection control part (SCCP), timers are specified to detect and activate changeover procedures whenever there is a link failure in a routing path. It is important that the values of these timers be sufficiently large so that satellite propagation delay will not be seen as an indication of a link failure.

In addition to timers, the NTD has been monitoring the impact of the development of additional packet-mode bearer services defined in Draft Recommendation I.122. Four such services have been defined, and there has not been widespread agreement on reducing the number to one preferred service. One such service, known as frame relaying, uses a protocol that does not perform any link-level error correction, and therefore relies on virtually error-free transmission such as can be supported by fiber optic transmission. A disadvantage of this service is that it experiences congestion problems because there is no longer a flow control between the end devices and the network at the link level.

A second service, known as frame switching, performs error correction at the link level and has a built-in congestion control mechanism. This service is suitable for satellite transmission, since it does not rely explicitly on error-free transmission (although satellites can now provide such high-quality links). In addition to lobbying for specific bearer services, the NTD has worked to ensure that unnecessarily stringent performance requirements are not forced on these services, which would rule out satellite-based transmission in favor of fiber optic transmission.

A larger issue that emerged during 1987 is the development of broadband ISDN (B-ISDN) standards. Broadband refers to digital rates higher than T1 rates (1.544 Mbit/s or CEPT 2.048 Mbit/s), and can be as high as 150 to 600 Mbit/s. These digital rates are intended to be supported over fiber optic transmission media, but so far the specification of standards has been kept independent of transmission media. The NTD has been active in ensuring that satellite-based services are an integral part of B-ISDN.

Quality of Service

CCITT Recommendations X.134 through X.137 define performance objectives for international packet-switched data communications services. Recommendation X.135 defines performance objectives for each of the three primary data communications functions: call setup/call clearing delay, data packet transfer delay, and throughput capacity. The NTD supported the COMSAT joint experiment with the National Telecommunications and Information Agency (NTIA), Boulder, Colorado, and TYMNET, Fairfax, Virginia, to ascertain the value of quality-of-service parameters in packet-switching networks. Identical tests were conducted on five different configurations. The first four fell into the category defined by CCITT as National B network, with a satellite as a part of the access section. The fifth was a loopback configuration over the satellite at the Clarksburg earth station.

Local Area Network Interconnection

The use of satellites for interconnecting local area networks (LANs) was investigated. LAN internetworking architectures and protocols were analyzed in terms of their efficiency over satellite links, and two detailed reports were prepared. The first analyzed the IEEE LAN protocols, and the second discussed various internetworking approaches, issues, and problems related to LAN interconnection.

Future Satellite Systems Study

A transoceanic cables study, which constitutes an important part of a much broader project, "International Fixed Satellite Services," sponsored by COMSAT Corporate Development, addressed the competitiveness of satellite vis-a-vis lightwave technology. The objective was to assess the technological status of undersea cable communications systems. The final report provided a cost projection for representative Atlantic Ocean Region (AOR) and Pacific Ocean Region (POR) cable systems in the 1988-2000 time frame, with a focus on technological growth. It also included features of planned and installed undersea fiber optic cable links.

COMSAT NONJURISDICTIONAL R&D

Network System Research

The NTD is conducting an ongoing research program to investigate, evaluate, and implement technologies for data communications and networks. A variety of network architectures and communications protocols have been implemented, and a wealth of information, experience, development tools, and expertise has been accumulated. A number of advanced protocols and network management systems were developed.

Routing Protocols: Packet-Switched Network

A key feature of the packet-switched network is the routing protocol used for forwarding the packets to their destinations. The effectiveness of the routing strategy plays a significant role in the cost and performance of the network. Various routing techniques were investigated, and a specific dynamic, adaptive, distributed routing technique (ADRP) was identified as a baseline protocol for the COMSAT Data Research Network. ADRP is an algorithm that is executed in unison by all nodes in the network. Each node exchanges information with its immediately connected nodes regarding traffic levels in its node. Through this exchange, an optimal and consistent set of routes is generated independently by each node, for each destination node. As traffic levels change or nodes fail, the routes are regenerated by all nodes; hence, traffic is routed around congested or failed nodes or areas. This algorithm is transparent to end users, and results in increased performance and availability of the network.

A data link protocol was also developed to provide reliability of packet transfer over the internodal links. This protocol monitors the state of neighboring nodes and congestion levels over links, providing information that is used by the ADRP.

Error and Flow Control

Error and flow control mechanisms used in packet-switched networks were investigated, and specific schemes were developed that operate efficiently over a satellite link for a wide range of bit rates and bit error rates. The interaction of different error and flow control functions at different layers in the ISO seven-layer model was studied. Also, the effectiveness of the frame relaying technique (a concept being developed by CCITT Study Group XVIII) over a satellite link with end-to-end error and flow control was analyzed. Different flow control procedures were investigated, and specific procedures were identified that perform most efficiently over satellite links. Simulation was used to verify and validate the analytical results and to study situations that were not tractable analytically.

Congestion Control

In addition to efficient routing and flow control techniques, a packet network also needs strategies for handling traffic surges. These large traffic fluctuations may begin as localized phenomena but could spread over larger regions, causing significant delays and low throughput over the entire network. The NTD investigated various congestion control techniques to alleviate this problem. New techniques based on transient queues and predictive optimum strategies were developed which are designed to handle a large class of congestion patterns with minimum computational complexity.

Switched SNA

The NTD data networking system also provides interfaces to networks that are based on IBM Systems Network Architecture (SNA) protocols. Geographically distributed IBM hosts and terminals may be interconnected in this network. The system provides a capability normally not available to SNA users—switched connections. In an SNA network, terminals are connected to terminal controllers, which in turn are connected via the SNA network to hosts. Because each terminal is "owned" by a host, a user cannot establish a session with another host on the network without logging into the owner host. With the SNA package developed for the NTD network, terminals and hosts are connected to the network via synchronous data link communications (SDLC) lines, and the network offers the terminal user a choice of connecting to any host on the network. This allows users to create cost-effective, wide-area networks using the additional capabilities of switched connections.

Network Management

Data communications technology and protocols have made steady progress over the last several years.

The number of public and private data networks is increasing rapidly, as are the size and complexity of each network. Coupled with this increased complexity is the additional factor of multi-vendor equipment within the same network. Management of these large, complex networks is a problem area which has only recently been addressed. The NTD has embarked on a program to investigate and implement network management strategies.

A number of areas have been identified under the umbrella of network management: network administration (network configuration and definition); fault management; problem management; statistics and reports (including billing and accounting); and network planning and design tools. One design goal of the network management system has been to avoid overloading the network operator with information about the network. Instead, network management should handle most routine (and some non-routine) problems automatically, with the operator being involved only in problems that the system cannot yet handle. Of course, all information is available to the operator when needed.

The NTD data network was used as a test bed (see Figure 1) to investigate several network management concepts. A few subsystems have been built and evaluated.

One important aspect of a network is how the nodes are initialized and downloaded with code and parameters. In 1987, a system was designed so that this process requires no operator intervention. A node may require initialization for a number of reasons. It may have been recently installed, or may have crashed due to a power outage or a transient hardware error. If a node contains its software and parameters in nonvolatile memory, it uses them to reboot quickly. However, if these files are missing or corrupt, then the node obtains the required files from a neighboring node or the Network Management Center (NMC), as appropriate. The software

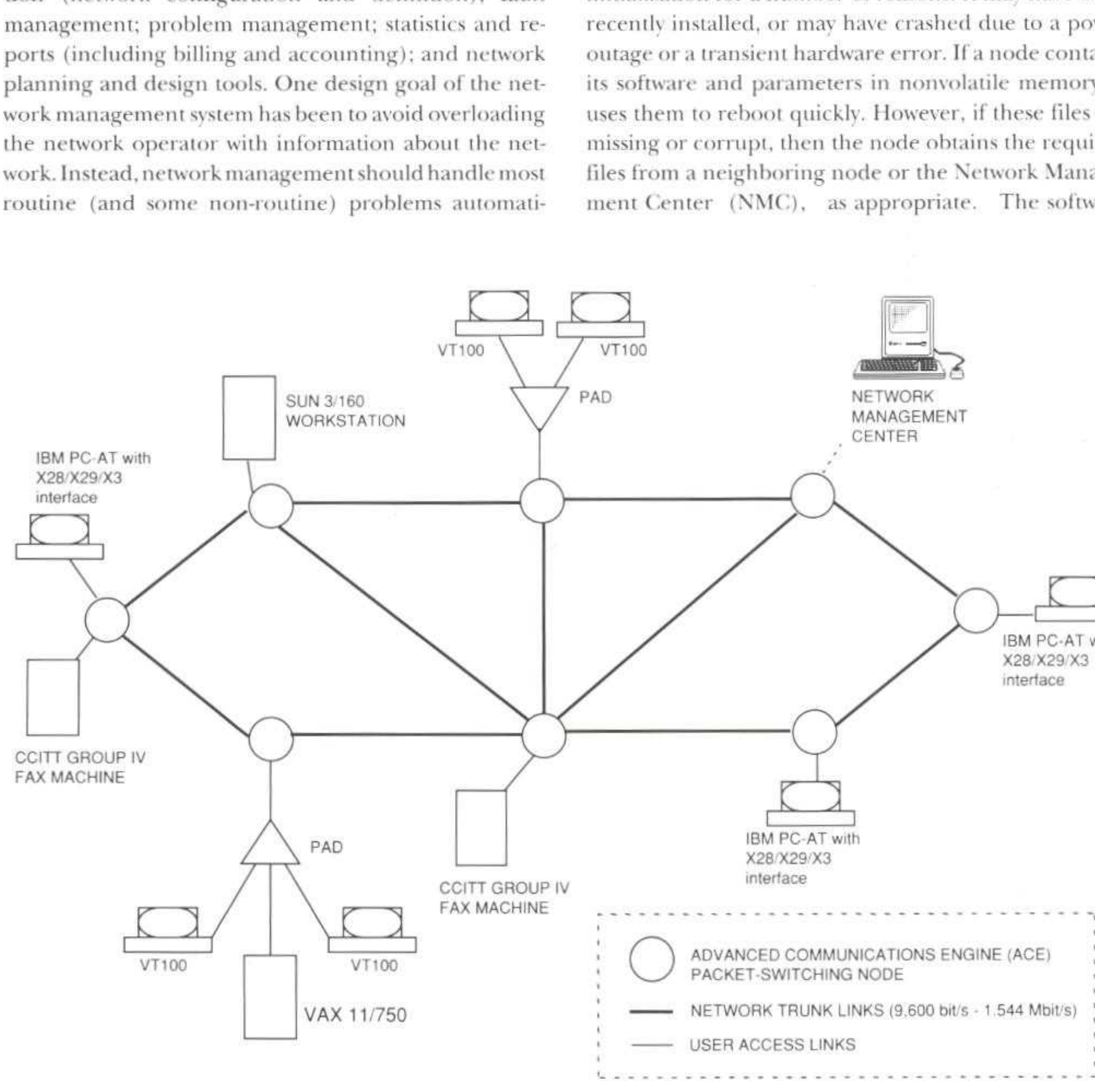


Figure 1. *NTD data network test bed*

required in order to perform this initialization is minimal and is stored in programmable read-only memory (PROM) in each node.

To provide status, topology, and routing information regarding the network, a network monitoring system was built at the NMC. This system collects information from various nodes and displays a graphic view of the entire network (using the virtual console system) on a Macintosh screen. A highly interactive interface allows an operator to observe different aspects of the network and its nodes on the screen.

Random-Access Notification Multiple-Access Protocol

Continuing the NTD's 1986 work in very small aperture terminal (VSAT) system development, a new multiple-access protocol called random-access notification (RAN) was formulated for the VSAT environment. The RAN protocol has the simplicity of operation of the slotted ALOHA protocol; however, its throughput is considerably better because it schedules the retransmission of collided or lost packets. The system parameters for the RAN scheme can be selected so that the average delay for RAN is less than the average delay for the reservation time-division multiple-access (TDMA) method. These performance advantages are obtained by introducing the concept of notification of new packets transmitted in a random-access mode, and by removing collided and lost packets from the random-access (contention) data slots to reserved slots dynamically allocated for retransmission. The RAN protocol has the flexibility to operate over a wide range of traffic and performance requirements, with reservation TDMA as one limiting mode of operation during certain traffic conditions.

Figure 2 shows the average delay as a function of throughput for a fixed offered traffic level (new packet arrival rate from all VSATs). In this example, the channel rate is 56 kbit/s, packet size is 128 bytes, and the network packet arrival rate is 30 packets/s. Note that, in this example, the RAN protocol has a better average delay than reservation TDMA up to approximately 55-percent throughput, at which point the RAN protocol transitions to a pure reservation TDMA scheme.

Optical Processing

In 1987, the NTD began developing a prototype optical switch matrix. This device uses integrated optical technology to fabricate waveguides, couplers, and switches on a lithium niobate ($LiNbO_3$) wafer. Lithium niobate

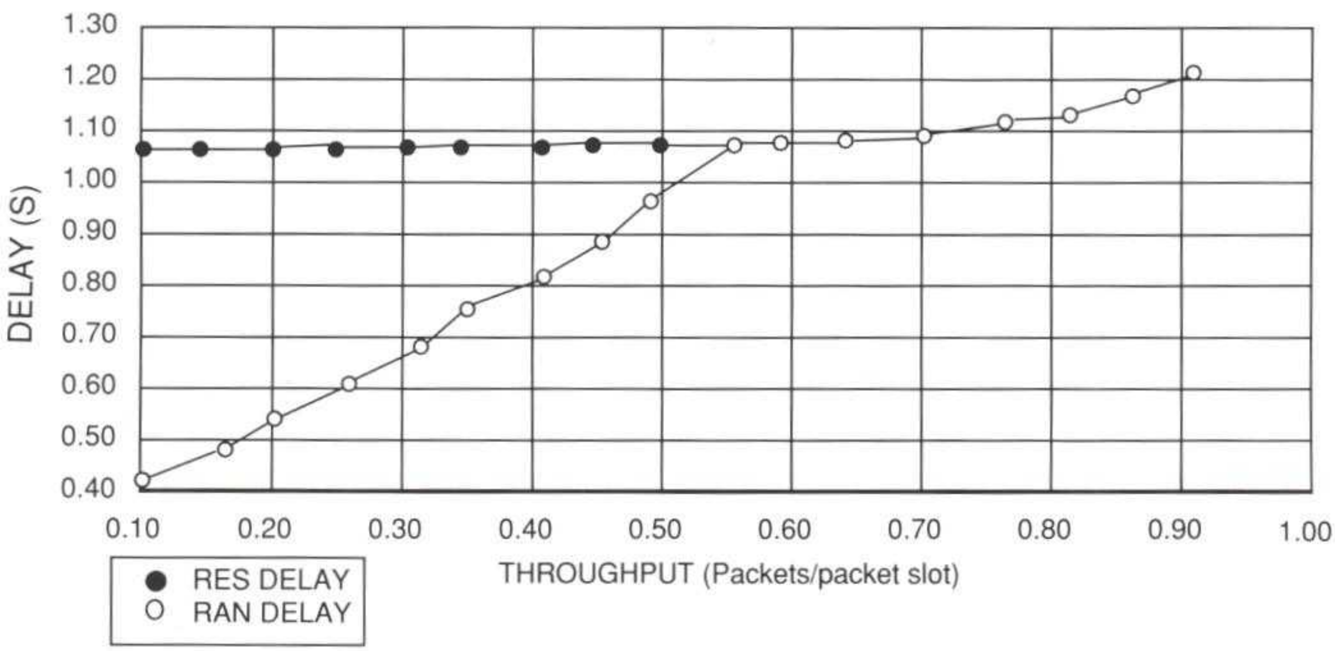


Figure 2. Average delay vs throughput

was selected since it has a very high electro-optic coefficient, low waveguide losses (typically 0.5 to 0.8 dB/cm), and uses very little electrical power to switch optical signals.

Two device fabrication processes were examined, one using titanium-indiffusion and the other proton exchange. In the Ti-indiffusion process, electron-beam evaporation is used to deposit a thin layer of titanium on the $LiNbO_3$ wafer, which is then heated at approximately 1,000° C, causing the titanium to diffuse into the wafer. This creates a channel having a higher refractive index than the surrounding $LiNbO_3$. The channel is stable over the long term; however, the channel edges are rounded, making it difficult to implement compact multiplexers and switches.

In the proton exchange process, aluminum is deposited on the $LiNbO_3$ surface on all areas except the waveguide channel, and the wafer is placed in a benzoic acid bath which is heated to about 130° C. This creates the desired waveguide channel via H^+ doping. The problem with this process is that the device is unstable for long-term operation because the H^+ migrates into the $LiNbO_3$ crystal or to the surface, destroying the channel characteristics. Further research is needed to develop methods for stabilizing the channel. The advantages of this process are that it is performed at fairly low temperatures and creates a relatively high-index channel having sharp, well-defined boundaries.

