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ACTS—Technology Description and Results

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Introduction

Active federal participation in the development as well as the encouragement of technological innovation has existed for a long time in the US. For example, in 1836 Congress appropriated $30,000 to subsidize Samuel Morse's first telegraph, an experimental line from Washington, DC to Baltimore. Government programs have differed in the extent to which they blend three conceptually distinct purposes: contributing basic research from which new technologies will be born, advancing technology for which government is the customer, and developing technology for use by the private sector.

There have been many successes and failures in all three categories, but perhaps the third category is the most difficult for government to sponsor. This is because the success of a program for commercial benefit depends on acceptance in the market place. It is difficult enough for the private sector to predict useful technology for future, uncertain markets, but it is even more difficult for public decision makers who are usually less skilled at forecasting commercial markets than their private sector counterparts. Secondly, the government support of R & D for commercial application involves industrial policy, which is normally highly controversial. A key issue in the debate is whether or not the government is likely to do more harm than good in sponsoring technology development.

The Advanced Communications Technology Satellite (ACTS) program is a government program of the third category, and this report is a case study of that type of sponsored research. ACTS was strongly debated over a ten-year period from 1983 to 1993. Both its advocates and adversaries spent a great amount of time and energy expressing their opinions and taking action to influence the program as it was conducted. For five years the administration adversaries succeeded in keeping ACTS out of NASA's budget request to Congress, and for those same five years, the congressional advocates restored the ACTS budget. The difference in philosophy and political rhetoric was as great as for any federal program.

This contractor report sheds some light on the core policy issues, the difficulties in executing programs with continual public policy disagreement, the usefulness of the developed technology to the private sector and the lessons learned. The authors were all closely associated with the program and have to be considered advocates. However, we have made a deliberate attempt to present both sides of the program and to make the material as factual as we know how.

The first chapter discusses the formulation of the program, its objectives, a brief description of the technology, the advocate and adversary viewpoints, and the contractual process. Chapters 2 and 3 provide a detailed description of the satellite and earth station technology and a technical assessment of the technology based on on-orbit results. Chapter 4 presents the applicability of the technology based on the results of user trials. Chapter 5 outlines the ACTS Ka-band propagation campaign and provides quantitative 30/20 GHz rain fade propagation measurements and presents some methods for mitigating the large fades.

Because of the continual controversy surrounding ACTS, the program execution was severely impacted. The difficulties imposed by this controversy as well as those due to technical and managerial problems are discussed in Chapter 6. Also presented in Chapter 6 is a discussion of those practices that were used to ensure that ACTS was a 100% technical success.

Extensive market research was conducted during the formulation of the ACTS program to identify future satellite markets and their demand. It is always difficult to conduct accurate market research. In Chapter 7, the results of the market research that were used in the program formulation are discussed as well as the accuracy of their predictions. As this chapter points out, the market research was quite visionary and played the key role in identifying the needed technology. The final Chapter 8 makes an assessment of how well the ACTS technology is being incorporated by the private sector.

The opinions expressed in this book are those of the authors and do not represent the views of any of the government organizations or companies that participated in the ACTS program. Also, a large number of very dedicated companies, organizations and people worked on ACTS, and that total team is responsible for its success. Because of the limited space available, it was not possible to include the names of all the people and organizations that participated in the program.

CHAPTER 1

Program Formulation

History has shown that leadership in communications carries with it substantial economic and political advantages. Communications are essential to all aspects of life including business, national affairs and cultural well being. Governments have always been involved in the regulation and technology for communications. In the US, the Federal Communications Commission (FCC) is the primary agency for regulation, and the National Aeronautics and Space Administration (NASA) and Department of Defense (DOD) programs have been responsible for many space communication technology innovations since the late 1950's.

This report about NASA's Advanced Communications Technology Satellite (ACTS) program covers two topics. One topic is the innovations or new technologies that were developed as part of the program and their significance. The other topic is the continuous debate that surrounded the ACTS program as to the proper role of government in sponsoring space communications research.

The difficulty in the government's sponsoring of space communications research is that it benefits some companies while putting others at a perceived or real competitive disadvantage. When **mission-specific** communications technology is developed by NASA or DOD, much of it becomes very useful in commercial satellite communications, but this type of technology development is viewed by the industry as non-intrusive and acceptable.

The ACTS program had a different objective. Its prime purpose was to develop technology for use in providing **commercial** communications (not a government specific mission), and it became embroiled in a continuous controversy as to what was the proper role of government for this purpose. The arguments made in favor of the program were that it was important for the government to ensure the US preeminence in satellite communications and to develop the technology to efficiently use the frequency spectrum. The main objections to NASA sponsoring the ACTS program was that it created an unfair competitive advantage for some companies and that it was not possible for the government to predict what technology was needed.

NASA SATELLITE COMMUNICATION PROGRAM FOR THE 1980'S

In 1978, as a result of the Presidential Directive, NASA began the process of rebuilding its R & D activities in the communication satellite arena [11,12,13]. The future technology program was planned in cooperation with the National Research Council's Space Applications Board Subcommittee on Satellite Communications, whose membership consisted of leading common carriers, spacecraft manufacturers, and representatives of communications users.

MARKET & SYSTEM STUDIES

In this first phase of the NASA program, market and system studies were conducted to determine future service demand and whether or not it could be satisfied by C and Ku band satellites. Two contracts were awarded to common carriers, Western Union Telegraph Company and US Telephone and Telegraph Company, a subsidiary of International Telephone and Telegraph (ITT) [14,15]. The emphasis of these studies was to forecast the telecommunications traffic that can be competitively carried by satellite. During this same time frame, two other system studies were conducted; one each by Hughes Aircraft and Ford Aerospace with supporting studies by TRW, GE, and the Mitre Corporation [16,17]. Their purpose was to identify the technology needed to implement cost-effective and spectrum-conservative communication systems. The results were combined to define potential operational system configurations, which could address the market for trunking and customer premises service expected in the early 1990's. System requirements derived from these postulated operational configurations formed the basis for the technology development program, which was to follow.

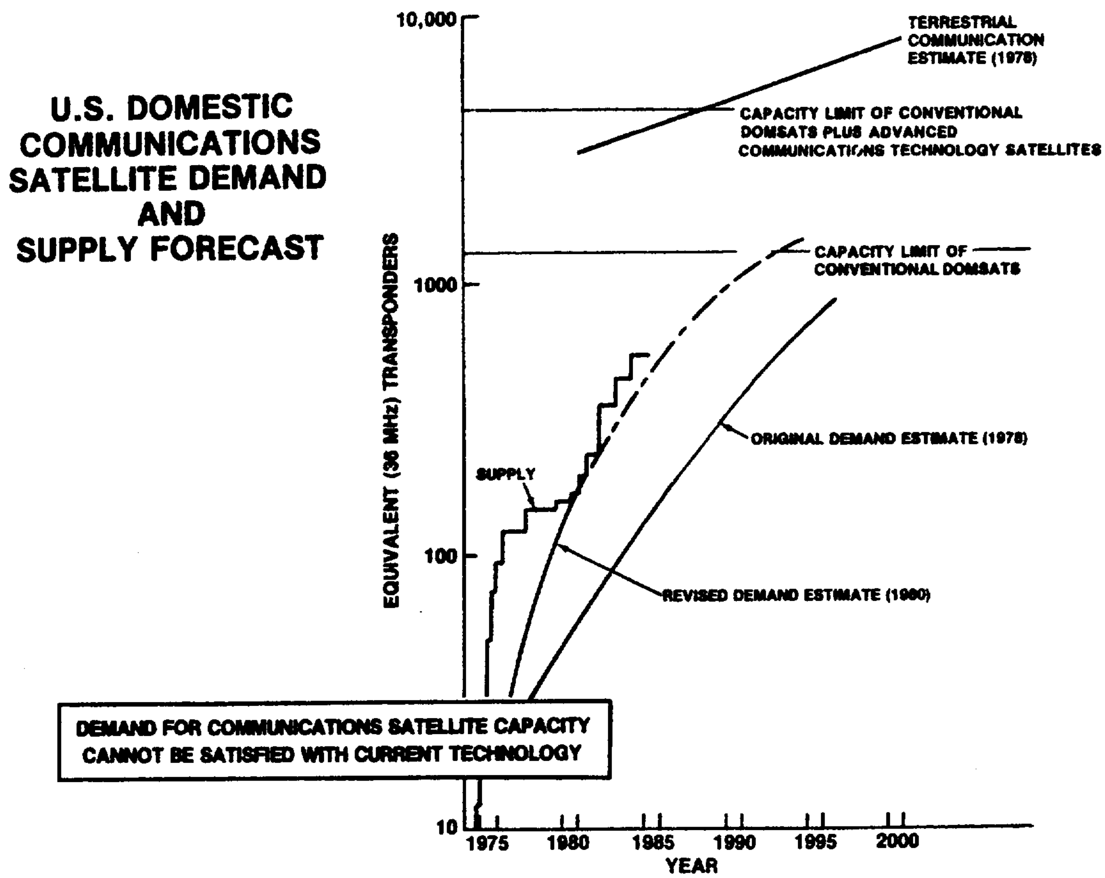
The market studies predicted that rapid growth in domestic voice, data, and video traffic would lead to a five-fold increase in US communication demand by the early 1990's. A combination of these market projections as well as communication satellite license filings with the FCC portended saturation, by the early 1990's, in the capacity of the North American orbital arc using the C- and Ku-frequency bands.

To relieve the pressure of this expanding market, the 30/20 GHz frequency band was needed. Although potential technological solutions to the use of 30/20 GHz were available, they involved high development risks and attendant high development costs that appear to be well beyond the funding ability of private industry.

As a result of these early studies, the new NASA Communication Program for commercial application was named the 30/20 GHz Program and was structured to:

- Develop selective high-risk, 30/20 GHz technologies focused on relief of orbit and frequency congestion and on developing new and affordable services.

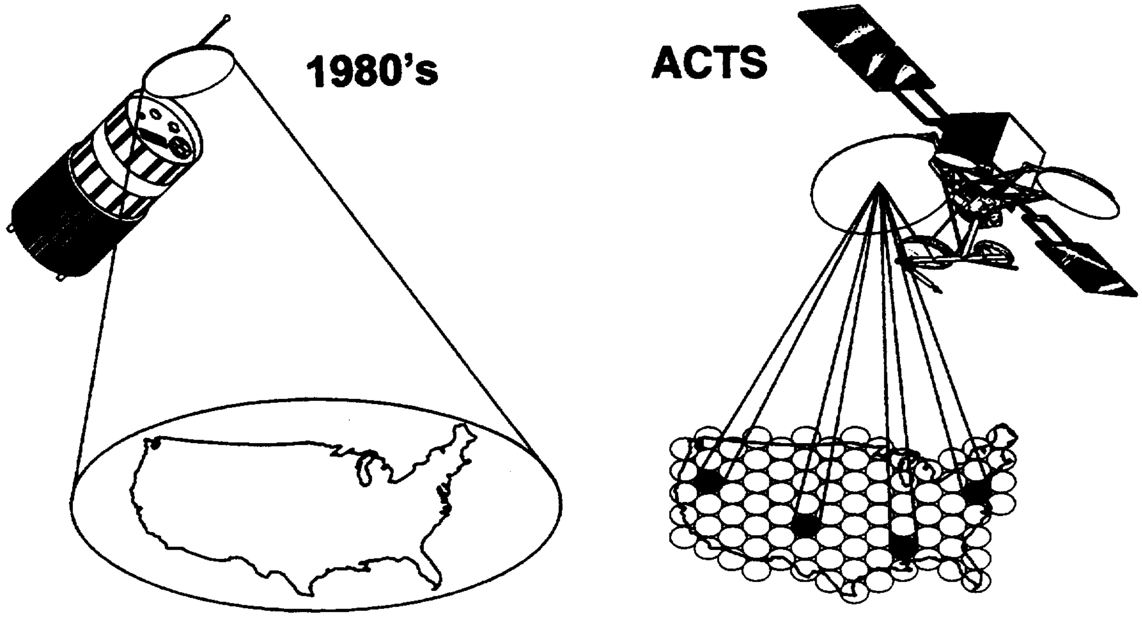
- Promote effective utilization of the spectrum and growth in communications capacity.
- Ensure continued US preeminence in satellite communications.



Satellite Addressable Market Demand

In 1979, the NASA Lewis Research Center (LeRC) in Cleveland, Ohio was designated by NASA Headquarters as the NASA lead center in planning and executing its commercial communication satellite technology R & D Program.

Early communication satellite systems employed simple bent pipe transponders with a single antenna beam to cover a large region such as the continental United States. One technique for more efficiently using the frequency spectrum is to cover the region with many small spot-beams so that the same frequency can be reused simultaneously in non-adjacent beams. Such frequency reuse increases the capacity of satellites by a factor of five to ten times greater than that of a single beam satellite with only a modest increase in spacecraft size, power, and weight. The technology to accomplish this high degree of frequency reuse employs antennas with high-gain, spot-beams and on-board switching and processing to interconnect the spot beams. In addition, the high-gain antenna allows for smaller aperture user terminals at higher data rates. This was the technology to be developed by the new NASA program.



Single Beam versus Multibeam Satellites

TECHNOLOGY FEASIBILITY & FLIGHT SYSTEM DEFINITION

In 1980, the program proceeded in two phases. The first phase was to continue the market studies to increase the confidence level in the forecast for saturation and to do proof-of-concept development of the identified technologies. The proof-of-concept program was a laboratory (breadboard) type development to prove that the technologies were feasible. Approximately $50 M was expended on the first phase. If the first phase proved successful, the second phase would consist of an experimental flight system development to demonstrate that the technologies could reliably provide communications services.

The first phase was fully supported by the entire service provider and satellite manufacturer community. The second phase of the program was the one that became controversial. The service providers had great concern about how reliably the technology would work in space, and therefore, argued for a flight program. However, some satellite manufacturers had reservations about proceeding with a flight program because they felt it would give the contractor for the spacecraft a competitive advantage. This controversy continued throughout most of the life of the ACTS program.

PROGRAM COORDINATION WITH INDUSTRY

To guide the program, two industry committees were formed. The NASA Ad Hoc Advisory Committee was created to provide general policy. The committee included notable representatives of both the system supplier and service supplier industry. Their contribution provided timely and sage review of the program as well as providing NASA with an insight into the industry philosophy relative to the roles and responsibilities of both government and industry.

NASA AD HOC ADVISORY COMMITTEE:

COMSAT: J. Harrington , Chairman, 1979
American Satellite Corporation: T. Breeden
Ford Aerospace: C. Cuccia
Stanford University: C. Cutler
Digital Communications Corporation: J. Puente
RCA: J. Keigler
AT&T Long Lines: R. Latter
COMSAT: B. Edelson
MIT Lincoln Laboratories: C. Niessen
Western Union: D. Nowakoski
Member-at Large: T. Rogers

The second industry committee formed was a Carrier Working Group (CWG) consisting of representatives from all the major satellite service providers. The CWG was charged with helping NASA formulate the technology and flight system requirements, developing experiments, and providing overall guidance. These requirements and experiments were deemed necessary to demonstrate the readiness of not only the technology but its service applications as well. Coordination was also established between the Department of Defense and NASA especially in developing various critical advanced technology components.

PROOF-OF-CONCEPT DEVELOPMENT

The purpose of the proof-of-concept (POC) technology developments was to demonstrate the technical feasibility of the key component building blocks [18,19]. The approach NASA used was to issue multiple-contracts to various aerospace and related companies for the development of each of the high risk technologies: *multiple spot beam antennas, baseband processor, TWTA's, wide band switch matrix, low noise receiver, GaAs FET transmitter, GaAs IMPATT transmitter, and ground antennas.* Duplicate awards for most of the critical technology components were employed to increase the probability of successful development and to produce multiple sources for communication hardware. In addition, multiple awards helped to ensure that a variety of perspectives and technical approaches were brought into each development. These contracts called for the development of the technologies, the construction of POC versions of the components and their testing in the laboratory to verify performance.

Carrier Working Group:

American Satellite: T. Breeden, L. Paschall, J. Johnson, O. Hoernig, F. Bowen, Jr.
AT&T Long Lines: R. Latter and B. Andrews
Bell Telephone Labs: R. Brown
Comsat General: J. Harrington, J. Kilcoyne, and C. Devieux, Jr.
GTE Satellite Corporation: G. Allen, T. Eaker, D. Piske and J. Napoli
Hughes Communication Services: C. Whitehead
ITT: R. Gambel and M. Nelligan
RCA American Communications: P. Abitanto, W. Braun, A. Inglis and R. Langhans
Satellite Business Systems: R. Hall and W. Schmidt
Western Union: J. Spirito, D Stem, and D. Nowakoski
Public Service Satellite Consortium: E. Young
US Telephone and Telegraph: G. Knapp
Southern Pacific Communications: C. Waylan and M. Gregory

The POC hardware substantially reduced the risk associated with the planned development of the flight system. Another output of these technology contracts was the prediction of feasible component, subsystem, and system performance levels. These projections were used by NASA to provide guidance for follow-on technology development. Service providers and manufacturers could also use these projections in their planning activities leading to commercial operational system designs for the early 1990's.

The Department of Defense (DOD) participated in the NASA POC Program. Several of the critical technology POC elements of interest to the DOD were co-funded by DOD and NASA.

To enable the effective transfer of information generated in the program, all contractors were required to prepare task completion reports. These reports were presented at periodic industry briefings hosted by NASA only for US interested parties.

FLIGHT SYSTEM DEFINITION STUDIES

The need for a flight test program reflected the fact that much of the required technology had never been demonstrated in space. The flight test was to ensure that the technology base was mature and validated, providing the level of confidence recommended by industry as being necessary for commercial exploitation. The initial planning called for two experimental satellites to be built and flown; one to demonstrate telephone trunking for high volume users in metropolitan areas, the second to demonstrate customer premises services using small and inexpensive earth terminals located at the customers' locations. In 1980, the two-flight concept was reduced to a single experimental spacecraft primarily emphasizing customer premises services. This proved to be a wise decision since the introduction of fiber optics a few years later significantly reduced the cost for terrestrial trunking services thus making satellites non-competitive.

In February 1982, Dr. Burt Edelson became the NASA Associate Administrator of the Office of Space Science and Application and played a very important role in keeping the program alive. When the program was being seriously threatened in 1982, Dr. Edelson restructured the NASA 30/20 GHz Program by broadening its applicability to the entire frequency spectrum for satellite communications. As a result, the experimental satellite system was renamed the Advanced Communications Technology Satellite (ACTS), and it was to be focused primarily on the technology of multibeam antennas and associated on-board switching and processing. Spacecraft capacity was reduced to a minimum for technical verification and experimentation only. Dr. Edelson provided key leadership for the ACTS Program during his tenure at NASA and has been a vocal proponent of the program and its benefits to the nation ever since.

Two other NASA managers who provided important leadership to the NASA Communications Program were Joe Sivo and Bob Lovell. Joe Sivo was the Chief of the Communications and Applications Division at the NASA Lewis Research Center in Cleveland, Ohio. Joe was the "Father of ACTS" and he led the Lewis team in the late 1970's and the early 1980's as NASA restructured its communication program. Bob Lovell became Chief of the Communications Division at NASA Headquarters and worked with both Dr. Edelson and Joe Sivo to structure the ACTS Program and guide it through the technical and political hurdles in the early 1980's. Without Sivo, Lovell and Edelson, the ACTS flight program would have never gotten off the ground.

Concurrent with the POC technology development, NASA was working with industry to define flight system concepts that would demonstrate both the ACTS technology readiness and service capabilities. During the 1981-1983 period, the major spacecraft manufacturers (Ford Aerospace now Space Systems Loral, GE, Hughes, RCA now Lockheed Martin and TRW) were funded by NASA to conduct a system study for defining a R & D spacecraft (ACTS) that could be flown by NASA. These studies were to determine the technology to be incorporated into the flight system. NASA then used the results from these system studies to develop the Request for Proposal (RFP) for the ACTS spacecraft and ground system. This RFP was issued by NASA in early 1983 with a proposal due date of June 1, 1983. Since the RFP required the development of very high-risk technology that had never been flown before, a cost plus fixed fee type of contract was specified.

The five separate flight system studies were conducted to get a wide range of views on what the ACTS spacecraft configuration should be and to promote competition for the procurement of the spacecraft. As it turns out this process did not accomplish the latter objective and was complicated by the fact that there was not a clear consensus as to the need for a flight program to prove out the feasibility of the new technology.

The Reagan Administration espoused a minimal government involvement ideology. At the time, the Republican administration took the position that it was not the proper role of the government to conduct a flight program for the purpose of proving technology for commercial purposes, especially for a profitable industry. There were many arguments presented by the Republican administration as to why the government should not sponsor the flight verification. These included that the government was not capable of predicting the technology for commercial application and the technology was not necessary because there was plenty of C and Ku band spectrum for future use. In addition, the administration did not feel the development of technology to more efficiently use the frequency via spot beams was required. However, as we know today, the use of spot-beams allows a great increase in the amount of frequency reuse so that a single satellite can have a very large capacity. Without this spot-beam increase in capacity, many of the current mobile and broadband satellite systems under development in the late 1990's, such as Iridium, Globalstar, Celestri, Spaceway, Astrolink and Teledesic, would not be economical. All the developers of these systems make the strong case that their spot beam systems meet the current FCC requirement to more efficiently use the spectrum. The FCC has added this requirement since they realized the frequency spectrum is a scarce resource.

Congress, in the 1980's was increasingly concerned about US economic competitiveness in high technology industries. They were sensitive to areas such as satellite communications, being challenged by foreign entities, where the federal government could further US competitiveness. The Democratic Congress listened to the arguments of the US industry in support of a flight verification program and decided it should be conducted. This debate on the need for the ACTS flight test, between the Republican administration and the Democratic- controlled Congress (including each side's constituencies) continued up through launch of the ACTS in September 1993. The later Chapters in this book cover this debate in much more detail. It suffices to say here that the difference in philosophy was very deep as attested by the fact that the Administration's budget left the program without funds for five years in a row, and Congress restored the funds in each of those five years. If nothing else, the ACTS Program may have set a record in this regard.

BIDDING ON THE ACTS CONTRACT

The response to the RFP was disappointing because only one proposal was received. The team submitting the proposal consisted of RCA as prime integrating contractor and supplier of the spacecraft bus with first tier subcontractors TRW for the communications payload and COMSAT for the Master Control Station. Second tier subcontractors included Motorola for the baseband processor and Electromagnetic Sciences for the spacecraft's antenna beam forming network. Since TRW, Motorola and Electromagnetic Sciences had developed major pieces of the ACTS technology in the Proof-of-Concept development program; this team was very competent. Because the team represented a large cross section of the US industry involved in satellite communications, NASA believed that objectives of the program could still be achieved by the single bid.

ACTS was to be placed into low earth orbit by NASA's Space Shuttle, and the RFP required that the payload be constrained to 1/4 of the Shuttle's cargo bay. Further, a Payload Assist Module (PAM) D perigee stage furnished by NASA was to be used to place ACTS into geostationary transfer orbit (GTO) after deployment from the Shuttle. These RFP requirements constrained the ACTS weight and size. The next alternative was to use a larger capacity perigee stage, a PAM A, which would have required the use of approximately 1/2 the Shuttle's cargo bay. NASA desired to restrict the payload to a 1/4 use of the cargo bay to limit the cost of the mission. This logic was somewhat questionable since the Shuttle was not always flown with a full load. In fact, the NASA cost model used a Shuttle load factor of 3/4 of capacity to determine the pricing for payloads. Potential bidders questioned this requirement and sought a change. Prior to the receipt of proposals on June 1, 1983, Robert Berry, Director of Space System Operations at Ford Aerospace wrote NASA on May 3, 1983 [20] and stated the following:

> *"We believe that the technical approach which would create the least risk to NASA would be a PAM-A configuration satellite, unconstrained by the volume limitations of the PAM-D family of perigee stages. We have made the case that it is in NASA's best interest not to discourage the offer of a PAM-A configuration. It seems obvious to us that NASA's objectives in achieving an ACTS program offering innovative and unique associations with other government or commercial users can only be satisfied with a PAM-A equivalent spacecraft. We further believe that as the definition of NASA's high technology payload evolves, weight, power, footprint area, thermal considerations and performance margins will move towards the limitation of the PAM-D configuration. On the other hand, ample margin would still exist with a PAM-A configuration.*
>
> *"Ford Aerospace had planned to offer a PAM-A class spacecraft for the ACTS mission. We also had received notification from another payload user of their firm commitment for another payload, which would have been incorporated, on our satellite configuration along with the ACTS payload. In addition, we had been informed by a satellite operating company of its interest in leasing the ACTS payload, thus providing potential cost reimbursement to NASA. However, RFP 3-511907 quantitatively defines the assignment of launch costs to overall program costs but offers no quantitative offset for the substantially greater capability of a PAM-A configuration. This quantitative imbalance confers an apparent competitive cost advantage to a PAM-D class satellite configuration even though that configuration will not support the full achievement of NASA's overall program objectives.*
>
> *"Should NASA subsequently decide that a PAM-A equivalent configuration is desirable for ACTS, Ford Aerospace would be pleased to offer a competitive solution".*

In an Aviation Week & Space Technology article in December 12, 1983 [21], Berry went further and said "There is no way the ACTS payload is compatible with the McDonnell Douglas Delta (PAM-D) class upper stage."

It was expected that the ACTS contractor would use a standard commercial bus to limit the non-recurring costs for the spacecraft. Ford Aerospace wanted to bid its standard PAM-A bus. As it turned out Berry's statements predicting that as the ACTS detailed design was developed the weight requirement would move toward the PAM-D weight limit proved to be true. The PAM-D approach was scrapped for the PAM-A capability not long after the ACTS development contract was awarded. What went wrong was that NASA's concern with limiting the ACTS Shuttle costs and its procurement regulations forbidding informal discussions with potential bidders after release of the RFP, forced the input from a contractor to not be treated seriously. In hindsight it is obvious it would have been better for the program to relax the PAM-D requirement.

The other major potential bidder for ACTS was the Hughes Aircraft Company (HAC). Although the reasons were not publicly stated, Hughes chose not to submit a bid for ACTS.

HUGHES Ka-BAND FILING

Hughes questioned the program in principle as unnecessary subsidization of commercial operations and as duplication of military technology development. To prove their point they filed an application with the FCC in early December 1983 for the development, launch, and operation of a two-satellite Ka-Band domestic system. Their satellites were to be equipped with high-power spot beams focused on 16 major US metropolitan areas. As such, it would allow the use of two-meter customer premises earth station for such business data services as teleconferencing, high-speed document distribution and remote printing. The first of their two proposed satellites was to be launched in December 1988.

Hughes noted in this filing that they expected the orbital allocations at the C- and Ku-bands to be exhausted following the next round of FCC assignments. In essence, Hughes agreed with NASA's C- and Ku-band saturation projections, which had been derived by Western Union. In fact Hughes quoted the Western Union market study in their filing. However, this filing was contrary to other statements made by Hughes during the same time period that warned of a coming glut in transponder capacity. This contradiction and other factors led to speculation by many observers [3] that Hughes opposed the ACTS flight program on pure competitive grounds. Nothing ever came of the Hughes filing, but it did set the stage for the consistent Administration opposition to ACTS.

The administration turned against continuing ACTS as a flight program after Hughes filed with the FCC. Since the ACTS system used the same frequencies, senior Hughes executives argued against continuing the program before the Office of Management and Budget and NASA, claiming that a government-funded program would be redundant. When the

Reagan administration sent its budget proposal for NASA to Congress at the end of January 1984, it reduced the funding to so small a level that a flight program could not proceed.

ACTS CONTRACT SIGNED

In the ensuing months, the battle over the ACTS flight program was waged in the US Congress. Congress became convinced that the ACTS program objectives were valid and important to carry out. In the latter part of May 1984, despite administration opposition, they approved a $40M increase for the ACTS program to reinstate the flight verification. After President Reagan signed the FY 1985 authorization and appropriation bills, it cleared the way for a contract signing with RCA on August 10, 1984 for the development of the ACTS flight system. This ACTS funding battle between the administration and Congress continued for the next four years with the administration trying to terminate ACTS each year.

As initially proposed by RCA, the ACTS system development was to take place over a five year period with an engineering model development being completed in three years. Because of the complexity of the coordination between the user terminals, the master control station and the on-board switch system in setting up on-demand circuits, the development included a comprehensive three-month ACTS system test of the ground system with the spacecraft. The proposed five-year development time contrasts with the normal commercial satellite development of three years and reflects the fact that the ACTS technology was well beyond the current state-of-the-art. With the ACTS contract award in August 1984, the planned scheduled launch date was September 1989. As described in a later chapter funding cut backs, development problems and other difficulties caused the launch to be delayed until September 1993.

CHANGING TIMES

This report deals in great detail with what is the proper role of government in technology development. We maintain that the NASA ACTS program served a very important purpose in advancing satellite communications because the satellite communications industry in the 1980's could not afford to take on the risk associated with needed technologies.

The reader should recognize that business climate in the 80's was entirely different than in the late 90's. Today, non-traditional satellite companies such as Motorola, Teledesic and Pasifik Satelit Nusantara (PSN), to name just three, have found investor partners that have put up billions of dollars to implement revolutionary new satellite communication systems employing advanced technologies. Iridium is a 66 LEO satellite system for providing mobile communication anywhere. Teledesic is a 288 LEO satellite system to provide broadband communications and be the Internet in the Sky. In the case of PSN the system is a GEO hand-held mobile communications system called ACeS. All three systems use multiple spot-beam antennas with on-board digital processing and the Teledesic and Iridium systems have intersatellite links to provide global connectivity. Because of the success of many new satellite systems such as NASA's ACTS, DOD's MilStar, and Hughes' DirectTV many satellite service providers now view new technology not as a major risk factor but as means to introduce new services. Another major difference today is the perceived market potential is <u>much</u> greater than in the 1980's.

In the 80's, communications satellites were still in their infancy and large sums of capital were not available for risky ventures. We believe that the ACTS flight program was a proper role for the government in the 80's. However, because of differences of the business climate and the maturity of many technologies, a similar flight program may not be necessary today.

CHAPTER 2

SatelliteTechnology

The National Aeronautics and Space Administration's ACTS program provided new technology for increasing the efficiency in using the allocated frequency spectrums and for implementing communications using Ka-band. Increasing the spectrum efficiency was achieved by developing high-gain, multiple, spot-beam antennas and on-board switching and processing that allowed for a great increase in the number of times the frequency can be reused by a single satellite [23]. In addition, the high-gain, spot-beams provided the very desirable benefit of allowing for smaller aperture user terminals at higher data rates.

The US Industry and NASA jointly defined the ACTS Program. ACTS was not intended to be an operational system but a test bed for verifying those advanced technologies beyond the ability of any one satellite company to finance. At this time, in the early 1980's, the US satellite carriers had great concern for the reliability of the ACTS advanced high-risk technology. They felt that a flight test was necessary to prove out the technology feasibility before they would incorporate it into their commercial systems. The ACTS program was designed to allow the US Industry to meet the communication needs of the 21st Century as well as to remain competitive in the international satellite communications marketplace. The motivation for the program and its merits are discussed in chapters 1, 7, and 8. What are described in this chapter are the technology advances made by the ACTS Program.

ACTS SYSTEM OVERVIEW

ACTS is an experimental on-orbit, advanced communication satellite test bed bringing together industry, government, and academia to conduct a wide range of technology, propagation, and user application investigations. NASA's Lewis Research Center awarded in August 1984 the ACTS contract to an industry team consisting of:

- Lockheed Martin, East Windsor, NJ for system integration and the spacecraft bus;
- TRW, Redondo Beach, CA for the spacecraft communication payload;
- Comsat Laboratories, Clarksburg, MD for the network control and master ground facility;
- Motorola, Chandler, AZ for the baseband processor; and
- Electromagnetic Sciences, Norcross, GA for the spot-beam forming networks.

The contract was actually awarded to RCA Astro Space of East Windsor, NJ which was subsequently acquired by General Electric, then by Martin Marietta and is currently part of Lockheed Martin. In 1988, as a result of a Congressionally mandated program funding cap, Lookheed Martin (General Electric Astro Space at that time.) assumed responsibility for completing the development of the communication payload. Subsequently, Lockheed Martin subcontracted with Composite Optics, Inc., San Diego, CA for the manufacture of the antenna reflectors and part of the bus structure.

ACTS was launched into orbit by the space shuttle Discovery (STS-51) on September 12, 1993 and achieved geostationary orbit at 100 degrees West longitude on September 28, 1993. As of the printing of this book, ACTS was still operating. By that time the on-orbit station keeping fuel had been depleted, so the operations continued with an inclined orbit using an autonomous on-board program that provided a bias in the roll axis to offset the inclination and maintain the spot beams properly located on the ground .

The ACTS system is made up of a spacecraft and ground segment [24 - 27]. The spacecraft consists of a multibeam communication payload and the spacecraft bus. The key technology components of the communications payload are the multibeam antenna (MBA) assembly, the baseband processor (BBP), the microwave switch matrix (MSM), and Ka-band components. The spacecraft bus houses the communication payload and provides attitude control, electric power, thermal control, command reception, telemetry transmissions, and propulsion for stationkeeping.

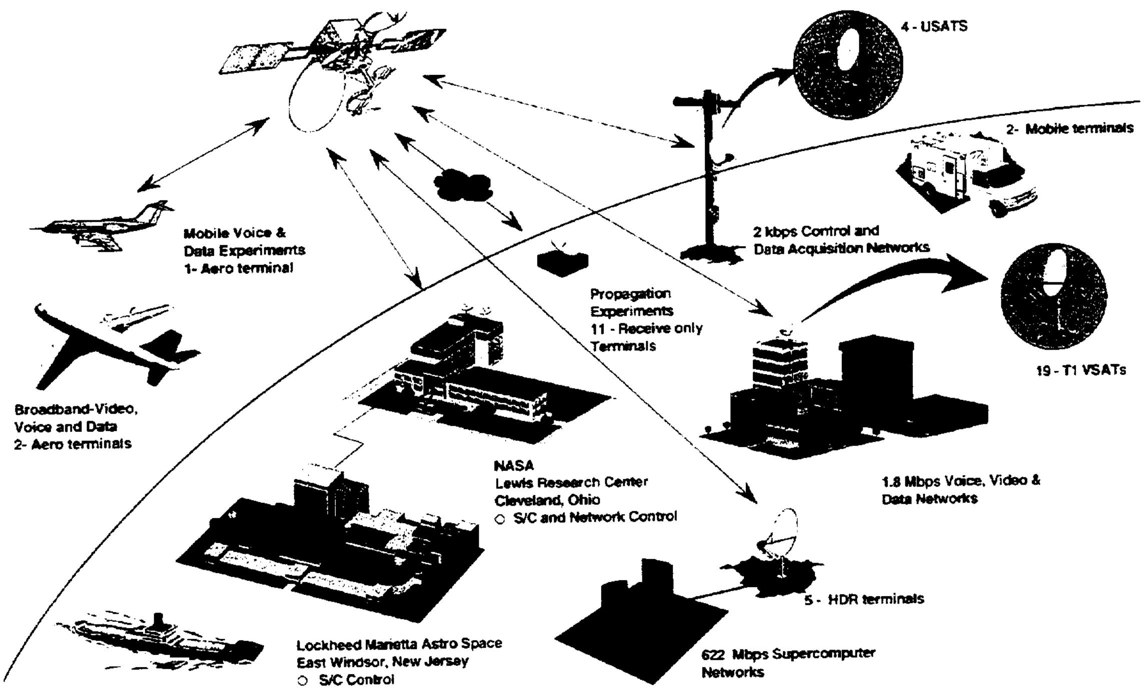
The ground segment is comprised of the spacecraft and communication network control stations and the user terminals. A Master Ground Station, located at the NASA Lewis Research Center (LeRC) in Cleveland, Ohio transmits commands to the satellite, receives all spacecraft telemetry and provides network control for all user communications. As part of network control, it processes and sets up all traffic requests, assigning traffic channels on a demand basis. A Satellite Operations Center was located at Lockheed Martin Astro Space in EAST Windsor, New Jersey and connected to the Master Ground Station via landlines.

In June of 1998, the Satellite Operations Center was transferred to the Lockheed Martin Communications and Power Center facility in Newton, PA. It has the prime responsibility for generating spacecraft bus commands and for analyzing, processing, and displaying bus system telemetry data. Orbital maneuver planning and execution are also handled by the Satellite Operations Center. The Lockheed Martin C-band command, ranging, and telemetry station at Carpentersville, New Jersey provided transfer orbit support during launch and served as an operations backup to the satellite operations center. In 1998, the backup function was transferred to the GE American Communications station in Woodbine, MD.

The ACTS communication payload provides service at digital data rates from kilobits per second (Kbps) up to hundreds of megabits per second (Mbps) via its various communication modes of operation. The major types of services include:

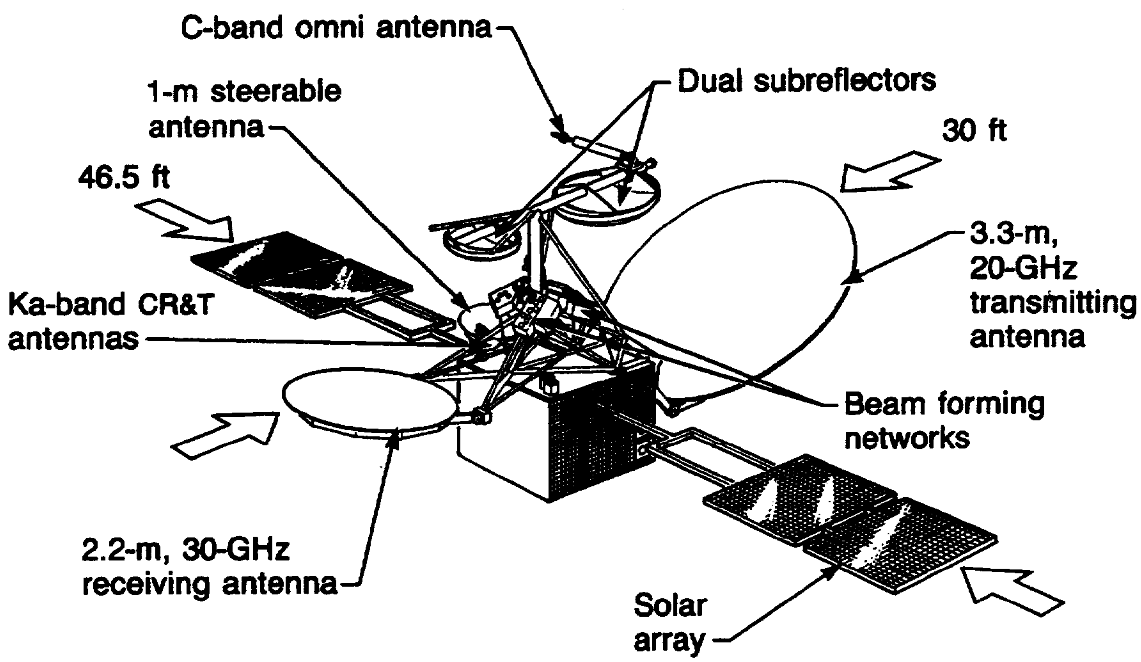
- On-demand, integrated voice, video and data services using T1 (1.544 Mbps) links to 4 foot customer premises terminals;
- Very high data rate (622 Mbps) networks;
- Broadband (T1) video and data for aircraft and ships;
- Aeronautical voice and low rate data;
- Low rate terrestrial mobile voice, video, and data;
- Interactive, multimedia services (1 Mbps outbound and 20 Mbps inbound) using 18 inch terminals.