Multiplexers are created by closely spacing the optical waveguide and etching periodic grooves 30 to 60 μm apart in the $LiNbO_3$ that separates the waveguides (coupling region). The geometry of the etched area controls both optical coupling and wavelength.

The refractive index of $LiNbO_3$ can be controlled with electric fields. Thus, optical switching can be accomplished by intersecting waveguides and properly placing electrodes to create an electric field in order to steer the optical beam into the desired output waveguide.

Network Architecture Study

The network architectures currently evolving in the telecommunications industry offer new user and network management services, and are being implemented using innovative multiplexing and switching techniques and higher transmission rates. During 1987, the NTD began a study to assess advances in device technology, switching systems, and networks to determine the effect these new systems will have on satellite earth station equipment, access techniques, and network management, and to provide guidance to architecture studies for future satellites.

Communications Controller

The NTD designed a controller module that can function in a time-division multiplex (TDM), random-access TDMA, or TDMA mode. The module comprises two standard random-access memories and a custom controller. The user programs the module for the operating mode and provides the necessary operational parameters. When interconnected with a commercial microprocessor, the module provides the complete control needed for point-to-point TDM, central hub networks, and full-mesh TDMA networks. The module's transmit and receive functions operate independently, allowing different outbound and inbound formats.

The custom controller was designed, and its operation simulated, in a computer-aided engineering (CAE) workstation environment. It has approximately 19,000 gates and is mounted in a 128-pin package. It interfaces with the user at speeds up to 2.048 Mbit/s.

Software Technology

Software is a critical and often expensive element in data communications and networks today, and will be increasingly so in the future. The NTD has been tackling this barrier with a large measure of success. It has long recognized the need for software development methodologies and architectures that allow the development of complex data communications software which is of high quality and is relatively inexpensive to build. To this end, the NTD has developed the COMSAT Multiprocessor Operating System (COSMOS) as the foundation for most of the software development in the division (see Figure 3). COSMOS consists of an ever-increasing number of reusable software components and an architecture (rules for synthesis) that allows development of simple to highly complex software systems in an incremental manner. COSMOS runs on a number of hardware platforms and has been used successfully in several different projects.

During 1987, the following enhancements were made to COSMOS:

- **SBE4 Board Port**. COSMOS was ported to run on the SBE4 processor board. This board contains a 68000 processor and four high-speed ports (up to 1 Mbit/s) that can be used for serial links employing a variety of different protocols. Software was developed to support both asynchronous and bit-synchronous protocols. This addition to the set of COSMOS-supported hardware platforms enhances the NTD's capability to provide high performance and cost-effective solutions for data communications problems.

- **68020 Evaluation.** COSMOS was ported to a board that contains the 68020 processor, in order to evaluate the processor and its performance for networking software. The 68020 is backward-compatible with the 68000 processor and outperforms it by a factor of 2 to 7, depending on the clock rate. The porting effort was incremental and consisted largely of modifications to device drivers necessitated by differences in I/O devices. This added capability enables COSMOS to be used for applications that require very high performance.

- **New Timer Package**. The timer package within COSMOS is responsible for creating "virtual alarm clocks" for applications. The newer protocols, especially ISO, require a large number of such software timers. The previous implementation of the timer package performed well only if the number of software timers was small. The NTD developed and implemented a new algorithm that allows an almost unlimited number of software timers with near-constant overhead.

- **Memory-Based File System**. A software package was developed that allows applications to store and retrieve data from files that are stored on nonvolatile memory boards. The interface (as seen by applications programs) is that of a standard file system, and all normal file operations are supported. This approach offers a substantial increase in capability, especially for applications that require long-term data storage and have high performance requirements. The design of embedded and unattended systems is also considerably simplified. This file system is currently used for the storage of code files, parameter values, statistical data, and diagnostic information.

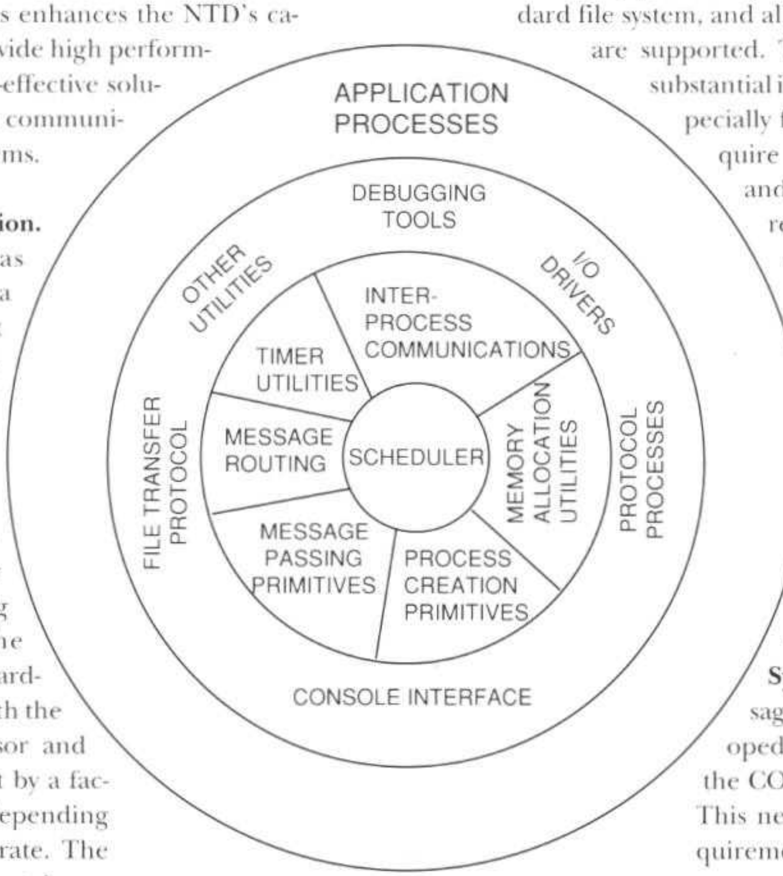


***Figure 3**. COMSAT multiprocessor operating system (COSMOS)*

- **Network Message System.** A network message system has been developed which is built on top of the COSMOS message system. This new system meets the requirements of complex data communications software containing many protocol layers. Instead of adding this burden to the COSMOS message system, a software package was developed which can evolve independently while retaining the simplicity and efficiency of the COSMOS message system.

- **State Machine Description Language.** Most real-time systems software and data communications software modules are specified in the form of finite-state machines, in which a software process travels through various states and performs various actions depending on the current state of the system and the next external event (reception of a hardware signal, reception of a message, expiration of a software timer, etc.). Traditionally, this specification is hand-coded using a programming language. The NTD-developed State Machine Description Language (SMDL) and SMDL compiler automate this process. The system specification is written using SMDL, and then processed by the SMDL compiler, which transforms it into an error-free and efficient implementation using C language. The C language code is then combined with other supporting software modules to produce the final executable code. This process considerably reduces both software development time and implementation errors.

- **Virtual Console System**. The virtual console system adds to COSMOS-based applications the capability to develop interactive, user-friendly interfaces. This system is especially suited for developing network management systems. The subsystem employs a Macintosh personal computer as an intelligent operator interface terminal. The interface is highly interactive and uses state-of-the-art techniques such as windows, pull-down menus, and buttons. The system consists of a library of routines available for COSMOS applications which can produce graphics and text and set up the required interface functions.

The virtual console manager (VCM) is a process that resides in the Macintosh. It receives commands from the applications in the form of messages, and uses the Macintosh toolbox routines to perform the various interface functions. It notifies the applications when the user selects objects or menu items or enters text in fields. The VCM allows multiple windows and multiple applications, and handles all window-refresh operations.

Artificial Intelligence

Since 1985, the NTD has been involved in applying engineering and expert system technology to two categories of telecommunications networking problems: network management and control, and network planning and design. The NTD had already successfully developed prototypes in both categories to demonstrate the feasibility of the technology for addressing networking problems. During 1987, work continued toward enhancing existing capabilities, defining larger domains of application in each category, and migrating to delivery systems such as PC-based systems.

As an example, a satellite network analysis package (MacSNAP) was developed and tested on the Macintosh. The purpose of the package was to provide high-level tools that would enable the user to identify a cost-optimized satellite network configuration (i.e., to select satellite and earth station characteristics) based on customer or user requirements.

The design of a realistic satellite network relies on a vast body of expert knowledge and information, such as characteristics of satellites in operation, orbital data, propagation and atmospheric data, geographical information, climate regions, earth station equipment characteristics, modem performance data, vendor constraints, regulatory constraints, and various costs and tariffs. The design choices are further constrained by cost, performance, and traffic requirements stipulated by the customer. The designer must have considerable expertise and experience to pool all of this information and arrive at a network solution. The required expertise consists principally of the knowledge of critical factors and margins in the system design, and the ability to make intelligent choices for tradeoff analyses. MacSNAP automates much of this process.

For the network customer, MacSNAP provides the intelligence to determine, for example, whether a feasible satellite network solution exists within the bounds of the customer's requirements and at what cost, without having to know the details of the analysis. The user need only specify very general requirements, such as the name of the satellite, type of earth station, station location, desired error rate, and availability. For the expert analyst, MacSNAP provides the tools to perform tradeoff and sensitivity analyses and obtain system requirements for the final network design.

MacSNAP derives its power from the integration of its analysis modules with an extensive database of operational satellite data, including INTELSAT satellites, measured data for TWTA characteristics, INTELSAT Standard earth station specifications, VSAT vendor specifications, INTELSAT and other earth station site coordinates, worldwide rainfall distribution by climate region, error performance curves for different modulation and coding schemes, International Radio Consultative Committee (CCIR) and CCITT recommended performance objectives (including availability requirements), and data for different rain models.

The MacSNAP package is designed to allow the user to investigate different network scenarios in order to compare cost/performance alternatives. This is made possible by the use of multiple blackboards in the MacSNAP architecture. The user may explore "what-if" scenarios to investigate, for example, how network cost might change if additional capacity is required. Individual scenarios or case studies can be saved on file for use in the analysis of other, similar scenarios. Thus, the user may have a customized network scenario corresponding to his current network configuration, which can subsequently be used to plan expansion and to forecast costs.

The System Development Division (SDD) is responsible for system design and development activities in support of the COMSAT lines of business, INTELSAT, and other COMSAT clients. SDD activities encompass the development of computer-based systems, including the design and implementation of software and the selection, acquisition, installation, and integration of hardware. Other SDD projects involve the development of digital hardware and microprocessor firmware for prototype equipment produced by COMSAT Laboratories, and the development of analysis and simulation techniques and computer software for evaluation and optimization of satellite communications systems and subsystems. State-of-the-art software development techniques are investigated and employed in the SDD, including the use of advanced methodologies, computer languages, and computer hardware.

COMSAT JURISDICTIONAL R&D

Interactive Channel Modeling Program (ICHAMP)

A baseline version of an interactive channel modeling program (ICHAMP) was developed in 1987. ICHAMP is a time-domain analytical simulator, developed on the IBM mainframe computer (Figure 1), which is used to determine the steady-state performance of digital or FM communications channels. The analysis algorithms used in ICHAMP were developed and tested previously in the COMSAT channel modeling program (CHAMP).

To activate the program, users define the channel to be evaluated by configuring the channel block diagram on the graphics terminal screen. Icons representing filters, amplifiers, signal generators, and signal operators are used to build the diagram, as shown in Figure 2. The user then draws the connectivities between the components and sets probes to indicate where channel performance should be evaluated. Multiple channels may be defined in order to represent adjacent channels. Individual channel component parameters are stored in a component database and may be edited. The channel block diagram is stored in a channel database which also may be modified by the user.

The baseline version of ICHAMP consists of the component and channel database management utilities, a baseline graphical interface, and a set of basic analysis capabilities. The program will be fully extended in 1988 to include a comprehensive set of analysis capabilities, output features, and full user documentation.

Link Budget Software Program

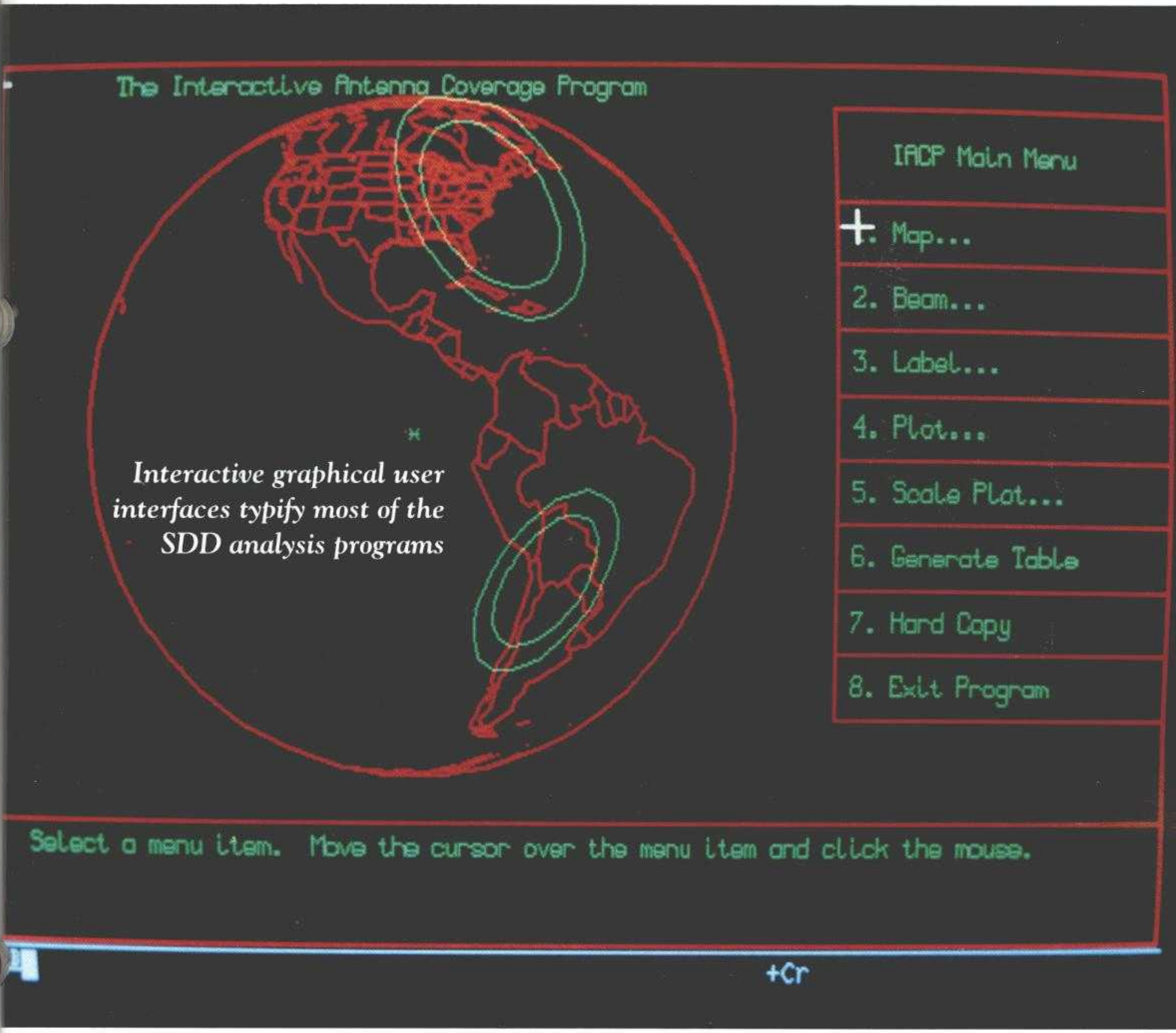
LINK, a program that evaluates the undemodulated performance of a satellite link between a single transmit and receive station pair, was developed jointly by the Communications Techniques Division (CTD) and the SDD and was completed in 1987. LINK enables the user to tailor a link budget for the up- and down-link earth station parameters and the satellite parameters. The primary interface to the program is a spreadsheet which allows the evaluation of multiple link budgets by varying certain link parameters. Multiple output options for reviewing printed or plotted results of these parametric evaluations are included (Figure 3). An optional LINK feature is its ability to determine operating parameter values, such as the high-power amplifier (HPA) power, or the transponder saturation flux density necessary to achieve a specified level of link performance. IBM mainframe and PC versions of the program were developed.

COMSAT SUPPORT

Communications System Planning Model

The Communications System Planning Model (CSPM) is a software tool being developed to support Intelsat Satellite Services (ISS) in performing near-term and long-range planning tasks for the INTELSAT Satellite System. The CSPM will replace the Long-Range Planning Model, which was instrumental in planning the INTELSAT V and VI systems. Complete program design and the implementation of the user interface were completed in 1987.

SYSTEM DEVELOPMENT



Interactive graphical user interfaces typify most of the SDD analysis programs

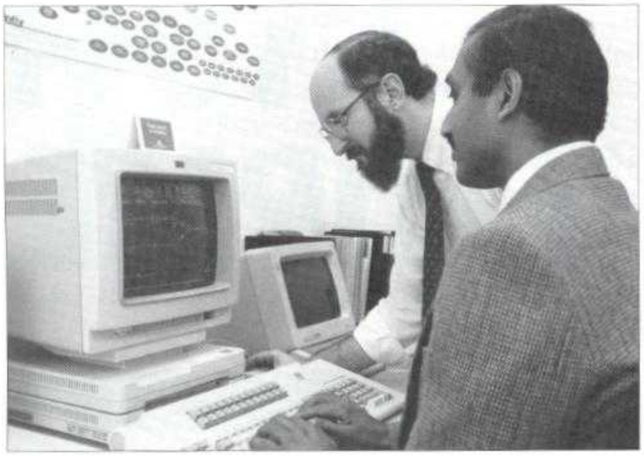


Figure 1. Interactive channel modeling software development

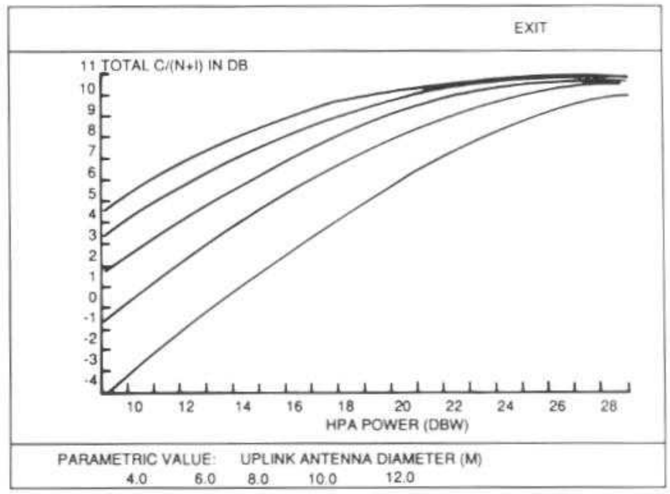


Figure 3. Plotted results of LINK parametric evaluation

The CSPM, developed on the IBM mainframe, may be used to model satellite systems that provide multiple services and transmission modes, including digital, voice, Intelsat Business Services (IBS), time-division multiple-access (TDMA), intermediate data rate (IDR), and single channel per carrier (SCPC). The program's analysis capabilities include traffic routing among satellites, traffic-to-transponder loading, and basic economic evaluation. It also features numerous traffic matrix manipulation capabilities to aid the ISS planner in traffic forecasting and in deriving special interest traffic matrices from the global INTELSAT traffic database (ITDB).

The user interface consists of pull-down menus with extensive editing capabilities that enable the user to easily enter, modify, and maintain the considerable data required for task planning (Figure 4). These data include earth station and spacecraft descriptions, satellite and equipment deployment information, traffic forecasts, and general system specifications.

ISS Database Management Facility

The ISS Database Management Facility (IDBMF) is being developed on the IBM mainframe as the central repository for satellite system data within ISS. This facility will provide ISS staff with current and accurate data for use in many planning, engineering, and marketing tasks. It will also supply data directly to many of the software tools used by ISS to simplify program execution, including CSPM, the Antenna Coverage Program (ACP), and the Satellite-On-Station Plan Program (SOSP). Some of

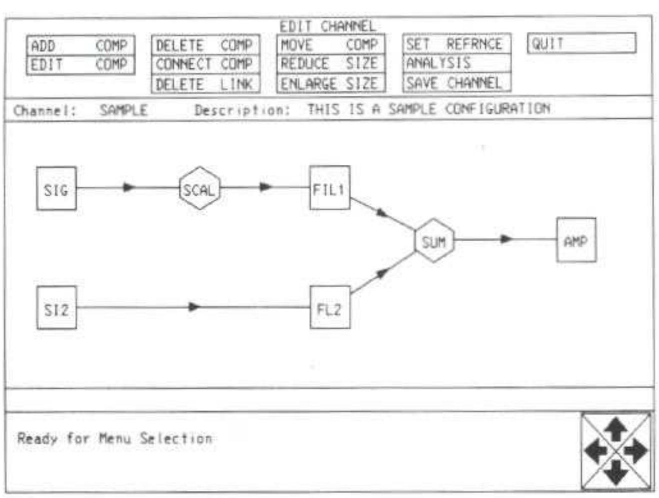


Figure 2. ICHAMP block diagram

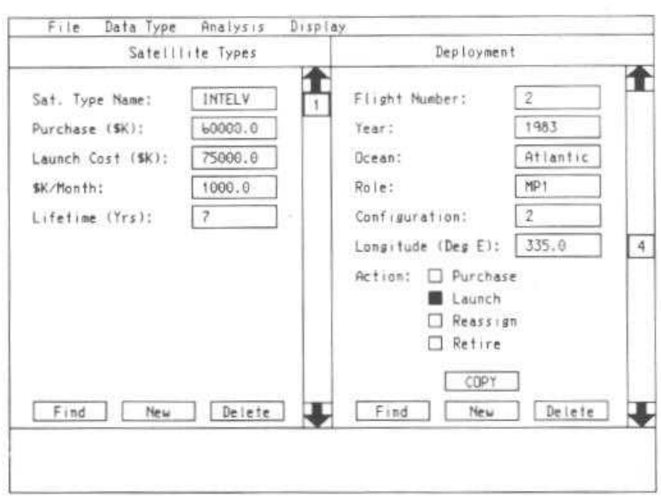


Figure 4. CSPM operator screen

the categories included in the database are earth station and signatory information, traffic projections, frequency plan data, antenna pattern descriptions, and satellite deployment information.

Access to the IDBMF is through a simple interface that enables the user to request various predefined reports or data graphs, either from a single data category or a combination of several categories. The generated reports and graphs are of high quality and may be used in presentations or documentation. Figures 5 and 6 show formatted output for INTELSAT signatory data. Specially formatted reports or graphs may be specified and readily produced.

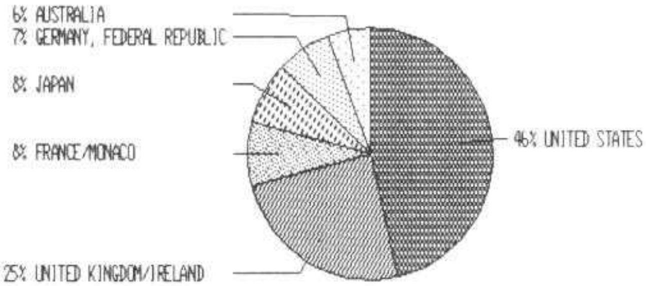


Figure 5. *Representation groups with 3.0 percent or greater voting share for INTELSAT*

REPRESENTATION GROUPS	VOTING SHARE
UNITED STATES	25.63
UNITED KINGDOM/IRELAND	13.60
FRANCE/MONACO	4.55
JAPAN	4.41
GERMANY, FEDERAL REPUBLIC OF	3.93
AUSTRALIA	3.15
BRAZIL/PORTUGAL/URUGUAY/CHINA	2.80
SPAIN/PERU	2.69
CANADA	2.68
VENEZUELA/ECUADOR/BOLIVIA/COLOMBIA	2.51
AUSTRIA/GREECE/SWITZERLAND/LIECHTENSTEIN	2.39
ITALY/VATICAN CITY	2.35
SAUDI ARABIA	2.04
IRAN/KOREA/PAKISTAN/TURKEY	2.02

Figure 6. *Groups with 2.0 percent or greater voting share for INTELSAT*

The overall IDBMF design was completed in 1987, and a significant portion of the earth station database was implemented.

Interactive Satellite Transmission Impairments Program (ISTRIP)

Development of the Interactive Satellite Transmission Impairments Program (ISTRIP) began in 1986 and was completed in 1987. ISTRIP determines the performance of carriers within a frequency plan in a frequency reuse system such as INTELSAT. The analysis evaluates the levels of adjacent-channel and co-channel interference, as well as intermodulation impairments for multiple carrier types such as digital, SCPC, TDMA, and frequency-division multiplex/FM. An algorithm that determines optimal power levels to maximize frequency plan performance for the individual carriers is also included.

ISTRIP is an interactive extension of the STRIP program, which was completed in 1986. The user interacts with a sawtooth plot of the frequency plan on a graphics terminal. By selectively moving individual carriers to new locations within the transponder bandwidth, the user may invoke the program analysis to determine frequency plan performance. The process of iteratively moving carriers may be continued until the desired level of performance is achieved (see Figure 7). The program also includes additional carrier editing capabilities, such as power level adjustments, coding specifications, and bandwidth allocations. The development of ISTRIP was a joint effort by the SDD and the CTD, and is available on the IBM mainframe.

INTELSAT SUPPORT

INTELSAT Burst Time Plan Software

The SDD continued to maintain and enhance the INTELSAT burst time plan (BTP) software system in 1987. This system consists of four programs used to develop network BTPs, as well as the individual earth station master time plans (MTPs) and condensed time plans (CTPs) for the INTELSAT TDMA system (Figure 8). In addition to the fast-reaction support provided to INTELSAT under this task, major developments in 1987 included adding the capability to generate variable-gain digital speech interpolation (DSI) sub-bursts and a new orderwire assignment algorithm. The SDD also assisted INTELSAT with specifications for extending the current software system for use with the forthcoming INTELSAT satellite-switched (SS)/TDMA system.

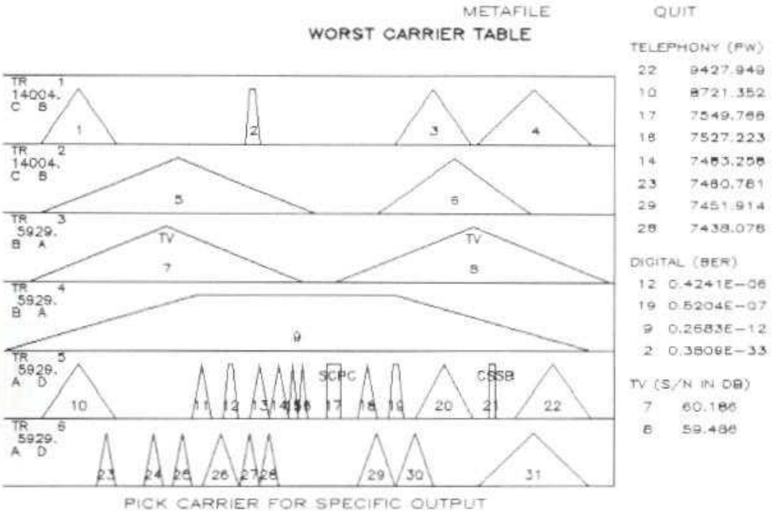


Figure 7. *ISTRIP user interface*

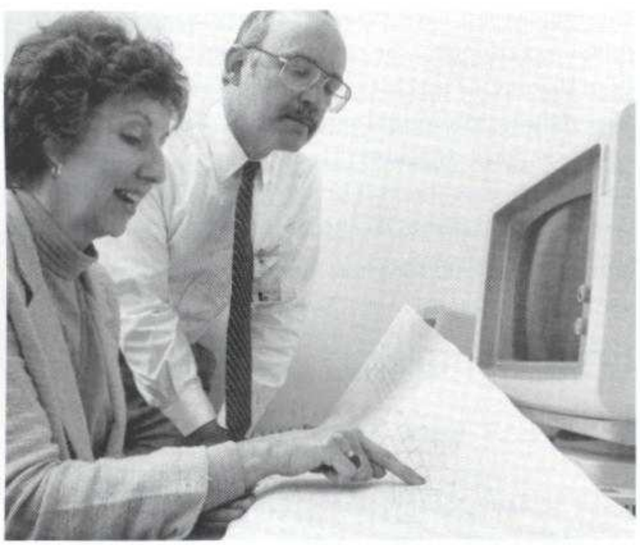


Figure 8. *INTELSAT TDMA burst scheduling analysis*

INTELSAT Bit Error Rate, Error-Free Seconds (BEEFS) Software

The INTELSAT Bit Error Rate, Error-Free Seconds (BEEFS) Program computes the performance of a single link of the INTELSAT TDMA system for both clear-sky and rain-degraded conditions. COMSAT installed the program on the INTELSAT MVS system in 1987, and extended the number of interfering carriers considered in the performance calculations. A report was written proposing an interface of the BEEFS program with the BTP software.

INTELSAT Outage Margin Program

Phase I of a two-phase program was completed in 1987 with the development of a baseline version of the INTELSAT Outage Margin Program (OUTMAT), which computes outage margins in the INTELSAT frequency division multiple-access (FDMA) system caused by rain impairments. The program takes into account multiple carrier types, coding specifications, and transmission modem characteristics, and uses the Rice-Holmberg measured parameters (i.e., annual earth station rainfall and thunderstorm activity measurements) to compute outage times for a specified frequency plan. The CTD and the SDD are jointly developing this software on the INTELSAT mainframe.

COMSAT TECHNOLOGY PRODUCTS VSAT SUPPORT

SDD software engineers provided significant support to COMSAT Technology Products in 1987 in the development of its very small aperture terminal (VSAT). This support continued after the sale of the VSAT to CONTEL-ASC.

In general, SDD VSAT support fell into three categories: maintenance of the original VSAT (VSAT I), augmentation of VSAT I, and design of an enhanced version of the VSAT (VSAT II).

Maintenance of VSAT I

In the original version of the VSAT, network management was performed on a Masscomp minicomputer. This software was converted to a MicroVAX™ in 1987. SDD software engineers also contributed to the conversion of the network management operator interface to the MicroVAX. This software provides the operator with a set of user-friendly screens, arranged in a hierarchical tree, that allow network management functions such as traffic monitoring and load balancing to be performed. In addition, on-line help and print functions are provided.

SDD software engineers also converted the statistics server to the MicroVAX. This process collects statistics from each hub chassis every hour, compensating automatically for special conditions such as remote processor switchover, counter rollover, byte swapping, change of time, and the addition or deletion of remote nodes. It also prints and archives a daily traffic summary report.

Enhancement of VSAT I

The original software for the VSAT hub chassis was not easily adaptable to the requirements of each new customer. SDD software engineers were responsible for a project to remedy this deficiency.

The first task was a massive migration of microprocessor code from the Masscomp to the MicroVAX. The code was rebuilt, tested, and corrected in its new environment. The network management code was changed from procedure driven to table driven, and upgraded to handle multiple outbound links, satellite interfaces, and node groups.

Another task involved the enhancement of COSMAX, the VMS version of COSMOS (a proprietary real-time operating system developed by COMSAT Laboratories). COSMAX was developed by SDD for use in the VSAT.

Design of VSAT II

SDD contributed software to the design of VSAT II, an advanced version of the VSAT I, in two major areas: network management and hardware evaluation. Initial design efforts in network management concentrated on integrating the VSAT II network management facility with one of several commercially available network management products under consideration. Several fault-tolerant hardware systems were evaluated, as were several workstation models.

COMSAT TECHNICAL SERVICES OUSDA TELECONFERENCING SUPPORT

SDD supplied project management and software engineering assistance to COMSAT Technical Services (CTS) on the Office of the Undersecretary of Defense for Acquisition (OUSDA) Teleconferencing Support Project. The contract is administered through the U.S. Air Force Headquarters Contracting Office at Andrews Air Force Base, and involves a total hardware and software solution providing sophisticated video program production and local and remote teleconferencing. The software can generate live and preprogrammed presentations under the control of a Management Control Facility operated in a classified environment, and includes a microprocessor-based subsystem that manages user interaction with 68 pieces of visual, audio, and video hardware. Included are five other computers and the Defense Contractors Telecommunications Network (DCTN). Also included is a VAX-based embedded processor providing users with commercial, off-the-shelf, high-resolution graphics and relational database capabilities. In addition, the VAX provides the VMS operating system and multiple languages for software development.

VOICE OF AMERICA ISU OPERATOR INTERFACE

Located at each remote relay station in the Voice of America (VOA) Satellite Interconnect System network is a 68000-microprocessor-based controller called the interconnect switching unit (ISU), which allows station operation from the central network control point. When necessary, personnel at the relay site may operate the station through the ISU operator interface.

The local operator can perform the following tasks:

- manage the presentation of alarms from the relay station equipment,
- monitor and display equipment status,
- control many of the subsystems, and
- obtain diagnostic information about the subsystems.