Terminals operated by various industry, government, and university organizations validated these services. In addition, more than ten beacon, receive-only propagation terminals are used for propagation studies and modeling.



Overview of ACTS System showing spacecraft, control stations and user terminals. Lockheed Martin operates the control facility in New Jersey while Comsat Laboratories performs operations in Ohio.

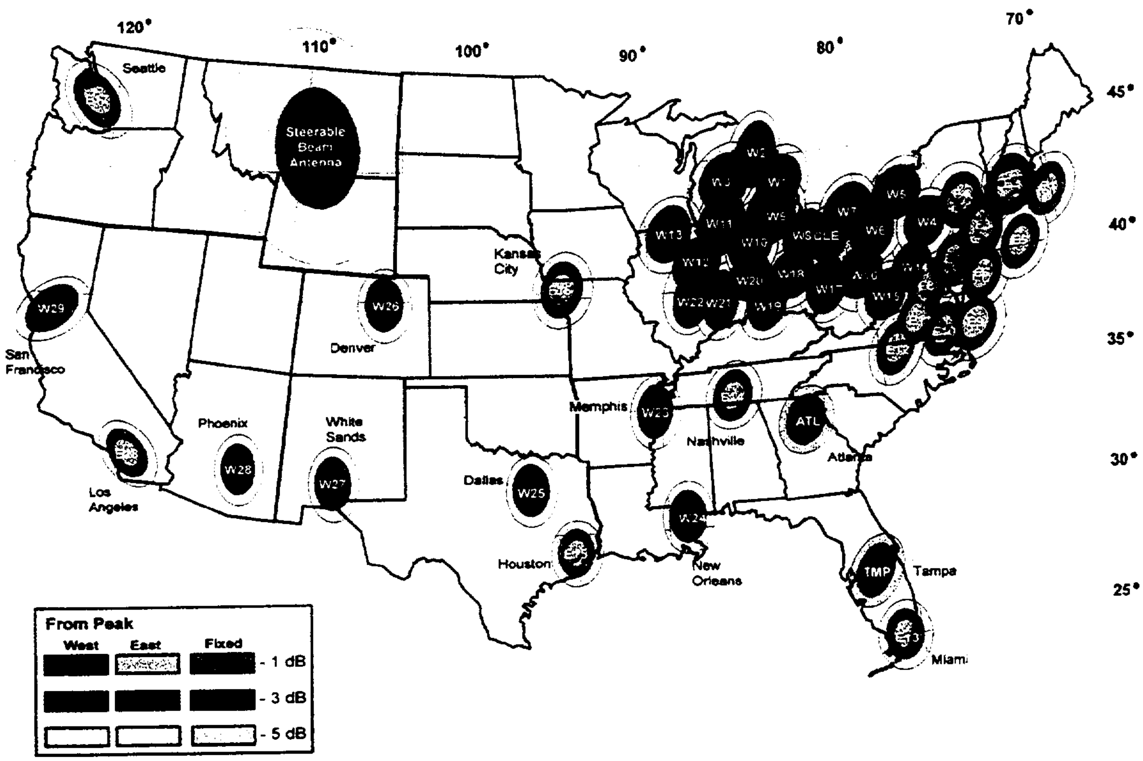
ACTS is a three-axis stabilized spacecraft weighing 3250 pounds at the beginning of its on-orbit life. It measures 47.1 feet from tip to tip along the solar arrays and 29.9 feet across the main receiving and transmitting antenna reflectors. The ACTS multibeam antenna is comprised of separate Ka-band receive and transmit antennas each with horizontal and vertical polarization subreflectors. The 7.2-foot, 30 GHz, receive antenna collects uplinked signals while the 10.8 foot, 20 GHz, transmitting antenna radiates downlink signals. Antenna feed horns produce narrow spot beams with a nominal 120 mile coverage diameter on the surface of the earth. Fast {less than 1-microsecond (μsec.)}, beam-forming switch networks consisting of ferrite switches, power dividers and combiners, and conical multiflare feed horns provide sequential hopping from one spot beam location to another. These hopping spot beams interconnect multiple users on a dynamic, traffic demand basis. A separate 3.3 foot, mechanically steered antenna, receiving uplink and radiating downlink signals, is used to extend the ACTS communication coverage to any location within the hemispherical field of view from ACTS' 100 degree West longitude position. Beacon signals at 20.2 GHz and 27.5 GHz are radiated from two small, separate antennas.



ACTS Spacecraft in its deployed configuration on orbit.

COMMUNICATION MODES OF OPERATION

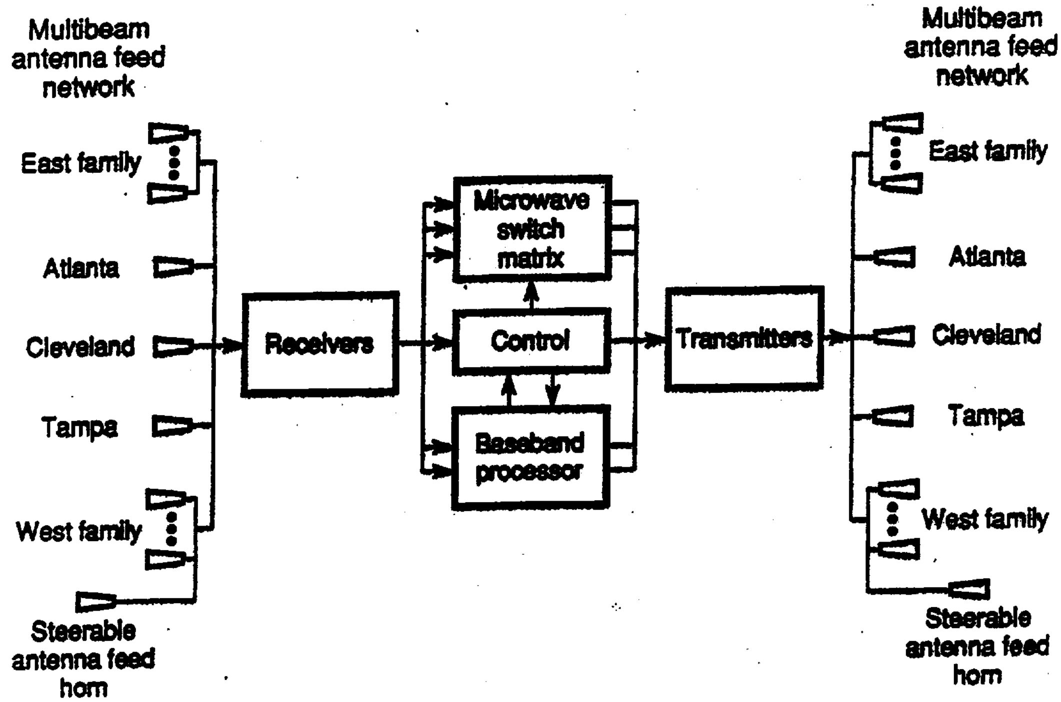
The multibeam antenna provides dynamic coverage with fixed and hopping spot beams. Each hopping spot beam can be programmed to cover a sequential set of spots and dwell long enough to communicate with users in each spot. By assigning each user an access time, several users can transmit and receive at the same frequency on a time-shared basis. This time division, multiple access (TDMA) technique requires a switching system on board the spacecraft to interconnect the beams and route messages. The ACTS communications payload provides two types of on-board switching to interconnect the multiple spot beams and to route signals to their appropriate destinations: (1) Baseband Processing and (2) Microwave Switch Matrix.



ACTS spot-beam ground coverage.

The BBP is a high-speed digital processor on the satellite that provides on-demand, circuit switching to efficiently route traffic among small user terminals. In essence, the BBP is the first "switchboard in the sky" to perform the same functions done by terrestrial telecommunication switch centers. Because its network is completely interoperable with the terrestrial system, ACTS can be considered as a single node in a combined satellite/terrestrial network. In addition, the BBP operates like a computer at digital baseband giving ACTS the capability to provide integrated multimedia services such as a combination of voice, video and data. Previous to ACTS, satellites had been primarily used to provide separate services such as TV programming distribution for cable and broadcasting companies, private data networks, and direct-to-the-home (DTH) TV programming.

ACTS conducts both time and space switching on board the satellite. The BBP switches traffic between the various uplink and downlink beams, automatically accommodating on-demand, circuit requests. In the BBP mode of operation, four simultaneous and independent hopping beams (two uplink and two downlink) provide flexible, demand access communications between small (4-foot diameter antenna) user terminals with a maximum throughput of 1.79 Mbps or 28-64 Kbps circuits. Each uplink spot beam receives multiple channels.



Five (5) antenna ports interfacing with the BBP/MSM transponders.

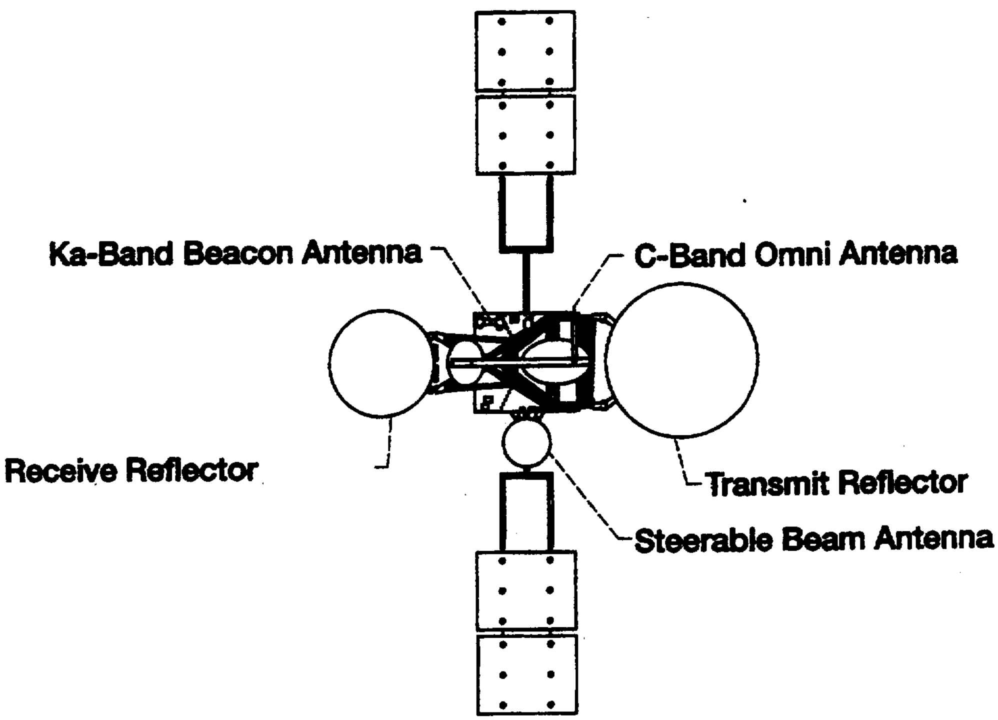
A user terminal is assigned an uplink channel and transmits its information using Time Division Multiple Access (TDMA). The receive signals are demodulated, decoded as required, temporally stored in memory, routed on a 64 kilobit individual circuit basis, modulated, encoded if required and transmitted in the proper downlink spot beam using a single TDMA channel. During the one-millisecond TDMA frame time, the beams hop to many locations, dwelling long enough to pickup or deliver the required traffic.

The MSM is an intermediate frequency (IF) switch capable of routing high volume point-to-point traffic and point-to-multipoint traffic over 900 MHz bandwidth channels. The microwave switch matrix operates based on satellite switched TDMA and dynamically interconnects three uplink and three downlink beams. The user terminals transmit TDMA bursts according to their destination. At the satellite, the 30 GHz bursts are downconverted to an intermediate frequency, routed to the proper downlink beam port, upconverted to 20 GHz, and transmitted on the downlink. The switch paths are changed during guard intervals between bursts. Fixing the beam interconnections in a static mode allows additional flexibility for a variety of continuous digital or analog communications. The MSM mode accommodates user terminals operating from low kilobits per second up to 622 megabits per second.

The ACTS system can be configured in the BBP mode, the MSM mode or a mixed mode. In the mixed mode both the baseband processor and the microwave switch matrix are operated simultaneously with some restrictions. The system can be quickly reconfigured from one mode of operation to another in a matter of minutes further adding to the system's flexibility. This flexibility along with the large total information throughput capacity allows a large variety of users to be accommodated concurrently.

ACTS PAYLOAD COMPONENTS

The key technologies developed and flight tested by ACTS are the multibeam antenna, the baseband processor, the microwave switch, along with RF components operating at the Ka frequency band. The next sections provide a comprehensive technical description of each of these major technology components of the ACTS payload.



ACTS antenna lay-out.

MULTIBEAM ANTENNA (MBA)

The ACTS multibeam antenna (MBA) provides very high- gain spot-beams enabling the use of smaller aperture user terminals and increasing the amount of frequency reuse. In the early 1980's, traditional C and Ku Band satellites reused their frequency spectrum once by utilizing cross polarization. The ACTS MBA provides for frequency reuse not only by cross polarization but also by spot-beam, spatial isolation. For ACTS, spots separated by one beamwidth can use the same frequency and polarization. Using this ACTS approach, commercial, multiple spot-beam systems being constructed in the late 1990's typically achieve a frequency reuse factor of 8. Increasing the frequency reuse allows the total communications capacity of a single satellite to be much greater. With a larger capacity per satellite, the economies of scale are such that the satellite cost per unit bandwidth are reduced by a factor of 2 or more.

The ACTS antenna system is comprised of a multibeam, high gain, hopping spot beam antenna; a separate mechanically steerable beam antenna (SBA), as well as two small beacon reflectors [28-30]. A C-band omnidirectional antenna, provided tracking, telemetry, and command during the launch phase, serves also as a back-up during on-orbit operations.

The multibeam antenna consists of separate receive (30 GHz) and transmit (20 GHz) antennas. Each consists of a main reflector, a nested assembly consisting of one front and one back subreflector and a pair of feed assemblies, one for horizontal and the other for vertical polarization. This Cassegrain type antenna was chosen to provide a compact design with a large focal length to minimize scan losses at the edge of the Continental United states (CONUS). A large equivalent focal length to aperture diameter was achieved using a hyperbolic subreflector with a high magnification factor. The MBA was designed so that the receive beam for a given coverage location was orthogonally polarized to the transmit beam in the same location. On-orbit, the spacecraft is oriented so the receive reflector is on the East Side and the transmit reflector is on the West Side.

The 20 GHz transmit antenna reflector is 10.8 feet in diameter and the 30 GHz receiver antenna reflector is 7.2 feet. This inverse scaling of reflector size with frequency produces spot beams having the same angular size in both the 20 and 30 GHz frequency bands, thus providing the same ground coverage footprint. Both antennas produce spot beams with approximately 0.3-degree beamwidth and gains ranging from 49 to 55 dBi. Spot beam ground coverage is on the order of 120 miles in diameter. For contract reasons, the ACTS MBA was configured to be a completely separate physical system that is bolted on the top of the bus at only three points. Although this simplified the contractor interface, it resulted in an extra heavy antenna assembly. Making the antenna an integral part of the bus system would have resulted in a much lighter system. Commercial satellites take this lighter-weight approach.

Since ACTS is a test bed, it is not intended to provide full US coverage. One of its prime goals is to demonstrate frequency reuse by means of hopping spot beams in two contiguous sectors. A contiguous coverage area of approximately 20 percent of the US was selected. In order to further enhance the versatility of the ACTS system and provide coverage to users in other parts of the country, isolated beams outside these two contiguous areas were identified and incorporated into the hopping-beam coverage network.

Each transmit and receive antenna supports 5 separate antenna ports. These five ports are for the three stationary fixed beams focused on Cleveland, OH, Atlanta, GA and Tampa, FL plus the east and west hopping spot beam families. The east beams are orthogonally polarized to the west beams in both uplink and downlink while using the same Ka frequency. The east family of beams is comprised of a contiguous sector called the east scan sector plus six additional isolated spot locations outside the sector. The west family comprises a west scan sector plus seven additional isolated spot locations. The mechanical SBA is also interconnected into the west family and functions as part of its hopping beam network. With this antenna system, ACTS can provide service to 51 separate spot-beam locations.

To prove out the antenna design, TRW fabricated and tested a breadboard multibeam antenna assembly. The main reflector was 8.9 feet in diameter. Testing on an indoor range verified that the antenna radiation patterns and scan characteristics were as predicted. It was found that the sidelobe levels were not significantly affected by the surface distortion of the subreflectors. In addition, the front subreflector only negligibly affected the sidelobes from the beams formed by the rear subreflector. However, the use of dielectric support ribs behind the gridded front subreflector introduced amplitude and phase distortions. These distortions resulted in a badly distorted far field radiation pattern. TRW concluded that the front subreflector must have no ribs. The successful demonstration of the breadboard MBA design provided confidence to initiate the development of the ACTS flight model MBA.

MAIN REFLECTORS

The reflectors were light, stiff, and strong with a root mean square surface (rms.) accuracy of 0.003-inches, and were thermally stable over large daily temperature gradients. The main reflectors, which were made of graphite epoxy skins bonded to a honeycomb core, were formed on a precision mold with a surface accuracy of 0.001-inches. Six-ply graphite epoxy front and back face sheets were bonded to a Kevlar honeycomb core. This reflector shell was supported by a backing rib structure with an egg crate design. The 10.8-foot, 20 GHz transmit and the 7.2-foot, 30 GHz receive reflectors weighed, respectively, about 80 and 30 pounds.

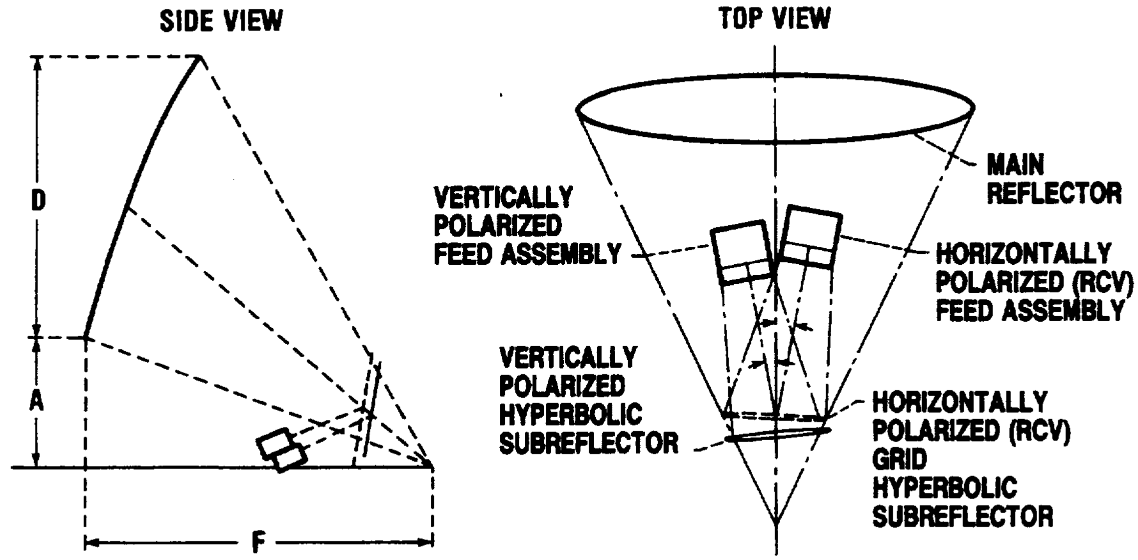
SUBREFLECTORS

Each subreflector assembly consisted of two offset hyperbolic surfaces arranged in a piggyback configuration. The front surface was a copper grid passing one polarization and reflecting the orthogonal polarization. The focal axis of each surface was tilted either plus or minus 10 degrees from the symmetry plane of the main reflectors so that the two orthogonal polarized feed assemblies could be placed in their respective focal regions without mechanical interference. The solid back surface was similar in design and construction to the main reflectors consisting of a graphite composite/Nomex honeycomb shell with supporting back ribs. The construction of the front surface was very different, being formed from Astroquartz sheets bonded to a Nomex core. Each shell had a thickness of approximately three-quarters of a wavelength at the frequency of operation. The polarizer grid consisted of an etched copper clad on a 0.0005-inch Kapton material that in turn was bonded to the front face sheet. A support ring bonded to the shell around the perimeter reinforced the front subreflector. As it turned out, this ring was not adequate to prevent thermal distortions that produced significant diurnal spot-beam drift. The two-way measured insertion loss through the polarizer grid was less than 1 dB. Reflection loss was measured at less than 0.25 dB.

Both the main and subreflector graphite fiber reinforced composite surfaces had high electrical conductivity and did not exhibit significant loss at the Ka-band frequencies. To limit temperature extremes, the surfaces of all reflectors and subreflectors were coated with a low insertion loss, thermal paint. In addition, the rear surfaces of all reflectors were blanketed for thermal control.

Lockheed Martin designed and Composite Optics fabricated all of the MBA flight reflectors except the steerable beam antenna, which was manufactured by Dupont Chemical. Although Composite Optics, at the time of the ACTS development in 1988, had already built fifty space based reflectors with thirty of them in orbit in 1988, the ACTS reflectors were a particular challenge because of their large size and stringent surface accuracy requirements. Composite Optics found that tooling manufacturing techniques used to develop antenna molds were critical in achieving the required high surface accuracy. In addition, the amount and area coverage of adhesive used to bound the outer skins to the inner honeycomb was critical in achieving reflectors that would not delaminate under the large thermal gradient expected on-orbit.

Layout of the main reflector, the two subreflector surfaces and the two feed assemblies. Layout applies for either the transmit or receive antenna.

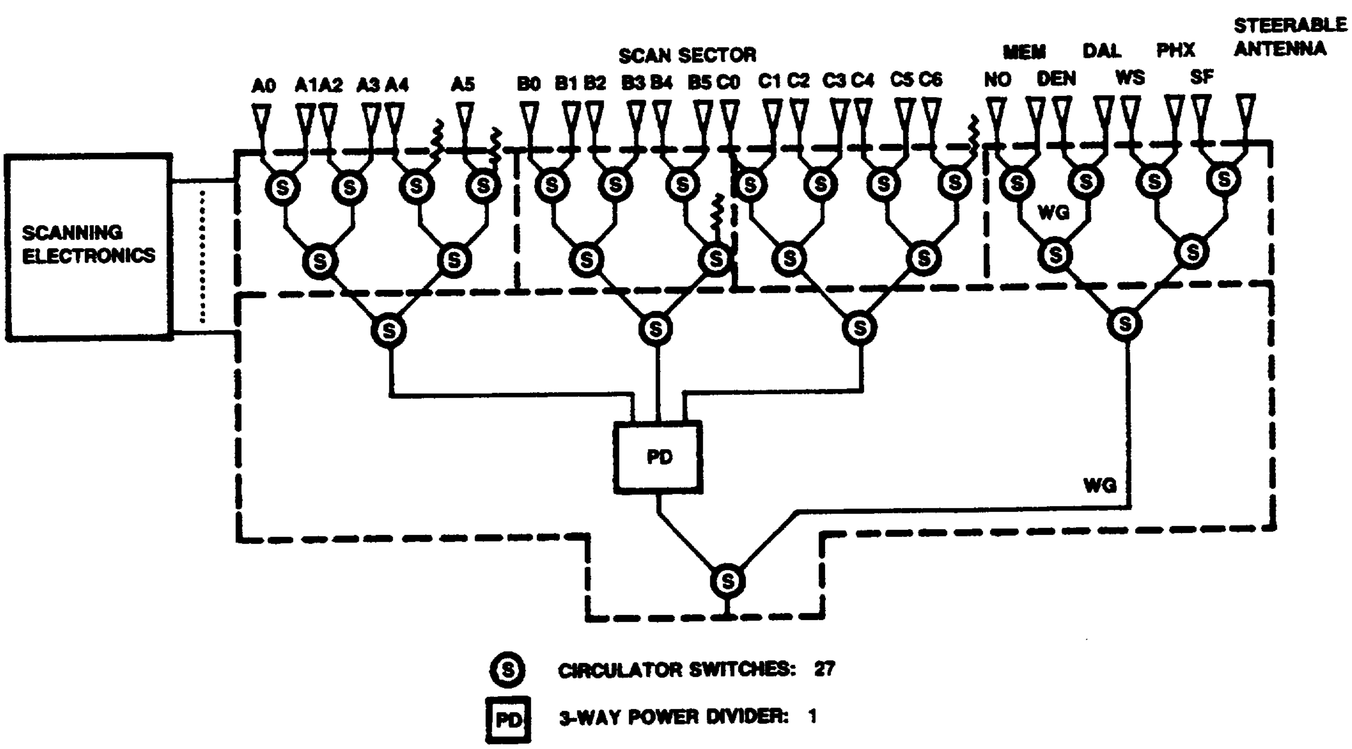


FEED ASSEMBLIES & BEAM FORMING NETWORKS

The receive and transmit antennas each operate with two feed assemblies (four total). The two feed assemblies for either the transmit or receive antennas had orthogonal polarization and contained a total of 51 feed horns. Three of these horns were driven directly and provided fixed spot beams at Cleveland, Atlanta and Tampa. The remaining feed horns were driven by two beam forming networks (BFN) and provided the hopping spot beams. These feed arrays were located in the focal plane of the reflector/subreflector system for the designated polarization. The ACTS BFNs built by Electromagnetic Sciences [31] consisted of three-way power dividers or combiners, sections of waveguide, and ferrite switches, implemented as a switching tree. Using the ferrite circulator switches, single feed horns were activated for the isolated spot beams while feed horn triples were activated for the sector spot beams. The beams were switched in less than 800 nanoseconds (ns). These switches were interconnected by gold-plated, electroformed, copper waveguide. Manufacturing tolerances of the BFNs were tightly controlled to assure that the three activated ports for each feed triplet were phase matched to within a few degrees over the receive and transmit frequency bands. These ferrite switches had a low insertion loss of approximately 0.1 dB, low mismatch loss, and better than 18 dB isolation across a 1 GHz bandwidth. The beam forming networks with electronics but without feed horns ranged in weight from 25 to 41 lbs. Using 1990's technology, Electromagnetic Sciences has stated that these weights could be reduced to 1/3 these values. The RF losess through the Beam Forming Networks were less than 0.6 dB for isolated spots and less than 1.2 dB for the scan sector spots. In the BBP mode of operation, a maximum of 48 hopping-beam locations can be interconnected and communications traffic exchanged over a frame period of 1 milliseconds. This process is repeated every millisecond enabling continuous communications between locations.

The feed assemblies incorporated three different feed horn types [32]. Multiflare horns with a 17-dB feed taper for low sidelobe performance were used for the Cleveland, Atlanta, and Tampa fixed spots. The isolated spots of the hopping beams used multiflare horns with a 10-dB feed taper for maximum peak gain. Multiflare horns were selected because they generate circularly symmetric radiation patterns and had a lower manufacturing cost compared to the dual mode or corrugated feed horns. The horns used in the triplet configurations were simple, single flare horns with a 3dB feed taper. The multiflare horns were manufactured of lightweight aluminum while the smaller, single flare horns were fabricated of electroformed copper.

Since ACTS was a test bed, the antenna focal planes were not fully populated with feed horns to provide complete CONUS coverage. The design, however, could be readily scaled for such coverage [31].



RF switch tree for the west beam forming network.

STEERABLE BEAM ANTENNA (SBA)

The ACTS system also incorporated a separate mechanically steerable beam antenna whose single reflector was used for both uplink and downlink. The SBA complemented the MBA by providing additional coverage anywhere in the Western Hemisphere as viewed from ACTS's 100-degree west longitude position. It had a maximum scan rate of 20 degrees per minute over a range of + or – 9 degrees which allowed it to track the shuttle, any satellite in low earth orbit, or an aircraft. Since the SBA feed is connected to the west hopping beam family, the SBA can be part of the BBP network as well as be used to track moving objects by physically moving the antenna reflector. The antenna employed an offset fed, parabolic; graphite fiber reinforced composite reflector 40 inches in diameter. The reflector feed was fixed and consisted of a diplexed, corrugated, dual band horn. Due to its smaller size, the gain of the SBA is approximately 6 dB less at 20 GHz than that of the MBA. Pointing is accomplished in two-axes by gimbal drives, which rotate the reflector surface in pitch and roll using open loop control. With a beamwidth of approximately 1.0-degree at 20 GHz and 0.75-degree at 30 GHz, the ground coverage spot was approximately 400 miles in diameter. Dupont Chemical manufactured the SBA using the same materials and fabrication techniques as the main reflectors. Special software developed for the ACTS program to evaluate the complex contours of the antennas proved invaluable. Using this software, errors were uncovered in the mold for the SBA, which were corrected before reflector fabrication began. Without this software, the errors would not have been detected until RF range testing conducted much later in the development cycle. Therefore, the software tool prevented costly re-fabrication and schedule delays.

ANTENNA SUPPORT ASSEMBLY

The antenna reflectors and feed assemblies were mounted to a low distortion truss system that was attached to the spacecraft's earth facing panel. The truss system was built with graphite epoxy tubes and titanium end fittings. The entire antenna assembly weighed about 900 pounds with the truss making up about half the weight.

ANTENNA POINTING

Once ACTS achieved orbit and deployed its antennas, the transmit and receive spot beams were brought into co-alignment. This was accomplished by slightly rotating the transmit main reflector using its two-axis drives. These on-orbit fine adjustments were necessary to remove beam mispointing due to residual gravity stress, assembly stress, alignment errors, and hydroscopic reflector distortions. The narrow beam width and the high gain slope of the MBA imposed a pointing requirement of at least a factor of 10 better than conventional CONUS-coverage antennas; i.e. of the order of 0.025 degrees maximum in pitch and roll and 0.15 degrees in yaw.

To achieve this pointing accuracy, an autotrack system based on Landsat technology was used to determine pointing errors in pitch and roll [33]. The autotrack error signals are referenced to the continuously maintained command carrier; uplinked from the master ground station in Cleveland and received by the Cleveland fixed horn. Yaw attitude is determined twice a day using sun sensors located on the east and west faces of the spacecraft. A software estimator provides the control signal during the periods when the sun sensors are not viewing the sun.

A momentum wheel and two magnetic torquers are used, respectively, for correcting pitch, roll and yaw errors. On-orbit test data demonstrated that the attitude control system provided the required pointing accuracy for the MBA.

DEVELOPMENT APPROACH

It was considered prohibitively expensive to test the RF performance of the MBA under simulated on-orbit thermal conditions. The approach taken from the very beginning of development was to rely on thermal and RF modeling to verify that the MBA was suitable for flight operations. As discussed below in the on-orbit performance section, this higher-risk but lower-cost development approach was not 100% successful. As it turned out, accurate modeling of the complex MBA was not completely accomplished even though a separate NASA design verification team, using detailed, independent models, checked the contractor design.

ASSEMBLY & TEST

A major challenge in the assembly of the MBA was to ensure that each component of the transmit and receive antenna was mechanically aligned with respect to its assembly and the other antenna such that the corresponding spot beam patterns would coincide with an accuracy of 0.015 degrees. In addition, it was necessary to continually check this alignment as the spacecraft went through various environmental tests. The reflectors, subreflectors, feed assemblies, and the antenna support structure were aligned using a theodolite based optical technique. To characterize the RF patterns and gain characteristics of the MBA, a spherical near field antenna test facility was constructed. The MBA was first tested on a spacecraft mockup and finally on the flight spacecraft itself. Tests were conducted before and after each environmental exposure to confirm that no changes had occurred to the antenna alignment.

INTERFACE BETWEEN THE MBA AND THE COMMUNICATION PAYLOAD

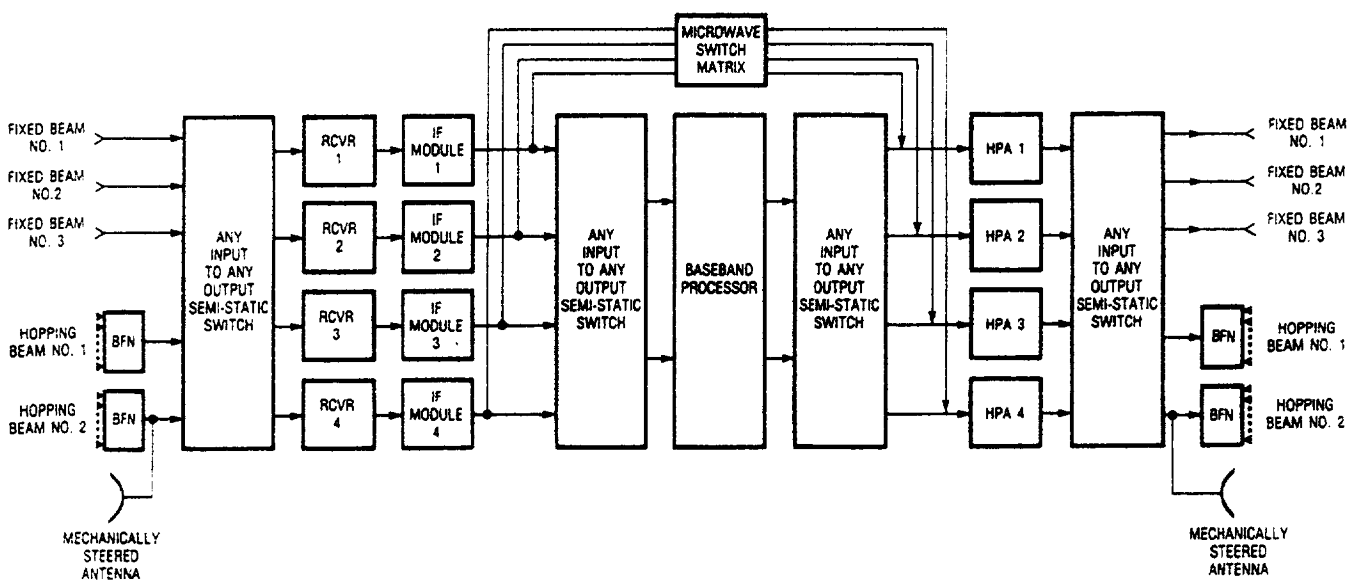
Uplink signals can be received through the five antenna ports. Each of the uplink signals can be directed to any of the four receivers by means of the waveguide input redundancy switch. Two beams can be connected to the BBP or any three beams can be connected to the MSM inputs. The four low noise receivers amplify the 30 GHz communication signals and down convert them to 3 GHz for routing by either the BBP or MSM. The receiver outputs can be directed to either the BBP or MSM using the receive-coaxial-switch-assembly. The receivers provide linear outputs to the BBP and saturated outputs to the MSM. After processing by either the BBP or MSM, signals are switched through the transmit coaxial switch assembly to any of the four upconverters. The upconverters convert the IF signals to 20 GHz for amplification in the 46 watt traveling wave tube amplifiers (TWTA). The outputs of the TWTA can be directed by the waveguide output redundancy switch to any of the three fixed beams or the two hopping beam ports of the transmit antenna.

BASEBAND PROCESSOR (BBP)

The ACTS BBP routs on-demand individual voice, video, data, and multimedia messages between a large number of small terminals [34, 35]. Key advantages of the ACTS BBP are the ability to:

1) automatically reconfigure message routing to accommodate dynamic traffic changes without the use of a terrestrial hub and double-hop transmissions;
2) provide additional link performance by the decoupling of the RF uplinks and the RF downlinks;
3) selectively apply forward error correction coding and burst rate reduction on individual messages to overcome localized rain fade; and
4) allow different uplink and downlink multiple access and data rates.

Communications payload diagram.