The controller is only occasionally used in this way, but when required must provide the operator with diagnostic and curative services. The operator interface, designed and implemented by SDD, incorporates a unique matrix menu selection system that allows the operator to zero in on a problem area with a few keystrokes. Since the detailed local station configuration is built into the software, the operator can control the station by selecting from a list presented by the operator interface. The ISU controller and its operator interface are examples of software designed to precisely match specialized customer requirements.

GEOSTAR CENTRAL DATA PROCESSING SYSTEM

COMSAT provides engineering support to the Geostar Corporation in establishing a nationwide position-determination system for mobile units using satellite communications. Each mobile unit in the Geostar system (typically a truck or a railroad car) will periodically transmit a brief message relayed by two satellites back to a central location (Geostar Central), where each unit's location will be calculated and stored. Subscribers to the system (typically trucking or railroad freight companies) may dial into Geostar Central to request reports of the current and past locations of their mobile units.

The SDD's role in this effort has been to design and implement a distributed processing network architecture and operator interface for the data processing system located at Geostar Central. A distributed processing architecture was selected to ensure high system availability and to facilitate future capacity expansion. This architecture permits an unlimited number of processors (in this case, HP-9000s) to be connected by one or more local area networks (LANs) in any configuration, and allows the network operator considerable freedom in reconfiguring the network to respond to equipment failures or increases in message traffic. The basic elements of the architecture are the Geostar networking software and the Geostar operator interface. Figure 9 shows the primary software components in this system.

Geostar Networking Software

The Geostar networking software is implemented in Pascal and C language for processors using the UNIX operating system. The software performs the following functions:

- provides a common, application-level interface for messages sent between processes, whether in the same or in different nodes,
- handles message routing through a specified itinerary of application processes,
- reroutes messages to backup nodes and processes in the event of equipment failure or congestion on specific nodes or links,
- supports multiple message priorities and the packing of messages into LAN packets to minimize CPU overhead associated with packet processing,

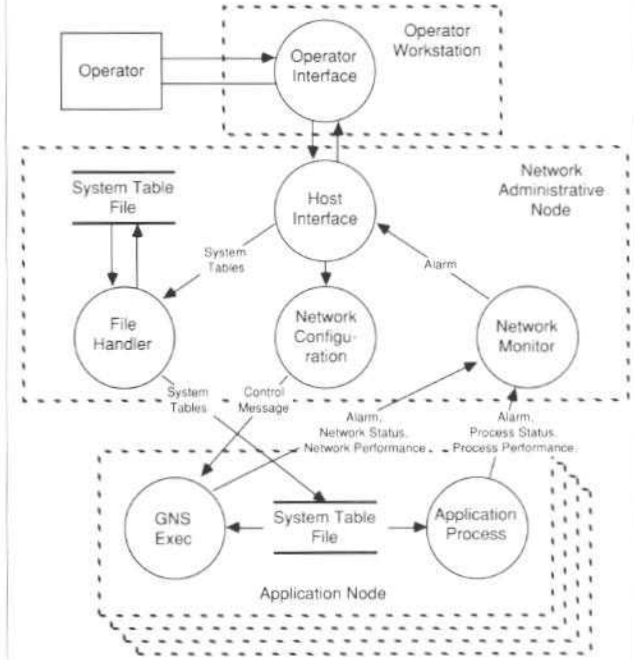


Figure 9. *Geostar Central software*

- supports the rapid reassignment of application processes to network nodes,
- supports the rapid on-line modification of link-level protocol parameters to permit the operator to fine-tune network performance, and
- provides interfaces for centralized monitoring of network status and performance, as well as dynamic updating of network tables to reflect changes in the network configuration or processing functions.

The operation of the network is controlled by the following system tables, which are maintained and updated by the network operator:

- Node Table, defining the network nodes.
- Process Table, defining application processes at each node.
- Link Table, defining the point-to-point links between each node and the associated link-level protocol parameters.
- Itinerary Table, defining the sequence of operations to be performed for each itinerary.
- Operation Table, defining the processes capable of performing each operation.

- Routing Table, defining, for each current and destination node, the next node to which a message should be sent (both primary and secondary paths are defined).
- Configuration Table, defining the network topology for display purposes.

The network is administered through a network administrative node, which performs the following functions:

- distributes control messages to other network nodes in order to reconfigure the network or to request specific status or performance data,
- receives alarms and status or performance data from other network nodes,
- distributes new system tables and controls the switchover procedure that defines the network configuration, and
- provides an interface to one or more operator workstations.

Geostar Operator Interface

The operator workstation consists of a Macintosh SE computer with a large-screen monochromatic display. The workstation software was developed in object-oriented Pascal and provides a full range of "Mac-like" features, including a mouse-controlled cursor, multiple windows, and pull-down menus. The oversized screen permits the operator to open and display a number of windows simultaneously, which is an important feature for network monitoring and control applications.

The basic functions of the operator interface include alarm handling, network status and performance monitoring, and network reconfiguration. The operator invokes alarm handling by opening the alarms window and/or the archived alarms window. All alarms generated by the network are sent to the administrative node, where they are stored on a disk file. Whenever the alarms window is open on a particular workstation, the administrative node routes alarms to that workstation, where they are displayed in the window. Menu selections enable the operator to silence an audible alarm and to acknowledge an alarm and remove it from the screen. The operator may also request that selected sets of archived alarms be retrieved and displayed in the archived alarms window.

Separate windows are provided for displaying network, process, and telephone line status. Network status may be displayed either as a network diagram showing each node and its current state (Figure 10), or as a table containing the same information. Information such as tables of each application process in the network, whether the process is responding to polls from the network administration node, and the current status of each telephone line connected to the subscriber server nodes, may also be displayed. In each case, opening the appropriate window causes the network administration node to begin polling each node or process.

The operator may open the network performance window to examine the performance of all queues at a specified node. These queues include those for each application process and for each outbound link. The information displayed for each (either in tabular or bar-chart form) consists of the current, average, and maximum queue size, as well as the current, average, and maximum throughput over a given time interval, as shown in Figure 11. Menu selections allow the operator to set the beginning of the time interval and adjust the scale of the bar charts. Network performance data displayed in this manner may assist the operator in locating sources of congestion in the network, and in determining the required changes to the network configuration.

The operator controls the network by starting and stopping individual application processes and by starting and stopping the flow of message traffic between processes. The operator may change the configuration of the network by creating a new set of system tables (each such set is known as a "scenario"), invoking a procedure to validate the scenario, downloading the new scenario to each network node, and initiating a switchover from the old scenario to the new.

DIGITAL RANGE PROCESSOR DEVELOPMENT

The COMSAT range processor (Figure 12) is a hybrid analog/digital device used in satellite systems to determine the slant range from an earth station antenna to the satellite. This distance is important for determining the orbit of a spacecraft during transfer orbit, and becomes part of the stationkeeping information once synchronous orbit is achieved. Accurate knowledge of spacecraft orbit is necessary for determining pointing data for earth station antennas, as well as for spacecraft stationkeeping.

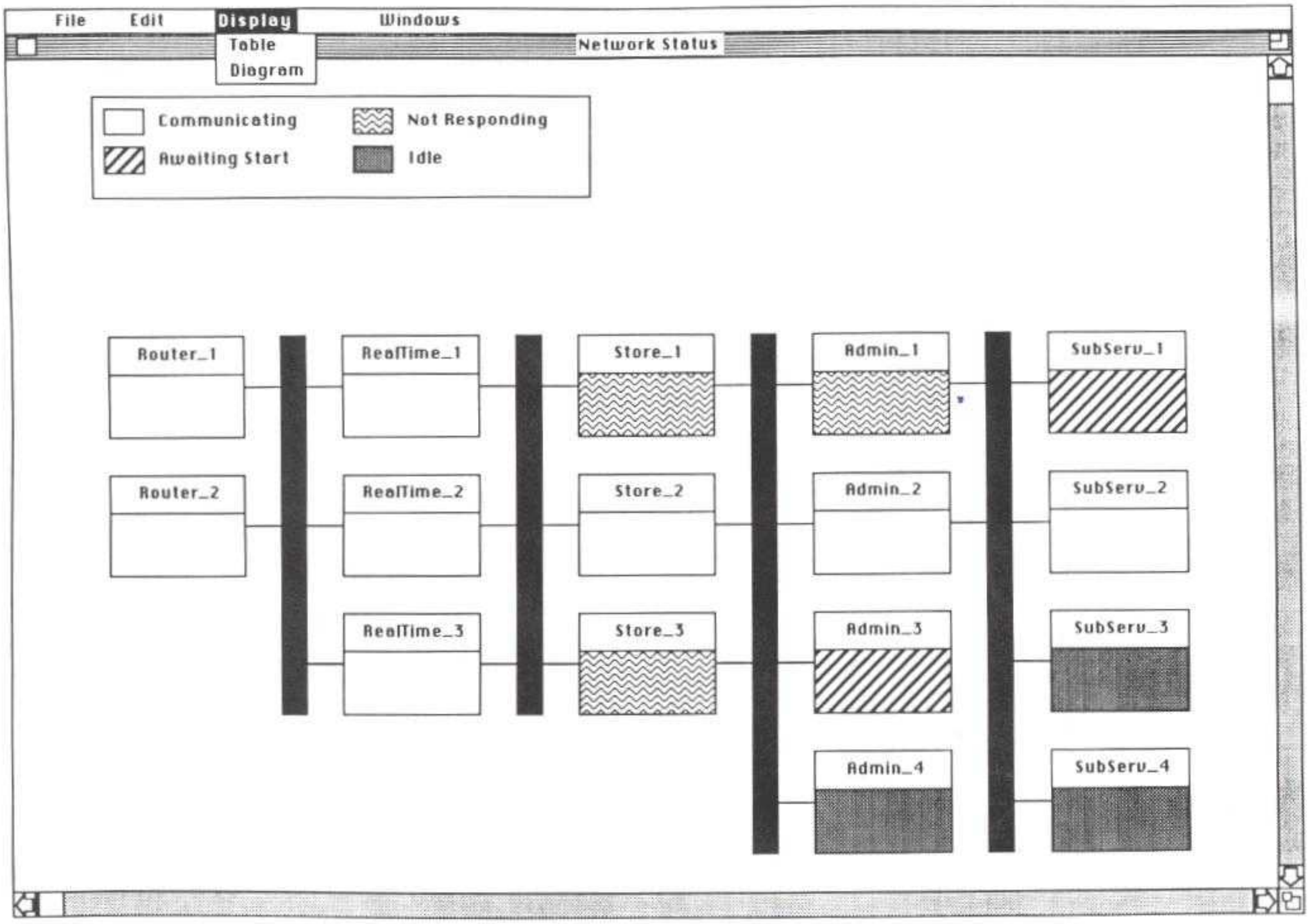


***Figure 10**. Network status displayed as a network diagram showing each node and its current state*

The COMSAT ranging system is a continuous-wave system. An RF carrier is transmitted from an earth station to a spacecraft, and then returned to the earth station through a spacecraft transponder. The RF carrier is modulated by a low-frequency tone. The phase shift between the tone transmitted and the tone received at the earth station is used to determine the distance to the spacecraft. Range measurements take longer with continuous-wave systems than with pulse systems, since measurements must be made with several tones to provide high resolution and to resolve range ambiguities.

The digital range processor currently under development by the SDD improves on this design by modulating the RF carrier with a complex continuous waveform composed of the sum of several sine waves. A series of complex digital processing algorithms then recovers the phase shift information from the received signal for each of the original tones by using a pair of special-purpose, high-speed digital signal processors supplied by Texas Instruments.

This all-digital approach has a number of benefits. Since the processing for all tones is performed simultaneously, it is possible to collect and process more data and still provide the final result in the same overall time period. This allows the operator to program the device for either greater speed or more accuracy than was previously possible. The tones transmitted can be completely programmed in order to avoid incompatibility with any elements of the transmit or receive chains in the earth station or the satellite. Finally, sensitive and expensive analog filters are completely avoided, reducing the production cost of the device and enhancing its ultimate reliability.

X.25 BRIDGE SOFTWARE FOR VSATs

An X.25 bridge process was developed and implemented as part of the SDD's ongoing support of VSAT technology. This bridge connects the X.25 protocol (used for interfacing to a customer's X.25-compatible

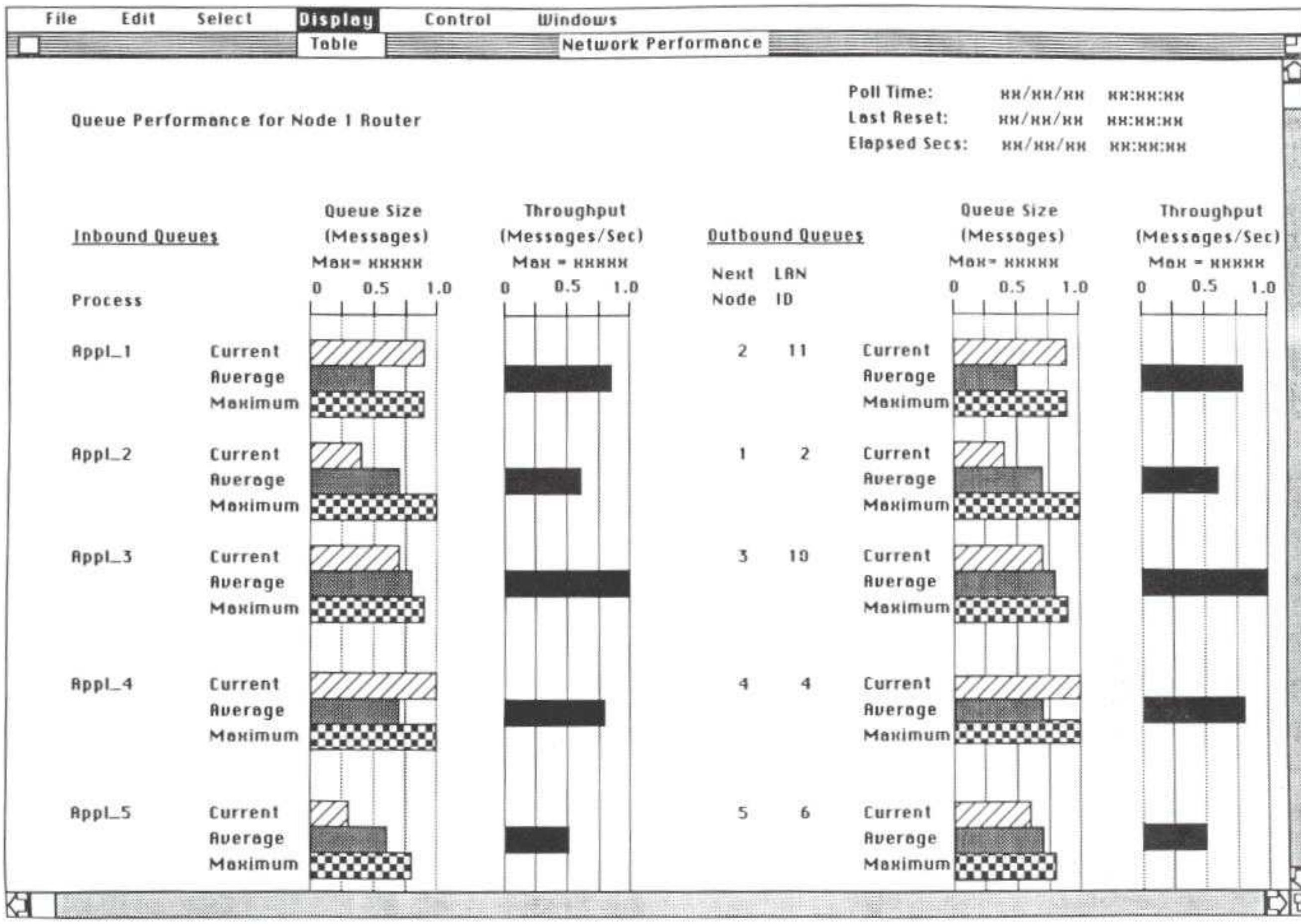


Figure 11. Current, average, and maximum queue size and throughput over a given time interval

data communications equipment) with the generalized network interface (GNIF) protocol used by the VSAT network. A commercially available software package was chosen to provide the VSAT system's X.25 interface. The GNIF protocol was developed to offer maximum performance and flexibility in the satellite segment of the VSAT system. The X.25 bridge provides an efficient facility in which these two packages are interoperable.

The bridge transfers packet-level data between the GNIF and X.25 environments while maintaining all the features of the ISO network level, including flow control and call processing. It consistently converts between the different memory management and scheduling techniques used in the X.25 and GNIF software. In an earlier generation of the VSAT system, four processes were needed to support the features now provided by the bridge alone. The bridge also provides several new features for the enhanced version, such as switched virtual circuits and improved flow control.