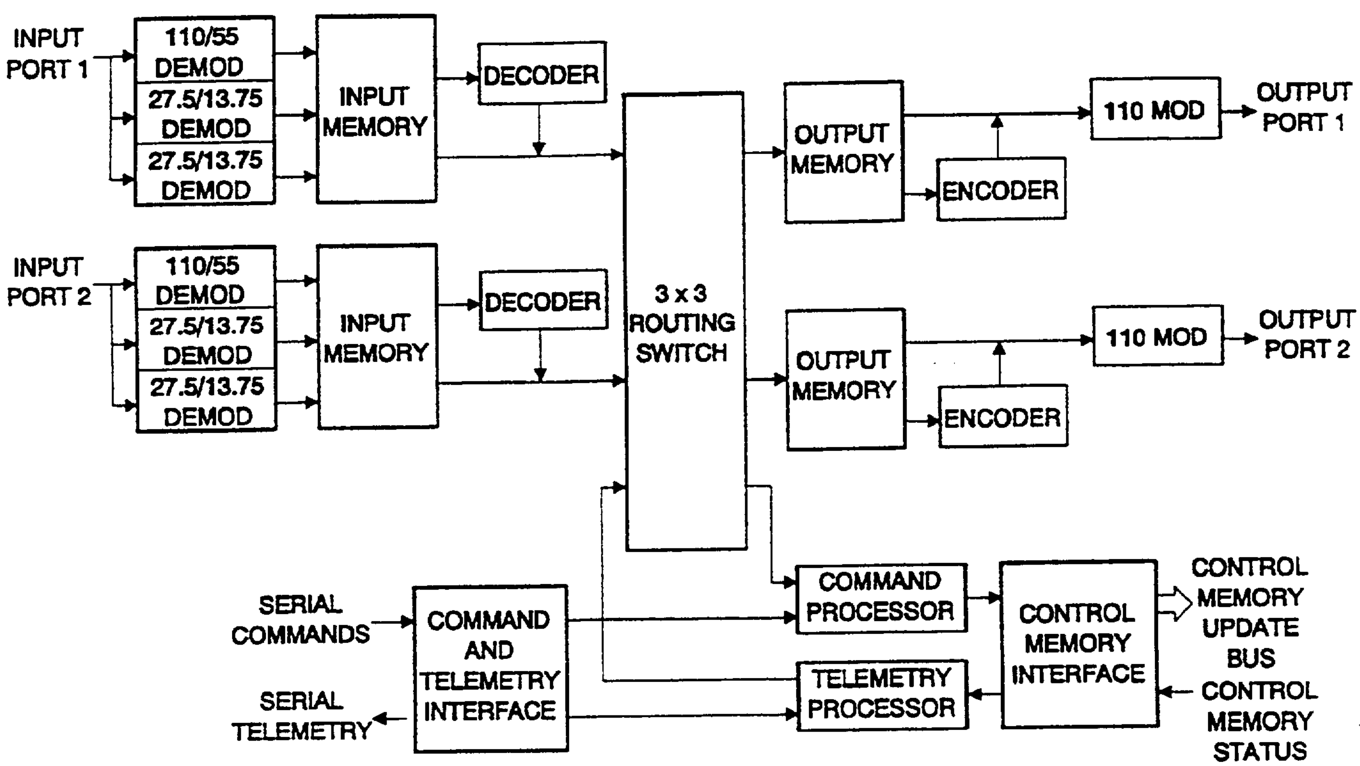


The BBP operates with two uplink and two downlink hopping beams. Each one of the four is time independent to provide flexible operations. All of the user terminals in the two hopping beam families (east and west) are completely interconnected in a mesh network through the satellite switch. The BBP operates in a TDMA format with a 1-millisecond time frame. Serial minimum shift key (SMSK) modulation is used for both the up and down links and was chosen since it has a constant envelope resulting in less intersymbol interference, lower side lobes resulting in less spectral regrowth, very resistant to phase errors and simplier implementation for the demodulator. A unique feature of BBP is that the uplink and downlink access formats are different. Uplink bursts at either 27.5 or 110 Mbps use combined Frequency Division Multiple Access (FDMA) and TDMA access. Downlink bursts at 110 Mbps are transmitted in a pure single channel per beam TDMA mode.

After an uplink burst arrives at the satellite, it is demodulated and stored in input memories. During the next frame, the data is read out of the input memories and routed through a digital switch and stored in output memories for the proper downlink beam. During the third frame, the output memories are read out and the data transmitted. The amount of BBP memory is largely dependent on the TDMA frame period. The shorter the frame period the smaller the memory size required resulting in less weight and power. TDMA frame efficiency (ratio of message bits to overhead bits) is higher for a longer frame period. ACTS spacecraft power and weight versus frame efficiency tradeoff resulted in a selection of a 1-ms frame period for both the uplink and downlink.

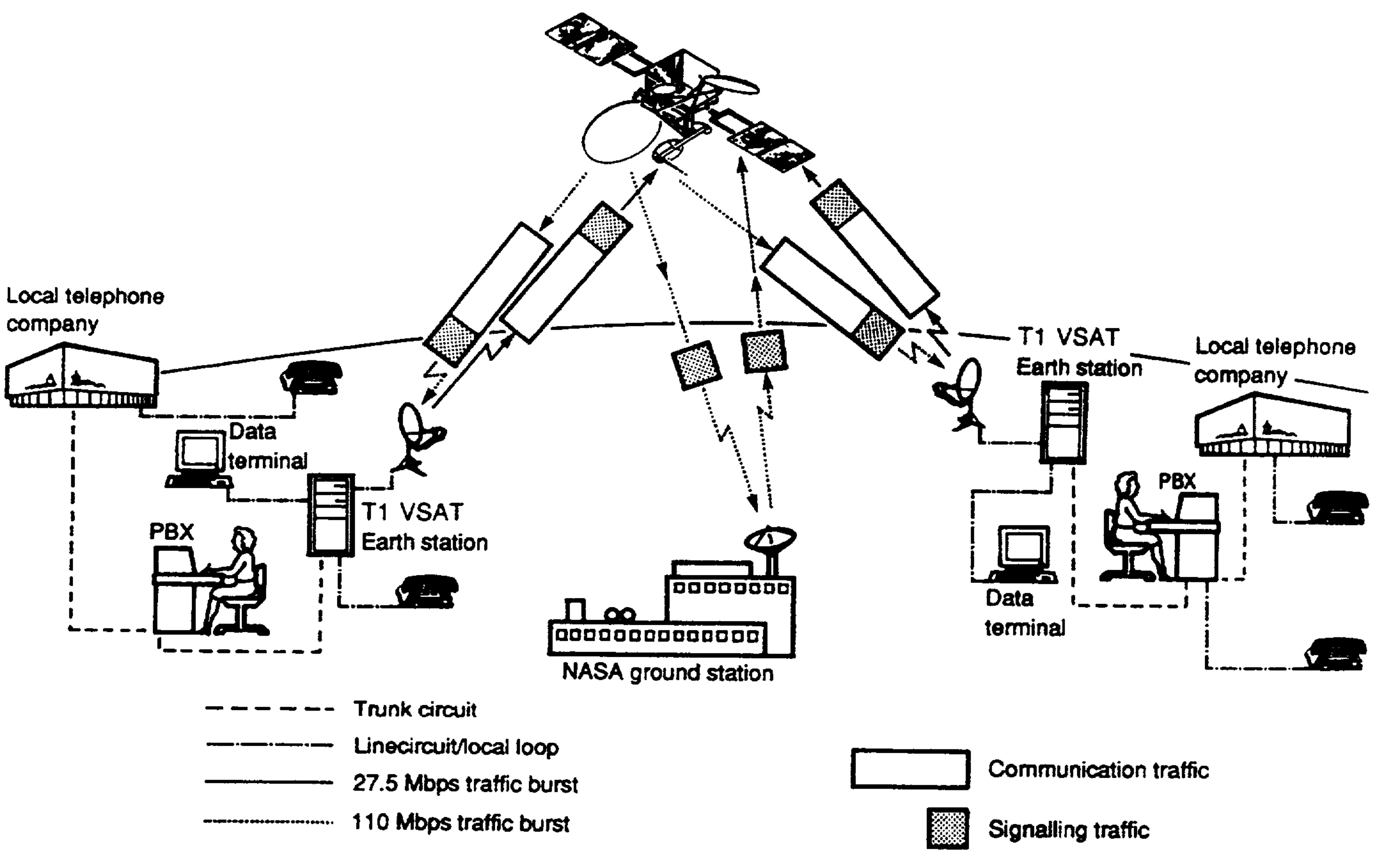
The BBP switches on a word-by-word basis where a word is equivalent to a 64-kbps-message channel. Any mix of voice, video, data, or multimedia messages in increments of 64-kbps can be accommodated. The four-foot user terminal can handle 28 64-Kbps channels for a maximum information throughput of 1.79-Mbps.

Baseband Processor diagram.



DEMAND ASSIGNMENT AND THE ORDERWIRE CONCEPT

All active terminals in the network are assigned dedicated two-way control channels, called orderwires, through which they maintain communications with the Cleveland Master Control Station (MCS). In the BBP network, the MCS is the centralized network control and monitoring facility. All traffic requests and circuit assignments are processed by the MCS. Users can change their requests for circuit capacity once every superframe, which is 75-ms. The BBP operates under stored program control. The control memories direct the operations of demodulators, decoders, the baseband routing switch, encoders and modulators, as well as the hopping sequence of the MBA's spot beams. In response to traffic requests, the control memories are programmed and dynamically modified by the MCS providing demand assigned multiple access (DAMA) operations.



On-demand, integrated services provided by the BBP. Complete seamless operation with terrestrial telecommunications.

Two control memories are used in the BBP: one on-line and one off-line. The on-line memory contains the current beam hopping and switch routing instructions. The off-line coding requests, etc., the control memories are swapped. This swap is performed in synchronization with changes in the burst time plans for terminals throughout the entire network. Ongoing traffic is not interrupted.

RAIN COMPENSATION

A key feature of the BBP is its ability to automatically implement coding and burst rate reduction to only those TDMA bursts experiencing fading conditions. During periods of rain, the RF transmitted and received signals at the earth stations can be significantly attenuated at the Ka-band frequencies. When the downlink signal attenuation exceeds a threshold, rain compensation is automatically applied. This consists of reducing the burst rate by a factor of two on the terminal uplink and the downlink, and simultaneously incorporating forward error correction (FEC) coding. This increases by a factor of four the number of time slots allocated to the station. In order to avoid affecting all the other stations burst times, the burst time for the affected station is moved from the clear part of the frame to a fade pool area reserved for providing additional time slots to stations requesting compensation. If compensation were not applied selectively, the effective information throughput would be reduced by a factor of four. The amount of capacity reserved for fade compensation is variable and can be adjusted as needed by the specific rain area of operation. The FEC process employs a maximum-likelihood convolutional code having a rate ½, constraint length 5, 2-bit soft decision quantization, and path memory length equal to 28. This combination of burst rate reduction along with FEC coding provides an additional 10-dB improvement in link margin. Fixed margins of 3 dB on the downlink and 5 dB on the uplink were provided to accommodate small fades without compensation. These fixed margins plus the 10 dB gain provided by rain compensation nominally allow the bit error rate to be maintained at $5x10^{-7}$ with service availability for CONUS of 99.5%.

This rain compensation is adaptive and only implemented when the fade for the 20 GHz signal exceeds a threshold. Using the in-band communication channel, each VSAT continuously estimates its downlink signal level. When the fade threshold is exceeded, the compensation is automatically applied within 1 second. When the fade magnitude reduces to a predefined cessation level, the rain compensation is removed. Since a very small percentage of user terminals simultaneously undergo fades exceeding the threshold at any time, only a small amount of on-board decoding capacity is needed. In the case of ACTS, the amount of decoding capacity is 6.8 Mbps per beam.

BURST TIMING

In order to limit guard time between bursts, it was decided that an uplink burst arrival at the BBP must be accurate to within +/- 60-nanoseconds (ns). The BBP uses a correlator to detect a 7 bit unique word and determines whether it is early or late. This information is transmitted to the user terminals in the form of a tracking error word (TEW). The ground terminals then adjust their uplink transmission bursts in the next frame according to the message contained in the TEW to maintain time synchronization with the spacecraft.

BBP DEVELOPMENT

Motorola developed the architecture for the BBP over a number of years starting in 1979 [34]. To prove that the BBP could be produced with an acceptable weight and power, a proof-of-concept (POC) model was developed during the period from 1980 to mid-1983. As part of this NASA POC program, Motorola developed custom large-scale integrated (LSI) circuits for certain high-speed functions of the demodulators, control memory update controllers, and decoders. This pre-flight POC program development successfully proved the feasibility of the switchboard-in-the-sky.

Comsat Laboratories led the development of the ground/spacecraft architecture for the TDMA, DAMA, system synchronization, rain compensation and network control. This was a very complex and large task that involved a high degree of coordination with NASA (the system integrators) and the spacecraft contractors. Comsat's contribution of the BBP architecture was as important as Motorola's hardware contribution. Both Motorola and Comsat Laboratories are to be commended for their principal roles in the development of a revolutionary technology.

BBP HARDWARE IMPLEMENTATION

The BBP hardware was partitioned into three flight assemblies: a Modem Unit, an Input/Output Memory Unit, and a Central Processor Unit [36]. Hardware partitioning was based on common design requirements for elements of the boxes and on the optimum allocation of signal and data interfaces. The Modem Unit housed 6 uplink demodulators, and 2 downlink modulators. The Input/Output Unit contained the input and output channel data memories, the decoders and encoders, the data routing switch, and the input and output channel control memories. The central processor received commands from the MCS and updated all control memories. The flight BBP weighs 121 pounds and consumes 199 watts of power.

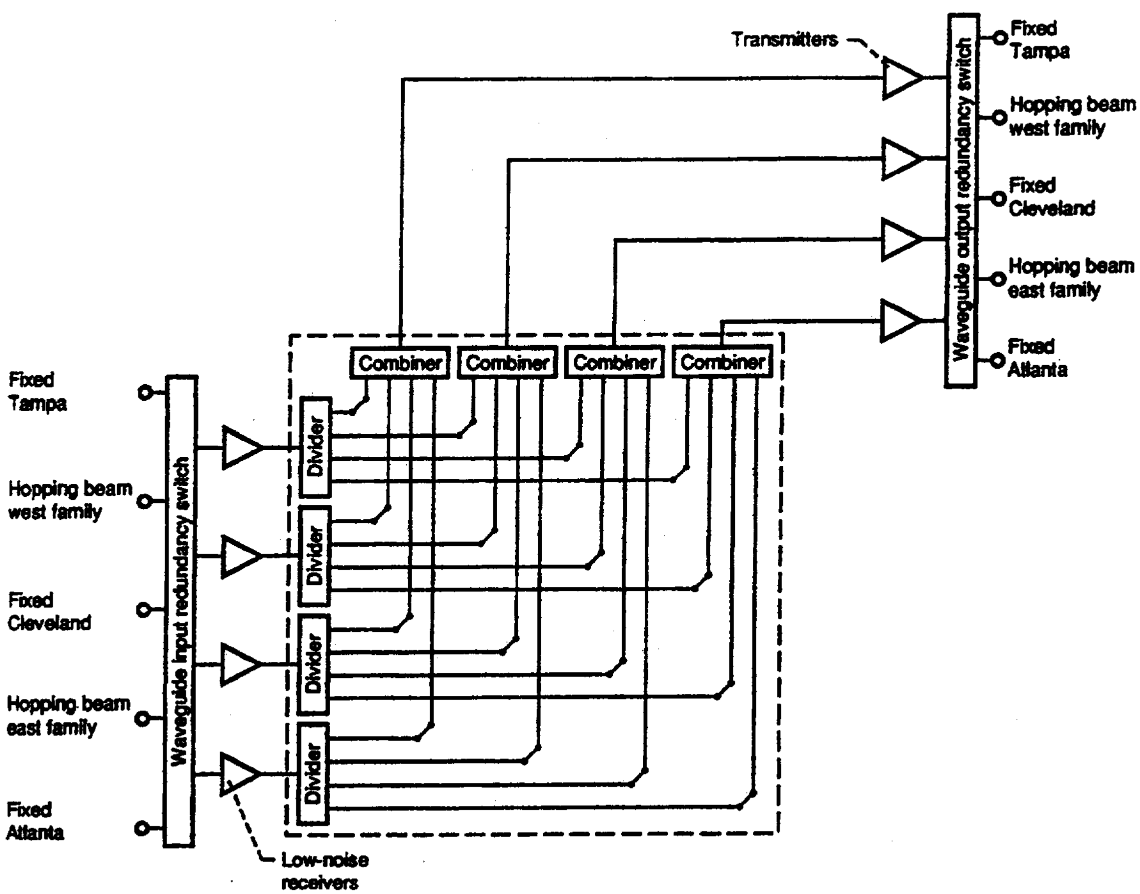
The low-power, high-speed processing requirements coupled with the space environment posed significant challenges to the BBP design. The key technologies developed by Motorola to enable the ACTS BBP included:

1) compact, low-power rapid acquisition burst demodulators operating at 27.5-Mbps to 110-Mbps;
2) forward error correction utilizing a <u>single</u> chip maximum likelihood convolution decoder;
3) a central processor architecture that provides circuit switching via commands from the master control station; and
4) a family of high speed, low power large-scale integration (LSI) and small-scale integration (SSI) circuits.

The expected two-year radiation dose was 10 KRAD. The LSIs, SSIs, and memories were tested to much higher levels. The LSIs and other integrated circuits were also life tested for 1000 hours at 150 °C junction temperature.

MICROWAVE SWITCH MATRIX (MSM)

The ACTS MSM is an IF switch capable of routing high-volume (696 Mbps) point-to-point and point-to-multipoint traffic. It is a solid state, programmable, 4x4, planar "cross-bar" switch [37]. Functionally, only a 3x3 configuration is used for connecting any three uplink beams to any three downlink beams. The 4x4-hardware implementation provides a three out of four redundancy. Unlike the BBP, the MSM does not store the incoming traffic messages in onboard memory. The cross points of the matrix switch use dual-gate, field effect transistors (FET) in a hybrid switch/amplifier configuration. The MSM routes signals over a 900 MHz wide transmission channel (1dB bandwidth, amplitude limited) between 3 to 4GHz. Input signal distribution and output signal combining are performed using passive recursive couplers. The outputs from the IF modules are run at saturated levels to ensure that the inputs to the MSM are all equal thus minimizing the cross talk between MSM single paths. The very fast (less than 100 nanosecond) switching time of the Gallium Arsenide FET amplifier switches permits efficient dynamic routing for use with TDMA communications traffic.



Microwave Switch Matrix operation at 3 GHz IF frequency with switching speed less than 1 microsecond. Built by Lockheed Martin Astro Space.

The simple connect-disconnect feature of the switch matrix allows for a variety of uplink to downlink antenna connections. A selection of beam-to-beam or broadcast connections that join a single uplink beam with several downlink beams is permitted The waveguide input redundancy switch (WIRS) permits the selection of any three-uplink beams from the five MBA antenna ports and likewise the selection of any three-downlink beams. The WIRS is electromechanical and is generally fixed for a long duration.

A programmable digital controller with dual memory banks controls the MSM. This digital controller, commanded directly by the 5-kbps spacecraft command channel, stores the matrix switch and antenna hopping sequence data for a TDMA frame. For each increment of time during a TDMA frame, the controller sequentially reads out the memory and changes the matrix switch connectivity and hopping beam positions. In this manner the TDMA bursts from terminals are sequentially switched on-board the satellite to the proper downlink beams The present TDMA plan is stored in the foreground memory. The background memory is programmed through the spacecraft command link to implement the next TDMA plan. A memory swap command from the ground is issued to change to a new TDMA burst time plan when desired.

RF Ka-BAND COMPONENTS

In addition to the MBA, BBP, and MSM, RF Ka-Band components were identified as high-risk technologies needed to support future commercial, Ka-band satellites. The ACTS developments for 20 GHz transmitters and 30 GHz receivers are described below.

20 GHz HIGH POWER TRANSMITTER

The ACTS transmitters consist of solid-state frequency upconverters followed by traveling wave tube amplifiers (TWTA) and provided operation over a 900 MHz pass band. Each TWTA used in the ACTS spacecraft consisted of a separately packaged 46-Watt, traveling wave tube (TWT) designed and manufactured by Watkins-Johnson (which was subsequently purchased by Varian and then Hughes) and a high voltage electronic power conditioner (HV EPC) manufactured by Lockheed Martin.

The ACTS TWT was originally designed for dual mode operation and achieved a DC to RF conversion efficiency of 43% and a low phase distortion (4°/ dB AM-PM). This design was an outgrowth of Watkins-Johnson Ka-band flight tube developments for both the European Space Agency' Olympus Program and the US Navy's FLT SAT COMM Program. The tube operated in the saturated mode with a saturated gain of 52.5 dB and was completely stable against oscillations. The saturated mode was chosen because the primary mode of communications on the downlink was single carrier TDMA and not multi-carrier operation. By careful mechanical design and the use of low outgassing potting encapsulation techniques, Watkins-Johnson developed a very compact, lightweight tube that weighed only 2.8 pounds.

30 GHz LOW NOISE RECEIVER

The ACTS receivers amplify the 30 GHz, TDMA uplink signals from the selected MBA beams and downconvert them to the 3-4 GHz IF signal for routing purposes. To achieve the required low noise, high gain performance, the first three amplifying stages of the receiver employed high-electron mobility transistors (HEMT). This technology produced a receiver with a 3.5-dB noise figure across a 900 MHz passband near 30 GHz.

HEMT devices have similarities with conventional GaAs FETs but differ in their carrier transport mechanism. HEMTs are fabricated on an AlGaAs/GaAs heterostructure and use metal electrodes. These devices have demonstrated lower noise and higher gains at 30 GHz than conventional GaAs devices. The HEMTs used in the ACTS receivers were manufactured by Lockheed Martin Electronics Laboratory (previously GE) in Syracuse, NY with an individual noise figure of 1-dB and a gain of 11-dB minimum. The three-stage amplifier had a rated noise figure of 3.4-dB beginning of life, 3.6-dB end of life, and an overall gain of 20-dB. The large bandwidths (900 MHz) and high frequencies (30 GHz) required the development of new methodology in manufacturing, alignment, and test. The performance of the hardware was much more sensitive to lead lengths and grounding than at the lower communication bands. New techniques were developed to provide consistent grounds, low voltage standing wave ratio connections, and adequate stress relief. Alignment required microscopic monitoring to determine tuning locations. Extensive use of test fixtures was employed to provide accurate and repeatable data.

SPACECRAFT BUS

The spacecraft bus was based on the Lockheed Martin (RCA) 4000 Commercial Series. The bus structure was a rectangular box roughly 70 inches along the vertical axes with a cylindrical center structure that housed the apogee kick motor (AKM). The antenna support assembly for the MBA was attached to the bus structure at only three points to limit thermal distortion in the MBA. The north and south-facing panel were each divided into three panels. These panels were used to mount most of the spacecraft bus and communication payload electronics equipment. The LNRs and BFNs were, however, attached to the MBA support structure to limit the length of the 30/20 GHz waveguide runs.

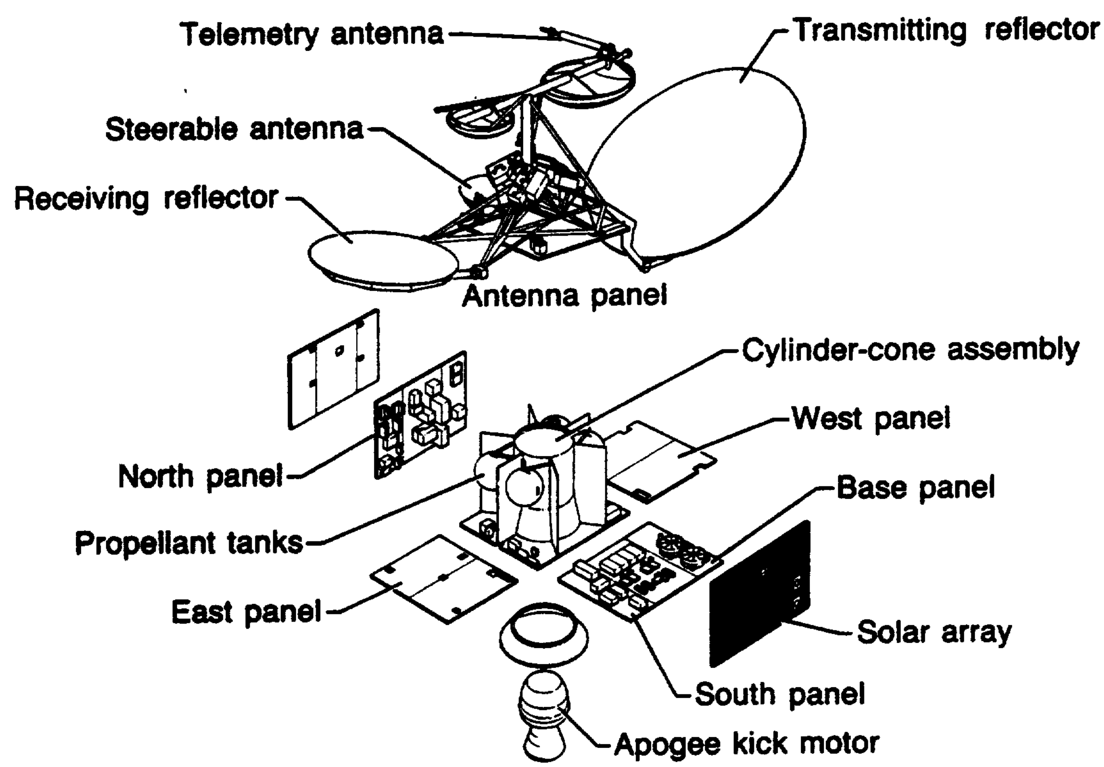
The electrical power subsystem is a direct energy transfer configuration consisting of solar array panels, storage batteries, and power regulation equipment. The four solar array panels (135 sq. ft.) provided a beginning-of-life power of 1836 watts.

The propulsion system consisted of a hydrazine reaction control subsystem and the apogee kick motor. The catalytic thrusters, propellant tanks, and the plumbing comprised the reaction control subsystem. This system was configured as a blow-down system utilizing hydrazine propellant pressurized with helium. Sixteen catalytic thrusters ranging from 0.2 to 1.0 pound of thrust were used. These thrusters were used primarily for orbit adjustment maneuvers but also participated in certain attitude control functions. Five hundred and eighty pounds of hydrazine propellant were on-board at liftoff. The apogee kick motor was the Thiokol solid-propellant STAR-37 FM model that was fired to move the satellite from the elliptical transfer orbit to the circular geostationary orbit.

Thermal control used a combination of heaters, a selection of finishes and multi-layer insulation blankets to maintain proper temperatures. Heat pipes were used under the traveling wave tubes and the baseband processor to remove heat efficiently from these high heat density components and thus limit the upper extreme of the temperature range.

A momentum wheel controls the spacecraft pitch attitude and a magnetic torque coil controls the roll attitude using error signals from either the autotrack or the earth sensors. A magnetic torque coil also controls the yaw attitude using signals from two sun sensors or a yaw estimator.

Spacecraft bus built by Lockheed Martin



In the earth sensor mode, the design requirement for roll, pitch, and yaw accuracy was 0.10, 0.10, and 0.25 degrees respectively. In the autotrack mode the design requirement for roll, pitch and yaw accuracy was 0.025, 0.025 and 0.15 degrees respectively [12]. The earth sensor mode of attitude control is primarily used during the eclipse shutdown period when the communications payload is turned off. The earth sensor is also used daily during the thermal transients of the subreflectors which affect the autotrack accuracy.

The ACTS flight system incorporated four Ka beacons for real-time fade measurement [6]. Two of these beacons were in the downlink frequency band while the others were in the uplink band. These beacons provide signal sources to make continuous measurements for propagation research. The downlink frequency beacons operate at 20.185 GHz with vertical polarization or at 20.195 GHz with horizontal polarization. These beacons primarily provide the normal spacecraft telemetry and ranging functions while producing a stable downlink signal to allow propagation measurements.

Both uplink frequency beacons operate at 27.505 GHz. Each beacon is vertically polarized and not modulated. In contrast with the telemetry beacons, which can operate simultaneously, only one uplink beacon can be powered at any one time. The 27.505 GHz frequency was selected to avoid interference with the communications signals. The beacon signals were derived from independent local oscillators and, therefore, were not coherent to each other. The beacon antennas provide broad coverage primarily to the continental United States.

ON-ORBIT PERFORMANCE

ACTS was launched on the space shuttle Discovery (STS-51) on the morning of September 12, 1993, and after deployment, the burn of Orbital Sciences' solid rocket stage resulted in placing the spacecraft in a transfer orbit that was within one sigma accuracy. This excellent performance of Orbital's TOS stage maximized the amount of hydrazine for on-orbit operations. A lot of the credit for the new TOS vehicle performance must go to the NASA Marshall Space Flight Center at Huntsville, Alabama which managed its development. The spacecraft arrived at its permanent orbit position at 100 degree West longitude on September 28, 1993. At this time ACTS entered into its pre-operational mission phase which consisted of spacecraft checkout followed by system and communication network checkouts. On December 1, 1993, with the completion of all spacecraft, ground system, and network checkouts, the operations program was initiated. ACTS on-orbit tests have shown that the communications payload and bus performances are in close agreement with the ground test results conducted during spacecraft development and assembly [39, 40, and 41]. After over 6 years of on-orbit operations, ACTS has exceeded its life time requirement, has proved to be extremely reliable, and has lost none of its communications capability.

BASEBAND PROCESSOR (BBP)

The demand assigned processing and routing of individual voice, data, video, and multimedia messages between multiple earth stations via the hopping beams was routinely accomplished by the BBP. Pre-launch reliability models showed the BBP as the overall driver of the communication payload reliability due to its circuit complexity and high parts count.

The payload probability of success was calculated as 0.78 at a 36% duty cycle for two years for 220 Mbps information throughput. No failures have occurred in the BBP except for a single anomaly attributed to a control memory bit latch-up that was cleared by a power recycle.

Testing and experimentation have shown that the spacecraft and the T1 very small aperture terminal (VSAT) ground terminals successfully met design performance specifications and requirements for acquisition, synchronization, timing, and message routing. The acquisition, synchronization, and timing process remained functional in rain fades at 30 GHz of up to 15 dB. Bit Error Rate (BER) performance ranged from better than 1×10^{-11} in clear sky conditions to not less than 5×10^{-7} in 15 dB rain fades when rain fade compensation was enabled.

Data has shown that the ACTS adaptive rain fade compensation successfully provides enhanced link margin automatically as needed [42, 43]. The transitions from uncoded to coded operation and back were accomplished with no loss in throughput and without errors.

The ACTS T1 VSAT employ a terrestrial interface unit that consists of a small programmable central office. This interface supports a variety of Bell standard hardware interfaces to provide seamless interconnectivity into the terrestrial telephone network; an important requirement for satellites operating in future national and global networks (NII/GII). The interface control software has been custom designed to provide protocol conversion between terrestrial circuit connect and disconnect protocols and the VSAT DAMA protocols. Analog voice is encoded by circuit line cards in the terrestrial interface at a rate of 64 Kbps. In addition, an echo canceling device is incorporated into each interface circuit card. This device employs digital signal processing and does an excellent job of eliminating all noticeable echoes. ACTS users found, under these conditions, that " the propagation delay was unnoticeable" for voice calls. Frequently users of ACTS say they do not believe they are talking over the satellite. The fact that the ACTS users have found the satellite delay unnoticeable seems to be contrary to previous experiences for geostationary satellites. We believe the reason for this is that in the past the echo was not consistently eliminated under all conditions and the voice quality was deficient. Extensive laboratory tests have been conducted and they support the conclusion that echo, not delay, is the principal cause of dissatisfaction to users.

The ACTS VSAT user interface also supports the connection of an Integrated Services Digital Network (ISDN) Primary Rate Data Interface (PRI). Operating at 1.544 Mbps, the PRI provides 23 communication channels and one signaling channel. Using this satellite ISDN capability, desk top conferencing quality was equal to that provided by terrestrial ISDN, call set-up times were fast taking only 2 to 3 seconds, multipoint video conferencing was reliably handled with the development of special interface software. Overall, seamless, high-quality, satellite/terrestrial ISDN services were reliably provided. The general conclusion from the ACTS ISDN program is that Basic and Primary rate ISDN can be readily incorporated into future satellite systems.

MICROWAVE SWITCH MATRIX (MSM)

The MSM mode of operation allows the full 900 MHz bandwidth of the transponders to be used with the hopping or fixed beams. Since launch, the Link Evaluation Terminal (LET) located at NASA LeRC has been periodically used to check out the signal paths through the transponder and the MSM. Close agreement has been obtained between the expected and measured values. TWTA output levels have remained steady at approximately 46 watts, providing a peak EIRP of 58-69 dBW depending on the downlink beams. TWTA parameters, as monitored via telemetry, have remained stable with over 44,000 hours (as of October 1998) on each of the three tubes normally used. In addition, no spurious shut downs have occurred. A continuous wave tone, uplinked from LET, was swept across the communication band, showing close agreement with ground test data across the 900 MHz bandwidth.

GIGABIT NETWORK

The ACTS gigabit network provided point-to-point and point-to-multipoint full duplex services using the satellite-switched TDMA capability of the MSM along with the hopping beam network [38]. The network and the associated high data rate (HDR) ground terminals were developed by GTE (formerly BBN) and Motorola under joint NASA and the Defense Advanced Research Project Agency (DARPA) sponsorship. The user interfaces were compatible with Synchronous Optical Network (SONET) standards and were readily integrated with standard SONET fiber-based terrestrial networks. The two rates supported were OC-3 (155.54 Mbps) and OC-12 (622.08Mbps). In addition, asynchronous transfer mode (ATM) communications could be readily run on top of the SONET structure.

The network control and management functions were contained in each HDR earth terminal with the operator's interface being centralized in a portable network management terminal (NMT). The NMT could be located at any HDR earth terminal site or, alternatively, at any location with a terrestrial Internet connection to any HDR earth station designated as the reference station.

Transmissions to the satellite were performed at 348 Mbps or 696 Mbps with staggered or offset BPSK (SBPSK) and staggered QPSK (SQPSK) modulations respectively. Using the 11.5 foot user terminals, the network provided an availability of 99% within CONUS for transmissions at 696 Mbps. All transmissions used a 232,216 Reed-Solomon block error correction code to achieve a BER of 10^{-11}.

ACTS tests and experiments have demonstrated the physical layer compatibility of the satellite SONET implementation with terrestrial SONET equipment and networking. In addition Asynchronous Transfer Mode (ATM) services have been implemented using the SONET structure and have demonstrated seamless satellite/terrestrial ATM services with low BER ($< 10^{-11}$).

MULTIBEAM ANTENNA (MBA)

A number of MBA performance evaluations have been conducted since launch [44]. These tests were designed to evaluate beam pointing stability, beam shape, antenna gain, sidelobes, cross polarization, etc. in the space environment. The test measurements found the MBA performance to be well within the design and pre-launch test range with the exception of beam pointing. Thermal effects created greater than expected pointing errors for the 0.30 degree spot- beams. These on-orbit thermal distortion effects on the MBA can be classified as:

a) Rapidly Varying; and
b) Diurnally Varying.

The Rapidly Varying thermal distortion is caused by non-uniform sun illumination on the front surface of both transmit and receive subreflectors. This thermal distortion causes a large temperature gradient in the front face of the subreflectors resulting in surface distortion on the order of 0.060 inches peak. This in turn produces beam movement or wandering of approximately 0.1 degree. The large subreflector temperature gradients occur for approximately a total of two hours each day and correlate with the rapidly varying beam wandering. Because this large thermal distortion occurs just on the front face of the subreflector, only the east beams are effected.

The Diurnally Varying thermal distortion causes a westward movement of the transmit beams starting at approximately 0200Z - 0400Z each day reaching its maximum of approximately 0.2 degrees at 0800Z and returning to the starting point by 1400Z. It is believed that this variation is caused by thermal expansion of the spacecraft bus which results in an apparent rotation in pitch of the transmit main reflector with respect to the receive reflector which is held fixed to Cleveland by the Autotrack signal.

In addition to these thermal distortions, two MBA non-thermal distortions have been observed. A 1 Hz oscillation distortion affecting all downlink beams is caused by induced mechanical noise on the transmit main reflector. The mechanical noise is generated by tiny step changes in wheel speed of the momentum wheel which cause movement in the transmit reflector around the biaxial drive pivot. The oscillation causes minimum signal variation (< 0.1 dB) at beam center that become large (> 3 dB) at beam edge. The amplitude was measured peak-to-peak to be 0.075 degrees. In addition, yaw errors are introduced by the attitude control system.

Using daily attitude control biasing, the beam pointing errors caused by thermal distortions have been minimized on ACTS so that acceptable communications performance could be achieved throughout the day. The ACTS beam pointing problems do not represent a technology barrier but point out the need for careful thermal and mechanical design for future MBA systems that have narrow spot beams. Since yaw errors can also cause significant MBA signal variations, future spacecraft need to improve the capability for more precise yaw control.

SPACECRAFT POINTING ACCURACY

In addition to thermal stability (see the above section), the MBA pointing performance relies on precise spacecraft pointing. The spacecraft pointing accuracy achieved in roll, pitch and yaw was 0.025, 0.025 and 0.20 degrees or less respectively. Only the yaw accuracy was slightly greater than its design requirement (0.15 degrees). However, this 0.05 degree greater yaw error does not have a significant impact on the MBA performance.

BEACONS

The uplink fade beacon at 27.5 GHz provides an unmodulated uplink band signal to propagationists via another CONUS antenna. The primary uplink fade beacon unit was found to be 4 dB low in RF power output when the system was turned on after launch. The backup unit was turned on in November 1993 and has been satisfactorily operating ever since. Since both beacons are connected to the antenna through a mechanical waveguide switch, the power shortfall may have been caused by a mechanical misalignment of the switch rotor caused by launch vibrations. The investigation into the cause of the problem has been delayed until ACTS reaches its end of life. This has been the only redundant unit brought into service because of a hardware malfunction since launch. The frequency of both the uplink and downlink beacons continues to be very stable, measured as < 1800 Hz diurnal variation and no more than –7400 Hz yearly drift.

SYSTEM RELIABILITY

The ACTS spacecraft payload and subsystems have accumulated over 5 years of on-orbit operations. Other than the switch to the redundant uplink beacon shortly after launch, as previously mentioned, all other systems and subsystems functioned with their primary units. The new switching and processing advanced technology units performed well after year-round, 24-hour-per-day operations. The MBA, while providing satisfactory RF links has revealed the need for careful thermal design to prevent spot-beam motion.

The ACTS overall success is attributed to extensive design analysis performed by the NASA-Industry teams and a rigorous ground test program. Future system operators of ACTS-type commercial satellites should feel confident that they can be put into service with acceptable risk.

CHAPTER 3

Terminal Equipment

Ka-band satellites represent the biggest single change to the VSAT industry since it began in the mid-'80s. There are two principal reasons. First, unlike the traditional, bent pipe satellite, Ka-band satellites will eventually be configured with onboard switching, eliminating the need to create private networks using a customer owned or shared hub terminal. The Ka-band satellite is the system which can potentially let the consumer go out and buy a VSAT, point it at the satellite and be on the network in a short time.

The second reason is that Ka-band geostationary satellites allow terminal sizes to be reduced to approximately 2 feet for an uplink TDMA burst rate of 384 Kbps using a single-device, 1-watt, 30 GHz power amplifier and a downlink TDM rate of 90 Mbps. With this size terminal, costs are further reduced, but more importantly, the installation can be readily made without significant facility modifications or municipal government objection, which is necessary in order to address the consumer or mass market. To reduce the cost of a VSAT below a $1,000, the number of units in an order need to be between 100,000 to one million units. Orders for VSATs today are in the range of 10,000 or less which really doesn't allow the use of high volume production techniques.

It should be realized that the spot-beam techniques used on ACTS can be applied at any RF frequency. However, the use of narrow spot-beams systems at many frequencies is not possible because they would interfer with existing satellite systems. For instance, it would be highly desirable to use ACTS type technologies at Ku-band whose frequencies impose significantly less rain attenuation than at Ka-band. This is not possible for GEO Fixed Satellite Services, but the SkyBridge LEO system is doing so.

ACTS TERMINALS

An integral part of the ACTS program has been to demonstrate the wide variety of services that can be provided using Ka-band, spot-beam satellites. Described in this chapter are the ACTS terminals and their operational performance. ACTS terminals were developed for Fixed Satellite Services, Mobile Satellite Services, Propagation Measurements and Network/Satellite Control.

Since the ACTS is only a test bed to prove out the technology, the number of terminals produced was very limited. As a result, low-cost, high-volume production techniques were not used in the manufacturing of the terminals. However, the ACTS terminal program demonstrates how on-demand, interactive, integrated services can be provided using very small aperture terminals that have the potential to be produced at low cost. Since the commercial ACTS type satellites will support a large number (approaching a million per satellite) of terminals, they will be produced in high volumes similar to that for consumer electronics.

FIXED SATELLITE SERVICE TERMINALS

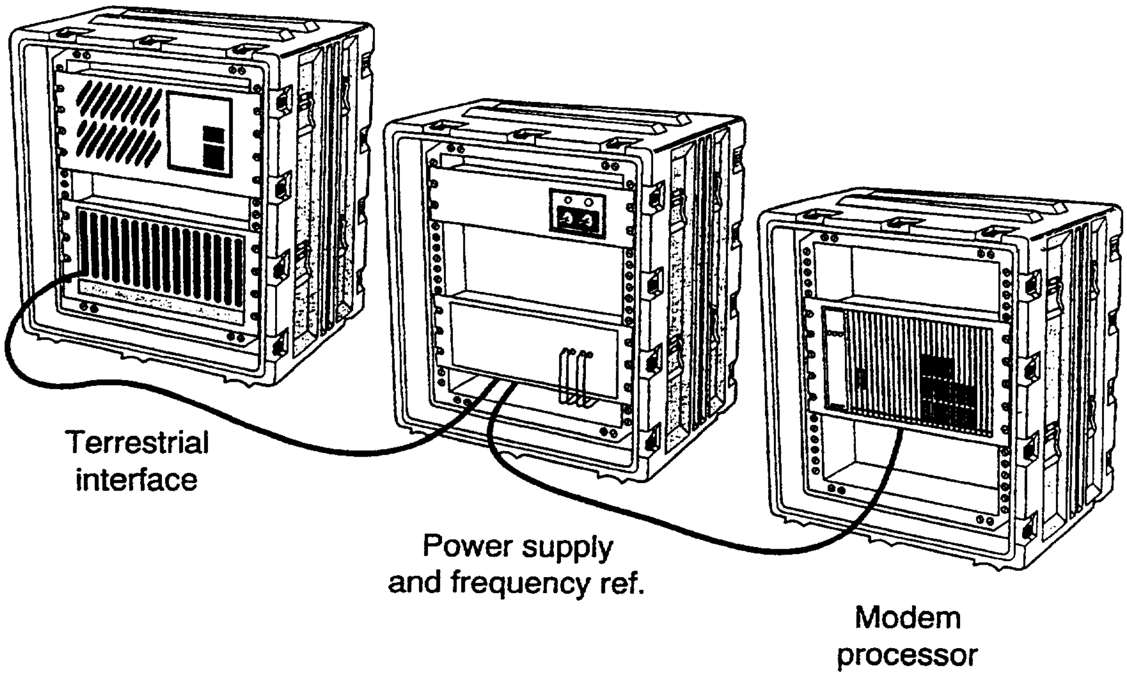
The three fixed satellite service terminals for ACTS are the 14 inch Ultra Small Aperture Terminal (USAT), the 4 foot T1-VSAT and the 11 foot High Data Rate (HDR) terminal. Both the USAT and VSAT are small terminals that can be easily sited on the users' premises. The USAT operates in a fixed-beam, FDMA access mode through the spacecraft microwave switch matrix with two-way communications provided between the USAT terminal and the 15 foot Link Evaluation Terminal (hub station) located in Cleveland, OH. The T1-VSAT is configured to operate in the ACTS' TDMA demand-assigned multiple access (DAMA) environment using the on-board baseband processor (BBP) and hopping beams at data throughputs up to 1.792 Mbps. The HDR uses the microwave switch matrix (MSM) and hopping beams at data throughputs up to 622 Mbps.

T1-VSAT TERMINAL

The ACTS satellite uses two narrow hopping beams at a frequency of 19.4 GHz on the downlink and two beams at 29.2 GHz on the uplink to create the T1-VSAT network. Data from the satellite is burst modulated on the downlink at a rate of 110.592 Mbps uncoded and 55.296 Mbps coded. On the uplink, the terminal burst rate is 27.648 and 13.824 Mbps for uncoded and coded bursts, respectively. Coded operation is used for a downlink reference burst sent at the beginning of each dwell to all terminals and for those uplink and downlink traffic bursts suffering significant rain fade. The satellite beams are electronically hopped between all locations during a 1 ms TDMA frame. During each 1 ms frame, user data is collected from and delivered to each terminal, along with orderwire information that controls the terminal access to the network. The Master Control Station (MCS) handles the coordination and control of the network. The T1-VSAT was developed by the Harris Corporation [47] to function automatically without operator intervention and provide two-way circuits in 64 Kbps channel increments up to a maximum of 28 channels (1.792 Mbps). In many ways the terminal resembles the current generation of Ku-band VSATs. Some unique features are described below.

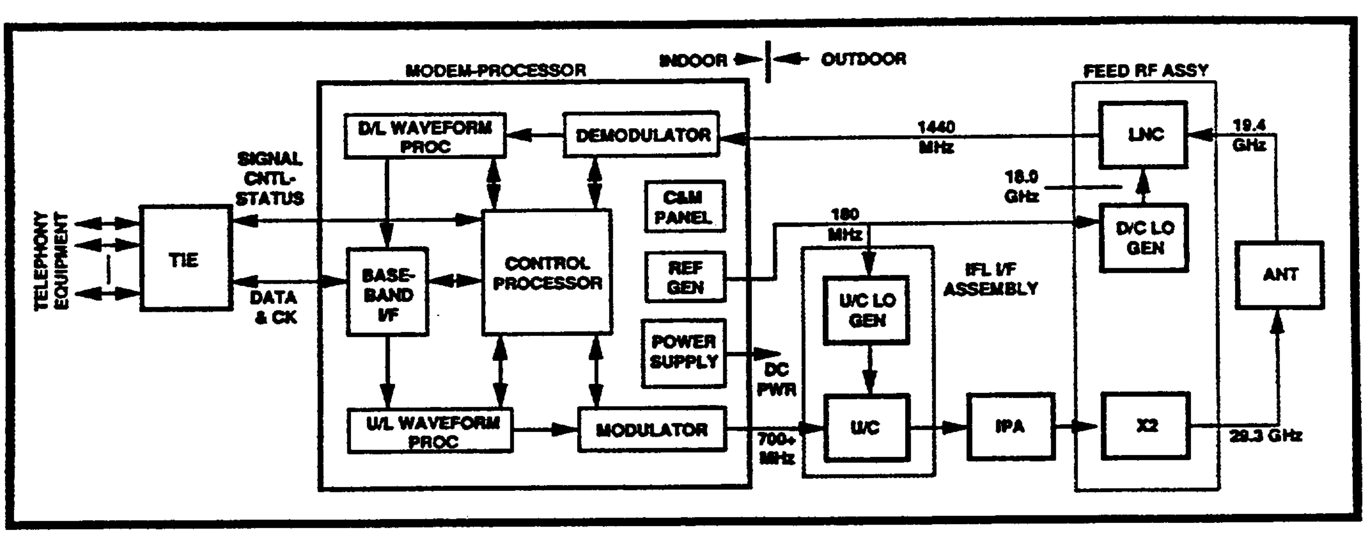
30 GHz TRANSMITTER: The outdoor unit contains the up and down converters, the low noise amplifier, the transmitter and 4 foot offset fed parabolic dish. Prodelin made the antenna. For low link margin areas such as those provided by the spacecraft's mechanically steered antenna, an 8 foot antenna is used. The most direct approach for the transmitter would utilize a 30 GHz solid state or traveling wave tube amplifier to provide the necessary gain and power. At the time of the development of the terminal, Ka-band commercial activity was non-existent so those 30 GHz power amplifiers represented a significant development effort and cost. As a result, the solution chosen was a solid state frequency doubler driven by a 50 Watt Ku-band traveling wave tube amplifier to produce an output power of 12 Watts and a total gain of 45 dB. The frequency doubler consisted of a power divider, four frequency doubling microwave diodes and a power combiner.

ACTS – Indoor Unit for T1-VSAT



Technology has progressed sufficiently so that today a total solid state amplifier is the best choice. This is demonstrated by the fact that commercial Ka-band systems under development are taking the solid state approach for 10 Watt output power. To reduce the need for costly high power amplifiers, the terminals for the current Ka Band systems transmit in a continuous stream, rather than the bursty TDMA approach used by ACTS.

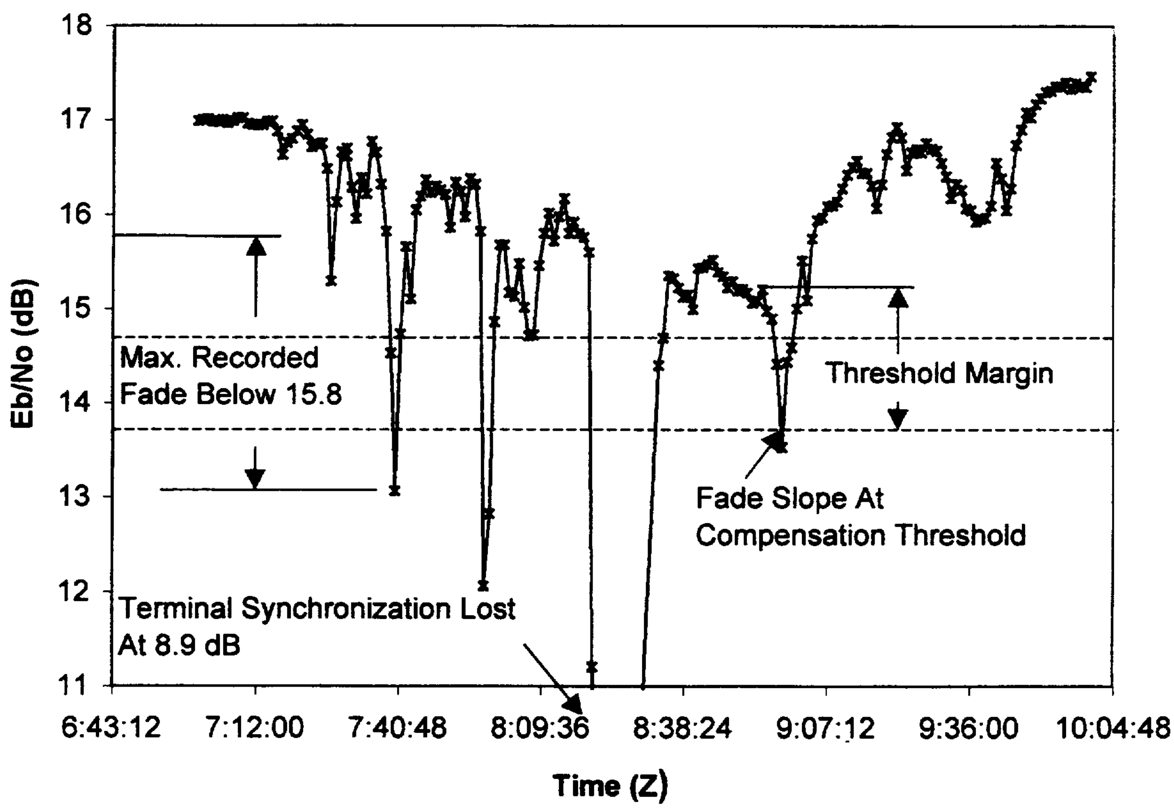
T1-VSAT Functional Block Diagram



ADAPTIVE RAIN FADE COMPENSATION: Spacecraft/VSAT link design is based on the requirement that uplink Bit Error Rate (BER) performance shall not degrade below 5 x 10^{-7} in rain fades of up to 15 dB (the end-to-end BER requirement is 1 x 10^{-6}). To meet the fade requirement the links were designed with fixed 5 and 3 dB of uplink and downlink signal margin, respectively, and to use adaptive rain fade compensation. The ACTS adaptive rain fade compensation is the process whereby a VSAT's data channel BER performance is automatically enhanced by burst rate reduction and error correction coding during a period of signal fade due to rain attenuation. The protocol is adaptive in that it includes a decision process so that fade compensation is implemented only when needed. This allows the sharing of the small pool of spacecraft decoding capacity among terminals in all beams.

When a terminal experiences a rain fade exceeding the compensation threshold setting, the uplink and downlink burst rates are automatically reduced in half to 13.75/55.0 Mbps. and the affected burst is coded with a rate 1/2 convolutional code. This rain fade compensation provides 10 dB of additional link margin that results in average service availability in the US of 99.5%. When the fade decreases enough to cross a cessation threshold, the coding is removed and the transmission burst rate is restored to its non-faded value. During this process there is no interruption to the user's service.

20 GHz rain Fade for VSAT # 7 at Clarksburg, MD on 1/20/95



Because the area covered by a spot beam is 120 miles in diameter, only a portion of the user terminals within that area will generally encounter significant rain fades. Therefore, the fade for each terminal is sensed individually.

SEAMLESS SATELLITE/TERRESTRIAL NETWORK: The VSAT terrestrial interface is a commercial, off-the-shelf Redcom Modular Switching Peripheral (MSP). The MSP is a small programmable central office, which is configured by the user with plug-in cards. The MSP supports a variety of Bell Standard hardware interfaces. Its control software has been custom designed to provide protocol conversion between the terrestrial the VSAT network protocols thus enabling the **seamless, on-demand, integrated voice, video and data services.** Clock rate difference between terrestrial circuits and the space segment are absorbed by elastic (plesiochronous) buffers at the input and output ports to the TDMA processor. The MSP control software supports full mesh voice services with Automatic Number Location protocols, full and fractional Tl services, National Communications System priority services and ISDN services.

T1-VSAT OPERATIONAL PERFORMANCE

Nineteen T1-VSATs including seven ruggedized units for the US Army have been installed and operated throughout the United States, Colombia, Brazil, Equador and Haiti. The VSATs met all requirements for providing on-demand, integrated services as is described in Chapters 2, Spacecraft Technology. Discussions here center on some unique aspects introduced by on-board switching.

PRELAUNCH USER TERMINAL, SPACECRAFT AND MASTER CONTROL SYSTEM TEST: The ACTS BBP operation represents a new mode of operation in which the user terminals, the spacecraft and the master control station are all required to meet a complex set of network and TDMA protocols. Prior to launch, a combined user terminal, spacecraft and master control station system test was performed for over three months on a two-shift per day basis to debug the software and hardware systems. This system test, which uncovered many problems prior to launch and is not normally done with a bent pipe transponder spacecraft, proved to be invaluable. Many of the problems uncovered during the test were fairly easily fixed on the ground, but would have been much more difficult to diagnose and fix after launch. The first time after launch that the BBP operation was initiated, user terminals successfully acquired the network and provided services. This was an amazing accomplishment considering the complexity of the BBP communications system that requires nanosecond timing coordination between the hopping beams, the BBP, the user terminals and the master control station.

USER TERMINAL TO SPACECRAFT TIMING: The timing accuracy required for a 27.5 Mbps TDMA burst to arrive at the spacecraft is +/- 60 nanoseconds or approximately +/- 2 bit times. This timing accuracy is needed to enable on-board switching at each individual 64 bit word (64 Kbps circuit) boundary. The timing is accomplished by using a very accurate spacecraft clock and having the BBP continually feeding back to each user terminal whether or not their bursts are being received late or early. With the simple BBP early/late feedback, a timing accuracy less than this requirement is readily met. The commercial BBP systems under development have TDMA uplink burst rates of T1 (1.544 Mbps) or less. With these lower burst rates, the ACTS timing accuracy is adequate to perform operations whereby the normal burst preamble for bit and unique word synchronization can be eliminated increasing the communications efficiency.

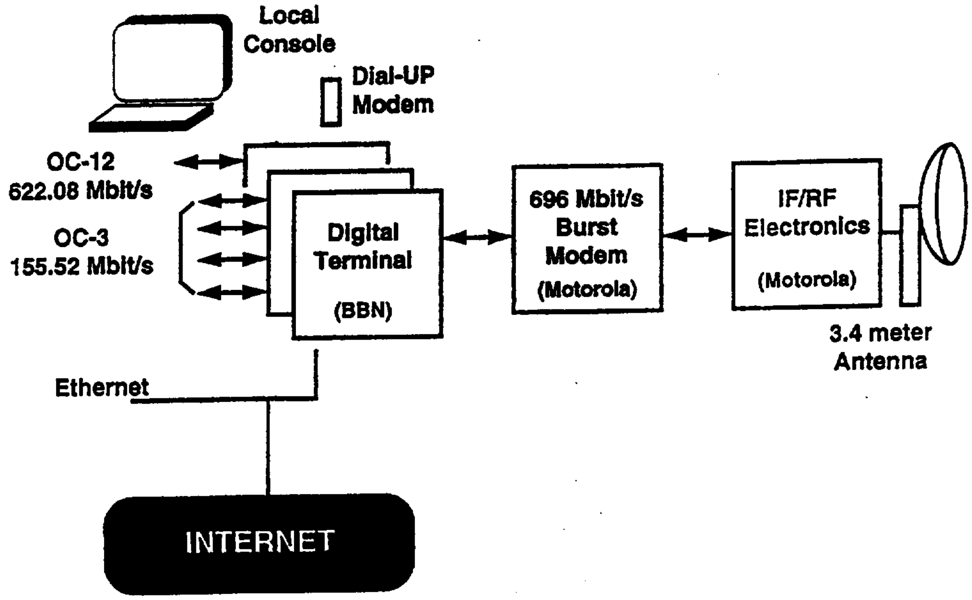
ADAPTIVE RAIN FADE COMPENSATION PERFORMANCE: The results of the ACTS adaptive rain fade compensation are very significant for future commercial Ka-band systems. Many of the new Ka-band commercial satellites use many low rate uplink channels which are digitally demultiplexed, demodulated and decoded on-board the satellite prior to switching at baseband. These new satellites normally use fixed satellite link margins with a concatenated error correction code consisting of a convolutional inner code and a block outer code to achieve the desired BER with a reasonable availability. However, decoding of the convolutional inner code increases the processing cycles per second and power in direct proportion to the code rate. For ACTS this is a factor of two. Therefore, adaptively including the convolutional code on only those few transmission that are encountering significant rain fade (this is the approach taken on ACTS) can save significant spacecraft power.

Analysis of many rain fade events for ACTS T1-VSATs has been performed [21] and shows that the adaptive rain compensation system is very reliable. In no case did the system fail to successfully implement the fade compensation once the fade implementation threshold was crossed. With ACTS it takes about one second to implement the compensation from the time the threshold is penetrated. During the one-second implementation period, even the most severe rain increases the fade by less than 0.1 dB. Once the rain compensation is incorporated, the total link margins available are nominally 15 and 13 dB, respectively, on the 30 GHz uplink and 20 GHz downlink. For most fades the end-to-end BER is maintained at less than the requirement of 1×10^{-6}. In the US, the 15/13 dB link margins are adequate to maintain the BER at or below 1×10^{-6} for 99.5 % of the time.

HIGH DATA RATE (HDR) TERMINAL

Combining its high-gain hopping beams, wideband transponders and microwave switch matrix, the ACTS satellite has the capability to support a gigabit satellite network (GSN). The HDR terminal development by BBN Systems and Technologies, Cambridge, MA and Motorola Government and Space Technologies, Chandler, AZ was sponsored jointly by NASA Lewis Research Center and the Computing Systems Technology Office of the Defense Advanced Research Projects Agency (DARPA) to create such a network [38]. The GSN system requirements include SONET compatibility, user throughput up to 622 Mbps, limited terminal transportability, and full mesh network connectivity using satellite switched time division multiple access (SS-TDMA). The satellite network, which from the end-users point of view has been designed to replicate the functions of terrestrial SONET-based fiber networks, has been described in Chapter 2.

The HDR terminal was designed to fit into a trailer (approximately 20'L x 8'W x 10.5'H). The bulk of the trailer is used for storage of the 11 foot antenna and waveguide. A small air-conditioned compartment in the front of the trailer houses the electronics. The actual set-up of the ground station (including connection to electrical service and data networks) requires on the order of four days.



The indoor (inside the trailer) electronics consist of the digital terminal, the burst modem, the up and down converters and the preamplifier and power supply for the 100 Watt, 30 GHz TWTA. The actual TWT is mounted outdoors on the antenna boom. Waveguide, power and control cables are run through a trailer bulkhead, into a raceway, out to the antenna. The decision to put the majority of the electronics inside and to use waveguide to and from the antenna was a compromise between providing climate-control for the electronics versus dealing with problems introduced by the long waveguide run.

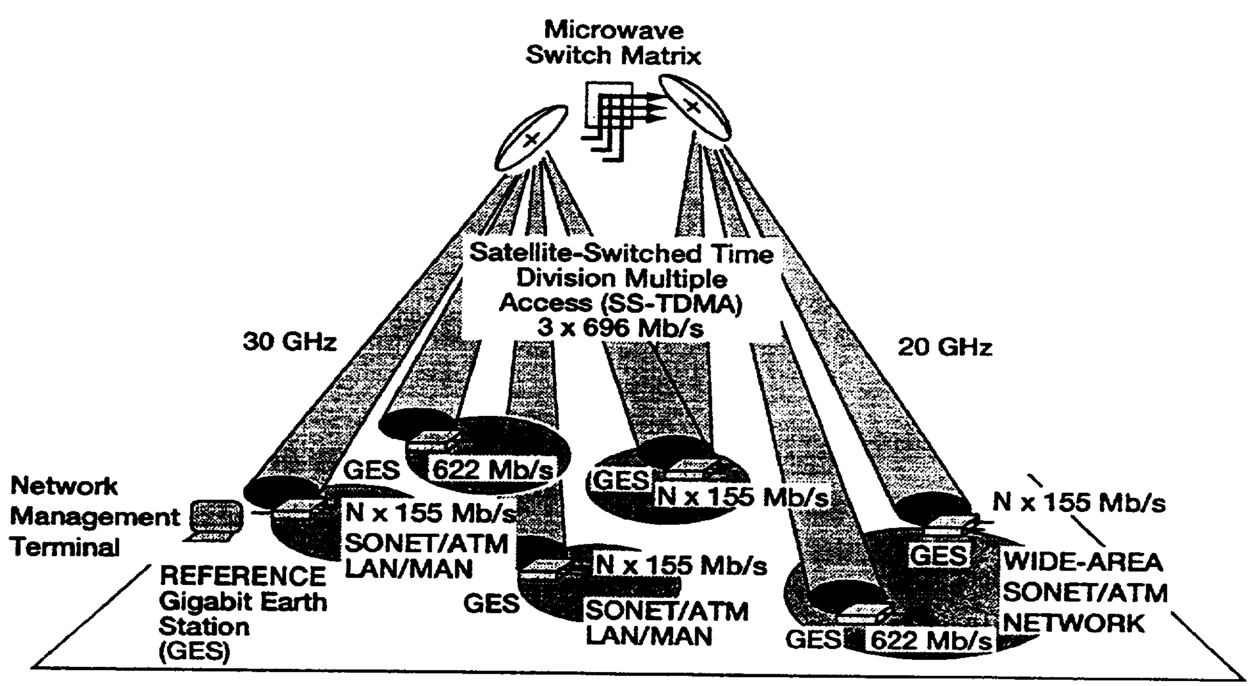
The digital terminal used to control each HDR terminal supports SS-TDMA transmissions, and provides over-the-satellite cross-connect SONET switching capability. TDMA bursts are constructed as a sequence of satellite cells preceded by a short preamble. Each satellite cell is composed of 648 bytes of data and 48 byte Reed-Solomon checksum. The satellite cells contain a fixed number of bytes and are either 8 or 16 microseconds in duration depending on whether the burst rate is 696 or 348 Mbps. The length of each burst is in multiples of the 32 microseconds slot period. The difference between the burst rate of 696 (or 348) and the user rate of 622 (or 311) is due to TDMA overhead and the incorporation of Reed-Solomon 232/216 block coding to achieve a 1×10^{-11} BER. Bursts arrive at ACTS phase locked to the 1000 slot space-time-switching plan (32 millisecond frame). Tight synchronization of all HDR terminals to the satellite's on-board switching and beam hopping plans allows very short guard time between bursts and simple satellite tracking.

DEVELOPMENT RISKS: The principal technical risks for the HDR terminal development were associated with the 696 Mbps burst rate. This rate presented significant challenges for the burst modems and the digital processor. The architecture and design approach for the digital processor is provided in [49].

The key modem technology developed for the ground station included the fast acquisition circuitry for the AGC, carrier and clock recovery [38]. The final preamble length achieved for the TDMA bursts is 1 microsecond.

The extreme hard-limiting and finite (albeit large) bandwidth of the ACTS transponder presented difficulties in the implementation of the modem. The hard-limiting was incorporated into the transponder channel to equalize the levels of signals in the ACTS Microwave Switch Matrix (MSM). The intent of this was to reduce the effect of leakage between channels, due to the finite isolation of the switch FETs used in the MSM. The bandwidth of the spacecraft channels is reasonably flat over about 800 MHz, and rolls off rapidly beyond. Inter-symbol interference distortion due to hard limiting can be minimized by the use of constant-envelope modulation. This was demonstrated in the use of 220 Mb/s modulation in the Link Evaluation Terminal [50]. For the HDR modem, staggered modulation was selected and filters were made as wide in bandwidth as possible, in order to provide a close-to-constant envelope.

ACTS Gigabit System Schematic



A further source of inter-symbol interference was the long (36 feet) waveguide runs to and from the antenna, which are responsible for group delay variations of almost 3 nsec across the downlink band (19.2 to 20.0 GHz), and approximately 2 nsec across the uplink band (29.0 to 29.8 GHz). There is a considerable deterioration in inter-symbol interference when using SQPSK at the 696 Mbps rate. The group delay variation is remedied with RF equalizers on both the uplink and downlink. Each equalizer consists of a cascade of three waveguide bandpass filters, designed to provide complementary group delay to that of the waveguide.

ULTRA SMALL APERTURE TERMINAL (USAT)

Commercial Ka-band satellites with on-board baseband switching being developed have terminal uplink rates ranging from 128 to 384 Kbps and downlink rates on the order of 30 to 90 Mbps. One of the benefits of on-board baseband switching is that the uplink and downlink rates can be asymmetric allowing, for example, video broadcast on the downlink and low rate data on the uplink for single hop communications. This results in a small terminal with a 20 GHz wideband receiver and a low-power, low-cost 30 GHz solid state transmitter. The NASA Lewis Research Center developed the USAT to demonstrate the potential capability of future commercial Ka-band satellite systems with this type of terminal.

The USAT consists of a 14 or 24 inch offset fed antenna manufactured by Prodelin, 30 GHz solid state power amplifiers ranging from ¼ to 4 Watts (the ¼ and 1.0 Watt were developed by LNR), 4.0 dB noise figure receivers by Miteq and Electrodyne, a 70 MHz user interface, and the necessary up and down converter equipment for frequency translation to Ka-band [51]. Ten were assembled using commercially available components. All components, such as the receiver, are constructed using piece parts at a low level of integration. In the future, a large number of this terminal type will be produced for commercial systems using application specific integrated circuits (ASIC) and monolithic microwave integrated circuits (MMIC) to reduce cost.

MOBILE SATELLITE SERVICE TERMINALS

Three different types of mobile terminals have been developed for use with ACTS. Each type is classified according to its antenna: a rotating reflector, a mechanically steered slotted wave guide and a phased array. The terminals were used in numerous land vehicle, ship and aircraft operations described in Chapter 4. Even with the ACTS narrow spot beams with gains in the neighborhood of 50 dBi, the mobile terminal antennas must have significant EIRP to provide satisfactory low data rate (2.6 Kbps) communications. As a result, personal communications using a hand-held terminal with an omni antenna is not feasible for ACTS and was not attempted. All these terminals operate in a fixed-beam, FDMA access mode through the microwave switch matrix with two-way communications provided between the mobile unit and a 4 to 18 foot hub station.

ROTATING REFLECTOR TERMINAL

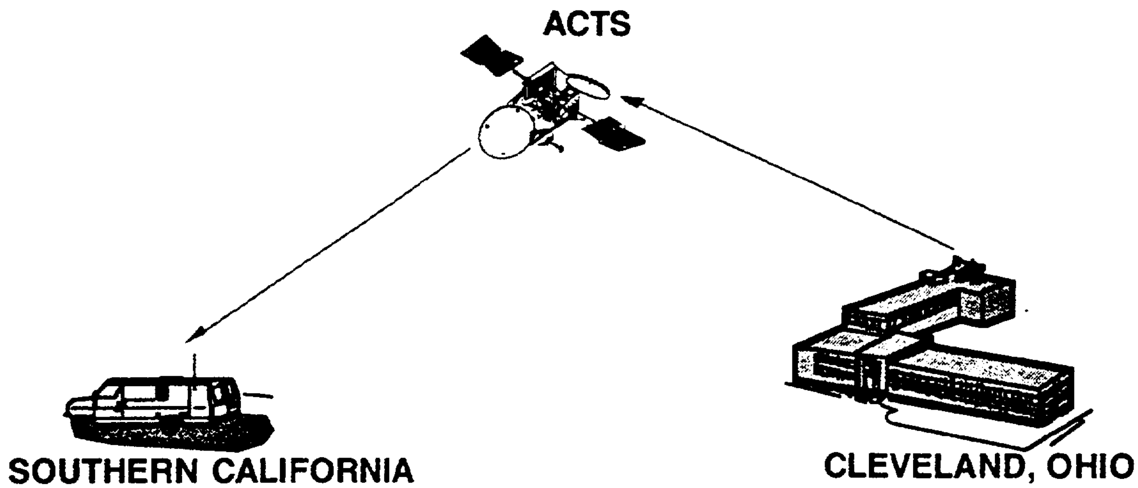
This mobile terminal was primarily used in conjunction with a land vehicle to communicate through the satellite with a fixed hub terminal and was developed by the Jet Propulsion Laboratory [52]. Using frequency division multiple access (FDMA), an unmodulated pilot signal is transmitted from the fixed station to the mobile terminal user through ACTS. The pilot is used by the mobile terminal to aid in antenna tracking and as a frequency reference for Doppler offset correction and pre-compensation. For system efficiency, the pilot signal is only transmitted in the forward direction. Hence for the setup for this terminal two signals exist in the forward direction, the pilot signal and the data signal. In the return direction (mobile terminal-to-ACTS-to-fixed station) only the data signal is transmitted. Operational data rates for this mobile terminal are nominally 2.4, 4.8, 9.6, 64, and 128 Kbps.

The antenna is the critical Ka-band technology item developed as part of this terminal design. A "passive" elliptical reflector-type antenna is used in conjunction with a separate high power amplifier (TWTA with 10-Watts output RF power) to produce a "fan beam". The antenna provides a minimum EIRP (on boresight) of 23 dBW, a G/T (also on boresight) of -5 dB/°K, and a bandwidth of 300 MHz. The maximum EIRP possible is 30 dBW. The reflector resides inside an ellipsoidal water-repelling radome of outside diameter approximately 8 inches (at the base) and a maximum height of approximately 4 inches.

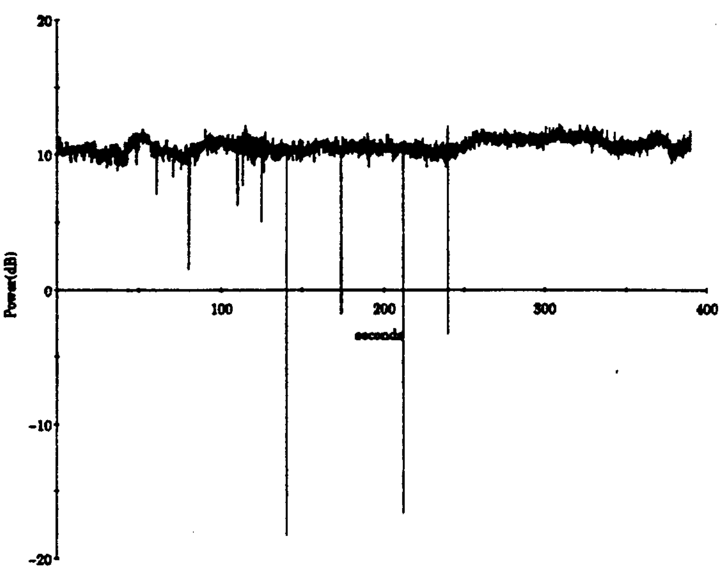
The antenna pointing system enables the antenna to track the satellite for all practical vehicle maneuvers. This antenna is mated to a simple, yet robust, mechanical steering system. A scheme wherein the antenna is smoothly dithered about its boresight by about a degree at a rate of 2 Hz is used. The pilot signal strength measured through this dithering process is used to complement the inertial information derived from a simple turn rate sensor. The combination of these two processes was designed to maintain the antenna aimed at the satellite even if the satellite is shadowed for up to ten seconds. This mechanical pointing scheme is one of the benefits of migration to the Ka-bands. The considerably smaller mass and higher gain achievable relative to L-band make the mechanical dithering scheme feasible and obviate the need for additional RF components to support electronic pointing. The necessary processing resides in the antenna controller.

The baseline modem implements a simple, yet robust differentially coherent BPSK (DPSK) modulation scheme with rate 1/2, constraint length 7 convolutional coding and interleaving. This choice of modulation scheme was mostly dominated by concerns over the performance impact of phase noise on-board the satellite. The performance specification of the modem is a bit error rate of 1×10^{-2} at an E_b/N_0 of 7.0 dB in an AWGN environment including modem implementation losses. Essential to the modem design is a built-in robustness to deep short-term shadowing. The modem 'free-wheels,' i.e., does not loose synchronization through signal outage caused by roadside trees and will reacquire the data after such a drop out. The modem has also been designed to handle possible frequency offsets due to Doppler and other frequency uncertainties on the order of 10 kHz changing at a maximum rate of 350 Hz per second.

Baseline AMT System Performance Test Configuration



ROTATING REFLECTOR TERMINAL PERFORMANCE: The mobile terminal was tested in a fixed position using ACTS to determine how well its demodulator and decoder performed. A bit error rate of 10^{-3} was achieved at an E_b/N_0 of 6.8, 6.7 and 8.5 dB, respectively, for data rates of 9.6, 4.8 and 2.4 Kbps. It was known well in advance of any tests that significant signal fading or blockage would occur due to obstructions from buildings, utility poles and trees. Moving vehicle tests verified the ability of the antenna system to successfully "free wheel" between deep fade or blockage periods experienced in a suburban area. When an obstacle shadows the satellite line-of-site for a period greater than 30 seconds, such as when driving behind a building, the antenna loses alignment with the satellite. When the obstacle is cleared from the satellite view, the antenna automatically re-initiates signal acquisition.



Typical JPL Propagation Data From Interstate Test Route

Although the JPL terminal was primarily used for demonstrating applications (see Chapter 4), propagation data was taken using the ACTS Mobile Terminal [53]. Johns Hopkins University and the University of Texas also prepared a mobile ground vehicle solely for the purpose of collecting propagation measurements at 20 GHz using the ACTS steerable beam antenna. Extensive propagation data was collected in Maryland, Texas and Alaska [54] and is reported in Chapter 5.

MECHANICALLY STEERED SLOTTED WAVE GUIDE TERMINAL

The ACTS Broadband Mobile Terminal was developed by NASA's Jet Propulsion Laboratory together with various industry/ government partners to investigate high data rate mobile applications of ACTS technologies [52]. The terminal was used on a C-141, a Saberliner 50 aircraft, an Army HMMWV vehicle, an oil exploration ship, and the USS Princeton. These operations demonstrated the viability of Ka-band aeronautical and mobile satellite communications at Tl data rates. Currently available commercial aeronautical satellite communications systems are only capable of achieving data rates on the order of tens of kilobits per second. The use of the Ka-band for wideband aeronautical communications has the advantages of spectrum availability and smaller antennas, while eliminating the drawback of this frequency band, rain attenuation, by flying above the clouds the majority of the time.

The heart of the broadband mobile terminal is the mechanically steered slotted waveguide antenna. This high gain mobile antenna employs an elevation over azimuth pointing system to allow it to track the satellite while the aircraft, vehicle or ship is maneuvering. EMS Technologies, Inc developed the antenna and radome. The antenna design utilizes two slotted waveguide arrays and is mechanically steered in both azimuth and elevation. The polarizer in front of each array achieves the required circular polarization.

The antenna radome was designed for low RF loss with the mechanical integrity to withstand the aerodynamic loads of a jumbo jet. The radome is shaped with a peak height of 6.7" and a 27.6" diameter; roughly the size of the SkyRadio radome currently flying on United Airlines and Delta Airlines aircraft. Antenna installation requires a 3.5'' diameter protrusion into the fuselage to allow the necessary signals to pass to and from the antenna.

The antenna is capable of tracking a full 360 degrees in azimuth and –50 degrees to zenith in elevation. The antenna has a transmit gain of 30 dBi and a receive sensitivity (G/T) of 0 dBi/°K which are greater than those for the rotating reflector terminal described earlier. The actual dimensions of the transmit and receive array apertures are each approximately 4" x 8", and the arrays are approximately 0.5" thick. The polarizers add another 0.3" to the total antenna thickness.