Figure 12. Range processor development

In 1984 the National Aeronautics and Space Administration (NASA) undertook a new research and development program: the Advanced Communications Technology Satellite (ACTS). The program goals are the development of basic technologies to ensure the availability of adequate and affordable satellite communications beyond the year 1990, and the continuing availability of U.S. satellite communications resources by effectively utilizing the limited resources of the geostationary orbital arc. ACTS system development continued in 1987. GE Astro Space (formerly RCA Astro-Electronics) is the prime contractor for the program and has responsibility for the spacecraft bus and the on-board multibeam communications package; the on-board baseband processor is being supplied by Motorola. The NASA ground station (NGS) and the master control station (MCS) are the responsibility of COMSAT Laboratories.

THE TECHNOLOGY NEEDS OF TOMORROW

A fundamental goal of the ACTS program is to ensure continued U.S. leadership in vital areas of satellite communications technology. A second goal is to develop communications techniques and equipment that exploit the spectrum-rich, but largely unused, K_a-band. A third is to investigate and verify system techniques for more effective use of all frequency spectrum resources allocated to satellite communications. The ACTS program proposes to meet all these objectives.

The following component technologies comprise the baseline ACTS system:

Spot-Beam Technology. Concentrating radio frequency (RF) energy into spot beams significantly enhances the ability to reuse an allocated frequency band, since RF energy is placed only where it is needed and not spread over an entire continent. Further, the higher levels of concentrated power associated with spot beams permit deployment of lower-cost terminal equipment. The use of fixed and hopping spot beams is an important extension of this technology.

On-board Switching Technology. This approach permits the interconnection of up-link and down-link spotbeams, thereby meeting subscribers' connectivity requirements and matching an established time-division multiple-access (TDMA) timing plan.

On-board Baseband and Remodulation Processing. Because it isolates up-link errors from down-link errors, remodulation is more effective than analog repeaters in isolating up-link errors, and allows mixed-rate up-links and down-links to accommodate networks of both large and small terminals. The resultant intermediate baseband signal can then be processed and bundled by destination in much the same way as with a terrestrial tandem message switch.

Demand-Assigned TDMA Networking and Control. The MCS uses TDMA/demand-assigned algorithms to couple and control ground segment and satellite resources. This approach provides cost-effective matching of the subscribers' transmission and connectivity requirements to the ACTS system performance envelope, as well as the optimal allocation of satellite resources such as power and spectrum to the users.

The ACTS experimental system will verify each of these critical technologies and test their combined effectiveness in a communications satellite system, while providing an in-orbit testbed that permits significant testing by the experimenter community.

THE ACTS SYSTEM

The ACTS system configuration consists of a flight segment and a ground segment (Figure 1). The ACTS spacecraft features two types of spot-beam coverage, fixed and variable, with each beam covering an area approximately 150 miles wide. Sixteen fixed spot-beam regions are available, each focused on a major U.S. city. Variable coverage is performed within two sectors (East and West) for high-speed, selectable pointing (hopping). This spot-beam pointing is programmed from the MCS so that movable transmit and receive beams dwell on a sequence of regions; the length of the dwell is

ACTS

Artist's rendition of the ACTS

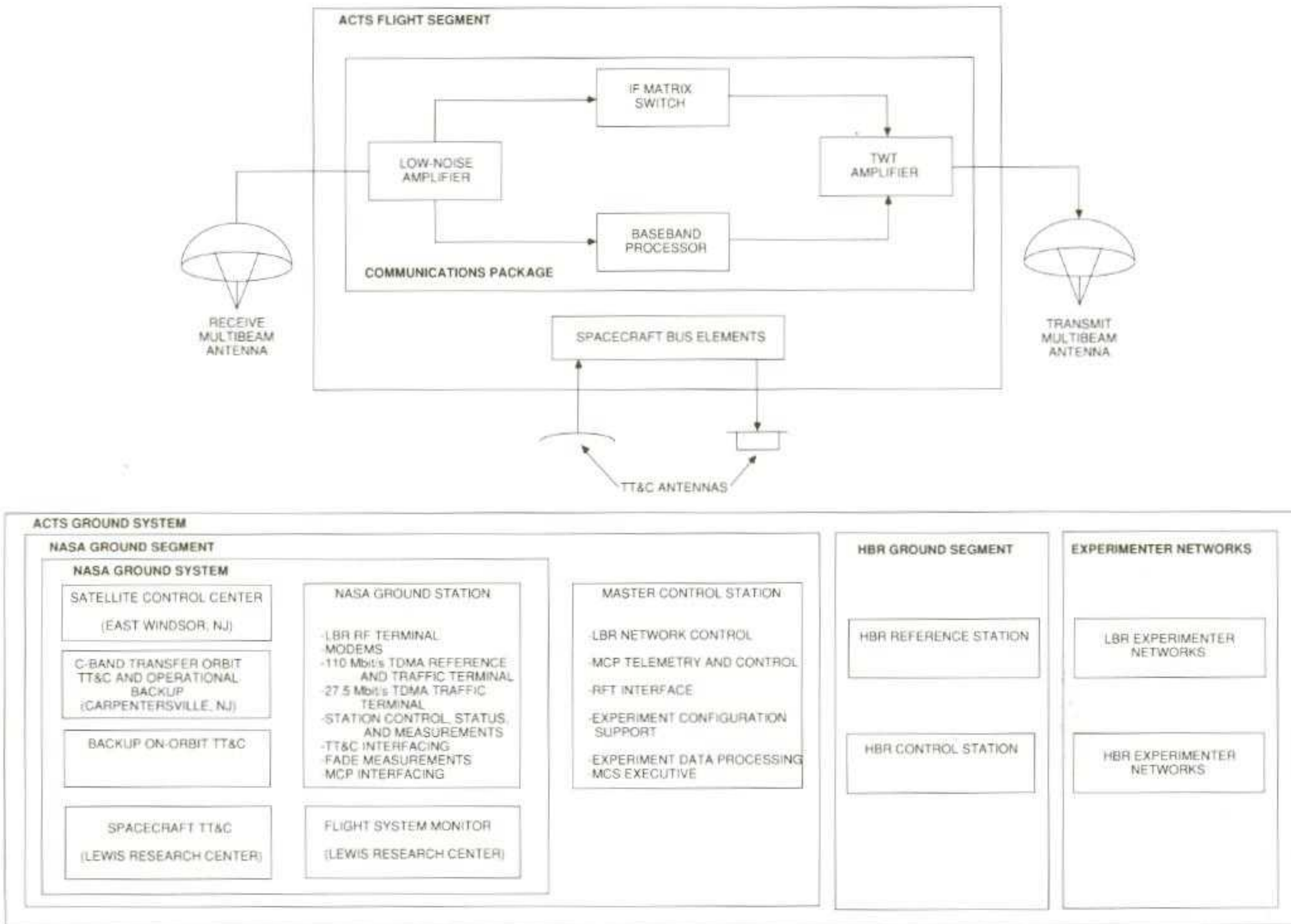


***Figure 1**. The ACTS system configuration*

related to the amount of traffic being passed. A small, steerable antenna has been added to the ACTS to provide Alaska/Hawaii coverage.

The up-link and down-link signals are classified as high burst rate (HBR) or low burst rate (LBR), and are carried in three wideband channels. The HBR signals, planned for 220-Msymbol/s burst rates, are routed through an on-board intermediate frequency (IF) microwave matrix switch which interconnects the up- and down-link spot-beam antennas. The LBR up-link signals, with burst rates of either 27.5 or 110 Msymbol/s, are routed through the baseband processor. After initial demodulation of the TDMA bursts, the signals are time-slot interchanged and remodulated for the down-link at a rate of 110 Msymbol/s. Forward error correction (FEC) and reduced modulation rates are applied adaptively to the transmission to permit operation during rain fades, with the decoding and reencoding performed in the baseband processor.

The ACTS Ground Segment

The ACTS ground segment has the following five distinct elements:

The NASA Ground Station consists of a single RF terminal (RFT), which is primarily responsible for translating LBR communications signals between the K_a-band interface with the ACTS spacecraft and the digital interface of the TDMA terminals, and is driven by two LBR TDMA terminals: the 27.5-Msymbol/s traffic terminal, with its terrestrial traffic interface equipment; and a combined reference terminal and traffic terminal operating at 110 Msymbol/s. The reference terminal is responsible for maintaining TDMA system synchronization and integrity, and serves as the control-message interface for the MCS. The NGS also includes GE-provided telemetry, tracking, and command (TT&C) equipment that interfaces with the RFT subsystem and which will be located at NASA's Lewis Research Center (LeRC) in Cleveland, Ohio.

The Master Control Station controls the LBR network and the on-board multibeam communications package (MCP), serves as the focal point for mission and experiment operations, and provides displays and reports that are required for orderly system operation.

The Telemetry, Tracking, and Command Facilities are related largely to spacecraft support operations such as stationkeeping. The GE facilities in Carpentersville and East Windsor, New Jersey, will perform this function. GE will also provide the TT&C elements to be located at the NGS.

The HBR Ground Segment will function similarly to the LBR NGS and MCS, but will be directed toward communications through the microwave switch matrix in the MCP. NASA is responsible for developing the HBR ground station, which will be located in the vicinity of the NGS.

The LASERCOM Experiment was dropped from the ACTS program in December 1987.

In addition to the ACTS ground segment, an experimenters' network equipped for either or both LBR and HBR operation will be incorporated into the ACTS system.

THE ACTS PROGRAM AT COMSAT LABORATORIES

ACTS Program Management Office

The ACTS Program Management Office (PMO) directs the program within COMSAT Laboratories, and manages the interface with GE and NASA. The PMO includes the technical managers of each of the major elements of the program, as well as cost and schedule control managers and staff.

Technical managers operate with counterparts in the various functional organizations, defining and scheduling the work to be accomplished and the resources required. Upon agreement, these parameters are entered into a computer-based ARTEMIS cost and schedule control system, which produces system and subsystem schedule networks and detailed cost projections for each element of the program. This information is continually monitored and updated, distributed to various COMSAT management levels, and reported on a regular basis to the customer.

During early 1987, a modified work plan for the program was established which encompassed the NASA funding constraints and the corresponding stretch in delivery and launch dates—the latter being November 1990. This revised work plan defined the technical milestones, staffing levels, and target completion dates for the Laboratories' effort on the ACTS program in 1987 and subsequent years.

With each iteration of the plan, the PMO cost- and schedule-control staff has become more adept at producing the considerable data and documentation supporting management needs of both COMSAT and its customers. Monthly status reports produced by the PMO provide an up-to-date, objective assessment of progress from the standpoint of resources expended, schedule status, and value earned (accomplishments).

Because of the governmental fiscal year funding constraints associated with the ACTS program, the PMO has been required to implement a complex management system to carefully monitor and control expenditures to avoid exceeding a specific annual budget limitation. This cost and schedule control system also must satisfy the criteria established by the government. At the end of 1987, NASA conducted a three-day compliance review of the performance measurement system (PMS) employed by COMSAT to manage and control the ACTS program. This system had been under development within the PMO for over two years and was a "customized" version of the Department of Defense (DoD) Cost and Schedule Control System Criteria. The results of the review indicated a high level of NASA satisfaction with the progress COMSAT Laboratories had made, with minimum adjustments required to reach full compliance in early 1988.

During 1987, the work on all of the subsystems moved from the functional description level of the developmental hierarchy to the design level. This included partitioning of functional responsibilities between hardware and firmware, development of schematics, identification and coding of software modules, and building and testing of breadboards and prototypes. Two major technical events were the two-day Subsystem Design Review of the MCS design in July, and the three-day Subsystem Design Review of the TDMA effort in August. The NASA/GE response to both of these preliminary design reviews was laudatory, citing the significant progress made in both technical areas and the exceptionally competent design approaches being pursued.

The percentage of COMSAT Laboratories personnel dedicated to the technical and administrative activities of the ACTS program increased from about 15 to 20 percent in 1987, and is expected to reach 25 percent for the next two years. Hence, ACTS-funded activities encompass almost every technical and support organization within the Laboratories. Through the experience gained on the ACTS program, each of these organizations is developing the new skills and disciplines required for any future major development program.

ACTS PROGRAM TECHNICAL DEVELOPMENT

The technical development associated with NGS and MCS implementation can be divided into five specific management areas: systems engineering, RF terminal development, TDMA terminal development, MCS development, and performance assurance.

Systems Engineering

COMSAT's systems engineering role in the ACTS program is twofold. Primarily, systems engineering is responsible for engineering, analysis, integration, and testing associated with COMSAT's deliverable hardware and software. A second responsibility is the direct engineering and analytical support of GE as prime contractor. Both roles draw heavily on the Laboratories' communications analysis resources. These responsibilities have led to significant engineering and analytical contributions, with the Communications Techniques Division (CTD) being the primary contributor.

During 1987, a transition began in the nature of these systems engineering activities. In previous years, efforts were concentrated primarily on analytical tasks which were necessary for the allocation of performance parameters to subsystem elements, and for the analytical verification of system performance. The development of software channel and network control models were major systems engineering activities. By year's end, those development efforts were completed and the systems engineering focus shifted toward the integration and test phase, which will lead to the verification of system performance. The channel and network control models were placed in service to predict baseline system performance, against which measured performance will be judged.

The development of a comprehensive specification document for the rain fade event detection function was typical. This function imposes requirements on all subsystems of the NGS/MCS, and is critical to the performance of the total ACTS system. Extensive and detailed interaction between COMSAT personnel and customer representatives was needed to refine the requirements in this specification, and several design approach iterations were considered before the final approach was chosen. Embodied within the document are the technical parameters for each element of the function, including the requirements for a detection algorithm developed by the CTD. Figure 2 illustrates a candidate concept of this detection process which would be implemented with unique detection parameters and

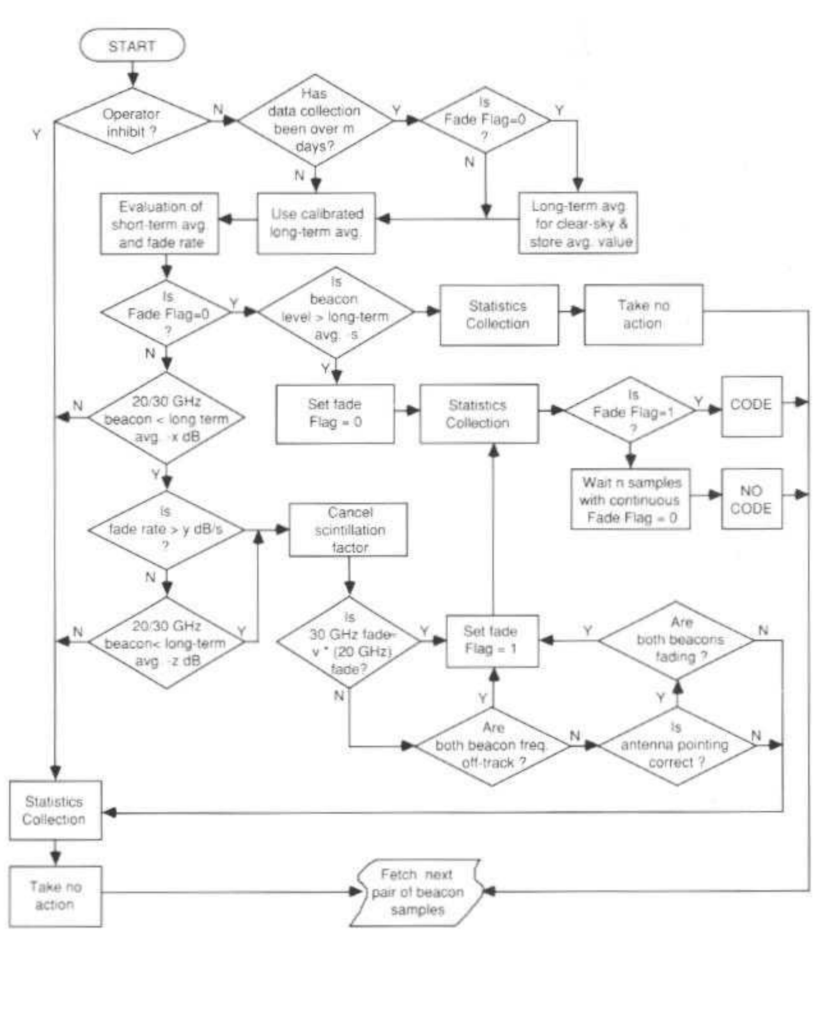


Figure 2. *Rain fade algorithm flowchart*

thresholds for each ACTS experimenter earth station.