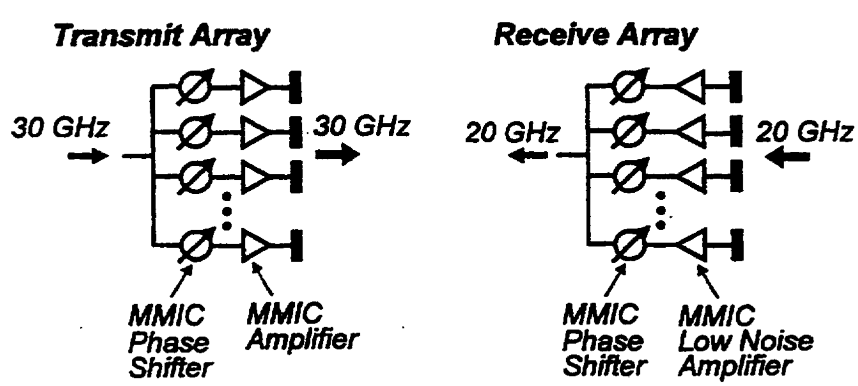
The antenna tracking mechanism was required to maintain pointing within 0.5 dB of beam peak throughout all phases of flight. The antenna positioner utilizes the elevation-over-azimuth mechanism with a precision of a few hundredths of a degree. This positioner is controlled by a tracking algorithm that utilizes three sources of information, a three-axis inertial rate sensor (IRS), an Inertial Navigation System input, and pilot signal strength feedback from a conical scanning of the satellite spot-beam. The IRS with 50 Hz bandwidth and mounted on the main antenna assembly provides the majority of pointing information for the tracking system. The overall tracking system accommodates tracking rates up to 60 degree/sec and 30 degree/sec/sec in azimuth, and 30 degree/sec and 15 degree/sec/sec in elevation The transmit side of the array is powered by a 120 Watt TWTA so that high rate data can be both transmitted as well as received.

MECHANICALLY STEERED SLOT WAVEGUIDE TERMINAL PERFORMANCE: Rockwell Collins outfitted a Saberliner aircraft with the terminal and performed various tests to determine how well the antenna system tracked the spacecraft for normal maneuvers. From the period starting with taxiing on the ground prior to take-off, followed by ascent including banking and ending at cruise altitude, the aircraft's received pilot signal-to-noise ratio peak-to-peak variation was less than 1.5 dB. This performance was judged to be quite good.

ACTIVE PHASED ARRAY TERMINAL

Active phased array antenna systems hold great promise to meet the demands of future satellites whereby a beam(s) can be rapidly steered to any location. For mobile or fixed-LEO user terminals they offer the additional potential advantage of being a slim flat plate shape or contoured to fit the surface of a vehicle or aircraft. To date, most success in active arrays has occurred at frequencies lower than the Ka-Band. A cutting-edge technology effort was undertaken by the NASA Lewis Research Center and the Air Force to develop 30 and 20 GHz GaAs MMIC devices that could form an active phase array antenna.

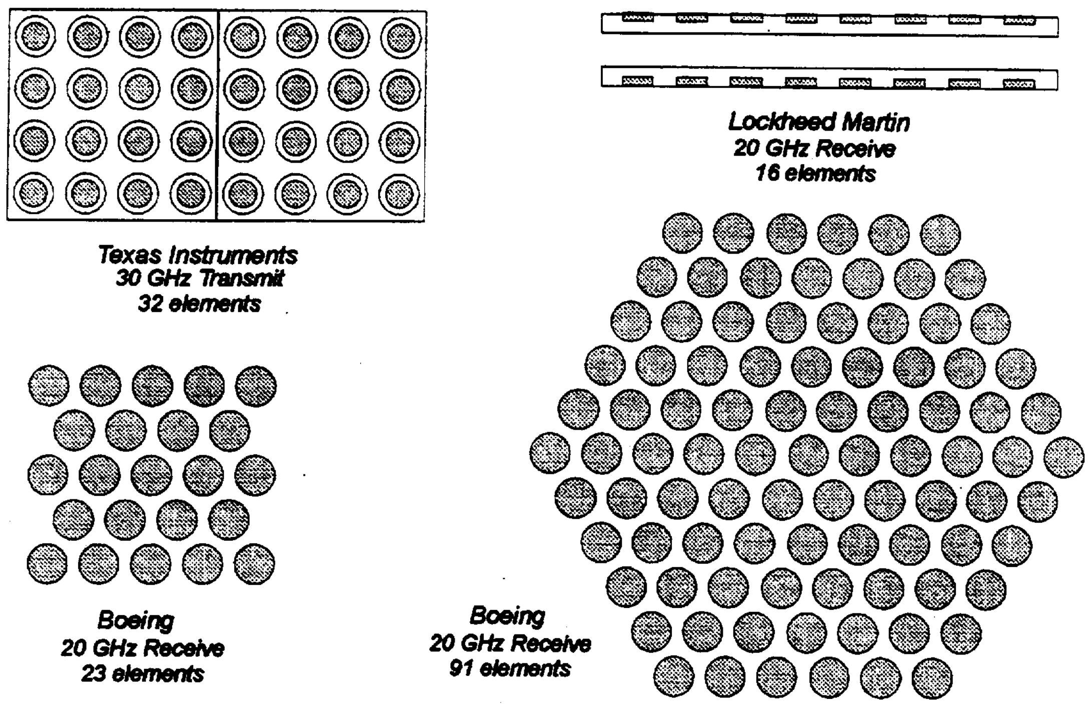
MMIC Phased Array Configuration



Each transmit element consisted of a separate 30 GHz MMIC phase shifter followed by an amplifier. Each receive element consisted of a separate 20 GHz MMIC low noise amplifier followed by a phase shifter. A single 30 GHz transmit array was developed by NASA Lewis Research Center and Texas Instruments. Three 20 GHz receive arrays were developed in a cooperative effort between the Air Force Rome Laboratory and

NASA and took advantage of existing Air Force array development contracts with Boeing and Lockheed Martin (previously General Electric). These active phased array antenna systems were mounted on ground vehicles and aircraft to demonstrate their capability to provide voice, video and data links through ACTS to a fixed hub terminal. Because the array antennas were limited in extent and experimental, these developments can be considered as an initial step toward the eventual development of practical systems for Ka-Band application.

Array Radiating Element Geometry – Actual Size



TEXAS INSTRUMENTS 30 GHz TRANSMIT ARRAY: The Texas Instruments (TI) 30 GHz transmit array has a total of 32 elements and consists of two 16 element 4 x 4 modules mounted in a protective experimental housing [55, 56]. The TI approach features a thin "tile" architecture in which the components are mounted in a plane perpendicular to the antenna boresight. Each of the two 16 element sub-array modules is 3.2 cm x 3.2 cm x 0.75 cm thick. The array element spacing of 0.8 of a wavelength supports scanning up to $\pm 30^0$ without grating lobes. The module design is based on a hybrid integration approach in which conventional wire bonding is used for interconnecting MMIC devices to the signal distribution layers.

Sixteen RF lines each feed a 4-bit MMIC pin diode phase shifter of switched line length type and a three-stage 100 mW PHEMT power amplifier and is electromagnetically coupled to a cavity backed, aperture coupled circular patch element. Logic commands for selection of individual phase bits and amplifier drain bias control (on/off) are transmitted via a serial data bus to a custom application specific integrated circuit (ASIC) which converts the serial data to parallel data for simultaneous control of the MMIC devices. A thermoelectric cooler and a small fan in the antenna housing provide thermal stability.

The measured output power for each MMIC power amplifiers is approximately 100 mW with 20 dB gain. For the subarray module, the roll-off in gain as a function of scan angle was measured to be less than 3 dB over a 30 degree scan angle. At boresight, the measured EIRP for the array is 23.4 dBW.

20 GHz RECEIVE ARRAYS: Although the Lockheed Martin and Boeing designs involve fundamentally different packaging concepts, both use a "brick" architecture in which the active components are mounted in modules parallel to the boresight of the radiating elements. The radiating elements have a nominal ½ wavelength separation supporting scanning to $\pm 60^0$ without grating lobes.

BOEING 20 GHz RECEIVE ARRAY: The small 20 GHz receive array built by Boeing is a "brick" architecture, but uses a different design concept than Lockheed. The array consists of a cluster of 23 active channels on a triangular grid with a half wavelength separation. Each channel is a separate dielectrically loaded circular waveguide into which a MMIC LNA and 4-bit phase shifter are inserted. The LNAs initially has a gain of 18 dB and a 9 dB noise figure. In addition to the active components, each module has DC circuitry and a logic chip for phase shifter control. In this array, the RF outputs of the 23 channels are combined in a multi-mode space feed. No active cooling is provided. The measured G/T of the array is -16.6 dB/^{0}K at boresight.

The large Boeing 20 GHz receive array which consists of 91 elements is essentially a larger (more elements) version of the 23 element array but it has significantly improved RF performance. The LNA devices used in this larger array have a noise figure of 2.5 dB. As a result, the measured G/T is –4.5 dB/degree K at boresight and –9.2 at a 70^0 scan angle.

LOCKHEED MARTIN 20 GHz RECEIVE ARRAY: The small 20 GHz receive array built by Lockheed Martin consisted of 16 dipole antenna elements arranged on a 2 x 8 rectangular grid with half wavelength separation. Two plug-in cards or trays each having 8 active receive channels form the array. Each active channel consists of a printed circuit dipole antenna connected by microstrip to a PHEMT low noise amplifier and a GaAs 3-bit phase shifter. Each channel has a logic chip for phase shifter control. The overall gain of each channel is 23 dB with a noise figure of 3 dB. The RF output of the 8 channels is combined in an 8:1 beamformer and amplified by a follower amplifier. The RF output of each tray is combined in a 2:1 beamformer. A fan cooled the array. The overall gain of the array from the array face to the final beamformer was measured to be 42 dBi The measured G/T of the array is -16.1 dB/degree K at boresight.

PHASED ARRAY CONTROLLER: Open loop steering was chosen after careful consideration of the antenna beam widths in combination with gyro accuracy, and by restricting the rate of attitude changes to a maximum of 10 degrees/second. A single software control loop processes position updates from the global positioning satellite (GPS), received once per second under interrupt control, and current gyro attitude (roll, pitch, yaw) measurements via an analog-to-digital converter board. Combining the GPS position information, current attitude information and the known position of the ACTS satellite, the proper steering angles are calculated and the antennas are electronically steered in the desired direction. Antenna updates occurred from 0 to 18 times per second under flight conditions maintaining acceptable link performance. While initially designed for the aeronautical terminal demonstration, the controller met the moving ground terminal (HMMWV) requirements as well.

Both aeronautical and ground vehicles tests were run using the phase arrays to determine how well the antenna systems performed for both commercial and military applications. Even with the limited and simple array controller, the antenna transmit and receive beams successfully tracked the ACTS satellite and provided useful two-way, low-data-rate communications. The successful performance of experimental, proof-of-concept MMIC K/Ka-band arrays in field demonstrations indicates that high density MMIC integration at 20 and 30 GHz is indeed feasible. The results of this program created a strong incentive for continuing the focused development of MMIC array technology for satellite communications applications, with emphasis on packaging and cost issues.

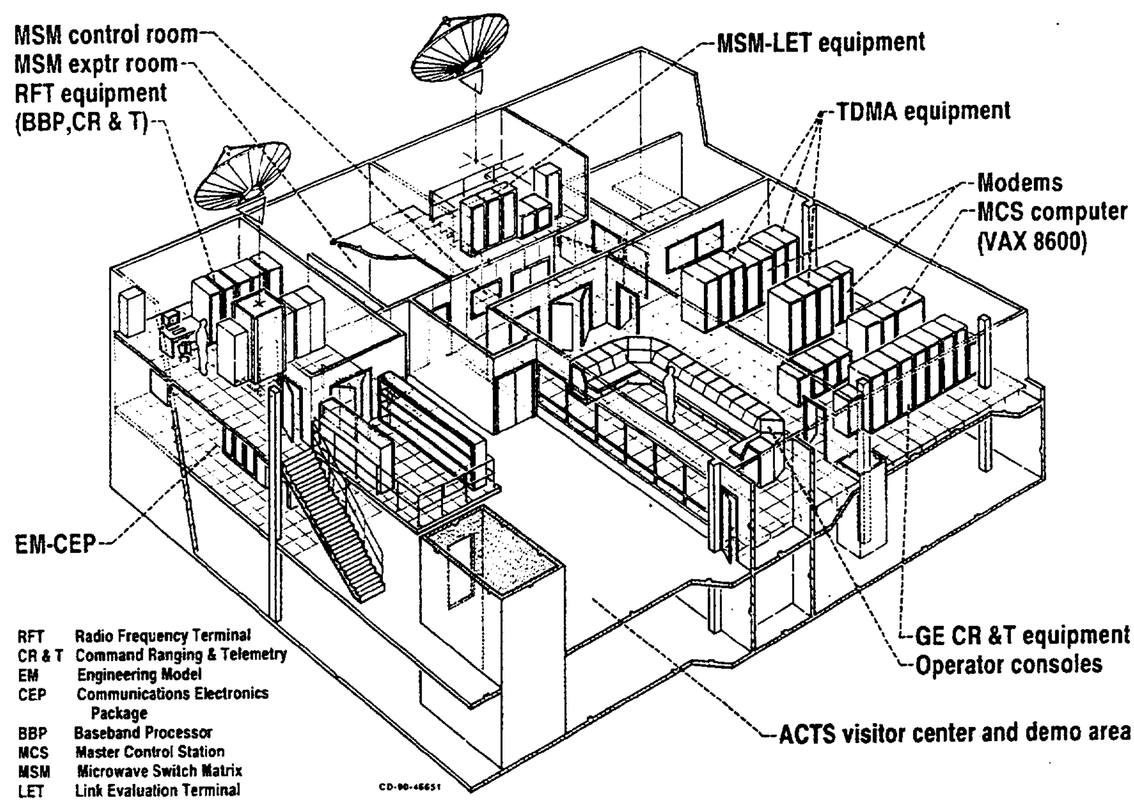
NETWORK AND SPACECRAFT CONTROL

Two major components of the ACTS ground system are the NASA Ground Station (NGS) and the Master Control Station (MCS), collocated at the NASA Lewis Research Center. Both were developed by Comsat Laboratories [57, 58]. The NGS provides the RF communications links by which the MCS performs its various network control and monitoring functions for the baseband processor mode of operation. In addition the NGS RF communications links are used by Lockheed Martins' spacecraft control center in East Windsor, NJ to receive telemetry information from the spacecraft and to transmit commands to spacecraft. In 1998, this spacecraft control center was moved to Newton, PA. The NGS/MCS combination also serves as a traffic terminal for communications data being transmitted in the baseband processor mode.

The NGS communication links with the spacecraft are conducted at the Ka-Band frequencies. When the link margins are exceeded by a rain fade, the communications network and the command and control capability for the spacecraft ceases. At that time the spacecraft operates autonomously.

The NGS 18 foot antenna system built by TIW provides nominal EIRP of 74, 68 and 77.5 dBW for, respectively, the BBP 110 Mbps, the BBP 27.5 Mbps and the S/C command uplinks. Similarly, the NGS G/T for the BBP 110 Mbps and the telemetry downlinks is, respectively, 30.3 and 30.7 dB/°K.

For Command, Ranging and Telemetry (CR&T) functions, the dynamic range for telemetry reception is 14 dB (100 kHz bandwidth). The command uplink uses two data rates, 5 Kbps or 100 Bps. At the normal operating EIRP of 79 dBW, the command link margins are, respectively, 18 and 27 dB.



NASA Ground and Master Control Station
Designed and Manufactured by Comsat Laboratories

Using the BBP 110 Mbps up and down links, the MCS/NGS communicates with the spacecraft to perform its BBP network control functions. These include sending BBP programming instructions to the spacecraft, receiving BBP status information, and sending and receiving orderwire messages for the user terminals. For these functions the link performance is specified at a BER of 1E-06 end-to-end, which is partitioned into 5E-07 each for the up and down links. The approximate clear air link margins (above 5E-07) are 14 and 20 dB, respectively, for the up and down links. Rain compensations (rate ½ FEC coding plus 50% reduction in transmission rate) adds 10 dB to each of these margins.

In summary, when the uplink rain fade exceeds approximately 28 dB, the BBP network will crash and the CR&T transmission will also be impaired. For the three years from 1995 through 1997, the number of BBP network rain outages each year were, respectively, 17, 24 and 4. The duration of each network outage was primarily a function of how fast the operator manually brought the system back up.

Propagation effects impact the NGS antenna pointing. This phenomenon is well known for Ku-band step tracking systems, and its potential for Ka-band is greater. In actual NGS operations, propagation anomalies can disrupt antenna pointing requiring operator intervention to restore operations. This effect is not chronic, and tracking is generally reliable during light fades. However, during heavy rain-fade events the antenna occasionally mispoints. The effect is common enough that antenna tracking is manually disabled when severe weather is expected.

ON-DEMAND, CIRCUIT CAPACITY

The MCS is responsible for the real-time control and monitoring of the ACTS BBP communications networks, as well as associated control of the spacecraft payload including the BBP. The ACTS architecture utilizes the features of the BBP to provide a highly flexible, high performance network, providing the user with circuit capacity on-demand in any increment of 64 Kbps. In addition, the architecture automatically provides rain fade compensation for any terminal in the network.

To perform its dynamic network control functions, the MCS accepts capacity requests from user terminals via the inbound orderwire (IBOW), then formulates and sends the appropriate assignment messages to user terminals via the outbound orderwire (OBOW). It also formulates BBP control messages and sends them to the BBP via the BBP control orderwire. The transmission of these messages is time coordinated to accomplish synchronized changes of the input memories, routing switch, and output memories of the BBP, and of the traffic bursts arriving from, and received by, the user terminals. Consequently, demand assignment changes occur without any interruption to the services being carried.

The DAMA functions performed by the MCS employ several algorithms, depending upon the circuit required (single/multichannel, single/multidestination). Development of these algorithms required 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. In particular the requirement to provide call setup times on the order of 3-5 seconds, and the complexities of programming the BBP, offered significant technical challenges. Several simulation programs were developed and utilized to test and refine alternative approaches to the DAMA problem.

The MCS programs the BBP using microcode-level instructions transmitted to the BBP via the 576 Kbps BBP orderwire channel. Because of the need to reprogram the BBP approximately every three seconds, a feed-forward protocol is used on the order-wire channel, eliminating the need for time consuming command acknowledgment. This protocol is designed to ensure the BBP is reliably programmed, even in the event of bit errors in the command channel. Characterization of the orderwire channel performance during system test showed that the orderwire circuits, both the traffic terminals and the BBP, were viable even with rain fades of up to 25 dB. At this point, the traffic circuits experience a BER > 1E-02, and thus are unusable, but the control circuits permit continued stable network operation.

System timing is an important consideration. The MCS contains a Cesium-beam reference oscillator, which provides the fundamental timing reference for the BBP network. The long-term stability of this oscillator is approximately 1 part in 2.5×10^{12}, consistent with Bell System standards. The MCS continually compares BBP on-board clock-drift to this frequency standard and adjusts the BBP clock accordingly.

For running and controlling the BBP TDMA network, the MCS employs a low performance VAX 8600 with a total of 200,000 lines of executable C-language code. The on-demand network control, although very complicated and sophisticated, was implemented using a fairly modest size program. In the network control center, one to two people are normally required to operate the BBP network.

PROPAGATION TERMINALS

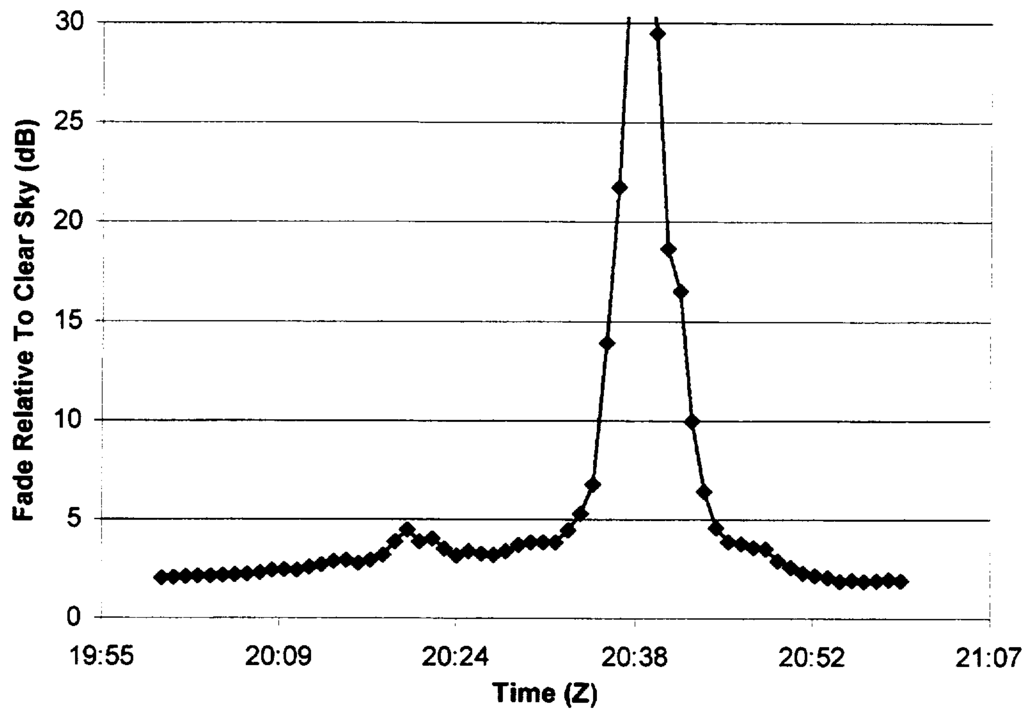
ACTS provides beacons at 20.2 and 27.5 GHz for use in making attenuation measurements. The NASA ACTS propagation program was designed to obtain slant-path attenuation statistics for locations within the United States and Canada for use in the design of Ka-band communications satellites [59]. Experimenters at seven different locations (British Columbia, Colorado, Alaska, Maryland, New Mexico, Oklahoma and Florida) collected propagation data for more than 5 years. Critical to these measurements was the design and calibration of the propagation terminals [60, 61]. All measurement sites had identical hardware and software and used the same calibration procedure to produce consistent data with an absolute attenuation measurement error of less than 1.0 dB. This high fidelity database is available on CD-ROM and is being added to the ITU world wide attenuation database.

The beacon signals at each frequency are collected using a 1.2 meter off-set fed Prodelin antenna, sent to a low noise amplifier, down converted, split and sent to a beacon digital receiver and a total power radiometer. All RF components, digital receivers and radiometers are enclosed in temperature controlled housings to maintain the desired accuracy and stability.

The digital receiver, which converts the beacon analog signal using a 12-bit converter, was developed to overcome the difficulties previous experiments had with analog systems. The shortcomings of analog systems included lack of stability, long acquisition times, and difficulty in manufacturing and maintenance. The beacon's signal power is normally reported at one sample per second, but for scintillation studies the data is reported at 20 samples per second. The radiometer receives its signal after many stages of amplification. As a result, the radiometer must be calibrated every 15 minutes by switching in a referenced load.

After the raw data are collected, the beacon signal level and radiometer voltage reading are processed to apply the calibration information and remove the beacon level offsets as well as an estimate of atmospheric absorption. The output of the calibration process is the beacon attenuation referenced to free space, sky noise temperature, the radiometer attenuation, and the weather sensor and other system status measurements. The propagation terminals produce attenuation data with accuracy, most of the time, of better than 0.3 dB over a dynamic range greater than 20 dB. It should be noted that the attenuation measurements include the effects of antenna wetting which becomes significant at Ka-band frequencies. The seven terminals have been very reliable with the terminal down time being less than 1 % of the total measurement period.

20 GHz Beacon Attenuation at Maryland Site (1/15/95)
Measured By Comsat Laboratories



CHAPTER 4

User Trials

From the very beginning, ACTS was intended to be an on-orbit testbed for validating both advanced Ka-band technologies as well as on-demand, integrated voice, video, and data services needed for the 21st century. As such, the User Program was an important element of the Program, and the US Industry played a key role in working with NASA to formulate it. NASA recognized that the full potential of the ACTS technologies could only be realized if industry assumed an active role in the conduct of technology validation as well as application trials. The development and flight validation of both the advanced technologies and new, advanced, and more cost effective services is allowing industry to adapt these technologies and services into their individual commercial requirements at minimal risk. As it turned out, ACTS development was very timely. The large market increase for integrated services requires that satellite systems provide digital communications in an on-demand basis and fully compatible with terrestrial networks.

CATEGORIES

The primary goals of the Program were to: 1) conduct a complete set of technology verification experiments that validated and characterized the ACTS technologies, 2) conduct a balanced set of user investigations and application demonstrations that evaluated on-demand, integrated voice, video, and data applications enabled by the ACTS technologies, and 3) collect a comprehensive series of propagation measurements to aid in the design of future Ka-band communication satellites systems. This chapter covers the user investigations. Chapter 2 presents some significant results from the technology verification experiments. Chapter 5 provides detailed information on the propagation measurements.

User application investigations comprised over half of the investigations conducted. They involved a variety of fixed, mobile, and video broadcast services. Most of the user trials were oriented toward services with commercial potential and included medical; business networks; terrestrial network restoral; science networks; ISDN networks; education; DoD tactical communications; broadcast video; supervisory control and data acquisition (SCADA); very high data rate SONET/ATM networks; aeronautical mobile; and protocol and network interoperability.

OPERATIONS

Operations were initiated on December 6,1993, after the completion of all spacecraft, ground system, and network on-orbit checkouts. The ACTS system offered considerable flexibility in accommodating multiple simultaneous and independent users in either the BBP, MSM, or mixed modes of operation. Reconfiguration of the spacecraft payload between the various modes of operations was accomplished in less than 30 minutes.

During the fall and spring equinox periods, the spacecraft solar panels were eclipsed up to 72 minutes per day. During this time the payload was shut down. Except for these eclipse shutdowns, experiment operations were conducted 24 hours per day, seven days a week, year round. Geostationary operations continued until July 1998.

INCLINED ORBIT OPERATIONS

The ACTS spacecraft was designed for four years of operation in orbit and was loaded with sufficient hydrazine stationkeeping fuel to provide that length of service. With a number of the experiments in progress, the continued strong demand for experiment time, and the interest of industry in continuing to use ACTS as a demonstration vehicle, NASA commissioned Lockheed Martin to investigate the feasibility of operating in inclined orbit long before the expected depletion of the hydrazine. Studies confirmed the feasibility and NASA directed Lockheed to implement the necessary autonomous control software to provide accurate pointing with the increasing inclination, while NASA equipped the ground stations with tracking capabilities to follow the daily excursions of the spacecraft above and below the equator. The spacecraft software modifications were completed and verified and operational procedures were established and verified long before depletion of the hydrazine. The modifications to the ground stations were carried out by NASA in the proper sequence to ensure the continuity of the experiments.

Hydrazine supplies were exhausted after 4 years nine months and full stationkeeping was discontinued in July 1998. With full stationkeeping, ACTS remained positioned at 100 degree west longitude and was maintained within a +/- 0.05 degree box. fuel. With no north-south stationkeeping, orbital inclination increases at a rate of 0.76 ^{0} per year.. Using only a very small amount of hydrazine for east-west stationkeeping, ACTS remains geosynchronous at 100 ^{0} west longitude +/- 0.05 ^{0}, with orbital eccentricity near zero. In this inclined orbit mode, using the on-board pointing adjustments and with ground station tracking ACTS operations are planned to be extended until September 2000 when the remaining hydrazine fuel will be used to raise the orbit of the spacecraft above the geostationary altitude and all on-board systems and subsystems will be turned off.

APPLICATION INVESTIGATIONS

As a forerunner to future commercial communication satellites, the ACTS testbed offered an extremely versatile platform to conduct a wide range of user service applications. In addition, ACTS demonstrated the capability to interoperate with the terrestrial networks providing the user with world-wide connectivity. This fits the telecommunications needs of today to serve the needs of a true global economy that has emerged requiring interconnectivity among all countries. ACTS has operated with a network of over 70 terminals of various types for both fixed and mobile services throughout North and South America and Hawaii. Data rates using these various types of user terminals ranged from 2.4 kbps up to 622 Mbps. Many of the terminals were integrated with fiber optic networks to form a hybrid satellite/terrestrial network to demonstrate, validate, as well as accelerate the role of satellites as key components in the information superhighway.

For instance, the high data rate terminals were integrated with the Bell Atlantic fiber in Washington, DC; the Sprint fiber network in Kansas City, Kansas; and the GTE fiber network in Hawaii. Many of the T1VSAT earth stations as well as the various types of USAT and mobile terminals were also connected into the public switched terrestrial networks.

Some of the user services that were investigated in the User Program are not yet available or effectively provided on a broad scale by today's commercial communication satellites. ACTS offered the potential to help spur the introduction of these new services as well as provided new ways to reach a larger number of users at a lower cost than possible with present technologies. While the applications experiments and trials were being run, engineering teams were carrying out technical validation experiments, evaluations, and characterizations on the ACTS communication links and networks.

The following sections provide a comprehensive overview of many, but not all of the various user tests and trials using the ACTS system. It is hoped that the reader will get a sense of the tremendous versatility of the ACTS system and the wide range of users and organizations that participated in the ACTS User Program.

MEDICAL

Fourteen and one-half percent of our GNP is spent on health care. In spite of this, many of our citizens, especially in the rural areas, do not have ready or easy access to quality medical care. Providing cost-effective health care to patients in isolated or remote areas far from medical centers is both a national as well as a global concern. ACTS provided high quality, wide bandwidth communication links to demonstrate telemedicine; i.e. remote medical diagnostics and consultation. The ACTS capability of using communications circuits on-demand has the potential of making telemedicine cost effective.

MAYO CLINIC

Led by Dr. Bijoy Khandheria, physicians from the Mayo Clinic in Rochester, Minnesota conducted extensive telemedicine trials over ACTS [63,64]. In one phase they used T1 VSATs to perform remote medical diagnosis and evaluation of patients in the Pine Ridge Indian Health Services Hospital on the Lakota reservation in Pine Ridge, South Dakota. The 45 bed Pine Ridge hospital provides health services to the reservation. The hospital had 15 positions for full-time primary care physicians and 87 nurses. Historically, it had been difficult to fill the 15 full time positions and physician turnover tended to be high. Because of the remoteness of the reservation, consulting and continuing education services were difficult to obtain for the health care professionals at Pine Ridge. Some 2500 hospitals, like Pine Ridge Clinic, which have limited medical personnel, serve about 24 % of the US population. T1-VSAT service provided Mayo physicians in Rochester, Minnesota with real time voice, video, and data connections with patients on the reservation hundreds of miles away. Physicians including specialists were able to see and talk to the patients as well as receive instantly information from such instruments as an electronic stethoscope, an ultrasound scanner, and an electrocardiogram recorder.

In one case, a child with skin lesions who had been treated for years without a cure was correctly diagnosed by the Mayo physician as having leprosy. Treatment was prescribed via ACTS and the patient was cured! During another session, a Mayo psychiatrist examined a patient via ACTS who was paranoid, prone to seizures, alcoholic, an inhalant abuser, and showed Parkinson-like symptoms. The Pine Ridge medical staff considered this one of their most challenging cases. Through the process of remote examination, the consulting psychiatrist was able to provide a keen insight, and a correct diagnosis. With the Pine Ridge Indian Reservation, the Mayo team carried out over 50 different clinical consultations involving 13 different medical specialties in addition to conducting physician education and training programs for health professionals. Most participants, doctors, nurses and patients, reported that the quality of the T1 video and audio signals was good and acceptable for delivery of basic educational and health services.

In other trials, the Mayo team in Rochester was connected by terrestrial fiber to the ACTS HDR earth station in Kansas City and via ACTS to another HDR earth station at the Mayo Clinic in Scottsdale, Arizona. Mayo Clinic was interested in demonstrating the clinical and technical feasibility of using combined satellite, terrestrial, and local hospital networks to provide on-demand, short duration access between remote hospitals and tertiary care centers. The medical areas addressed were angiography, echo-cardiology, family medicine, and radiology. Again numerous consultations and diagnoses were conducted, this time using X-ray, magnetic resonance imaging (MRI), ultrasound, and computed tomograghies (CT) in addition to patient-doctor sessions and expert group consultations. The average file size of the images transmitted was 300 megabytes. The data rate used over ACTS was 155 Mbps which allowed an image to be sent to the remote specialist in less than one minute. The Mayo network consisted not only of a satellite and terrestrial links but also included the hospital's local area networks at both facilities. The teleradiology experiment alone involved 13 Sun workstations, connected into the hospital network, for collecting, transmitting, receiving, and reviewing the MRI and CT images.

Conducting over 100 different trials, Mayo demonstrated the ability of ACTS to deliver high quality imagery in real time over a hybrid satellite/terrestrial/local hospital area network system. Mayo's overall conclusion was that the use of ACTS-like technologies for real-time, interactive, quality health care delivery was feasible, with a high degree of acceptance on the part of both doctors and patients. As a result of the ACTS trials, the Mayo's catheterization and echocardiography laboratories have started programs for doing remote interpretations.

KRUG LIFE SCIENCE

In another telemedicine trial, Krug Life Science and the NASA Johnson Space Center (JSC) in Houston, Texas, examined patients at the Fitzsimmons Army Medical Center in Boulder, Colorado, using the T1 VSAT links. Using a portable, high-resolution retinal-imaging camera, Houston specialists examined in real-time, live color images of the retinas of 53 patients in Boulder.

Remote diagnoses made by the consulting specialists in Houston were 100% in agreement with those made by the Army ocular specialists in Boulder. As a result of these successful demonstrations at T1 rates, JSC developed a T1 network of medical consultants to provide support during shuttle operations as well as during astronaut training in Russia.

Billings, MT, was the site of another telemedicine trial where an ACTS USAT was coupled with a Telemedicine Instrument Package (TIP)developed by Krug Life Science and NASA JSC to monitor the health of astronauts in space. The TIP is a suitcase size, portable diagnostic center that includes an electrocardiogram, blood gas content detector, electronic stethoscope, and a special camera for dermatology examinations. Although designed and developed to be used on the shuttle and the space station, the TIP can be applied on earth, particularly in rural medicine or remote workplaces such as an off shoreoil platform, to improve the quality of and access to medical care.

Using the TIP and a LeRC supplied 23-inch diameter USAT operating at T1 (1.544Mbps) rates, doctors at St. Vincent Hospital in Billings, MT, conducted various staged trauma trials and demonstrations with patients at the Exxon Corporation refinery and at the Crow/Northern Cheyenne Hospital. The Exxon refinery, located in the Billings area, has an occupational medical clinic. The Crow/Northern Cheyenne Hospital is a 24 bed rural hospital located in south central Montana.

Doctors were pleased with the diagnosis quality, high-resolution video, audio, and data transmission provided by ACTS and the TIP. The results demonstrated the ability of rural health care professionals to use satellite technology to send patient's vital information to a hospital hundreds or thousands of miles away for proper evaluation by qualified medical staff. In many cases, such telemedical evaluations provided not only expert consultation but also alleviated the need to transport a patient to a regional hospital saving unnecessary travel as well as undue stress to the patient.

CLEVELAND CLINIC AND THE UNIVERSITY OF VIRGINIA

The Cleveland Clinic, the University of Virginia, and the NASA LeRC teamed up to investigate the use of satellite-based telemammography [44]. Breast cancer is the second leading cause of cancer-related deaths among American women, although it is 90% curable if detected early enough. Breast cancer screening through mammography is recommended for tens of millions of American women. In 1996, an estimated 56 million US women were of the recommended age for annual mammography screening. Mammography requires skilled and experienced radiologists, who are usually located in large medical facilities, to interpret the images . People in rural, low-density population areas generally have no direct access to such expertise.

Telemammography using terrestrial means is not an option because the high data rate telecommunications infrastructure required to transmit the large data files does not exist. T1 (1.544 Mbps) satellite links can provide affordable connectivity for those patients, allowing direct and immediate access to mammography experts. Using satellites, the possibility exists to greatly improve mammography screening, especially in remote areas where patients might have to travel several hours for their annual screening. Whereas current mammography films are shipped to an interpretation center, resulting in days or weeks before the results are known, the potential for near real time mammography screening via satellite means that a patient can receive results right after the screening. In the 7-10% of the cases requiring follow-up, patients are immediately available thus eliminating the requirement for a revisit to the screening center.

The ACTS T1 links alone could not provide adequate capacity for fast transmission of the large files associated with mammography, so the team decided to investigate advanced data compression techniques. Large patient files of up to 320 megabytes result from multiple views, high image resolution requirements, and the need to compare current to previous breast image. At a T1 rate, it would take 27 minutes to transfer them. However, by using data compression techniques, the transmission time can be drastically reduced while still allowing for quality diagnosis. So far more than 5,000 digitized mammography images have been transmitted over ACTS - all have been received without error. Most of these images were mammography film images scanned at 100-micron resolution; some were scanned at 50-micron resolution.

These transmitted images were compressed (using wavelet image compression) at ratios of 8:1 to 30:1. Some uncompressed images were also transmitted. Radiologists at the Cleveland Clinic have been able to detect the application of image compression, when viewing the de-compressed images on a high-resolution gray scale monitor, down to ratios of 16:1; one radiologist could detect it at 12:1.

The Cleveland Clinic has performed clinical ROC (receiver operating characteristic) studies of the 8:1 compressed, satellite transmitted images. Using a blind study of 60 cases (where each case consists of four images), the satellite-transmitted, 8:1 compressed images were compared to the original film images. The result is that diagnostic accuracy of the compressed, transmitted images was found to be equivalent to the original film. With a 8:1 image compression, the set of four mammographs can be transmitted in about 3 minutes which is acceptable for near real time analysis. Additional test are continuing with patients at the Ashtabula County Medical Center in Ashtabula, Ohio whose images are transmitted to specialists at the Cleveland Clinic.

By making use of the T1 rate connections, the basic image transmissions and remote diagnosis can be augmented by teleconference capability to provide teleconsultation with the remote physicians, or directly between patient and specialist. Satellite telemammography alone represents a potential market of tens of millions of telemedicine sessions for future commercial satellite service providers.

EMSAT AND JPL

EMSAT and JPL successfully demonstrated the use of the ACTS Mobile Terminal (AMT) for emergency medical communications [66]. The experiment highlighted the feasibility of mobile satellite communications to provide better pre-hospital communications than were available with current terrestrial radio technologies. It evaluated the transmission and reception of satellite digital voice for two-way, pre-hospital communications, one way transmission of patient data from field paramedics to the base hospital, and telemetry of patient assessment data to the base hospital. These trials simulated communications with paramedics at the accident scene and enroute to the hospital. Voice and data transfers were tested at 2.4, 4.8, and 9.6 kbps rates. Results indicated that satellite communications for Emergency Medical Service is possible and desirable. For each data rate, communications were clear and usable, an improvement over the current radio frequency communications.

UNIVERSITY OF HAWAII, GEORGETOWN MEDICAL CENTER AND OHIO SUPERCOMPUTER CENTER

The University of Hawaii (UH), the Georgetown University Medical Center (GUMC), and the Ohio Supercomputer Center (OSC) teamed in a DARPA sponsored trial to test, evaluate and demonstrate the use of the ACTS gigabit network in radiation dose treatment planning [67]. This trial was really an illustration of how communication links can provide for a collaborative effort among remote centers of excellence.

Radiation treatment has been the main treatment for cancer for decades. The idea behind radiation therapy is to deliver a tumorcidal dose of radiation to the tumor while minimizing doses to the surrounding normal tissue. The results of the treatments depend greatly on the planning. To "kill" deep-seated tumors, it is necessary that the radiation be cross-fired from a number of different angles, all aligned to intersect the tumor. Treatment planning assures that the beams do intersect the tumor. Conventional treatment planning is performed on two-dimensional slices of CT images and is generally not adequate. Three-dimensional (3D) treatment planning has recently emerged which considers the three-dimensional structure of the patient's anatomy. Such planning allows 3D beams, which deliver a more conformal dose on the tumor and offer the promise of a more effective treatment. However, 3D planning is currently very restrictive due to the limited access to powerful supercomputers. The computer requirement involves 3D computations and 3D graphics rendering. It requires a high performance supercomputer to allow physicians to view the anatomy, draw beams, and evaluate dose distributions. A high-speed computer workstation is then required to compute and even optimize dose distributions based of the beam characteristics and anatomy information.

Gigabit satellite networkscan be provided by ACTS allowing remote supercomputer centers to perform the necessary computations and 3D graphics visualizations in near real time for interactive planning sessions with treatment physicians. In this field trial, GUMC obtained a set of MRI and CT scans from a cancer patient and sent them via ACTS at 155Mbps to UH where the imagery was stored and a 3D profile was developed. The 3D profile was sent to GUMC. GUMC used this 3D profile to develop an initial radiation beam treatment profile, which was returned to UH. Based on this radiation beam profile from GUMC and the patient's MRI and CT scans, a dose computation software program was run on an UH supercomputer. From UH, the results of the dose computation were sent via ACTS to OSC where it was fused with the patient's MRI and CT data, transmitted from GUMC. At OSC a visualization of both of the patient's imagery scans and the dose treatment plan was performed on a high performance Silicon Graphics workstation. The visualization in video form was sent to GUMC for evaluation. Radiologist at GUMC sometimes required additional iterations that were subsequently performed in near real time at UH and the OSC.

The ACTS high-speed data links were used to link the UH and OSC centers of excellence and their supercomputer capabilities together to perform a service for GUMC. This successful trial of distributed treatment planning via the ACTS gigabit network is expected to stimulate new medical services as well as motivate networks that transcend time, distance, and resource barriers. With high-speed networks, medical resources can be interactively shared in real or near real time by medical personnel on a global scale.

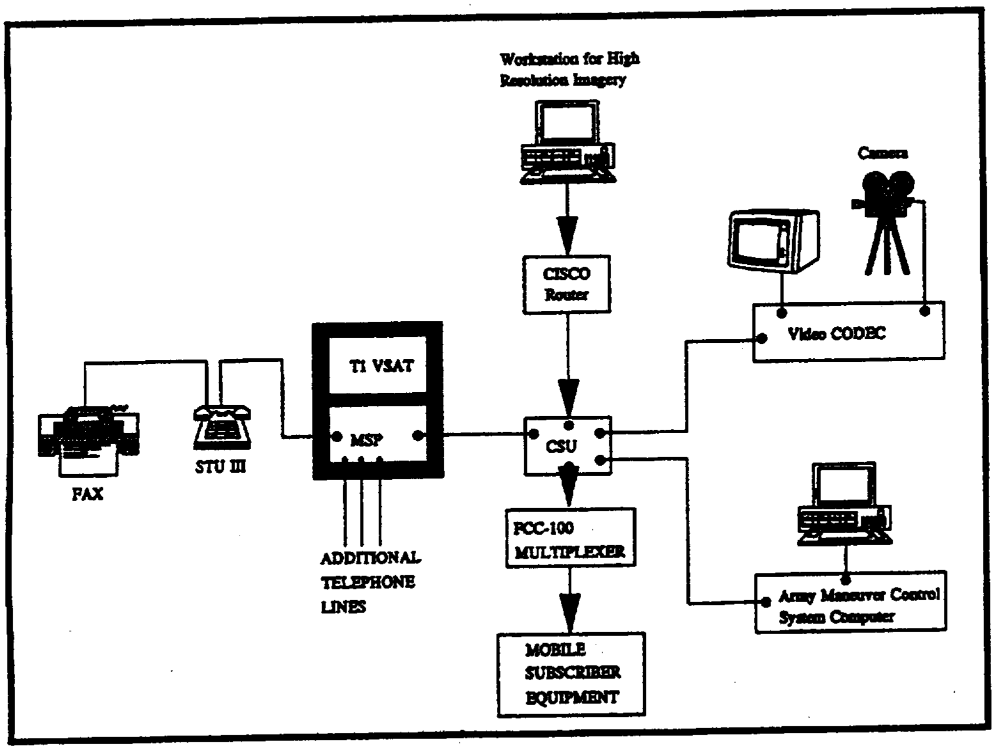
MILITARY APPLICATIONS

The battlefield is dynamic and mobile as evidenced in the Gulf War. Providing the battlefield commander with updated intelligence, targeting, weather, and command information is vital. Operations require tactical commanders to operate independently. To date, communications capabilities providing intelligence and command orders to such tactical units have been limited to simple voice and low rate, narrow bandwidth communications.

The Army Space Command spearheaded a number of Army organizations to evaluate the use of ACTS to provide tactical commanders with on-demand, wide–bandwidth, integrated services to the battlefield. Seven T1 VSAT's were ruggedized and configured to be highly transportable to support tactical operations.

The objectives of the Army's Program were to test and evaluate the use of ACTS advanced satellite technologies in multiple field exercises to more realistically simulate battlefield communication requirements for future military satellite communication systems. In a number of operational field trials and demonstrations with tactical units, ACTS was used to provide on-demand, integrated voice, video, data between forward tactical units and geographically dispersed rear echelon commands. The T1VSATs provided the local commanders with control of large amounts of bandwidth (1.544Mbps) and the ability to dictate the assignment of bandwidth or user services. Some of the many Army communications needs tested were:

- video teleconferencing for command and control;
- reconnaissance imagery;
- integrated weather charts/imagery;
- mobile phone base station relay;
- telemedicine;
- logistical supply;
- video conferencing for morale boosting;
- interconnection into the Defense Commercial Telecommunications Network (DCTN) to provide a seamless satellite/terrestrial network.



US Army equipment configuration.

HAITI OPERATIONS

The Army used its seven T1VSATs in support of Operation Uphold Democracy in Haiti [68]. Three VSATs were located in Haiti while others were located at Ft. Bragg, North Carolina, Ft. Drum, New York, and at the Army Space Command Headquarters in Colorado Springs, Colorado. At Ft. Bragg the VSAT was tied into the Defense Communication Telephone Network (DCTN). This connection allowed units in Haiti to videoconference with military bases around the world. The VSAT also connected into the Army's own tactical radio network.

At Ft. Drum, a connection was made from the VSAT into the US public switched telephone network. This capability expanded the communications capability in Haiti to full interconnectivity with the US.

ACTS provided secure video for daily conferences between the Joint Task Force in Haiti and commanders back in the US. US Army Colonel James Campbell reported that battlefield commanders were able to solve unique military problems using this capability. The participation of many people at each end of the link and the ability to see their body language added substantial value over voice and low bandwidth videocons. In addition to supporting command operations, the ACTS video conferencing capability was used to support Morale Conferences between soldiers in Haiti and their families back home in the US. The Walter Reed Medical Center in Washington, DC connected via landline to the COMSAT VSAT in Clarksburg, Maryland also provided telemedicine support to the Haiti operations. President Clinton's address on October 6,1994, to the commanders and troops in Haiti was transmitted over ACTS when a last minute glitch interrupted the planned communication links.

MOBILE VEHICLE COMMUNICATIONS

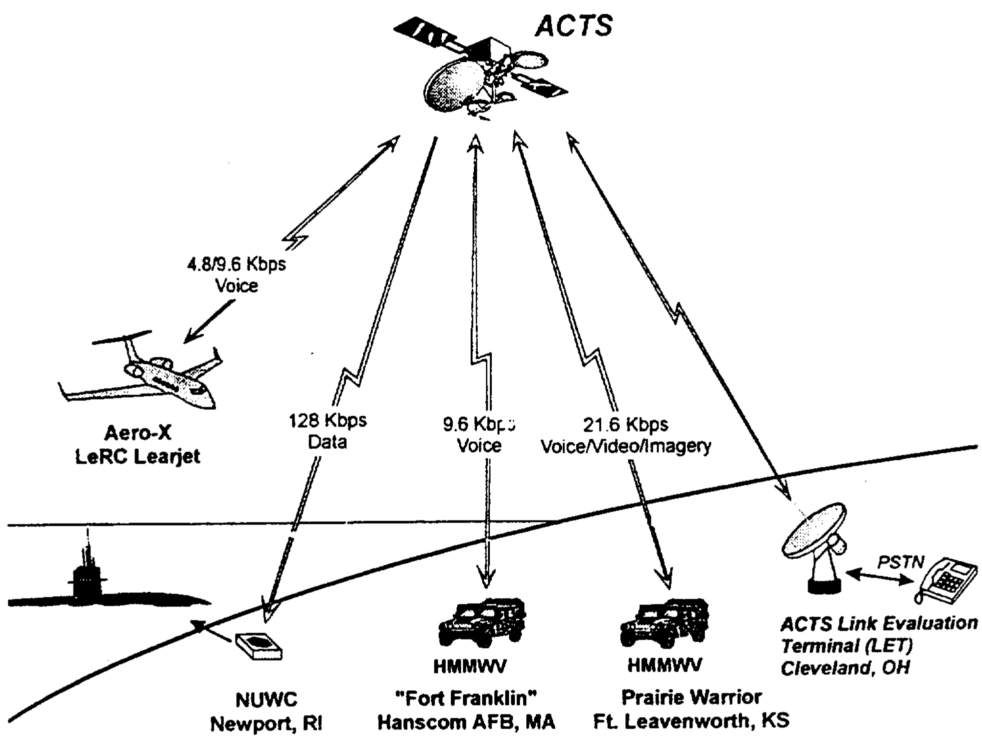
In mobile communications tests, the Army used both mechanically rotating antennas and solid state phased array terminals.

Rotating Reflector Terminal: In one trial, the ACTS Mobile Terminal (AMT) communications equipment and tracking reflector antenna shown in Chapter 3 were used to test and evaluate video transmissions and receptions from a moving ARMY High Mobility Multipurpose Wheeled Vehicle (HMMWV) [69]. Battlefield video imagery and control data were transmitted to and from the vehicle via ACTS. The smaller equipment size, especially the antenna, and the higher data rate capability provided by the ACTS Ka-band spot beams enabled this application. In another trial the same equipment was mounted and tested in an Unmanned Ground Vehicle under development by Lockheed Martin for the US Army. Satellite systems have the potential to increase the range as well as the data rate of such unmanned robotic vehicles.

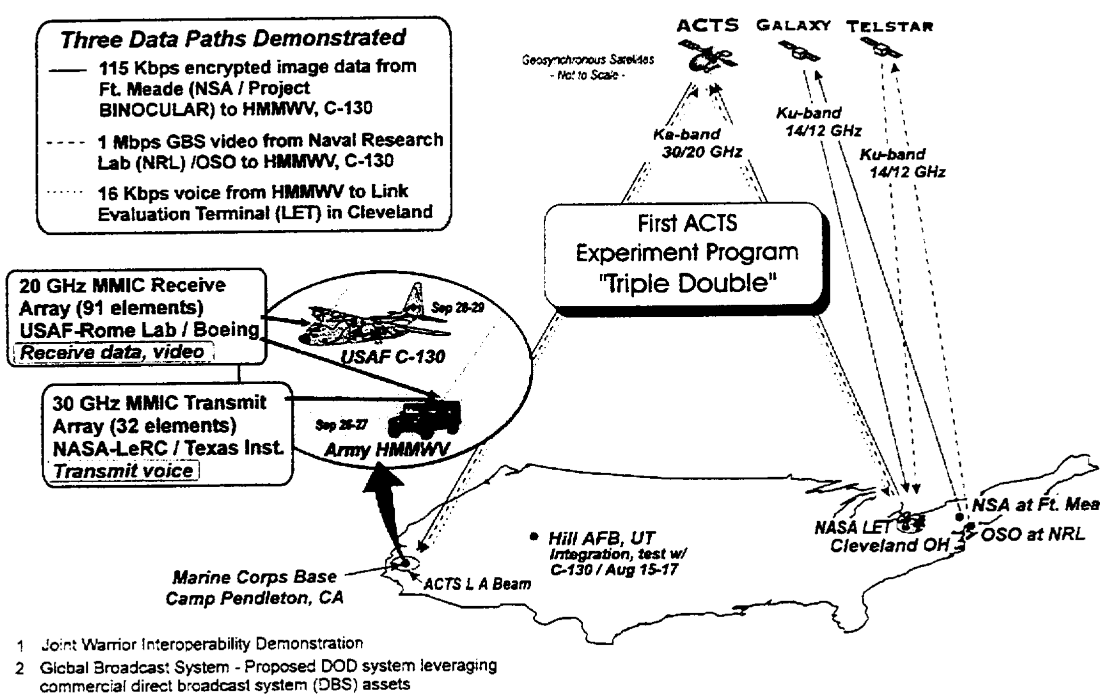
MMIC Arrays: The Department of Defense was also especially interested in the potential of the MMIC arrays to provide integrated voice, video and data communications. The advantages of arrays (small, conformal, and with electronic steering) were showcased to the military services. The MMIC phased array antennas which are described in Chapter 3 were mounted in a HMMWV as well as a C-130 aircraft and participated in a number of Army and Air Force exercises and demonstrations in a one-year period between September 1994 and September 1995 [70].

Voice, data, imagery, and slow scan video links were established and tested via ACTS. Four different MMIC arrays [Texas Instruments, Boeing (2}, and Lockheed Martin] were used in the course of these demonstrations. Each array is electronically steered. Using the HMMWV, engineers from the Lewis Research Center demonstrated duplex voice communications at 9.6 kbps using a variety of commercial as well as standard military communications equipment. In conjunction with the Prairie Warrior exercise at Ft. Leavenworth, Kansas, duplex voice and video transmissions to and from the HMMWV at a data rate of 21.6 kbps were achieved using a commercially available videoconferencing system. Although the video was slow scan at these rates, it nevertheless demonstrated the potential of mobile, interactive video communications. In a demonstration to the US Navy at Newport, Rhode Island, the MMIC arrays were used to receive a 128 Kbps video and data from ACTS in a simulated operational situation of high bandwidth information sent via a satellite to a submarine.

The most ambitious MMIC array demonstrations took place as part of the Joint Warrior Interoperability Demonstration 1995 (JWID-95). Between September 26-29, 1995, at Camp Pendleton, CA, links were successfully established between ACTS and both a HMMWV and a C-130 aircraft using the MMIC arrays. In one test, 115 Kbps encrypted image data were transmitted from Ft. Meade, MD via a Ku-band Galaxy satellite to LeRC and relayed via ACTS to both the HMMWV and the C-130. In another test, 1 Mbps video was transmitted from the Naval Research Lab via a second Ku-band satellite and relayed via ACTS to both the HMMWV and the C-130. In a final test 16 Kbps voice was transmitted from the HMMWV.



MMIC phased array demonstration with ACTS.



Overview of ACTS MMIC phased array demonstrations that were part of JWID-95.

Active MMIC phased arrays are of great interest to both the military and the aircraft industry because they can provide electronic beam steering in a compact configuration conformal to a vehicle or aircraft surface, unlike mechanically steered reflectors which require radomes protruding above the surface. For the same reasons, proposed FSS LEO satellite systems such as Teledesic and SkyBridge highly desire the use of arrays in the user terminal The successful performance of the experimental, proof-of-concept arrays has helped to create a strong incentive for continuing the focused development of MMIC array technology for satellite communications.

BUSINESS NETWORKS

Practically all aspects of modern commerce have become heavily reliant on communication technology over the past decade. Business networks using VSATs are among the fastest growing applications of communication satellites. VSAT networks in the early 1990's were arranged in a star configuration with all traffic routed through a central hub earth station. This arrangement necessitated a double hop to the satellite for VSAT-to-VSAT traffic. For voice applications, double hop through a geostationary satellite is unacceptable because of the undesirable long transmission delay. Using ACTS technology with high gain antennas and the capability of performing on-board switching, double hop is eliminated and single hop, VSAT-to-VSAT is accommodated.

NATIONAL COMMUNICATIONS SYSTEM (NCS)

From the federal response perspective, there are functional requirements outlined and managed by the National Communications Systems (NCS) to restore services for emergency operations in case of natural or man-made disasters. One of the main functions of the NCS is to provide low data rate (T1) communications restoral during these disasters, and the NCS sees satellite communications as the chief means of aiding in this cause.

To this end, NCS, NASA, Mitre Corporation, along with JPL planned and executed a series of simulated emergency communications restoral tests and trials using ACTS T1VSAT's [71]. In performing the tests, terrestrial T1 connectivity between Reston, VA and Pasadena, CA was initially established and then disrupted. Using special software, connectivity was manually reestablished via two T1VSATs. For operational type emergency restoral systems, software would be developed to automatically reestablish the severed connection. The ease of implementation and the effectiveness of such a system were the key parameters evaluated. Both full T1 trunk and individual 64 Kbps circuits were tested. Another noteworthy aspect of these tests included "call prioritization and preemption" where higher priority callers usurped communications channels from lower priority users. These tests proved highly successful. NCS concluded that the ACTS system provided high quality, consistent, secure and clear voice communications. Further, it was possible to maintain communications with a very low bit error rate. Establishing on-demand calls that met the NCS's security requirements was easy and relatively efficient. Call prioritization and the use of Personal Identification Numbers also worked well.

HUNTINGTON BANK

The increasing dependence on communications by businesses brings with it more stringent reliability requirements on the networks. In some areas of business, such as the financial sector, government regulations require each company to prepare and test business restoration plans. Most businesses combine two strategies to provide the protection that they need: redundancy and backup systems. Frequently satellites provide the backup.

Ohio University led an experiment sponsored by Huntington Bank designed to determine if satellite circuits were technically compatible with terrestrial transmission equipment and terrestrial network management systems [72]. These are important considerations if satellite networks are to be considered for redundant or backup operations. In the past terrestrial and satellite networks had been completely separate with each having its own set of equipment and no interoperability between them.

In one series of tests, customer transactions, ATM transactions, account balances, transfer of fund data, and computer scanned check data were all transmitted over ACTS in tests of instant, on-demand switchovers. Fifteen separate bank data circuits were successfully and seamlessly routed from Sun Recovery Services in Philadelphia via hybrid ACTS/terrestrial network. Full compatibility was found between the ACTS system and the terrestrial network. The T1VSATs could be integrated into the Huntington Bank's T1 network in a straightforward manner without the need to develop special configurations for the terrestrial equipment. Circuit setup times on ACTS were within the range needed for redundant circuits; the times are comparable to or better than on-demand terrestrial T1. No problems were found in the cutover to the ACTS circuits. Terrestrial T1 carrier networks use a low-speed, out of band channel to monitor T1 circuit equipment. ACTS currently does not support this channel. However, all in-band network management control, such as those typically found in end-user T1 equipment, did function without any problems.

NBC

In another user trial, NBC used T1VSATs to transmit video between different fixed broadcast locations. Their experiment demonstrated that T1, and even sub-T1, video and audio can be used to provide real time video and audio feeds for network news applications. The quality of the ACTS links was such that the transmitted imagery and audio was maintained at sufficient fidelity to be broadcast directly in real time on the network.

The ACTS Mobile Terminal (AMT) was also used in tests and demonstrations with NBC. Current communications capabilities for mobile newsgathering by ground vehicles are limited to cellular telephone service-when available. Once on scene and once the satellite news gathering (SNG) van is *stationary*, video can be transmitted. Using ACTS and the AMT, a full duplex compressed video link at data rates up to 768 Kbps was established while on the move. Interconnecting the link into the terrestrial network allowed the video to be delivered to NBC Headquarters in New York City. NBC gained significant insights which will help guide development in new and exciting means of improving news gathering capabilities.

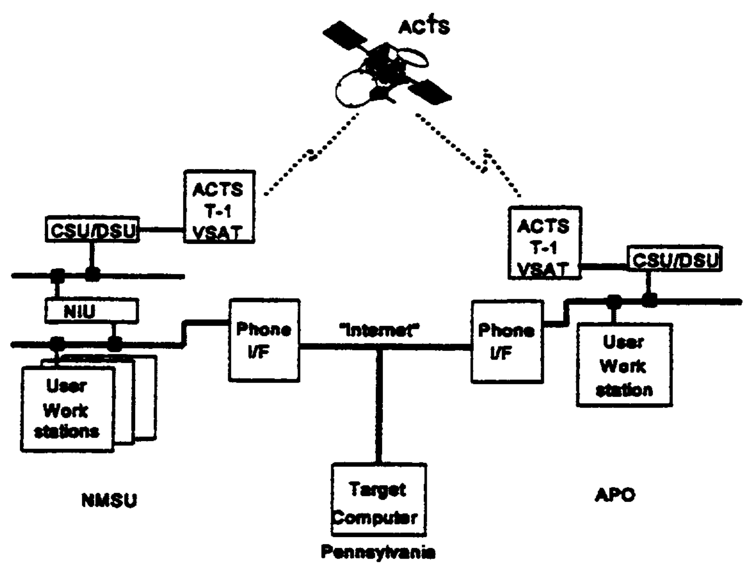
SMALL BUSINESS

The commercial Ka-band, spot-beam satellite systems under development are intended to serve small businesses, home offices, and regional offices using small user terminals at a total throughput of 16 Kbps to 384 Kbps and sometimes larger. For such applications, the communications are primarily for telephony, multimedia, video conferencing, file transfer, E-mail and Web browsing. These specific on-demand services were performed in an integrated fashion in many different user trials using the ACTS T1-VSAT network which illustrated to service providers the potential for spot-beam, on-board processing satellites to meet the general needs of the business community.

SCIENCE NETWORKS

ACTS provided real time links in two separate experiments to investigate the use of satellites for remote astronomy. In the first user trial, T1VSATs were installed at the Apache Point Observatory in southern New Mexico and on the campus of New Mexico State University (NMSU) in Albuquerque, NM [73]. ACTS provided a 1.79 Mbps link to the observatory. The observatory's sensors primarily produced a digital output, for example a charged coupled device's image of objects in the sky, thereby allowing the digital transmission of the observatory's data products in real time. During an observing session, the telescope user remained at his home institution and did not have to be physically present at the telescope.

Experiment configuration between Apache Point Observatory and New Mexico State University.



This link also allowed operations and control of the telescope facilities by remote users using the same interfaces as on-site observers. The ACTS trials allowed NMSU to test the ability of the remote interface to give the user a "touch and feel" for access and control. In this aspect, the real time nature of the link was critical to the safety of the 11.5 foot telescope as it was moved under remote control. A wide band (1.544 Mbps) channel was also required to handle the data generated by the telescope's array of sensors. In addition, the ACTS trials included the testing and evaluation of additional communication links to support the non-real time data network used to support observatory management, data base sharing, computer and video conferencing, and other collaborative services for the science community.

Overall, this experiment showed that the satellite link was a highly reliable means of delivering data to remote users from around the US. From a real time control point of view, the ACTS links response time was very satisfactory and similar to that experienced in previous remote control tests using terrestrial links. The second trial involving the Keck Peak Observatory on the island of Hawaii is described in the next section on very high data rate applications.

VERY HIGH DATA RATE APPLICATIONS

The 900 MHz wide bandwidth of the ACTS transponders provided a unique capability to handle data rates of hundreds of megabits per second, which are not available with today's conventional satellites. HDR earth stations were developed to exploit this capability and deliver 155 Mbps (OC-3) and 622 Mbps (OC-12) digital services. The use of SONET physical layer protocols allowed seamless interconnections into the terrestrial fiber network. ATM communications were readily run on top of this SONET structure.

This capability opened up a whole new range of applications associated with geographically distributed computing, especially those associated with high-speed workstations and supercomputers. Although once the domain of university and government researchers, additional non-research applications are growing such as the cancer dose treatment planning outlined in the section on Medical Experiments. The satellite/terrestrial networking trials using ACTS provided the capability to make such supercomputers available in an on-demand, non-dedicated basis for those organizations and applications that don't require or can't afford a dedicated supercomputer. Such capability will provide more effective resource sharing and improved utilization of computing resources.

REMOTE COMPUTING

AERONAUTICAL MODELING: The Boeing Commercial Airplane Group in Seattle, WA, conducted a series of interactive computational flow dynamic simulations to develop an engine control system by remotely flying an engine model in a "numeric wind tunnel."[74] The inlet simulation that was developed by Boeing was executed on the LeRC Cray supercomputer and controlled by the Boeing engineers in Seattle. Flow visualization information from the Cray was transmitted via the ACTS gigabit network to Seattle, while setup and control information and commands were transmitted from Seattle.

The large data throughput provided by ACTS allowed the Boeing staff to view flow visualization "movies" of the simulation in near real time. The immediate feedback allowed the data to be examined and operation points readjusted in near real time to develop the necessary inlet operating control characterizations. By comparison, Boeing, using local workstations, found that the iterative process in just determining good initial conditions would typically take several days and running just one simulation would take weeks. ACTS made this possible in minutes.

Determining the results for multiple operating points required months on local work stations, while the ACTS-Cray combination streamlined the process to a few hours. Not only did the ACTS interconnect physically speed things up, but it enabled the quick detection of errant runs and allowed appropriate human intervention, permitting parameters to be quickly reset for another trial.

In addition, Boeing used some of the inlet characterizations gleaned from the ACTS tests to make more efficient use of the configurations being tested simultaneously in an actual wind tunnel. Boeing felt that in the future, use of a supercomputer via very high data rate connections could ultimately reduce resources, optimize wind tunnel tests (which are very expensive), and potentially alter future design and manufacturing processes. In the future, companies may routinely access various facilities, such as supercomputers or wind tunnels, via high-speed links for a more cost-effective utilization, higher productivity, and faster turn around.

While these inlet simulations were being run on the ACTS network, a team of Bellcore, Sterling Software, and LeRC engineers were evaluating and characterizing the performance of the ATM protocol being used to support the HDR transmissions. In general, the communication links performed very well, with zero ATM cell loss, a bit error rate comparable to fiber, and delivery of full raw-channel bandwidth. However the propagation time delay in going to and from the satellite can severely hamper the throughput of the communication channels. It was noted that the protocols and application codes needed to be modified to work well on a high bandwidth, high latency network. The combined computer-satellite links used a complex protocol stack of user datagram protocol (UDP), transmission control protocol (TCP), Internet protocol (IP), ATM, and SONET. Tests with some modifications made to the protocols demonstrated throughputs up to 58 Mbps for TCP and approximately 120 Mbps for UDP on a 155mbps ACTS channel. To improve these throughputs, further modifications need to be made to the transport layer protocols. Such modifications were made and test results are reported in the later section on Protocols and Standards.

<u>**ASTRONOMY:**</u> A team from the JPL, California Institute of Technology (Caltech), and the University of Hawaii, conducted a number of experiments between the Keck telescopes mounted atop the Mauna Kea volcano on the island of Hawaii and an astronomy laboratory located at Caltech in Pasadena, California via ACTS [75]. In remote astronomy, typically an investigator collects a data set or image with a remote instrument, examines the data with local computers, and then takes another data set with improved control or calibration parameters. Networking instruments in this fashion allows more scientists to use the facility, permits more rapid analysis of the data, collaboration among the science teams, and even makes possible the use of the facility in a classroom setting. For this experiment, in addition to the ACTS'155 Mbps link, terrestrial fiber networks were used in both Hawaii and in California. In Hawaii, GTE fiber links were used to con-

nect the ACTS HDR terminal in Oahu to the Keck telescope, while in California the ACTS HDR terminal was interconnected to the CASA gigabit terrestrial fiber network at JPL. Using the CASA network, a variety of supercomputers and high speed work stations could be used to enhance Keck observations in real time, during the data acquisition phase, depending on the specific algorithms used. The Keck instruments are complex and extensive calibration data are required to remove the instrument's signature in an optimum way. Frequently a number of iterations are necessary to calibrate and to set the control conditions for a particular observation. For instance, atmospheric turbulence might be compensated for a given observation.

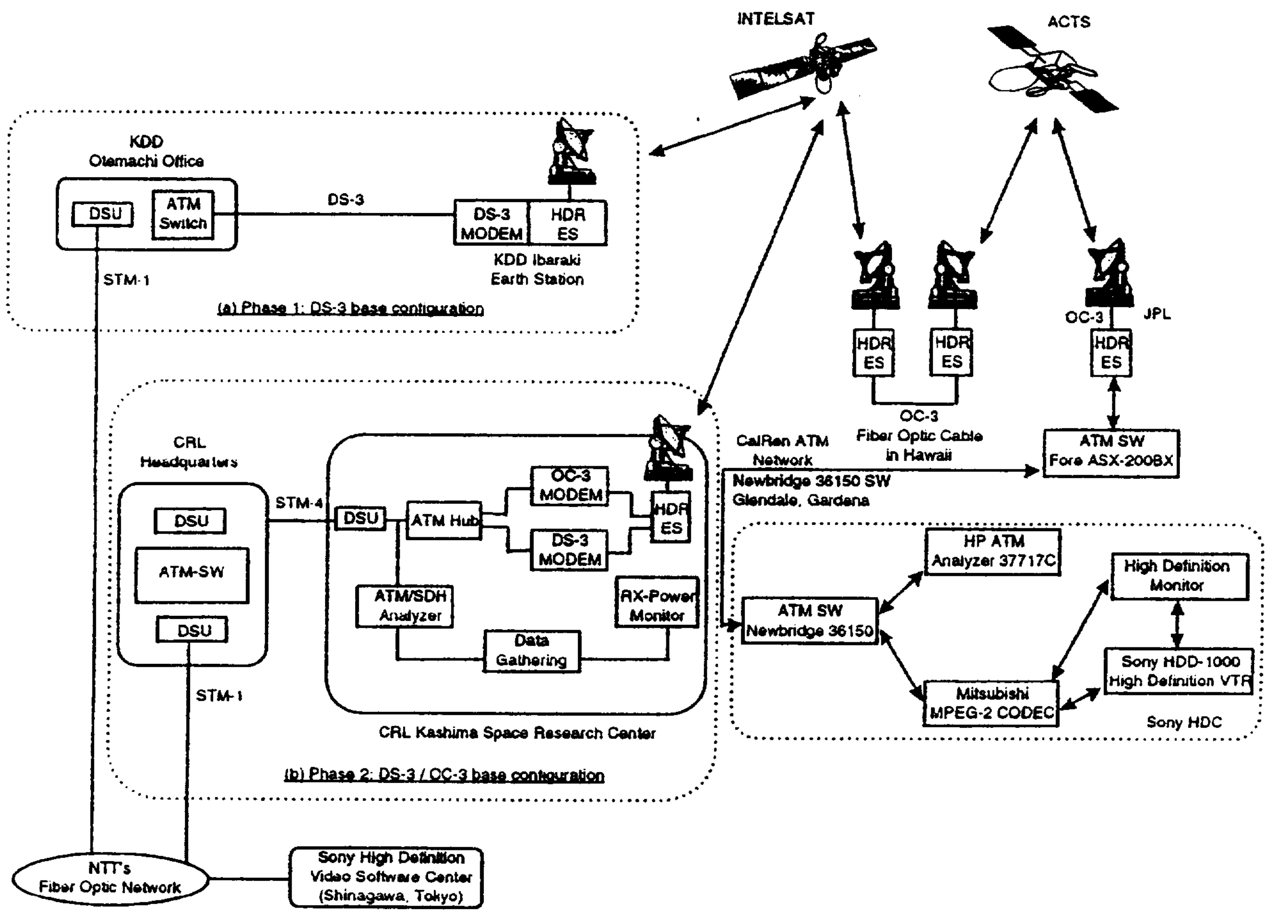
The high resolution of the telescope's various sensors generated images and data sets of hundreds of megabits. Being able to process the data in near real time, as provided via ACTS, provided faster and more extensive near real time calibrations as well as near real time data examination. As in the Boeing experiment, changes could be made after examining the initial image sets and additional images or data could be collected, tremendously enhancing the capability to collect valid data. In the future, such high data communication links will reduce the time lost to travel and allow more scientists to use the facility and join in collaborative research.

<u>**MOVIE PRODUCTION:**</u> In the first steps to establish new, very high data rate global telecommunications networks, researchers in both the US and Japan cooperated in a multi-satellite/terrestrial hookup between the two countries to transmit high definition video (HDV) [76]. The purpose of the experiment was to demonstrate broadband satellites' capability in delivering digital image traffic at transmission rates up to 155Mbps (OC-3). For this experiment, the Sony Studio in California was connected via terrestrial fiber to the HDR earth station at JPL. ACTS provided the link from JPL to Hawaii where the data was then relayed via the Intelsat 701 Ku-band satellite to Japan and onto the Sony Studio via terrestrial fiber.

Sony's purpose in conducting this experiment was to investigate the rapid transfer of high definition video (HDV) masters from remote shooting locations to post production facilities for digital editing, dubbing, and the addition of special effects. For today's movies, the background is frequently "composed" in postproduction with selected images to create the appearance of subjects being filmed in various backgrounds or amidst special effects. In the traditional way of film making, it generally takes weeks and many iterations between the director and the film laboratory to produce the images matching the director's vision. Distant collaboration between the people involved in the shooting and the editing will reduce processing time and expenses by allowing, among other things, scenes to be "re-shot" in near real time while the actors and remote directors are on location and the set is still intact.

The projected business application of this experiment is to have the ability to interconnect all organizations involved with the making of a movie with global, wide bandwidth links. The ultimate aim is to have complete electronic transmission of the image all the way from the studio to the theater. Post production compositing performed in Tokyo on a green-screen HDV clip transmitted from Los Angeles and the comparison of an HDV clip to its original source after one trans-Pacific satellite round trip demonstrated the capability of the satellite channel to successfully transfer HDV. The conduct of this experiment again demonstrated the striking capabilities of satellites to seamlessly interconnect with high speed terrestrial networks at OC-3 data rates on a global scale.

Schematic overview of the Sony remote movie production network.



DISTRIBUTIVE HIGH SPEED COMPUTING

GLOBAL CLIMATE MODELING: Two different teams conducted collaborative computer modeling experiments. A JPL and GSFC team investigated global climate modeling using a coupled atmospheric-oceans climate model [75]. GSFC ran the atmospheric model while JPL ran the ocean model. Boundary condition data were continuously exchanged via ACTS 155 Mbps links while these models were being separately processed on the JPL and GSFC supercomputers. A major objective was to explore approaches and performance issues for running complex models on heterogeneous computer architectures via a satellite link. With gigabit interconnections like ACTS, decomposition and distribution enables the concurrent utilization of computational resources at geographically separated locations and speeds up model execution. The models were successfully run using ACTS. The coupled ocean-atmospheric modeling task is analogous to many of the future NASA modeling applications being planned in the NASA Earth Sciences Enterprise.

GREAT LAKES WEATHER MODELING: A second team consisting of the Ohio Supercomputer Center (OSC) in Columbus, OH, the National Center for Atmospheric Research (NCAR) in Boulder, CO, and the Great Lakes Environmental Research Laboratory (GLRL) in Ann Arbor, MI, performed a collaborative climate simulation in the Great Lakes region [77]. Cray supercomputers at OSC and NCAR, separated by 1200 miles, were connected and operated in parallel via the ACTS 155 Mbps channels. GLRL was connected to OSC via T3 terrestrial landline. All three sites interacted and collaborated while an atmospheric, lake, and wave model were running in parallel at OSC and NCAR which required exchanging boundary conditions (i.e. surface heat and momentum fluxes, wave heights and direction, lake surface temperatures). The results provided sophisticated flow visualizations of the air-lake interaction for Lake Erie for a given set of meteorological conditions. The success of this experiment illustrated how Great Lakes forecasters can generate better meteorological and marine forecasts using distributive computing.

The ACTS gigabit satellite network is the first satellite based network to provide network connections at rates up to 622 Mbps, and with sufficient signal quality and transport mechanisms to be integral with terrestrial fiber optical SONET networks. The ACTS gigabit satellite network provides BER performance comparable to fiber lines, especially for long-haul links. As such, it demonstrates that satellite are a technically viable medium for providing very high data communication services alone or in concert with terrestrial networks as part of the information superhighway.

OIL EXPLORATION

Oil exploration remains one of the most risky parts of the petroleum business. Most of the new frontiers of oil exploration are in deep waters, hundreds of miles offshore. Seismic acquisition vessels survey vast ocean areas collecting data that can be analyzed by geophysicist hoping to locate the most promising drilling blocks. A single ship can collect as much as 3 terabytes of raw data every week. Currently data is collected on magnetic tapes and either flown from the ship or unloaded when the ship docks every few months. From these magnetic tapes, seismic data is transferred to a supercomputer center where sorting, screening, and other processes render it for study by oil company geophysicists. After review, the geophysicists may require additional data to be taken which starts another long acquisition cycle involving a ship revisit, which may take six months to a year to arrange.

"Delivery by satellite" has the potential to revolutionize the process as well as the time frames in the collection and analysis of seismic data. The NASA ACTS team joined with the ARIES team to test and demonstrate the power of wideband satellite links inter-connected with multiple terrestrial networks to preview the information superhighway of tomorrow [78, 79, 80]. ARIES, an acronym for ATM Research and Industrial Enterprise Study, was initiated at Amoco in 1993. The original goal was to build a small ATM high-speed network with which to study the emerging ATM technology and how such networks could provide a competitive business advantage to Amoco. The initial 17 vendor partners that joined Amoco have grown to 35, and the project has been transferred to American Petroleum Institute where the widespread value to all members of the petroleum industry was recognized.