Integration and test planning efforts focused on the definition of the specific sequence of events to be accomplished during the test and evaluation phase of the program. Because of the uniqueness of the evaluation of a satellite-switched communications system, COMSAT's test activities are significant to the total ACTS program. Whereas analog regenerative repeater systems permit the loopback of test signals through spacecraft transponders, satellite-switched systems, with their essentially independent up- and down-links, place new demands on communications systems test programs. The isolation of the up-link from the down-link signals, which yields inherent communications signal quality advantages, requires rethinking of classical spacecraft communications test techniques. These difficulties are further compounded by the hopped spot-beam antenna coverages and the digital regenerative repeaters of the ACTS spacecraft.

The initial validation of the COMSAT-supplied NGS/MCS elements will be performed using the engineering model of the ACTS spacecraft communications payload. This model will be delivered to COMSAT Laboratories by GE/NASA and will be a major element of the special test equipment in the COMSAT test program. Testing with the engineering model will provide baseline data for evaluation of the COMSAT equipment with the flight spacecraft, both at COMSAT and at GE, prior to launch. The engineering model will facilitate the precise control of link parameters, which would be more difficult with the completed flight spacecraft. This approach allows COMSAT engineers to refine the many performance parameters associated with the technically complex NGS/MCS within a laboratory environment.

RF Terminal Development

During 1987 substantial progress was made toward completion of the RFT of the NGS. The Microwave Technology Division (MTD) was responsible for the major portion of this task, except in the particular areas of modems and traveling wave tubes (TWTs), where the specialized skills of the Communications Techniques (CTD) and the Applied Technologies Divisions (ATD), respectively, were utilized.

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 also will handle the TT&C function, and will include equipment to measure the signal strength of up to three beacons down-linked from the satellite. These measurements will provide, in 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 1987 was completion of the design of virtually all the analog circuitry in the RFT subsystems, and the fabrication, assembly, and test of breadboard versions of many of these subassemblies. The completed subassemblies include up- and down-converters for both the communications and TT&C signals, redundantly switched LNAs at 20 and 30 GHz, and the transmitter for both the LBR communications and the spacecraft command signals.

The initial assemblies of these subsystems are being used to verify the electrical and mechanical design at this level , and were made to detect design flaws and permit design or rework prior to final manufacture and assembly. Tests to date have been very successful. No significant changes will be required to those assemblies already tested, as they have shown performance meeting or exceeding all subsystem requirements.

Figure 3 is a photograph of the initial assembly of the command up-converter. Two such units, to provide redundancy, will be located in the mezzanine area of Building 55 at LeRC and will convert a command signal at a 70-MHz IF to the 29.975-GHz transmit frequency.

The initial assembly of the LBR up-converter is shown in Figure 4. One unit will be located in the mezzanine area, and will convert the LBR signals from 3-GHz IF to the C6, C7, and C10 transmit frequencies of about 29.3 GHz.

Figure 5 is a photograph of the RF circuitry, which will be located on the main floor of Building 55. This assembly will accept 3-GHz signals from the two LBR modulators, adjust their power levels, and combine them for transmission through the interfacility link cable up to the mezzanine level.

Work has been progressing in other areas of the RFT as well. The LBR multiplexer depicted in Figure 6 must transmit 50 W of LBR transmitter power, which demands low loss. At the same time it must provide stringent filtering to limit the leakage of LBR transmit power and TWT noise into the up-link fade beacon receiver, and provide a very low-loss reflection to the up-link fade beacon signal received from the spacecraft.

Filters are used to control and separate wanted and unwanted RF signals. Figure 7 shows an assortment of the

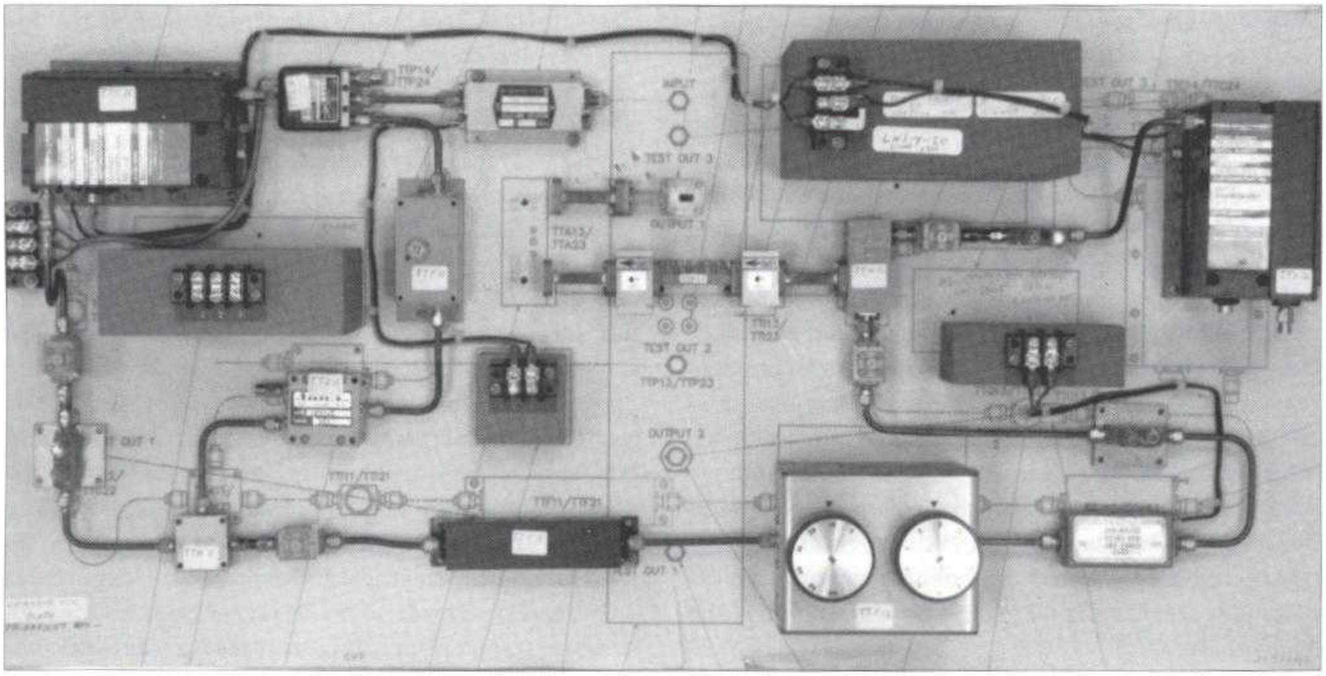


Figure 3. *Initial assembly of the ACTS RFT command up-converter*

20- and 30-GHz filters which will be used in the RFT. In the first row are commercial filters that comply with COMSAT-developed electrical performance specifications. The filters in the next row were electrically and mechanically designed at COMSAT Laboratories. The filters in the third and fourth rows are 20-GHz filters; those in the bottom two rows are 30-GHz filters.

As this work peaks, increasing attention is being given to the next phase of the in-house work: developing the RFT integration and test plan. In this phase the subassemblies already developed will be integrated into the racks that ultimately will be installed at LeRC.

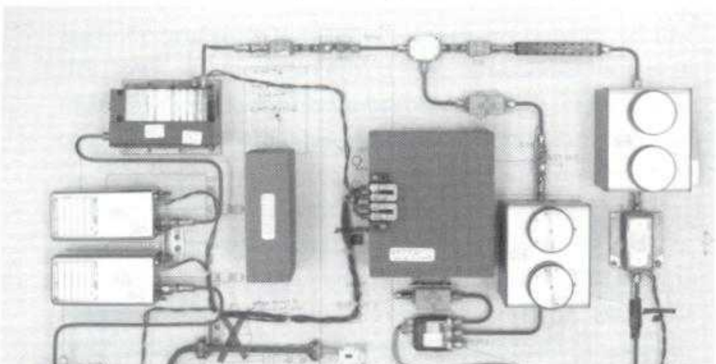


Figure 4. *Initial assembly of the LBR up-converter of the ACTS RFT*

The need to measure rain fade attenuation using signals transmitted from the spacecraft has presented special challenges. Measurements of rain fade attenuation using spacecraft signals generally employ dedicated beacons. In the ACTS system, the requirement is for two of the three rain fade attenuation measurements to be made using modulated spacecraft carriers/beacons. The modulation may be that associated with digital telemetry, analog telemetry, or ranging tones. The need to extract fade data from these modulated carriers over a wide dynamic range has required the development of innovative circuits and techniques.

Efforts have been made in designing and implementing loopback circuits. The loopback subsystem will permit the operation and checkout of all elements of the RFT (and NGS) without the need for a spacecraft. This capability will be used during installation and checkout of the station, as well as for diagnostic purposes during operation.

The RFT will perform many of its functions, and be monitored, under computer control. The functions will be controlled by the RFT supervisor, an HP 9000/350C computer. Other elements of the digital circuitry will be located in the rain fade measurement equipment, the antenna control unit, and the experiment measurement equipment. The supervisor hardware and peripherals

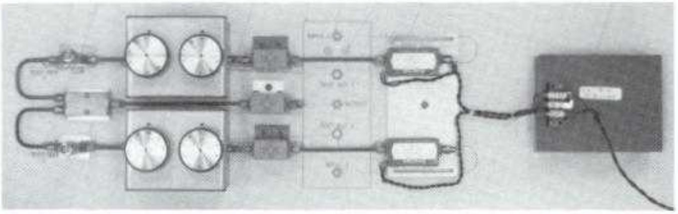


Figure 5. Initial assembly of the IFL cable device

have been procured, and the software is currently under development.

Other digital control capability is required for the dedicated processing of the three channels of data from the analog rain fade attenuation measurements, and for the transmission of the resulting data to the MCS in real time. The design of this hardware and software is in progress.

In parallel with the hardware development at COMSAT Laboratories, the microwave transmitters and high-speed digital modems are being developed under subcontract to COMSAT. Two such subcontracts have been negotiated and placed, and are now being monitored by COMSAT. The transmitters for the LBR signals will produce about 50 W of power at 30 GHz, and are scheduled for delivery from Hughes Aircraft in early 1988. The modem subcontract with Motorola will produce 27.5- and 110-Mbit/s serial minimum-shift keying modulators and demodulators for the LBR communications signals.

The placement of further subcontracts for the command transmitters and for the 5-m station antenna was planned in 1987. The command transmitters form

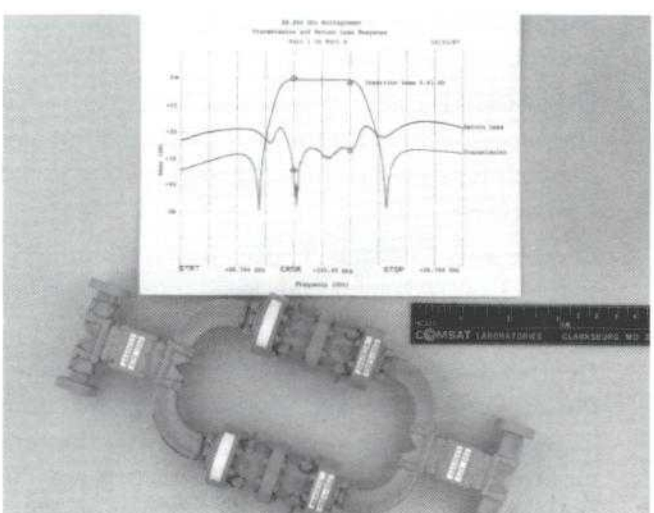


Figure 6. The LBR multiplexer

part of the TT&C facility, which will monitor and control those parts of the spacecraft not directly involved in the communications function.

TDMA Terminal Development

COMSAT Laboratories is developing two TDMA terminals that will be integrated into the ACTS NGS: a 110-Msymbol/s TDMA terminal serving as both the LBR reference terminal and as a traffic terminal; and a 27.5-Msymbol/s TDMA terminal serving as a stand-alone traffic terminal. The reference terminal acquires and synchronizes to the baseband process (BBP)-generated TDMA frame to transfer the MCS control and status orderwire channels to the BBP and to the LBR terminals. The reference terminal preprocesses these orderwire channels, which have a combined maximum rate of 1.476 Mbit/s. The reference terminal also continuously compares BBP on-board clock drift to a local frequency standard, and periodically reports deviations to the MCS. The MCS then up-links 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-Msymbol/s terminal provides service for eight T1 interfaces (1.544 Mbit/s) and six interfaces operating at 6.312 Mbit/s. The 27.5-Msymbol/s terminal provides service for four T1 interfaces and two 6.312-Mbit/s interfaces. Together the terminals can interface 1,072 64-kbit/s equivalent voice channels to the LBR network. Call processing functions within the terminals provide for both single-channel dynamic routing using dial digits and multichannel trunk routing in either point-to-point or broadcast connections.

The Network Technology Division (NTD) has primary responsibility for TDMA terminal development, ranging from architectural concept through design and production and into subsystem acceptance testing. The NTD will also provide support during system integration and acceptance testing. Support for the development of the error control encoder/decoder comes from the CTD.

The NTD has developed 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 lowest level functional elements in terms of hardware/software partitioning and tradeoffs to map

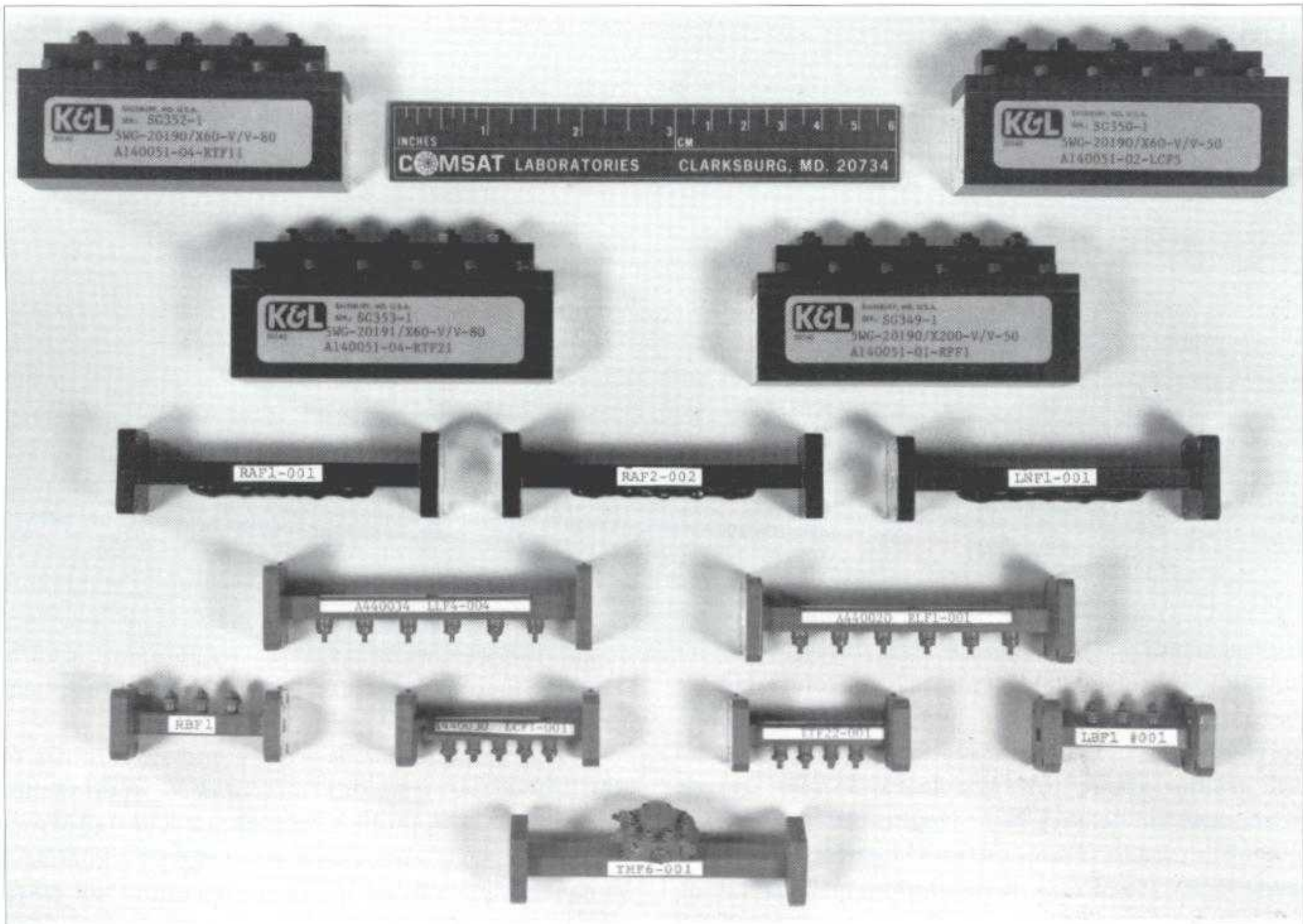


Figure 7. Filters for 20- and 30-GHz operations in the ACTS RFT

functional requirements into the physical implementation. The lowest levels include detailed electrical design of hardware using computer-aided engineering (CAE) workstations (as shown in Figure 8), logical design and coding of embedded microprocessor software, and overall integration and test of the terminals. This meticulous, top-down approach ensures that the design implementation fulfills all program requirements.

Figure 9 is a functional block diagram of the 110-Msymbol/s terminal design. The 27.5-Msymbol/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 requirements for each are given below.

TIE

- **T1 and 6.312 Interfaces** Provide terrestrial line interface, plesiochronous buffering of channel data, and T1 supervisory signaling processing.
- **Transmit and Receive Bus Controllers** Provide digital switching of channel data to/from the burst controller or the signaling extraction/signaling generation (SXU/SGU) hardware under call processor control.
- **SXU/SGU** Provides dual-tone multifrequency dial digit 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 Call Processor** Procesess supervisory and address signaling to/from experimenter channels, sends and receives orderwires 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.

Figure 8. CAE workstation in operation

TDMA Burst Controller

- **Receive and Transmit MCS Interfaces** Provide high-speed transfer and preprocessing of orderwire channels to/from the MCS, as well as the BBP and traffic terminal network.
- **Receive and Transmit Traffic Interfaces** Buffer channel data to/from the TIE and route channels into MCS-assigned satellite slots.
- **DAMA (Receive and Transmit Frame Management).** Dynamically alters TDMA frame structure and traffic slot assignments in response to MCS orderwire commands, and performs synchronous burst time plan changes.
- **Receive and Transmit Timing and Control** Acquires and maintains synchronization to the BBP TDMA frame.
- **Receive and Transmit Space Segment Interfaces** Multiplex/demultiplex channel data to/from the

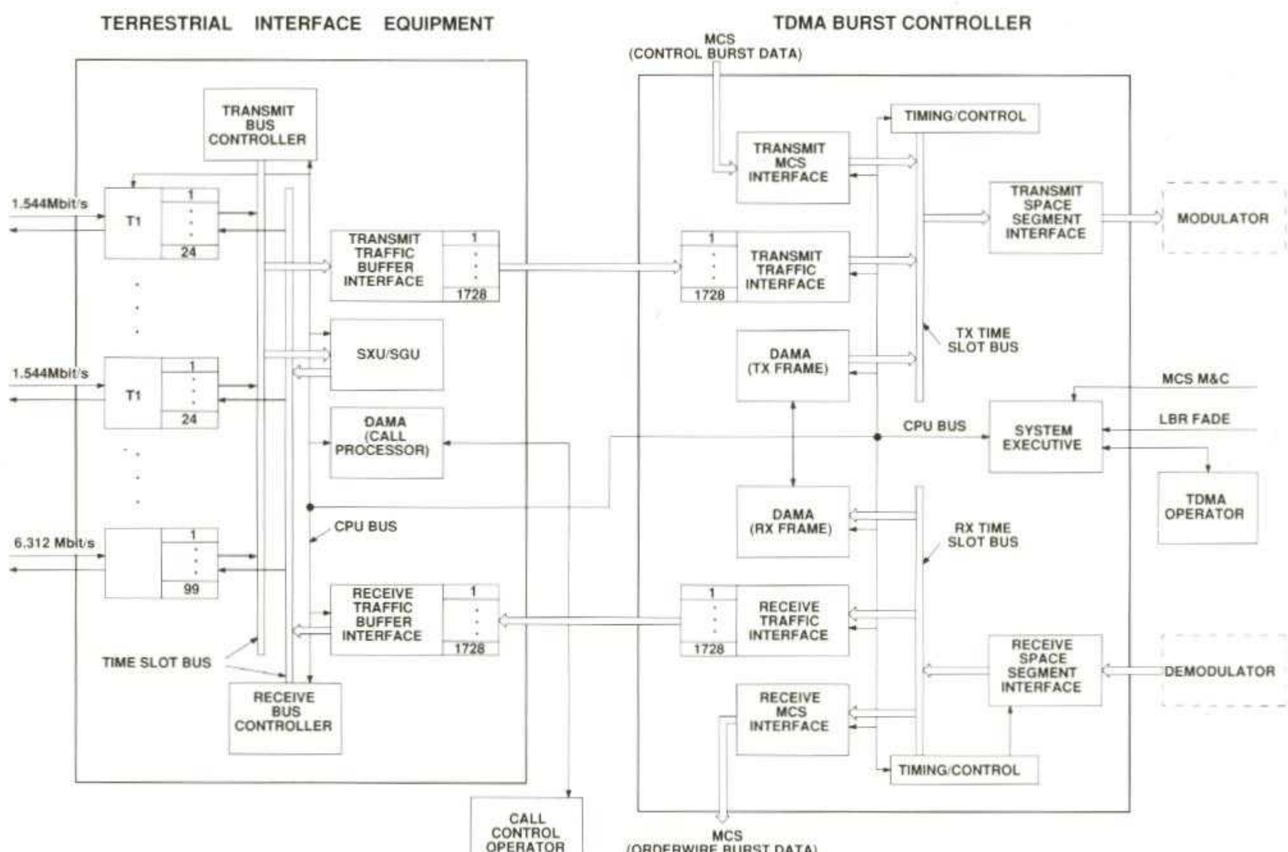


Figure 9. NGS TDMA terminal functional block diagram

TDMA bursts at either the 110- or 27.5-Msymbol/s serial rates, and provide FEC encoding/decoding at R = 1/2 and k = 5.

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

The terminal design presented in Figure 9 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 (PAL) hardware and microprocessor software ensure a design which can be easily adapted to the needs of NASA's experimental program, as well as to the operational requirements of future commercial terminals in the ACTS system.

Overall, the TDMA terminal design requires approximately 40 unique hardware module designs and 100 software processes and interrupt-service-routine designs. During 1987, system functional analysis and partitioning tasks were completed, and work was begun on the detailed hardware and software designs. In August 1987, at a Subsystem Preliminary Design Review held for NASA and GE Astro Space, an extensive presentation was made detailing the design methodology, the results of system functional analyses and terminal partitioning tasks, and overall progress to date. The review was highly successful in demonstrating compliance with all of the ACTS program requirements. NASA and GE Astro Space both expressed a high degree of satisfaction with the development approach and full confidence in the future success of COMSAT TDMA development.

MCS Development

Figure 10 is a functional block diagram of the MCS, which is responsible for the real-time control and monitoring of the ACTS LBR communications networks, as well as associated control of the ACTS payload, including the BBP. It also supports ACTS experiments by controlling system configuration parameters and managing record data.

The MCS is implemented entirely in software, hosted on a VAX 8600 super-minicomputer (Figure 11), and consists of the following eight software subsystems:

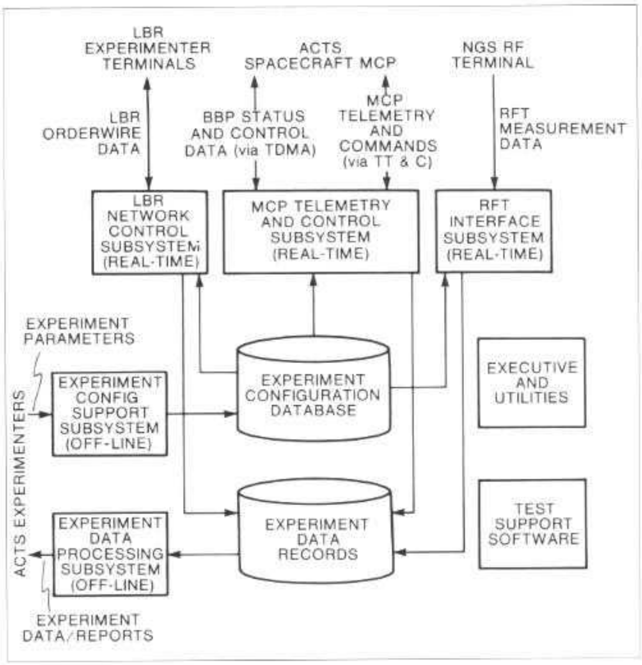


Figure 10. *MCS functional block diagram*

- **LBR Network Control.** Provides real-time monitoring and control of ACTS LBR networks, call-by-call DAMA functions, adaptive fade compensation, control of terminal acquisition, and recording of network performance data.
- **MCP Telemetry and Control.** Provides real-time monitoring and control of the ACTS MCP (including the BBP, the scanning beam antenna, and the MCP master oscillator), and operates in conjunction with the LBR network control subsystem.
- **RFT Interface.** Records RF measurements made by the NGS RFT.
- **Experiment Configuration Support.** Provides off-line functions to configure the MCS and MCP for specific experiments.
- **Experiment Data Processing.** Provides off-line management data recorded by the MCS during ACTS experiments.
- **Executive and Utilities.** Controls the startup and shutdown of the MCS and provides a library of reusable utility routines.
- **Test Support Hardware.** Provides nonoperational test software consisting of simulators used in testing the LBR, MCP, and RFT subsystems.

The DAMA functions performed by the MCS employ several algorithms, depending on the type of connection required (single/multichannel, single/multidestination, etc.). The development of these algorithms required careful consideration of conflicting objectives and constraints, including response time, frame utilization, BBP operational constraints, recovery from errors in control messages, experimental flexibility, and implementation cost.

Figure 11. The MCS VAX 8600 development installation

In particular, the requirement to provide call setup times on the order of 3 to 5 seconds, and the complexities of programming the BBP, offered significant technical challenges to the ACTS MCS and TDMA teams. Several simulation programs were developed to test and refine alternative approaches to the DAMA problem. The resulting system design and algorithms developed by COMSAT will fully demonstrate the flexibility and efficiency available in a TDMA network with an on-board baseband switch. A first release of the MCS DAMA software was completed and tested by the end of 1987. This release provided the DAMA functions associated with initialization and acquisition of the reference terminal equipment and TDMA traffic terminals. Work has begun on development of the DAMA software that will provide on-demand call connect/disconnect services.

Associated with the LBR network DAMA functions are the control and programming of the BBP. The BBP is essentially a TDMA terminal in the sky, under the complete control of the MCS. The MCS generates the BBP microcode-level instructions and transmits them to the BBP via a 576-kbit/s LBR command channel provided by the TDMA reference terminal. Since the BBP must be reprogrammed approximately every 3 seconds, a feed-forward protocol is used on the command channel to eliminate the need for a time-consuming command acknowledgment. This protocol was designed to ensure that the BBP is reliably programmed, even in the event of bit errors in the command channel. By the end

Figure 12. Operator displays of the MCS LBR burst time plan information

of 1987, all of the software associated with the programming of the BBP was coded, and the extensive testing process was initiated.

The operator interfaces to the MCS consist of textual and graphic displays implemented on color graphic CRT terminals. Since all control and monitoring functions are associated with the operator interface, these programs are among the largest and most complex in the MCS. Figure 12 depicts an LBR burst time plan display, showing the location of the scanning beam dwell periods and traffic bursts within each LBR TDMA frame. By the end of 1987, the LBR subsystem operator interface software was completed and the MCP subsystem operator interface software was approximately 70-percent complete.

For the total MCS project, approximately 92,000 lines of code (LOC) of an anticipated 130,000 LOC for the entire system had been produced by year's end. Twenty-seven of 50 programs were completed, and the first four subsystem builds were successfully integrated. These four builds include the LBR subsystem software which controls the startup of an LBR network. As currently defined, the MCS will be constructed by integrating 22 builds, each of which is composed of two or more programs. This incremental development/integration approach provides for early testing and demonstration of key features of the system, and permits maximum use of parallel development activities, which in turn shortens the total project schedule.

Work on the MCS project has been performed by COMSAT Laboratories' Systems Development Division (SDD). The SDD has brought to bear its well-established methodology, including software design, coding, testing, and documentation standards; an effective configuration management/software performance assurance system; and an ever-expanding set of sophisticated software development tools and reusable utility software. The effectiveness of this methodology is evidenced by the fact that measured productivity for the MCS project is approximately 38 percent higher than industry norms.

Performance Assurance

During 1987, the COMSAT Performance Assurance (PA) team focused on operational validation of the PA program as it applies to ACTS hardware, software, and firmware. The team's activities included parts procurement, design review, inspection, drawing control, and product safety.

The control techniques were exercised from the receipt of procured equipment and components at the Laboratories, through to stock, and are operating well. The inspection and quality assurance methods used on the procured products also are performing well, identifying the specific items and allowing for cost-and schedule-effective dispositioning. The ACTS-controlled stockrooms have begun to accumulate products, and the controls in place are producing positive results. There has been some fabrication inspection activity, and the process is resulting in assemblies compliant with contracted requirements and high quality standards.

Meetings of the key PA program control groups (the Configuration Control Board, the Software Review Board, and the Material Review Board) have been held with good results. Formal PA reviews have been held for both in-house manufacturing and out-of-house parts/system procurements. These reviews will continue through the entire build cycle and through system-level integration and test of the ground system. Hazard and safety analysis procedures have been implemented and are in use to support parts procurement and assembly build and test.

The change management procedures for both in-house and out-of-house activities have been implemented and have established the standard level of control necessary for this type of comprehensive program. Drawings and hardware and software configuration control have now been merged into one operational control system.

Software PA personnel have implemented the configuration control database for all related MCS software, and are now receiving RFT and TDMA inputs for appropriate application. At year's end, the CMS library contained 3,700 of a projected 5,000 ACSII source and test files related to the LBR, test support, and the MCP subsystems. The module management system database stores the executables and binary files associated with the above subsystems.

In the areas of manufacturing and fabrication, the PA team continues to control and monitor the preparation of subassemblies, assemblies, and subsystem hardware (both in- and out-of-house). The procedures developed to manage ACTS hardware and software deliverables have been implemented. The management procedures implemented encompass the entire hardware build cycle from design, procurement of parts and components, inventory control, kit assembly, and fabrication, through final test and checkout.

The guideline documents and methods developed earlier for program safety and maintainability have been implemented, requiring some training for key personnel.

PUBLICATIONS

The following is a list of 1987 publications by authors at COMSAT Laboratories. Copies may be obtained by contacting the authors at COMSAT Corporation, 22300 Comsat Drive, Clarksburg, MD 20871-9475.

ASSAL, F. T., and Zaghloul, A. I., "Efficient Combined Global/Spot Beam Configurations for Satellite Communications," IEEE International Symposium on Antennas and Propagation, Blacksburg, VA, June 1987, *Digest*, pp. 564-567.

ATIA, A. E., "RF and Microwave Filters Technology: Past, Present and Future," RF Expo East '87, Boston, MA, November 1987, *Proc.*, pp. 364-365.

BONETTI, R. R., "Potential Impact of High TC Superconductors in Satellite Communications Components," RF Expo East '87, Boston, MA, November 1987, *Proc.*, p. 362.

BONETTI, R. R., and Williams, A. E., "Quadruple-Mode Filters," IEEE MTT-S International Microwave Symposium, Las Vegas, NV, June 1987, *Digest*, pp. 145-148.

BONETTI, R. R., and Williams, A. E., "A Review of Dielectric Resonator Filter Design," International Microwave Symposium, Rio de Janeiro, Brazil, July 1987, *Digest*, pp. 673-680.

BONETTI, R. R., and Williams, A. E., "Advances in Dielectric Resonator Filter Design," RF Expo East '87, Boston, MA, November 1987, *Proc.*, pp. 231-237.

BONETTI, R. R., and Williams, A. E., "Application of Dual TM Modes to Triple- and Quadruple-Mode Filters," *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-35, No. 12, December 1987, pp. 1143-1149.

BUTLER, D.,* Chauchard, E. A.,* Webb, K. J.,* Zaki, K. A.,* Lee, C. H.,* Polak-Dingles, P.,* Hung, H-L. A., and Huang, H. C., "A New Optoelectronic Continuous Wave Millimeter-Wave Source," 12th International Conference on Infrared and Millimeter Waves, Orlando, FL, December 1987, *Digest*, pp. 140-141.

CAMPANELLA, S. J., "Satellite Communications," *Space*, Vol. 3, No. 4, September—October 1987, pp. 40-47.

CLARK, C. J.,* Chauchard, E. A.,* Webb, K. J.,* Zaki, K. A.,* Lee, C. H.,* Polak-Dingles, P.,* Hung, H-L. A., and Huang, H. C., "Optoelectronics CW Microwave Source," Topical Meeting on Picosecond Electronics and Optoelectronics, Lake Tahoe, NV, January 1987, *Digest*, pp. 269-271.