A series of application trials and demonstrations were conducted by the NASA-ARIES team to show that high speed, satellite data links can extend the reach of the networks to remote and underserved regions not reached by fiber. A T1 VSAT earth station was placed on West Delta 90, an oil platform in the Gulf of Mexico, 40 miles off the Louisiana coast.

In another demonstration, the mechanically steered, slotted waveguide antenna station (2 Mbps) was placed aboard the seismic exploration vessel M/V Geco Diamond plying the waters 120 miles offshore also in the Gulf on Mexico. In these tests, the ACTS links demonstrated how megabytes of seismic or production data could be relayed in real time to supercomputer centers for immediate analysis. The processed data was exchanged in near real time with geophysicists at various oil company sites around the country over the ARIES terrestrial network. Collaborative interaction allowed additional processing, review and analysis of the data sets. The use of ACTS compressed into days what normally took up to a year to complete. Researchers could literally "steer" the seismic vessel to reexamine promising areas before it left the area. Charles Dibona, president of the American Petroleum Institute, estimated that reduced time for completing seismic surveys could save the energy companies $200,000 a month for each survey, a considerable saving when you consider that hundreds of these surveys are conducted each year.

The ARIES tests and demonstrations also provided an excellent opportunity for the various application and network interface manufacturers as well as the terrestrial wireline carriers to test the interoperability of their various hardware, switching equipment, and fiber lines. The success of the ARIES/ACTS tests and demonstrations attest to the power of wide bandwidth satellite links coupled with fiber to revolutionize businesses, like the petroleum industry, by compressing the time between data collection, processing, and analysis.

GLOBAL INTEROPERABILITY

Video Conferencing: A satellite hop, a skip underneath the ocean on fiber, and finally a jump to the final destination via satellite. As has been discussed, ACTS has participated in a number of satellite/terrestrial interoperability trials and demonstrations. On September 17, 1997, ACTS and Italsat-2, the second operational Ka Band Italian satellite serving Italy and Europe, were used in the first ever two Ka-band satellite link connecting attendees at the 3rd Ka-band Utilization Conference in Sorrento, Italy with participants in Canada and the US. The network consisted of an ACTS link from Cleveland to the Canadian Research Centre in Ottawa, Canada and then via fiber across the Atlantic and through Europe to the Telecom Italia CSELT laboratory in Turin, Italy. From Turin the network was connected via Italsat-2 to Sorrento. Full duplex, 2.048 Mbps (E1, a European telephony standard analogous to T1) traffic was routed over the network using the ATM protocol. The live multicast videoconference (at 128 Kbps video data rate per link) enabled sites in the US, Canada, and Italy to simultaneously interact. Workstations using multiple windows displayed not only the speakers but also the charts used in their presentations.

The overall quality of the video and audio was excellent. The content of the slides was clearly visible in the windows while the small video of the speakers was enough to observe hand gesture, voice inflections, and general body motions. The delay of the double hop link did not detract from the videoconference. User application equipment was able to synchronize the video and audio to adjust for any delays. The double satellite transmission delay was detectable. However, once the participants became accustomed to talking over this link, the impact of the delay became negligible. This demonstration provided another glimpse of the power of satellites working together with terrestrial networks to provide global interconnectivity. The demonstration could not have taken place without the tremendous cooperation of all the groups involved and the leadership of the Canadian Research Centre. It showed also the unifying power that common protocols can have in interconnecting totally separate and isolated systems.

AERONAUTICAL APPLICATIONS

The demand for reliable data, voice, and video links between aircraft and ground has increased dramatically in the past decade. A clamor for increased passenger communication services is fueling this demand. In addition, reliable global aeronautical communications are required to support air traffic control as well as airline operations and administration. The S sand L-band frequencies employed by the current systems support only low data rates (tens of kilobits per second) and are becoming highly congested. Ka-band offers outstanding promise to accommodate aeronautical communications because of the large available bandwidth and higher data rates. In addition, Ka-band has the potential for supporting user equipment that is significantly smaller and in some cases simpler than at L-band. Ka aeronautical links will not be plagued by shadowing and will largely avoid rain fades by flying at altitude. Satellite aeronautical communications should be an important new growth area for the telecommunications industry.

LOW DATA RATE TRANSMISSION USING MMIC ARRAYS

Aeronautical tests have been conducted via ACTS using two different types of antennas systems: proof-of-concept MMIC phased arrays with electronic steering and a slotted waveguide array with mechanical steering (see Chapter 3). A NASA Lear jet was outfitted with proof-of-concept MMIC phased array antennas built by Texas Instruments, Boeing, and Lockheed Martin [81]. Separate antennas at 20 and 30 GHz with dimensions of only a few centimeters on a side were used. Two-way voice and low rate data at 4.8 and 9.6 Kbps transmissions were successfully completed during the flights.

This was the first time an electronically steered Ka-band MMIC array system had been demonstrated in an aeronautical terminal link with a satellite. As part of the test and evaluation program, demonstrations were provided to various airline, government, and equipment manufacturers. Demonstrations were held in both Cleveland and Dayton, Ohio; Washington, DC; Baltimore, Maryland; Boston, Massachusetts; Dallas, Texas; Los Angeles, California; and Seattle, Washington. The audiences at each location varied in composition with top level representatives from American Airlines, Hughes, Mitre Corporation, Lockheed Martin, Boeing, Texas Instruments, and Westinghouse among the industry attendees. In addition government representatives from the Air Force, Army, NASA, Rome Labs, and the National Communication System also attended. The successful results of the MMIC phased array tests and demonstrations have created a strong incentive for continuing the focused development of MMIC array technology for satellite communications applications. In a letter to Donald Campbell, LeRC Director, Larry Winslow, vice president of engineering for Boeing, cites that the development of phased array antennas at Boeing for both commercial and military applications has been significantly aided by the LeRC ACTS demonstration program. He stated that *"The performance demonstrated in these activities has contributed to the overall concept credibility, adding assurances that the continued development will have a worthwhile payoff."* He went on to state that *"NASA's work, which is designed to further development of technology that can be used by American industry, has often accelerated the rate of progress possible by the industry"*. In the future, the use of small, conformal, phased array antennas will provide electronic steering, lower installation costs, and lower drag profiles than mechanically steered reflectors.

SLOTTED WAVEGUIDE ANTENNA AT T1 RATES

Using the slotted waveguide antenna, two different series of aeronautical tests and demonstrations were conducted [82]. In the first, the antenna was mounted in a Rockwell/Collins Saberliner 50 aircraft. Serving both the commercial and government aeronautical markets, Rockwell was interested in validating and characterizing the T1 transmission performance of a Ka-band system to and from a business aircraft with an eye towards future business development.

In the second, the antenna was mounted and flown aboard the NASA Ames' Kuiper Airborne Observatory (KAO). The KAO, a C-141A jet aircraft, carries a 0.9 meter reflecting telescope used for infrared astronomy. With the KAO, a number of successful experiments were carried out, including the PBS sponsored "Live from the Statosphere".

"Live from the Stratosphere" was a multimedia educational program which included live, two way video, audio, and broadcasts from KAO to the ground. The video and audio were sent via a combination of commercial satellite and landlines to Public Broadcast Service stations (PBS) on the East Coast where the program was produced and sent out live for broadcast on PBS channels and NASA TV. During the broadcast, selected sites at museums and schools were given the opportunity to communicate directly with the crew and scientists aboard the KAO. One group of students at the Adler Planetarium in Chicago was able to control the KAO telescope. During other KAO research flight, scientists from the University of Chicago's Yerkes Observatory tested and demonstrated remote control and operation of the telescope aboard the aircraft. The scientists had immediate access to the telescope's imagery, and video teleconferencing over the link allowed real time scientific collaboration. This experiment showed that interactive video conferencing sessions could be successfully accomplished with three satellite hops. During these research flights, another group successfully tested and evaluated a remote failure and diagnosis monitoring system, eliminating the need for a technician to travel on the aircraft. This was the first time that an Internet connection was made to an aircraft in flight.

The aeronautical trials pioneered and tested using ACTS will serve as a proof-of-concept for development of global, wideband aeronautical communications services.

MARITIME APPLICATIONS

The use of the slotted waveguide antenna was already chronicled in the petroleum exploration tests and demonstration with the seismic vessel Geco Diamond. This mobile terminal was also installed on the US Navy Cruiser USS Princeton (CG 59) and remained aboard for one year during which time the Princeton was deployed in the Eastern Pacific, Sea of Cortez, and the Caribbean [83]. The US Navy desired to increase the capacity of the communications links available to its deployed forces and looked to ACTS to provide a chance to test an early prototype of future operational capacity. The ACTS terminal provided full duplex communications at data rates up to T1 (1.544 Mbps).

The link was used for voice, Internet, and video traffic. These tests also provided the first Ka-band mobile propagation data in a marine environment. The ACTS link gave the USS Princeton access to medical, logistical, maintenance operations, training, personnel, and weather forecasting services. In addition to directly enhancing the Princeton's mission effectiveness with work related services, ACTS allowed officers and crew to stay in touch with their families via interconnections through the public telephone network and E-mail.

While cruising off the coast of southern Baja California in February 1997, the Princeton received word that the 66 year old master of the Greek bulk cargo vessel Phaethon was in medical distress with severe abdominal pains and cramping. The Princeton proceeded several hundred miles to rendezvous with the Phaethon. The Princeton's medical officer rendered immediate aid and used real time video conferencing via ACTS with the Naval

Medical Center Balboa, CA. A urologist from Balboa, examining the patient via the ACTS video link, determined that he had a blocked urinary tract and guided the Princeton's medical officer through a specialized course of treatment. The timely intervention provided by the ACTS link was recognized as vital to saving the life of the Greek Captain.

The communication services that ACTS brought to the Princeton served as a model for the future of satellite communication services for all Navy ships. With extended deployment, a ship's needs for greater connectivity with the information infrastructure ashore becomes critical for mission effectiveness and crew morale. ACTS provided the Navy with invaluable opportunities to demonstrate the many ways that full duplex, high data rate satellite communications can enhance the quality of life at sea.

In a continuing effort to enhance satellite communications connectivity to naval forces the Office of Naval Research once again teamed with NASA. In October 1998, LeRC, the Naval Research Laboratory (NRL), and a team of various commercial equipment suppliers successfully demonstrated a two-way mobile network operating at 45 Mbps. LeRC engineers assembled a 4 foot diameter terminal from commercially available hardware. Using a 120 watt TWTA and a fully articulated tracking pedestal, they transferred data from the Motor Yacht Entropy operating in the choppy waters of Lake Michigan via ACTS to the HDR terminal at LeRC. Communication transfers included TCP/IP based file transfers, interactive and variable TCP/IP based multimedia, production quality video, and CD quality audio.

SUPERVISORY CONTROL & DATA ACQUISITION APPLICATIONS

The use of Ka-band and spot beam antennas has the potential to reduce the size and cost of earth stations for low data rate (Kbps) applications. Ultra Small Aperture Terminals (USAT) with antenna diameter of 14 inches and less than one watt of transmitting power can be used to provide supervisory control and data acquisition (SCADA) services. SCADA systems typically involve a central processing point collecting real time information on a continuous basis from remote points for purposes of monitoring and control. Systems of this type are employed in electric, gas and water utilities, oil and gas production fields, and gas pipeline systems.

SCADA applications are one example of a much broader class of low throughput data applications. This general class of applications represents a very large market that could be cost effectively served with the type of low cost ground terminals made possible by using the ACTS Ka-band spot beam technologies.

In a joint undertaking, NASA LeRC and Southern California Edison (SCE) tested the 14 inch diameter USAT at data rates of 4.8 Kbps, in the SCE operational SCADA network in southern California[84]. The purpose of this network is to monitor the status of the electrical distribution grid and provide path and redundancy switching for failure recovery. In this test, a SCADA master computer at SCE's Vincent Regional

Control Center polled a USAT at the unmanned Goldtown substation every 4 seconds. The availability of the Ka-band system was compared with that for the current Ku-band VSAT system in use by SCE.

SCE alone has over 10,000 points in their electrical grid over a 50,000 square mile area which they would like to monitor and control. Such wide geographical dispersal provides an ideal stage for the use of satellites. At the time of this experiment, they were monitoring only approximately 900 major substations because of the relatively high price using Ku-band VSATs. The price objective was $75 per month per location. The hope is that with the development of Ka-Band commercial systems the price for conducting SCADA operations will become inexpensive enough to allow wide spread deployment of a satellite SCADA network.

DISTANCE EDUCATION APPLICATIONS

Education and training are key to increased personal knowledge and national productivity. In this era of changes in the classroom and evolution in the workplace, students and employees need better access to educational and training facilities to remain professionally competent. Satellites have been and continue to be used to deliver broadcast type distance education and training. In 1996, more than 70% of corporate satellite networks were used for training and new product information. Distant learning offers a dynamic method to train hundreds or thousands of employees simultaneously.

In education, there are about 6.9 million students attending some 22,400 rural schools in the US. This accounts for 17%of the regular public school students and 28% of regular public schools. Nearly three quarters of all rural public schools have fewer than 400 students. To serve these smaller enrollments, innovative instruction practices are needed to educate these students and train their teachers adequately. Satellite communications seamlessly integrated with the terrestrial network will contribute significantly to this process. High-data–rate, low-cost communications using small earth stations offered by the ACTS like systems have the potential to raise the use of satellite-delivered education to a new plateau.

For the ACTS distance learning trials, each duplex video link was at a minimum of 384 Kbps (maximum of T1), and Compression Laboratories video equipment specifically designed for distant learning was installed at all locations. The multiple channels offered by the T1 VSATs allow not only video broadcasts of classroom instructions but also the simultaneous capability for return video and audio links to allow better instructor/student interaction.

Three different teams used ACTS to investigate various aspects of distant education. Georgetown University (GU) led the Latin America Distant Education Experiment. GU conducted a number of different types of classes with both Javeriana University in Bogota, Colombia and Catolica University in Quito, Ecuador.

Working with a team of industry organizations and the World Bank, GU evaluated the effectiveness and economic viability of offering not only academic courses but small business development training classes as well. In developing countries, satellites offer the most reliable and cost effective means to conduct overseas training programs. A location can be immediately connected into a satellite network without reliance on local terrestrial links.

GU offered classes and seminars in business, Latin American studies, medicine, nursing and linguistics [85, 86]. Seminars on small business development were targeted to small enterprises that operate in Colombia and Ecuador. The seminars covered such topics as marketing, growth and expansion, import/export regulations, and capitalization. The intent of the program was to increase the resource base for small businesses in Latin America. A yearlong series of classes were conducted at GU where students in Latin America 'attended" via ACTS. The transmission quality was excellent and the system provided an opportunity not only for the University and Small Business Development classes but also a means for conducting a number of telemedical conferences.

The ACTS satellite education program enhanced the regular classroom experiences of the GU students by incorporating professor and students from Latin America into the classroom via satellite. Their experience shows that distance education has the potential to dramatically change the teaching of international studies by incorporating foreign students and scholars directly into the curriculum.

ACTS provided for more interactions between the instructor and the student by moving distance education learners out of a one-way classroom environment and into a more traditional one. As one author put it, "*technology is taking the distance out of distance education.*" With the potential for Ka-band satellites to deliver the necessary service for distance learning at a low cost, this superior capability will become much more affordable.

STANDARDS & PROTOCOLS

One of the key challenges facing the satellite industry today falls under the banner of Standards and Protocols. Until recently satellite networks have typically been operated as isolated, private networks. However, if satellites are to play a key role in the NII/GII, they must provide seamless interoperability with both existing and evolving terrestrial networks. There are terrestrial data protocols and standards in use today or under development that are in some cases incompatible with satellite systems or can make a satellite network very_inefficient. This is especially true for ATM and the Internet protocol suite TCP/IP, the two main driving protocol standards being implemented in high-speed terrestrial networks.

In recognition of the importance of TCP/IP to both terrestrial and satellite systems, many satellite companies have become involved in research and development in the field, joining companies representing terrestrial communications and computer interests. These include Bellcore, COMSAT, Lockheed Martin, Hughes, Motorola, Cisco, Orion, Cray, Sterling Software, Mitre, NCAR, OSC, Ohio State University, Ohio University, BBN, University of Maryland, Ames, ATT, Teledesic, LeRC, GSFC, and JPL (see references 87-96).

In June 1998, the NASA LeRC held a major conference at Cleveland, Ohio dedicated to satellite protocol issues, in which much of the current efforts were highlighted. NASA was urged by the attendees to continue using ACTS to promote advances in satellite/terrestrial interoperability [96a]. Numerous approaches to address the effects of satellite channel errors and latency have been investigated using ACTS.

A few of the many accomplishments are the following. Ohio University developed a modification to TCP/IP that allowed file transfer to take place at near the full 1.5 Mbps rates of the T1VSAT's. Bellcore conducted a series of ACTS experiments to test and evaluate seamless operations for delivery of personal_communication services, especially wireless packet, to scope out issues that may be important at the L- and S-bands for mobile services. In tests using the ACTS gigabit network, NCAR and OSC modified and enhanced the TCP/IP and achieved transfer rates over 120 Mbps in a 155 Mbps OC-3 channel.

The Joint Industry-Government TCP/IP High-Speed Performance Experiment – Team

COMPUTER INDUSTRY	COMMUNICATIONS INDUSTRY	SATELLITE INDUSTRY	GOVERNMENT LABORATORIES
SUN	SPRINT ADVANCED TECHNOLOGY LABORATORY	LOCKHEED MARTIN	NASA LEWIS RESEARCH CENTER
MICROSOFT	CISCO SYSTEMS	HUGHES SPACE & COMMUNICATIONS	NASA JOHNSON SPACE CENTER
DEC	FORE SYSTEMS	SPACE SYSTEMS LORAL/GLOBALSTAR	NASA JET PROPULSION LABORATORY
INTEL	AMPEX DATA SYSTEMS	SPECTRUM ASTRO	LAWRENCE LIVERMORE NATIONAL LABORATORY
PITTSBURGH SUPERCOMPUTING CENTER			NAVAL RESEARCH LABORATORY

One of the most important protocol experiments carried out over ACTS has been dubbed 118X [87], to indicate one satellite, eighteen organizations, and the dispelling (X-ing) of the myth that the delay inherent in GEO satellite transmission precludes operation of the TCP protocol. The ACTS high data rate team has been working with industry and other government groups, shown in the table below, to test and demonstrate the performance of TCP/IP over ACTS to dispel the myth about operating with TCP/IP over very high speed satellite links. In late 1998, this team consisting of computer, networking and satellite companies as well as government laboratories tested key TCP/IP performance enhancements. Their primary goal was to optimize the point-to-point transfer of data between two locations across the satellite using TCP/IP over ATM among multiple computer platforms and operating systems. The memory to memory transfer tests over the ACTS 622 Mbps ATM link were conducted using a wide variety of computers. Throughput performances were achieved in both homogeneous (over 500 Mbps) and heterogeneous (over 350 Mbps) vendor environments. Such successful trailblazing experiments and demonstrations help to hasten the introduction of such services in future generations of geostationary communication satellites.

CONCLUDING REMARKS

In the early 1980's when the foundations of the ACTS Program were being debated and established, the first personal computers were just being introduces by IBM. Today we have a plethora of communication devices not only at work but also in our homes. Personal computers, faxes, e-mail, cordless and mobile phones, pagers, and the Web are almost indispensable in the fabric of our everyday business and personal lifestyles. Access to information is indispensable for national and international economic development.

ACTS triggered and accelerated the shift from the static, bent-pipe satellite repeaters of the past to a new stable of agile, on-demand, wide bandwidth, all digital class of satellites that will lower the price for interactive services. In the 1980's, satellites mainly served the top US corporations and the government. The forthcoming generation of Ka-band satellites, modeled after ACTS, will provide services to not only a whole range of businesses but potentially into the home as well.

Through the ACTS User Program, the basic technologies of switching, spot beam satellites have been tested, characterized, and validated. Trials with the ACTS networks have demonstrated and validated the use of digital, on-demand, integrated services via satellites and shown that Ka-band spot beam systems with on-board switching and processing can provide these services reliably and with suitable availability.

CHAPTER 5

Ka-Band Propagation Effects

The NASA Propagation Experiment Group (NAPEX) has been in existence since the 1960s, sponsoring various experimental, theoretical studies, and model developments on the characterization and effects of earth-space path radio signal impairments at various frequencies. NAPEX has always had a strong partnership with industry, other government agencies, and universities to leverage NASA assets and other resources to obtain propagation data. In 1987, in a meeting at COMSAT, the NAPEX Group first discussed redirecting its efforts to concentrate on the upcoming opportunity to be provided by ACTS to record and collect Ka-band propagation measurements and study fade mitigation techniques [99].

In November 1989, NASA, through NAPEX, formally announced its decision to support ACTS propagation measurements and began the planning for such measurements by sponsoring the first ACTS Propagation Studies Workshop (APSW) in Santa Monica, CA. This workshop was attended by representatives from industry, academia, NASA and other users of propagation data. At this workshop, the group addressed a number of topics, including the need for propagation data and the configuration and number of propagation terminals required for gathering these data. Participants defined the overall goals of the ACTS Propagation Campaign and delivered a set of recommendations regarding propagation studies and experiments that would use ACTS. They also provided guidelines regarding measurement parameters and requirements. In subsequent workshops, held at the rate of two a year, the plan was refined and the top-level requirements for the development of a receive-only propagation terminal and the data collection software were developed.

The overall goals of the ACTS Propagation Campaign are to:

- Characterize all the important Ka-band frequency impairments including attenuation due to rain, clouds, gaseous absorption and scintillation;
- Determine the characteristics of fade rates and durations on Ka-band satellite links;
- Expand the propagation research base in all US rain climate zones;
- Study fade compensation techniques; and
- Characterize Ka-band propagation effects on mobile satellite links.

Although most mobile and personal communications systems will operate below 3 GHz, frequency congestion will inevitably force system planners to use the Ka-band frequency for such applications as aeronautical and maritime mobile communications. In additions, the military has a strong interest in using Ka-band for mobile communications. At the time of the ACTS Program, no method was available to make Ka-band satellite link predictions for mobile applications.

ACTS PROPAGATION EXPERIMENTS

The ACTS Program released a NASA Research Announcement (NRA) entitled "ACTS Propagation Experiments Implementation Program" for funding propagation measurements [59]. In May 1992, ten organizations were selected to carry out a series of propagation measurements.

LONG TERM ATTENUATION MEASUREMENTS

Seven experiments involving eight organizations were selected to receive the ACTS Propagation Terminals for making long term in situ measurements.

SITE	ORGANIZATION	PRINCIPAL INVESTIGATOR
Clarksburg, MD	COMSAT	A. Dissanayake
Fairbanks, AK	University of Alaska	C. Mayer
Ft. Collins, CO	Colorado State University	J. Beaver
Las Cruces, NM	• Stanford Telecommunications • New Mexico State University	• L. Ippolito • S. Horan
Norman, OK	University of Oklahoma	R. Crane
Tampa, FL	• Florida Atlantic University • University of South Florida	• H. Helmken • R. Henning
Vancouver, BC	• University of British Columbia • Communications Research Centre	• B. Dow • D. Rogers

These selected sites span many rain climate zones from subarctic Alaska to subtropical Florida and from arid New Mexico to temperate Maryland. The slant path to ACTS encompassed a range of elevation angles from as low as 8^0 for Alaska to as high as 52^0 for Florida. Experimenters at these sites were funded by NASA to collect and analyze data for **five** years. (Additional measurements are being considered to be taken during the inclined orbit operations phase of ACTS beginning in 1998.) The length of five years was decided upon for the following reasons:

- Attenuation by rain is a random process. The percentage of the time exceeded versus fade depth distributions observed in one year may be a poor predictor of the distribution to be observed in the next year. With only two years of data collection, statistical errors will far exceed measurement errors.

- Past empirical observations have shown weather cycles on the order of seven years. For this reason a five-year observation period seems to be the minimum duration.
- Originally, the plan was to gather data for only two years. However, after two years some of the sites showed results that substantially deviated from the norm.
- A subgroup of the Satellite Industry Task Force (SITF) strongly recommended that the program be extended to five years.

OTHER PROPAGATION EXPERIMENTS

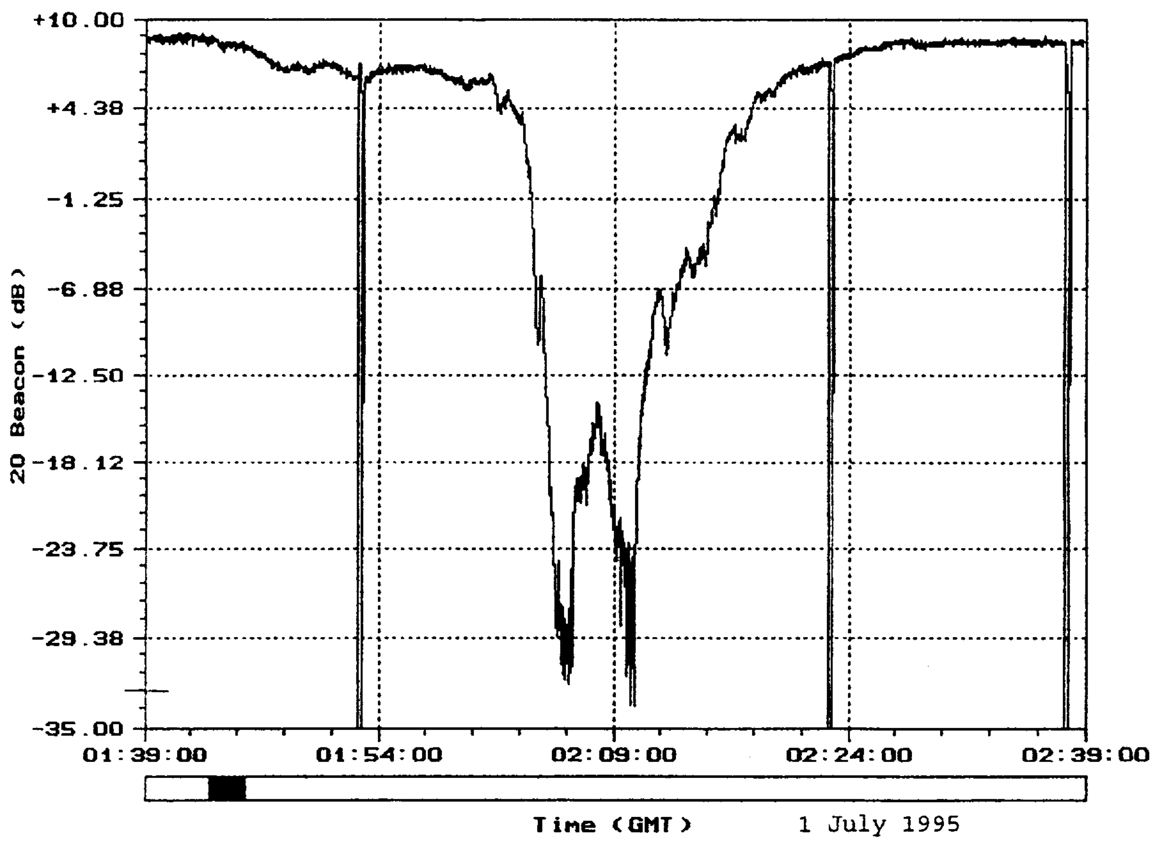
Three other experiments involving four organizations were selected to conduct shorter-term investigations related to other aspects of propagation. These experiments included wide-area diversity, uplink power control, land mobile satellite measurements, and satellite channel characterization. In addition, LeRC investigated fade mitigation techniques using adaptive convolutional coding and burst rate reduction, wet antenna effects, depolarization effects and collected propagation data at the Master Control Station in Cleveland. JPL made propagation measurements as part of the various land and aeronautical mobile communications tests and experiments they conducted.

EXPERIMENT	ORGANIZATION	PRINCIPAL INVESTIGATOR
• Up-Link Power Control • Wide Area Diversity	COMSAT	A. Dissanayake
Land Mobile Satellite Measurements	• Johns Hopkins University • University of Texas	• J. Goldhirsh • W. Vogel
Wideband Propagation Effects	• Georgia Tech Research Institute • Georgia Institute of Technology	• D. Howard • P. Steffes

PROPAGATION EXPERIMENT OPERATIONS

By launch, all propagation terminals were deployed and ready to collect data. The propagation beacons are described in Chapter 2. On Thursday morning, September 23, 1993, at approximately 10a.m. EDT, the 20.2- and 27.5 GHz beacons were switched on for the first time while ACTS was drifting to its 100^0 west longitude location. The University of British Columbia acquired the beacons at 11:02 a.m. EDT. Over the next day and a half, all the other propagation sites acquired the beacon. Of note, the University of Alaska acquired amid a few snowflakes, and the University of New Mexico captured data from a rain event on the first day that it received the beacon signals. The time period from launch through the end of November 1993 was used as a shake down period to learn how to effectively use the propagation terminals and wring out the system. An improved version of the preprocessing software was completed and delivered to the experimenters. On December 1, 1993, after completing all checkouts, the propagation experiments were declared operational and the data collection phase began.

Rain Fade Event at White Sands, NM, July 1, 1995
(Fades much greater than –25 dB are suppressed due to limitations in dynamic range)



The basic recording mode of the APT collected beacon and radiometer data continuously at one sample per second. These data were combined with a time stamp, meteorological observations, and recorder status information and stored in daily output files. These raw or unprocessed daily data files were preprocessed to produce attenuation, fade duration, interfade intervals, sky brightness temperature, and rain rate histograms.

While beacon data collection continued, other propagation experiments were also being conducted. The University of Texas and the Applied Physics Laboratory of Johns Hopkins University collaborated on a mobile propagation investigation [54]. The objective of these measurements was to establish the extent of fading caused by roadside trees, obstacles, terrain, and urban structures on the 20 GHz downlink signal emanating from ACTS. Data, which was collected using a van with a computer controlled tracking antenna mounted on the roof, will be used to construct models for use in future mobile communication satellite designs. Measurements were taken in Texas with bare tree conditions and in Maryland and Alaska with full foliage trees. The Maryland measurements were made over the same set of roads previously used to collect data at UHF and L-band, enabling frequency scaling of fade statistics to be modeled between UHF and Ka-band. In Alaska, measurements indicated that for a low elevation angle of 8 degrees, a margin of 25 dB is required for 90% availability.

In another experiment, Georgia Tech characterized the impact of propagation impairments on candidate modulation schemes such as CDMA and phase shift keying, which are being considered by future commercial, Ka-band systems [100]. JPL also measured and characterized the fading characteristic of the Ka-band channel in various suburban environments as they conducted land mobile user application experiments [53].

FADE COMPENSATION TECHNIQUES

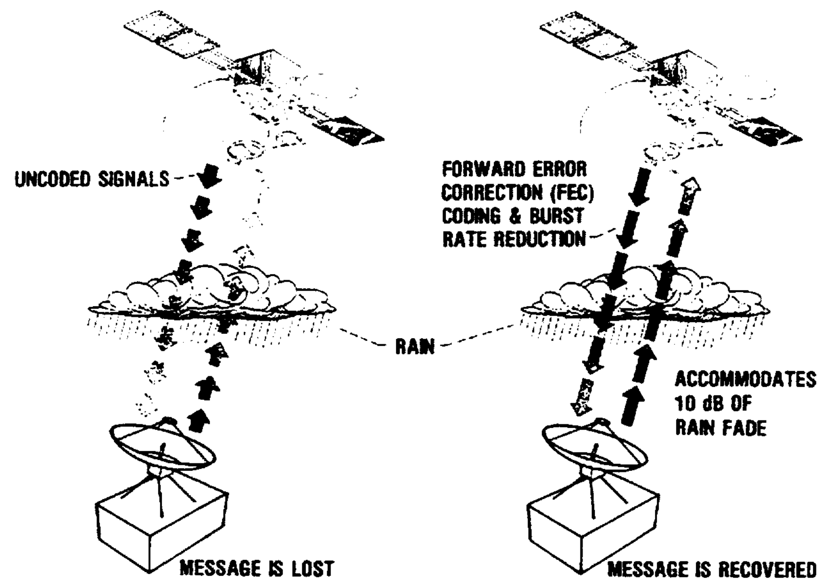
Two primary methods for overcoming the severe rain fades at Ka-band are to increase the terminal to satellite link margins or to provide earth station spatial diversity. Earth station diversity, although very effective, is cost prohibitive for low-data-rate user terminals because of the need for two terminals with an interconnecting link. To increase the link margin, most geostationary satellites find it effective to heavily code the links for error correction. For a regenerative satellite with baseband switching, the uplink burst transmissions therefore needs to be decoded (such as on ACTS) which consumes substantial on-board power.

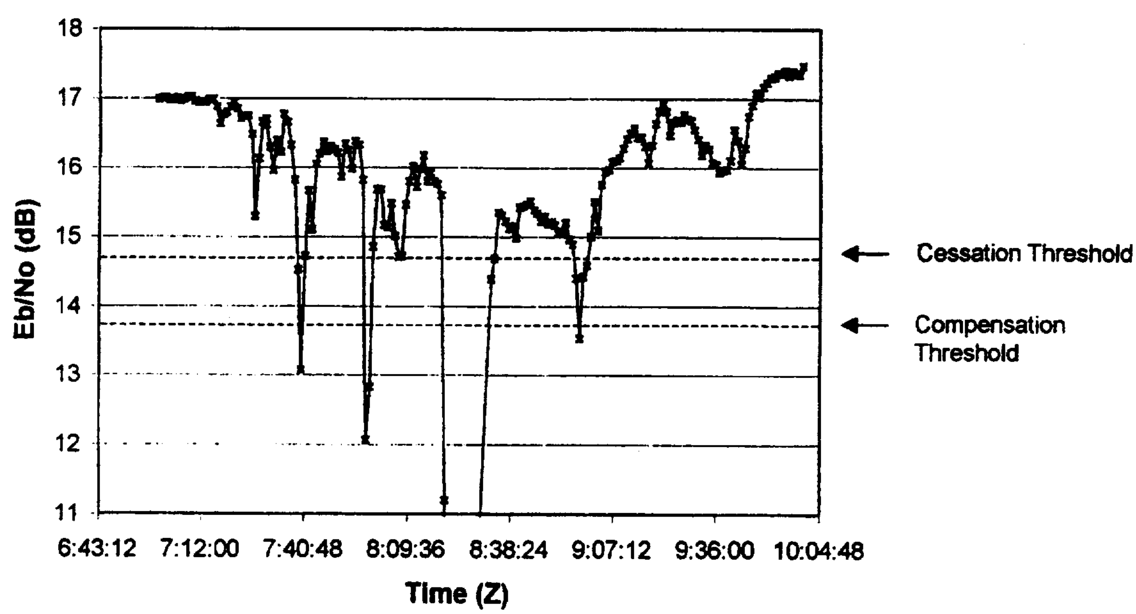
To reduce the amount of on-board power required for a concatenated code, adaptive fade compensation can be implemented whereby during non-fade periods the inner code (normally a convolutional code) is not applied. The system monitors the signal strength for each terminal and during large rain fades adaptively applies the convolutional coding. Since only a very small percentage of terminals in a multibeam satellite will be encountering significant rain fade at any one time, significant power savings for the digital on-board demultiplexer, demodulator and decoders (up to half of the power required) can be attained using this technique.

ADAPTIVE UPLINK FADE COMPENSATION

ACTS tested the reliability of adaptively applying coding and burst rate reduction on the uplinks for the VSAT network [101, 102]. The technique used is described in Chapter 2. ACTS is the first satellite system to use rain fade compensation on an operational basis. The data collected and analyzed by LeRC using the extensive VSAT network operating with the baseband processor showed that the adaptive rain fade compensation system was very reliable. The protocol automatically detected fades and provided 10dB of additional margin to maintain the BER at the service requirement. In no case did the system fail to successfully implement the fade compensation once the fade implementation threshold was crossed. The transitions to and from coded operations were accomplished without any loss of data. Implementing adaptive rain compensation techniques on future communication satellites has the potential of significantly reducing the communication payload weight and power. AstroLink, a Ka-band system proposed by Lockheed Martin, plans to use adaptive fade compensation on the uplink just for that reason.

ACTS Adaptive Rain Fade Compensation





20 GHz RAIN FADE FOR T1 VSATON 1/20/95
(Four fade compensation events occurred at 7:39:45, 7:58:12, 8:20:08 and 8:57:43. Each data point is average of 125 ms measurements over a one minute interval. The measurements are made by the VSAT in channel estimator.)

TRANSMITTER POWER CONTROL

On ACTS, adaptive downlink power control was considered for conserving power on board the satellite. Using this scheme, the downlink, 20-GHz TWTAs were to run in a backoff condition except when terminals in a spot-beam encountered significant rain fade. When faded, the RF power for the affected beam/TWTA would be increased to compensate for the fade. After the ACTS TWT was developed, it was found that the DC power savings for a regenerative satellite with baseband switching using this method were not great enough to justify the added complexity of implementing the method. However, newer TWTAs, that have greater efficiencies in the backed-off mode, may make this method worth while.