CLARK, C. J.,* Chauchard, E. A.,* Webb, K. J.,* Zaki, K. A.,* Lee, C. H.,* Polak-Dingles, P.,* Hung, H-L. A., and Huang, H. C., "Monolithic Microwave and Millimeter Wave Phased Array Application of a New Optoelectronics Source," IEEE 6th Annual Benjamin Franklin Symposium on Advances in Antenna and Microwave Technology, Cherry Hills, NJ, March 1987, *Digest*, pp. 74-76.

CLARK, C. J.,* Chauchard, E. A.,* Webb, K. J.,* Zaki, K. A.,* Lee, C. H.,* Polak-Dingles, P.,* Hung, H-L. A., and Huang, H. C., "Studies of a New Optoelectronic Microwave Source," *Lightwave Technology*, Vol LT-5, No. 3, November 1987, pp. 388-397.

DIMOLITSAS, S., and Bhaskar, U., "Hurwitz Stability Analysis of an ADPCM System," *COMSAT Technical Review*, Vol. 17, No. 1, Spring 1987, pp. 105-125 [CTR87/317].

DIMOLITSAS, S., Corcoran, F. L., Onufry, M., and Suyderhoud, H. G., "Evaluation of ADPCM Coders for Digital Circuit Multiplication Equipment," *COMSAT Technical Review*, Vol. 17, No. 2, Fall 1987, pp. 323-345 [CTR87/324].

DIMOLITSAS, S., and Gunn, J. E.,* "A Length Adaptive Transversal Data Echo Canceller," *Signal Processing*, Vol. 12, No. 3, April 1987, pp. 321-324.

EGRI, R. G., Karimullah, K., and Assal, F. T., "A 120-Mbit/s TDMA QPSK Modem for On-Board Applications," *COMSAT Technical Review*, Vol. 17, No. 1, Spring 1987, pp. 23-54 [CTR87/314].

EKELMAN, E. P., "Antenna Diagnosis Using Microwave Holographic Techniques on a Far-Field Range," Meeting of the Antenna Measurement Techniques Association, Seattle, WA, September—October 1987, *Proc.*, pp. 180-186.

FANG, R. J. F., Bhaskar, U., Hemmati, F., Mackenthun, K. M., and Shenoy, A., "Design of an MSAT-X Mobile Transceiver and Related Base and Gateway Stations," *COMSAT Technical Review*, Vol. 17, No. 2, Fall 1987, pp. 421-466 [CTR87/328].

GELLER, B., and Goettle, P., "Miniaturized High-Efficiency Push-Pull and Single-Ended Power Amplifiers for Active Aperture Systems," Government Microcircuits Applications Conference (GOMAC), October 1987, Orlando, FL, *Digest*, pp. 425-426.

GUPTA, R., Anderson, S., and Getsinger, W.,* "Impedance Transforming 3-dB 90° Hybrids," IEEE MTT-S International Microwave Symposium, Las Vegas, NV, June 1987, *Digest*, pp. 203-206.

GUPTA, R., Anderson, S., and Getsinger, W.,* "Impedance Transforming 3-dB 90° Hybrids," *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-35, No. 12, December 1987, pp. 1303-1307.

GUPTA, R., Fu, M., Baker, W., and Edwards, R., "A Broadband MMIC Dual-Gate FET Switch Module With On-Chip TTL Control Interface," 17th European Microwave Conference, Rome, Italy, September 1987, *Proc.*, pp. 243-248.

GUPTA, R., Holdeman, L., Potukuchi, J., Geller, B., and Assal, F., "A 0.05- to 14-GHz MMIC 5-bit Digital Attenuator," IEEE GaAs IC Symposium, Portland, OR, October 1987, *Digest*, pp. 231-234.

GUPTA, R. K., Reynolds, J. H., Fu, M. C., and Heikkila, T., "Design and Modeling of a GaAs Monolithic 2- to 6-GHz Feedback Amplifier," *COMSAT Technical Review*, Vol. 17, No. 1, Spring 1987, pp. 1-22 [CTR87/313].

GUPTA, R., Smith, T., and Reynolds, J., "GaAs MMICs: CAD, Modeling, and Process Monitoring," *Microwave Journal*, Vol. 30, No. 8, August 1987, pp. 95-111.

HEMMATI, F., "Decoding the Eight-State Partial Unit-Memory Code," *COMSAT Technical Review*, Vol. 17, No. 2, Fall 1987, pp. 311-322 [CTR87/323].

* **Non-COMSAT author**

HUNG, H-L. A., Ezzeddine, A., Holdeman, L. B., Phelleps, F. R., Allison, J. F., Cornfeld, A. B., Smith, T., and Huang, H. C., "K_a-Band Monolithic GaAs Power FET Amplifiers," IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium, Las Vegas, NV, June 1987, *Digest*, pp. 97-100.

HUNG, H-L. A., Ezzeddine, A., McNally, P. J., and Huang, H. C., "A GaAs MMIC Broadband Distributed Amplifier," IEEE 6th Annual Benjamin Franklin Symposium on Advances in Antenna and Microwave Technology, Cherry Hills, NJ, March 1987, *Digest*, pp. 54-57.

HUNG, H-L. A., Ezzeddine, A., Phelleps, F. R., Bass, J. F., and Huang, H. C., "GaAs MMIC Power FET Amplifiers at K-Band," 17th European Microwave Conference, Rome, Italy, September 1987, *Proc.*, pp. 255-260.

HUNG, H-L., Phelleps, F., Bass, J., Cornfeld, A., Ezzeddine, A., and Huang, H., "A 2-W Multistage K-Band GaAs Monolithic FET Amplifier," IEEE GaAs IC Symposium, Portland, OR, October 1987, *Digest*, pp. 239-242.

HUNG, H-L. A., Smith, T., Huang, H. C., Polak-Dingles, P.,* Webb, K. J.,* Lee, C. H.,* "Optical Electronic Characterization of Monolithic Millimeter-Wave Integrated Circuits," 12th International Conference on Infrared and Millimeter Waves, Orlando, FL, December 1987, *Digest*, pp. 87-88.

HYDE, G., Guest Associate Editor, *IEEE Journal on Selected Areas in Communications*, Special Issue on "Satellite Communications Towards the Year 2000," Vol. SAC-5, No. 4, May 1987.

JACH, T.,* Hembree, G.,* and Holdeman, L. B., "Observation of Whisker Growth on Gold Thin Films Using Reflection Electron Microscopy," (Abstract), *Bulletin of the American Physical Society*, Vol. 32, No. 3, 1987, p. 770.

KAO, Y. S., and Lee, L-N., "Time-Multiplexed Analog Transmission of Three Broadcast-Quality Television Channels Through One Satellite Transponder," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No. 4, May 1987, pp. 676-684.

KAPPES, J. M., "An Adaptive Equalizer for 120-Mbit/s QPSK Transmission," *COMSAT Technical Review*, Vol. 17, No. 1, Spring 1987, pp. 55-86 [CTR87/315].

LYONS, J. W. III, and Ozkul, A., "In-Orbit Performance of INTELSAT IV-A Spacecraft Solar Arrays," *COMSAT Technical Review*, Vol. 17, No. 2, Fall 1987, pp. 403-419 [CTR87/327].

MACKENTHUN, K. M., "Modulation Selection for the Mobile Satellite Experiment (MSAT-X)," *COMSAT Technical Review*, Vol. 17, No. 2, Spring 1987, pp. 87-103 [CTR87/316].

MAHLE, C., Hyde, G., and Inukai, T., "Satellite Scenarios and Technology for the 1990s," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No. 4, May 1987, pp. 556-570.

MAIN, E. L., "Learning to Fly a Satellite," *Space*, July—August 1987, Vol. 3, No. 3, pp. 25-27.

MASS, J., "A Simulation Study of Rain Attenuation and Diversity Effects on Satellite Links," *COMSAT Technical Review*, Vol. 17, No. 1, Spring 1987, pp. 159-188 [CTR87/319].

MEULENBERG, A., Dozier, C. M.,* Anderson, W. T.,* Mittleman, S. D.,* Zugoch, M. H.,* and Caefer, C. E.,* "Dosimetry and Total Dose Radiation Testing of GaAs Devices," *IEEE Transactions on Nuclear Science*, Vol. NS-34, No. 6, December 1987, pp. 1745-1750.

MEULENBERG, A., and Hung, H-L. A., "Degradation Mechanisms in Irradiated GaAs MMICs," GaAs Reliability Workshop, Portland, OR, October 1987, *Program and Abstracts*, pp. 25-26.

MOTT, R., "A GaAs Monolithic 6-GHz Low-Noise Amplifier for Satellite Receivers," IEEE MTT-S International Microwave Symposium, Las Vegas, NV, June 1987, *Digest*, pp. 561-564.

PALMER, L., "Space Communications: Systems and Technology," Symposium on NASA Space Communications Research, Development, and Applications, *Proc.*, pp. 78-97, Space Applications Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, DC 20418.

PAUL, D. K., "High-Power Semiconductor Diode Lasers: Reliability Data and Lifetest Methodology," Fiber/Lase '87—Conference on Fiber Optics Reliability: Benign and Adverse Environments, San Diego, CA, August 1987, *Proc. SPIE*, Vol. 842, D. K. Paul, ed., pp. 86-94.

POKLEMBA, J. J., "Pole-Zero Approximations for the Raised Cosine Filter Family," *COMSAT Technical Review*, Vol. 17, No. 1, Spring 1987, pp. 127-157 [CTR87/318].

POKLEMBA, J. J., "An All-Pole Approximation for the Reciprocal sin $(x)/(x)$ Frequency Response," *COMSAT Technical Review*, Vol. 17, No. 2, Fall 1987, pp. 467-479 [CTR87/329].

POTUKUCHI, J., Gupta, R., and Mott, R., "Design and Development of Monolithic Subsystems for Satellite Applications," IEEE Military Communications (MILCOM) Conference, Washington, DC, October 1987, *Conf. Rec.*, pp. 661-665.

RHODES, S. A., "Differentially Coherent FEC Block Coding," *COMSAT Technical Review*, Vol. 17, No. 2, Fall 1987, pp. 283-310 [CTR87/322].

ROGERS, D. V., "Rain Effects on Slant Propagation Paths," International Microwave Symposium, Rio de Janeiro, Brazil, July 1987, *Proc.*, Vol. 2, pp. 1279-1286.

ROGERS, D. V., and Allnutt, J. E.,** "A Practical Tropospheric Scintillation Model for Low Elevation Angle Satellite Systems," 5th International Conference on Antennas and Propagation, York, U.K., 1987, IEE Conference Publication 274, pp. 273-276.

SAYEGH, S. I., Kok, Y-L.,* and Hong, J-H.,* "An Algorithm to Find Two-Dimensional Signals With Specified Zero Crossings," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-35, No. 1, January 1987, pp. 107-111.

SNYDER, J. S., "Programmable Convolutional Encoder and Threshold Decoder," Vol. 17, No. 1, Spring 1987, pp. 189-200 [CTR87/320].

SURYADEVARA, O., deBettencourt, J. T., and Shulman, R. B., "Network Control Processor for a TDMA System," *COMSAT Technical Review*, Vol. 17, No. 2, Fall 1987, pp. 347-365 [CTR87/325]

---

* **Non-COMSAT author**

TULINTSEFF, A.,* and Sorbello, R. M., "Currents and Radiation Fields of Electromagnetically Coupled Microstrip Antennas," IEEE International Symposium on Antennas and Propagation, Blacksburg, VA, June 1987, *Digest*, Vol. 2, pp. 928-931.

VAIDYANATHAN, H., "Long-Term Storage of Nickel-Hydrogen Cells," Space Electrochemical Research and Technology Conference, Cleveland, OH, April 1987, *Proc.*, pp. 41-48, NASA Conference Publication 2484.

VAIDYANATHAN, H., and Dunlop, J. D., "Performance of Nickel-Hydrogen Cells for Battery-Powered Electric Propulsion Operation in GEO," 22nd Intersociety Energy Conversion Engineering Conference, Philadelphia, PA, August 1987, *Proc.*, pp. 882-884. Available from AIAA, Washington, D.C.

WHITE, L. W., Palmer, L. C., Chang, P. Y., and Shenoy, A., "Application of Software Simulation to DBS Transmission Design and Evaluation," *COMSAT Technical Review*, Vol. 17, No. 2, Fall 1987, pp. 367-401 [CTR87/326].

ZAGHLOUL, A. I., Assal, F. T., and Sorbello, R. M., "Multibeam Active Phased Array System Configurations for Communications Satellites," IEEE Military Communications (MILCOM) Conference, Washington, DC, October 1987, *Conf. Rec.*, pp. 289-293.

ZAGHLOUL, A. I., and Mailloux, R. J.,* "MMIC Phased Arrays," Antenna Applications Symposium, Allerton Park, IL, September 1987, *Proc.*, pp. 1-29.

ZAGHLOUL, A. I., and Mailloux, R. J.,* "Report From 1987 AP-S Workshop on MMIC Phased Arrays," *IEEE Antennas and Propagation Society Newsletter*, December 1987, pp. 14-19.

ZAGHLOUL, A. I., Siddiqi, S., and Bornemann, W.,** "Phased Arrays Versus Reflector Systems for Multibeam Satellite Applications," URSI Radio Science Meeting, Blacksburg, VA, June 1987, *Program and Abstracts*, p. 141.

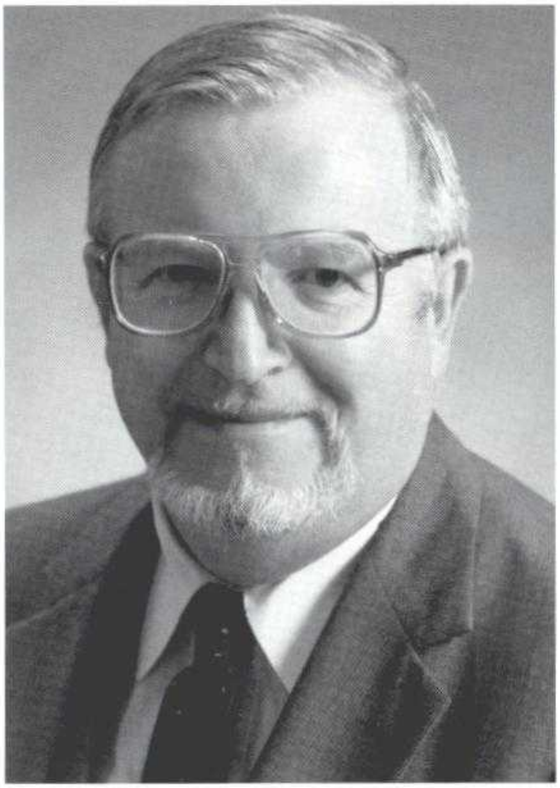
ZAKI, K. A.,* Chen, C.,* and Atia, A. E., "Dual-Mode Dielectric Resonator Filters Without Iris," IEEE MTT-S International Microwave Symposium, Las Vegas, NV, June 1987, *Digest*, pp. 141-144.

ZAKI, K. A.,* Chen, C.,* and Atia, A. E., "Improved Selectivity Dual-Mode Dielectric Resonator Filters," International Microwave Symposium, Rio de Janeiro, Brazil, July 1987, *Digest*, pp. 627-632.

ZAKI, K. A.,* Chen, C.,* and Atia, A. E., "New Realization of Dual-Mode Dielectric Resonator Filters," 17th European Microwave Conference, Rome, Italy, September 1987, *Proc.*, pp. 169-174.

ZAKI, K. A.,* Chen, C.,* and Atia, A. E., "Canonical and Longitudinal Dual-Mode Dielectric Resonator Filters Without Iris," *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-35, No. 12, December 1987, p. 1130-1135.

*** Non-COMSAT author**



Dr. Geoffrey Hyde

Dr. Rusell J.F. Fang

The Institute of Electrical and Electronic Engineers (IEEE) this year awarded the grade of Fellow to **Dr. Geoffrey Hyde** and **Dr. Russell J.F. Fang** for their significant scientific accomplishments.

Dr. Hyde received his Fellow for pioneering contributions to the theory, development, and application of large spherical and toroidal reflector antennas. This design makes it possible for one antenna to simultaneously communicate with multiple satellites. These antennas are now in regular use worldwide.

Dr. Fang received his Fellow for pioneering contributions to advanced modulation/coding techniques and transmission systems modeling. This work has significantly improved the transmission efficiency and quality of satellite communications, and has opened new opportunities for the industry in traditional telephone trunking and in the evolving mobile communications market.

In addition, **Dr. Otakar A. Horna** of COMSAT Laboratories was issued U.S. Patent 4,645,883, "Improved Double-Talk and Line Noise Detector for Echo Cancellers," on September 2, 1987.