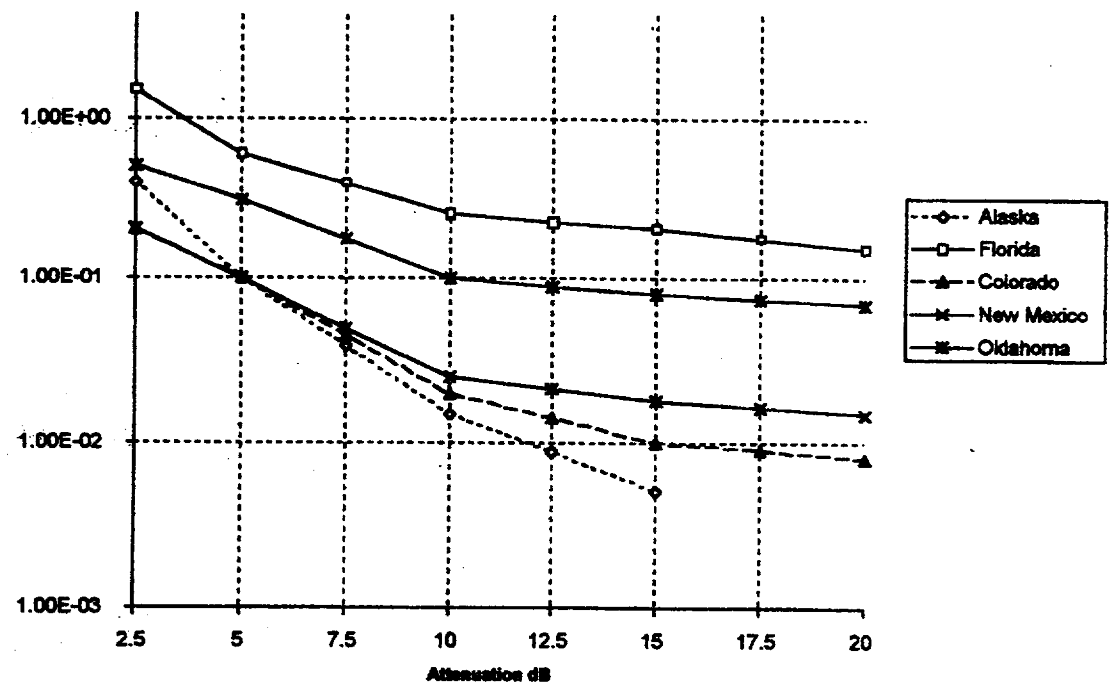
Uplink power control is a technique that most satellites employ because of the need to maintain a relatively constant signal level at the satellite in the presence of various fading conditions along the propagation path. This is true whether the type of satellite is regenerative or bent-pipe. COMSAT conducted an experiment to investigate the limitations of uplink power control in early 1995 [103]. The power control experiment involved estimating the uplink fade at an earth terminal by using a downlinked signal and increasing the transmitting power of the uplink carrier to compensate for the estimated 30 GHz uplink fade. The ACTS transmitted beacon signal in the uplink frequency bands was used to precisely measure the actual uplink fade. The experiment ran for six months. Using this fade detection method, the uplink power control accuracy could only be maintained within approximately +/-2.5 dB over a range of fades up to 18 dB at 30 GHz. The error increased as the fade depth increased. The main reason for the error is that the frequency scaling models were not able to accurately predict the 30 GHz uplink fade from the measured fade at the 20 GHz downlink frequency. The control algorithm also introduced errors.

Rather than use the open loop power control scheme described in the previous paragraph, the proposed commercial regenerative satellites with baseband switching actually plan to monitor the signal for each TDMA burst that arrives at the satellite using the on-board demodulated output. The estimated accuracy for measuring the uplink fade via the on-board processor is +/- 1 dB, which is a considerable improvement over the method discussed in the previous paragraph.

SITE DIVERSITY

Wide area site diversity entails the use of separated earth terminal sites, all connected into the same network, to combat rain fade. Rain cells are generally less than 10-20 kilometers in length and oriented in certain directions. Site separation must be such that two or more earth terminals sites will not be "significantly rained upon" by the same rain cell. Under these conditions the fading at one site tends to be not correlated with the fade at other sites. Terrestrial interconnections among the sites allow redistribution of traffic assigned to the faded earth terminal to those not undergoing fading at the moment.

Site diversity has a significant advantage in improving link availability in the presence of severe rain. COMSAT and Johns Hopkins University conducted a site diversity experiment using three sites more than 30 kilometers apart in Maryland and Virginia [104]. The key objectives of this experiment [105] were: (1) to develop a diversity site switching methodology based on monitoring propagation conditions at each terminal; and (2) to investigate network control aspects required in diverting traffic between terminals to minimize call blocking or packet delay. Testing over three months demonstrated the viability of wide area diversity as a means of combating fades and increasing the availability of VSAT terminals. The average time to effect a switchover was 3 seconds. The range of variation on switching time was very small and the maximum value observed was 5 seconds. Data buffering must be provided to avoid data loss during the switchover.



Four -Year ACTS Rain Attenuation Statistics At 20.2 GHz For Five Sites, Measurement Period From December 1993 – November 1997 (See page 140 for site description. The vertical axis is percent time attenuation exceeded).

WATER ON THE ANTENNA

Additional signal losses are caused by wetting of antenna surfaces by rain or snow.[60, 106, 107]. Wetting consists of a thin water coating and beads of water on the VSAT's antenna reflector surface and/or on the antenna feed horn window. The amount of water coating a surface depends upon the material, surface roughness, elevation angle and exposure of the surface to aging. Water on the antenna surface besides attenuating the signal causes scattering losses due to the raindrops and creates a distorted reflector surface that reduces the antenna gain. The water coating on the feed window distorts the electric field distribution of the feed horn causing an attenuation of the signal traversing the window.

Reflection from the ACTS propagation terminal antenna surface was complicated by the existence of a crinkled plastic dielectric coating over the conducting surface of the reflector, which provides a spacer separating the partially reflecting water layer and droplets from the conducting surface. Because the plastic surface was not smooth, the antenna collects a small amount of water on the uneven surface. However, the ACTS propagation feed window was coated with a hydrophobic coating so that its surface shed water very readily.

The problem of water on the surfaces of the antenna was considered during the Olympus propagation experiments. None of the antennas used in the Olympus experiments produced attenuation values as high as those observed in ACTS. The Olympus antennas were of a different design and did not have a crinkled plastic surface covering the reflector surface.

Various tests were conducted on the ACTS propagation terminals by hand spraying water on the surfaces. Based on those tests it was estimated that the wet antenna could produce as much as 3 dB of attenuation at 20.2 GHz and 5 dB at 27.5 GHz in addition to the path attenuation during periods of heavy rain. During periods of condensation or dew on the antenna, attenuation values as high as 4 dB have been observed at 27.5 GHz.

Acosta [107] performed comparison measurements using two ACTS antennas, one shielded and one not shielded from the rain. His fairly extensive measurements at 20 GHz show that the:

1. Maximum antenna wetting factor was between 3 and 4 dB; and

2. Higher antenna wetting attenuation tend to occur at rain rates of the order of 10 – 40 mm/hr.

It should be noted that at rain rates above 40 mm/hr the measurements may be invalid due to the dynamic range limitation of the measurement equipment. The magnitude of the effect of water on the antenna reflector and feed surfaces is a function of the antenna design. A better design should reduce the attenuation observed and measured in these ACTS tests.

MODELING

Extensive experimental research has been performed on the direct measurement of propagation effects on earth-space links, beginning in the late 1960's. In parallel with this measurement activity, various propagation models have been developed for the prediction of RF attenuation. Virtually all of the propagation models use surface measured rain rate as the statistical variable and assume an aR^b type approximation between rain rate R (millimeters per hour) and rain induced attenuation along a unit path length between the user terminal and the satellite. "A" and "b" are frequency and temperature dependent constants. Prediction of the percentage of time exceeded versus attenuation for a period (one year or month) is a two-part process. First a model of the rain rate versus percentage of time exceeded is needed for the geographical location of interest. Given the rain rate model, an integrated attenuation model over the path length must be used to predict the associated attenuation.

Some 10 models for predicting rain attenuation are available [108]. A 1996 study of these ten models by the International Telecommunication Union (ITU) using 186 station years of propagation data in the ITU database found that no single model was best in consistency and accuracy.

One of the key activities of the ACTS Propagation program was to compare the results of the measurements with these various prediction models. Crane and Dissaynayke compared the ACTS results [109 & 110] with a combination of four attenuation-prediction models coupled with three different rain-rate prediction models. The Crane-Global rain climate model [111] combined with the DAH attenuation–prediction model [112] gave the best results.

In 1997, Feldhake, Ailes-Sengers, et al., using 21 station years of new ACTS data, taken exclusively in the Ka-band across North America, compared the ACTS measurements with the same ten models used in the ITU comparison [108]. In general, they found that the model errors were slightly greater than typical (30% to 40%). The ranking based on the ACTS data was not highly correlated to the previous ITU model comparison with the exception that the DAH was best. These models will be compared with the full 5 years of ACTS beacon measurements when data collection is completed in 1998. (Plans for additional propagation data collection during the inclined orbit phase of ACTS operations are being considered.).

The Crane Global RF attenuation model [113] is based on the physics of attenuation by rain and predicted rain-rate probability distributions. Clouds as well as antenna wetting effects are not included. The above comparison showed that the Crane Global model attenuation predictions were consistently low as one might expect. Other models are more empirically derived from measurements and inherently include these other effects. In order for a physical based attenuation model to do better at prediction, a model for antenna wetting effects needs to be included. Roberto Acosta of NASA has developed an antenna wetting effect model based on measurements [107, 156]. Using this model, Robert Crane [157] adjusted the ACTS rain attenuation measurements to remove the attenuation due to antenna wetting. Crane reports [157] a much improved agreement between his two-component model and the wet antenna adjusted ACTS rain attenuation measurements. Since the effect of antenna wetting is significant future user terminals need to incorporate features that minimizes the effects of antenna wetting.

Another important consideration will be the validation of the models at low elevation angles. Very little data exists below an elevation angle of 20^0. Low elevation angle data is particularly important for tropospheric scattering. The ACTS site at the University of

Alaska, Fairbanks, AK, has an elevation angle of 8^0 and will provide 5 years of measurements from which to validate low elevation angle models.

Because of the severe propagation effects at Ka-band, it is important to refine the old models and develop new models that improve the capability for the system designer to better predict needed link margins. Included should be the capability to realistically combine the effects of rain, gaseous and cloud attenuation, scintillation, etc. In the design of future commercial systems every dB will count. Insufficient margins will reduce availability and excess margins will increase earth terminal size and cost.

CONCLUDING REMARKS

The work done by the ACTS propagation experimenters in characterizing the Ka-frequency band and its increased susceptibility to rain and other atmospheric and transmission path impairments is critical for the development of the next generation of satellites that plan to use these frequencies. One of the key features of the ACTS Propagation Program was that all 7 ACTS sites used the same collection hardware and employed the same software to process the raw data. Thus, the data are easily compared and are equally valid for all the rain climates in which studies were conducted.

The ACTS Ka-band propagation measurement data set is the largest set of Ka-band measurements in North America. Empirical cumulative distribution for satellite-to-space path attenuation relative to clear sky values will have been compiled for 35 path years of data when the ACTS propagation campaign ends in late 1998. The five years of measurements provides a statistically adequate time period for data collection. The five years of data produce a distribution estimate with only an 11% uncertainty. To date, only three locations worldwide have produced observations of 5 years of more. The ACTS propagation data should more than triple the amount of data available.

These propagation statistics are for two frequencies, 20.2 and 27.5 GHz, with elevation angles ranging from 8-52^0, latitudes ranging from 28 to 65^0, and five different rain climate zones.

In addition, the accuracy in prior propagation measurement campaigns was generally less than 1 dB. ACTS measurement precision was about 0.5 dB with a RMS measurement error of 0.1 to 0.2 dB. For locations within CONUS, the dynamic range was better than 20 dB.

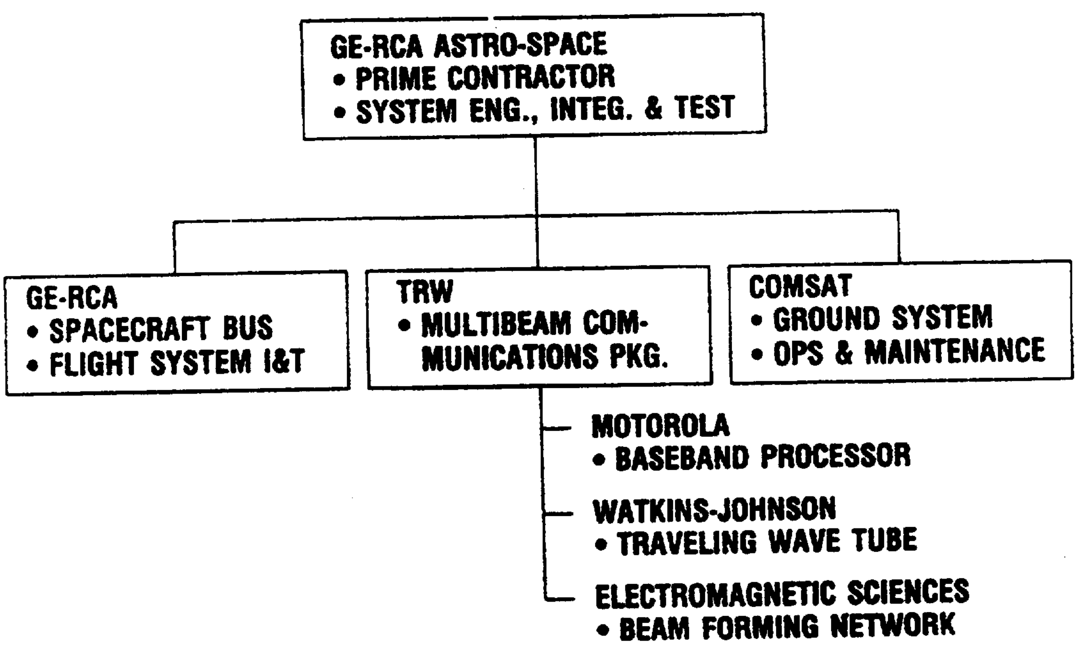
Fade compensation techniques will play a critical role in future commercial exploitation of the Ka-band frequencies. The research performed using ACTS on fade mitigation techniques has proved that adaptive coding can be effective in compensating for severe rain fades and saving spacecraft weight and power. The initial summary comparison of ACTS Ka-band data with prediction models does indicate a need to revise the models. The ACTS data will accelerate efforts to improve existing models for predicting atmospheric impairments of Ka-band satellite links to meet the urgent needs of the US satellite communication industry as they plan for the commercial utilization of the Ka-band frequencies.

CHAPTER 6

The ACTS Development

The NASA Lewis Research Center (LeRC) awarded the prime contract for the spacecraft, master control station and two years of on-orbit operations to RCA (which in time merged successively with GE, Martin Marietta and Lockheed Martin) on August 10, 1984 for $260M. The contractor team consisted of RCA as the system integrator and provider of the spacecraft bus, TRW as subcontractor for the communications payload and COMSAT as subcontractor for the master control station. The $260M did not include the cost of the Shuttle launch or the booster to place the spacecraft in a transfer orbit from low-earth, shuttle altitude to geosynchronous altitude. The cost for the launch and the PAM-A booster was not included in the prime contract.

At the time of contract award, the LeRC's cost estimate for the ACTS system development was $329M. This estimated cost included the prime contract, the LeRC contingency (approximately 15%), and other development costs including support for long lead technology development. This $329M total did not include the additional program funds levied by NASA Headquarters for taxes that occur at the agency level.



Initial Contractor Team for ACTS System Development (1984)

The ACTS system design, development and launch preparation period was initially planned for 60 months, with the launch of the spacecraft projected for September 1989. The normal commercial communication spacecraft at the time was being developed in about 3 years compared to this 5-year plus duration. The extra time for ACTS was judged to be necessary to overcome new technology hurdles, to develop an extensive communications payload engineering model, and to conduct a three-month, pre-launch Systems Test for checkout of the complicated network between the on-board processor, the master control station and the user terminals. The engineering model for the payload was included to remove development risk. The ground/spacecraft system test is not normally conducted in producing a commercial "bent-pipe" type spacecraft but was deemed necessary for this first generation, on-board processing satellite.

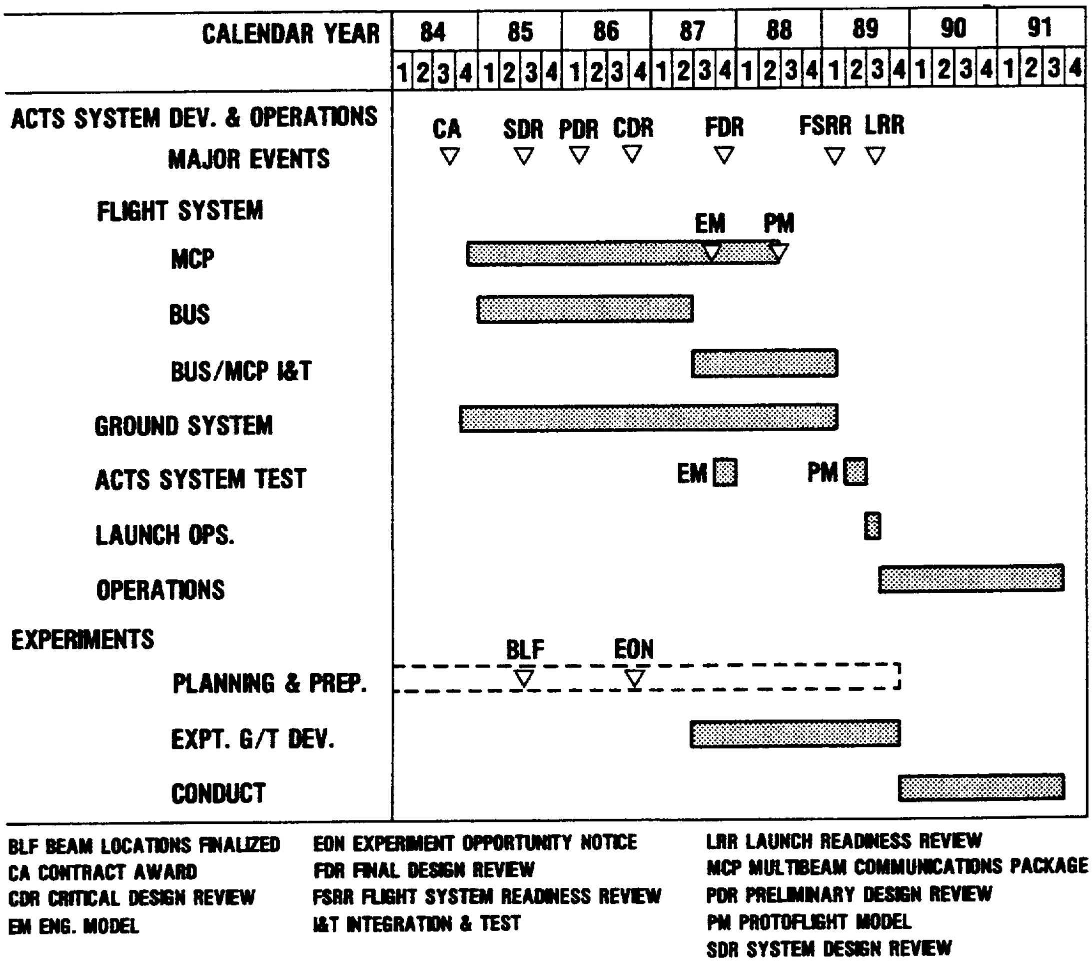
Because of the high technical risk and one-of-a-kind nature of the ACTS development, the only practical procurement mechanism was a cost plus fee type contract. Under this type of contract, the government takes on all cost risks. Because the technology being developed was for commercial application, the fee allotted for the contractors was fixed at 5.5%, which was considerably below the 12 to 13% normally collected. With this fee arrangement, the contractors were, in essence, making a direct contribution toward the funding of the program, which at the time of award of the contract was approximately \$20M(The fee difference between the normal 13% and the ACTS contract 5.5% fee.). In addition to the lower-than-normal fee, RCA contributed approximately \$2M for the Steerable Antenna that was added to the spacecraft after contract award. This Steerable Antenna proved to be a valuable addition and was extensively used during ACTS operations. All the major contractors on the team contributed their own funds to purchase terminals and/or to support the planning, solicitation, and the conduct of experiments or user trials. This amounted to approximately \$4 to \$5M more in contractor contributions.

THE ACTS DEVELOPMENT SCORECARD

At the "bottom line" level, the technical, schedule and cost performance is readily expressed.

- The launch occurred on September 12, 1993 some four years after the original planned date.
- The NASA LeRC cost for the program grew from \$329M to \$481M.
- All technical objectives were met or surpassed.
- Its lifetime expectancy was exceeded by more than three (possibly as many as five) years. Only minor spacecraft anomalies occurred, none of which decreased its communications capacity.

A quality product was produced at considerably more money and time than initially anticipated. Development of high-risk technology is seldom produced in less time and at less cost than planned. In the rest of the chapter, we will discuss the primary reasons for the cost growth, the schedule extension and the attainment of a quality product.



Initial ACTS Development Schedule

ELEMENTS OF COST GROWTH

TECHNICAL CHANGES

From the start, the LeRC project management philosophy was to write the ACTS technical requirements in terms of general functional capability, not to dictate the detailed technical approach, and to change the technical requirements as little as possible. This latter philosophical item meant resisting outside influence to add "goodies" beyond the original scope. By taking this approach, the NASA LeRC project management team could ensure its integrity (i.e. not trying to get added features for no or little increase in cost). This objective was mostly accomplished. Over the lifetime of the program the technical scope changes to the development contract resulted in a net reduction in cost.

Early in the development program, the contractors suggested and NASA implemented technical changes to reduce the program costs. These included deleting a full-up engineering model for the multi-beam antenna, a spare flight model BBP and a diversity earth station. In addition, the Baseband Processor's downlink burst rate and total throughput were cut in *half* and the number of spot-beam locations was significantly reduced. In total, more than $25M in technical scope was removed from ACTS.

FUNDING CONSTRAINTS

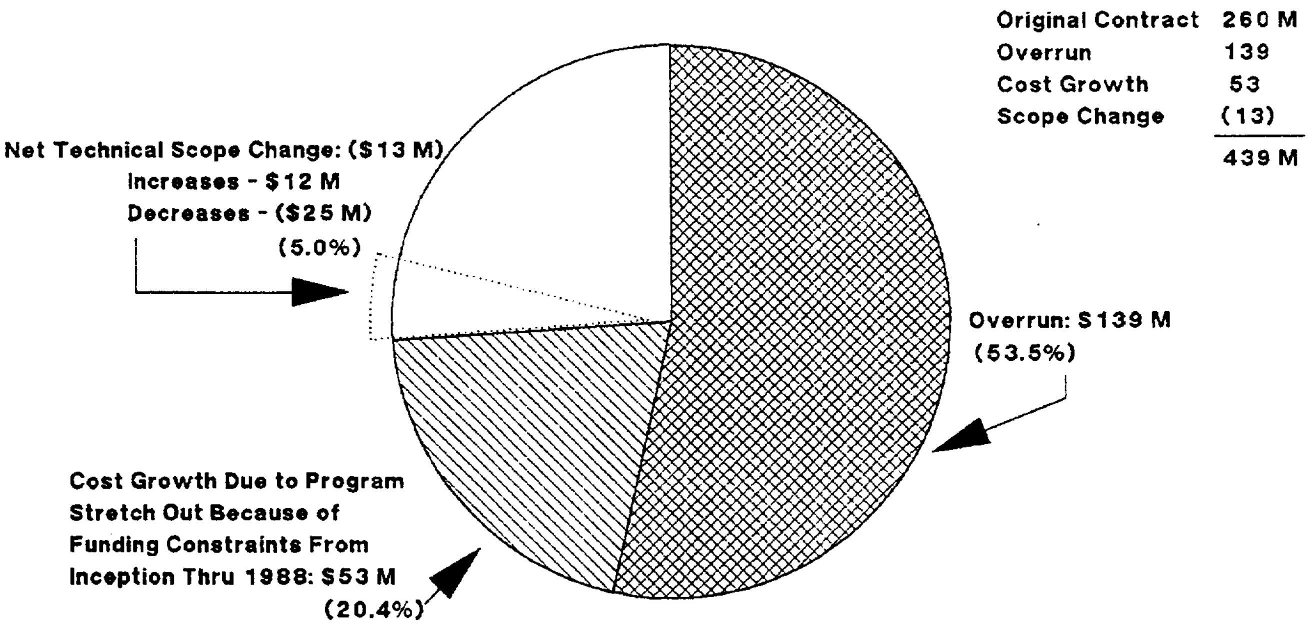
The control of the amount of funding any program receives each year is in the hands of the NASA administrator, the Federal Government administration and the US Congress. The administration's Office of Management and Budget (OMB) zeroed-out funds for ACTS in its yearly budget requests to Congress for Fiscal Years 1985 and 1987 through 1990. The Congress was then put in the position to reinstate funding for the program over the objection of the administration. This process frequently resulted in less funds being appropriated than originally planned with a resultant slip in the development schedule and an overall growth in the total project cost. The reason that the total project cost grows with a stretch out in funding is that many people (such as project controllers and system engineers) must remain assigned to the project as long as it is in the development stage. Frequent re-assignment of key individuals to other projects with a loss of their knowledge and ownership is not practical. In addition, with the large number of subcontractors, the effort to create a new plan after each funding cut takes considerable time and effort (money).

The first time that funding was zeroed-out was in December 1983 just prior to the planned contract award. As explained in Chapter 1, the administration chose to do this when Hughes submitted their filing for their own Ka-Band satellite and claimed that the NASA program was unnecessary (Hughes never carried through and actually built the spacecraft). This OMB action caused the development contract award to be delayed 8 months from December 1983 until August 1984. When the funds were finally reinstated for the project, they were done so at a lower level than the development plan required. Worse than the effect of the reduction in funding was probably the impact on contractor personnel. Many of the contractor people who had worked on the proposal were no longer available for assignment to the project eight months later. Therefore, new individuals who were not familiar with the project and who could not be held responsible for the proposed development plan had to be assigned. This is not the way to start a project!

Fiscal year funding constraints were imposed upon the development program four times causing schedule stretch and increases to the total program cost. The total project cost growth due to program stretch out was $53M.

OVERRUN

Contractor overrun was $139M. The overrun, which occurred mostly during the second and third years (1986 and 1987) of the development contract, was primarily due to the TRW communications payload subcontract. LeRC project management believed one of the main reasons for the TRW cost growth was that TRW and their subcontractors underestimated the true development cost in their proposal. "Buying in," where a contractor deliberately underbids a contract, has always plagued the government in cost-plus programs, and it appeared that ACTS was no exception. This was not totally the fault of the contractor. The contractors knew the government's target price for ACTS and made sure they met it in their proposals.



Elements of ACTS Contractor Cost Growth As of January 1988

Another reason for the TRW overrun is believed to be the low priority TRW placed upon the program. At the time of the ACTS contract, TRW had many classified programs that provided them with long-term revenue and profits. ACTS, being a one-of-a-kind spacecraft, appeared to have significantly lower priority than those for the military programs. Few seasoned veteran engineers and managers were assigned by TRW to ACTS. In some cases new employees were assigned temporarily to ACTS until they received their security clearances. After receiving their clearances they were transferred to higher priority government programs. Having more veteran engineers on the program would have gone a long way toward eliminating many technical and management problems with a resultant reduction in overrun.

THE CAPPED PROGRAM

As the overrun grew, Congressional support for the program started to wane. By late 1987, it was clear that if the program was to continue, some sure way to limit the cost growth was needed. The choice that satisfied Richard Mallow, the chief congressional staffer on the House appropriation committee in charge of NASA's budget, was to cap the total NASA cost for the project. This cap was to apply to all levels including NASA Headquarters, the NASA LeRC project group and to each of the development contractors. All contracts were to be changed from cost plus into ones that were capped. Mallow desired that the ACTS program be capped at $499M.

With three years of work completed, a lot of the risk associated with the ACTS development was removed or better understood. As a result, the LeRC project management felt that conversion to capped contracts was feasible. At this time, TRW had already incurred costs for approximately $153M and wanted $72M more to complete the payload under a capped contract which they were very hesitant to accept (The original contract value for the communication payload was only $106M).

When all of the costs were received from the contractors for completing the project under capped contracts, the total exceeded the $499M Mallow target. For this reason it became necessary to restructure the development team to realize additional savings. The program shifted from a prime contract to two associated contractors.

First, it was decided to drop TRW as the subcontractor for the communications payload and have GE complete the payload using TRW's 2nd tier subcontractors (GE projected they could finish the payload for $14M less than TRW). The second part of the restructuring was to have NASA LeRC become the integrating contractor with one contract with GE for the spacecraft and another contract with COMSAT for the Ground Segment. This eliminated considerable GE costs for managing the integration of the spacecraft and ground segment activities. Net savings were realized because NASA LeRC was able to perform the integration tasks without increasing the program staff.

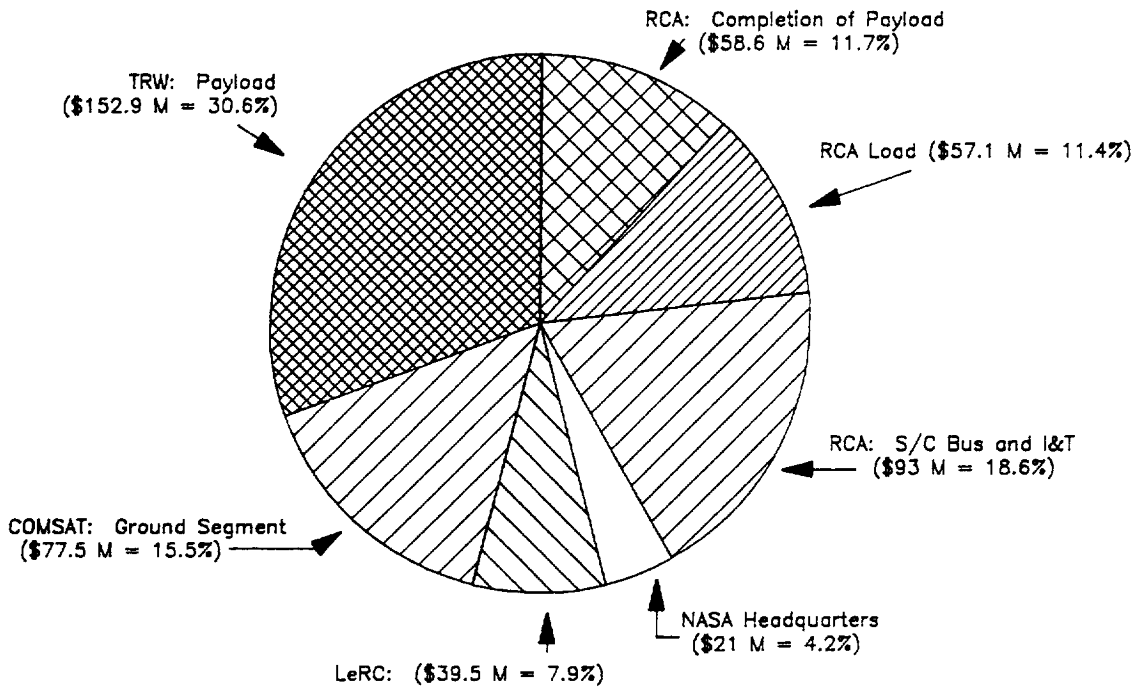
With this shifting of responsibilities, the completion of the ACTS development and two years of on-orbit operations became possible within Mallow's target of $499M. After subtraction of the NASA headquarter's taxes, the total amount of funds available to the project office at NASA LeRC for the ACTS development and the first two years of operations was $478M. This amount, however, allowed NASA LeRC to hold only several million dollars for contingency purposes.

Much of the credit for *'saving the program'* must go to Charles Schmidt and the original RCA AstroSpace team members who were motivated to honor their original commitments and take on considerable risks to complete the payload development under a capped contract. The acceptance of capped contracts by GE, COMSAT, and Motorola showed their belief in the value of the ACTS technology. The conversion worked. All parties reached agreement in January 1988. In a letter from Senator William Proxmire (D-WI) and Representative Edward P. Boland (D-MA) (chairman respectively of the Senate and House Subcommittees on HUD-Independent Agencies) to James Fletcher, the administrator of NASA, the Congress agreed to the $499M cap and to provide $76M for both FY 1989 and 1990. From that time forward, cost growth concerns lessened and everyone turned to concentrate on the task of developing a quality product.

The capping of the program provided some measure of assurance to the development team that their funding would stabilize. However, one year later in January 1989 OMB once again zeroed-out the ACTS funding in the administration's FY 1990 budget request to Congress. Once again the Congress reinstated the funds for ACTS. This was OMB's final attempt to cancel the ACTS Program.

COMPLEXITIES ASSOCIATED WITH A LARGE PROGRAM

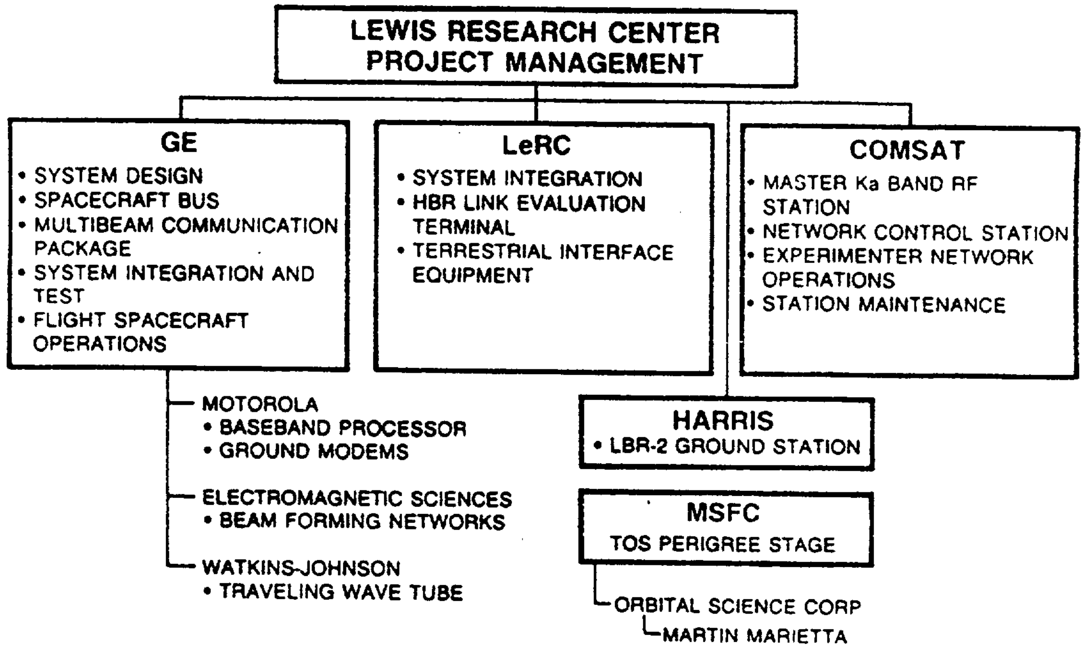
When the development contract was awarded in August 1984, the contractor team consisted of RCA as the prime, TRW and COMSAT as first tier subcontractors for, respectively, the spacecraft communications payload and the master control station. Below the first tier subcontractors there were approximately 15 major second-tier subcontractors. Some of the second-tier subcontractors such as Motorola for the Baseband Processor ($46M) and Electromagnetic Sciences for the Beam Forming Network ($9M) were developing high-risk, advanced technology components.



Breakdown of ACTS $499M Cost Cap by Organization

For a first generation system like ACTS, layers of contractors can create major complications. For instance, TRW was awarded a definitive contract by RCA on February 25, 1985. Electromagnetic Sciences (a subcontractor to TRW) completed no substantive work on the Beam Forming Network until after it signed a letter contract with TRW on April 3, 1985. In August 1985, the ACTS System Design Review identified that EMS and TRW could not complete the Multibeam Antenna system including the BFN for the allocated budget. To reduce costs NASA LeRC decreased the BFN scope as recommended by the contractors. The definitized contract between TRW and EMS wasn't signed until July 1986, which was almost two years after awarding the prime contract.

As the above example illustrates, the process of finalizing the requirements and contracts for a new system can be very complex and time consuming. The elimination of RCA as the prime contractor and TRW as the payload subcontractor went a long way to decrease the high degree of organizational layering.



ACTS Project Organization after Capping of the Program in January 1988

The restructuring of the development team in 1988 was certainly a correct step for improved performance. There had been considerable friction between the prime contractor (RCA), the first-tier subcontractors Comsat and TRW and some of the second-tier subcontractors, which made problems more difficult to resolve and contributed to schedule delays. A committee consisting of executives above the program manager level from NASA and each contractor was established to resolve top-level issues and reduce friction. Even though it helped it was not enough. When NASA took over the system integration role and in effect became the prime contractor, much of this friction was eliminated. At this time, NASA engineers took over the lead of the working groups (RF, command and telemetry and on-demand network control) that were responsible for coordinating the interface requirements between the spacecraft and ground system. NASA promoted as rapid a technical resolution of problems as possible, and then funded any resulting contractual scope changes using its contingency funds. Use of NASA contingency funds for this purpose went a long way toward improving relations between the financially pressed contractors.

The approach that LeRC took for managing the ACTS Project was to have a strong technical, cost and schedule team that could delve closely into all aspects of the contractor activities. The ACTS Project organization mirrored that of the contractor team, and monthly performance meetings were held at all major contractor facilities including those of the principal *second-tier* subcontractors. In addition NASA project personnel participated in the standard design reviews including those for all first and second tier subcontractors. The idea was to have enough in-house knowledge and expertise to perform in-depth assessment of all issues so that the government team could make *independent but practical* decisions, be proactive in solving problems and help ensure a quality product.

practical decisions, be proactive in solving problems and help ensure a quality product. Initially the government project team did not have all the necessary skills needed to accomplish this, but by the time of the restructuring it did, and that allowed it to assume the role of integrating 'contractor' for the ACTS system. This role involved more than just managing the spacecraft and master control station integration; it also included managing the more than seven types of user terminals.

For each of the four times that funding constraints were imposed on the program, a six month or so process took place whereby funding cuts were allocated at each contractor level, new ***longer*** schedules and ***increased*** contract values negotiated, and a new launch date established. This whole process distracted the development team from their main tasks and consumed a large number of man-hours. It also gave the contractors an opportunity (it is the governments management job to make sure it doesn't happen) to 'get well' for some of their own problems. One of the practices for good project management is to never take an action that gives the contractor a reason for failing to meet the development schedules, such as program funding cuts.

The impact of funding constraints on a complex development program like ACTS can be disastrous. As bad as those impacts can be (on ACTS they increased the total cost by $54M), top-level government administrators and the US Congress seem to ignore the consequences and just consider funding cuts an inevitable part of generating a yearly budget.

COMPLETION OF THE COMMUNICATIONS PAYLOAD

At the time that the program was capped in January 1988, the flight Baseband Processor was 85% completed by Motorola, the flight Beam Forming Networks were due to be delivered by Electromagnetic Sciences two months later and the 20 GHz flight Traveling Wave Tubes were completed and in test at Watkins-Johnson. In addition 70% of the TRW flight drawings were released and the engineering unit models had completed test. The biggest deficiency was with the mechanical design of the Multibeam Antenna (MBA) for which TRW had only completed 35% of the drawings.

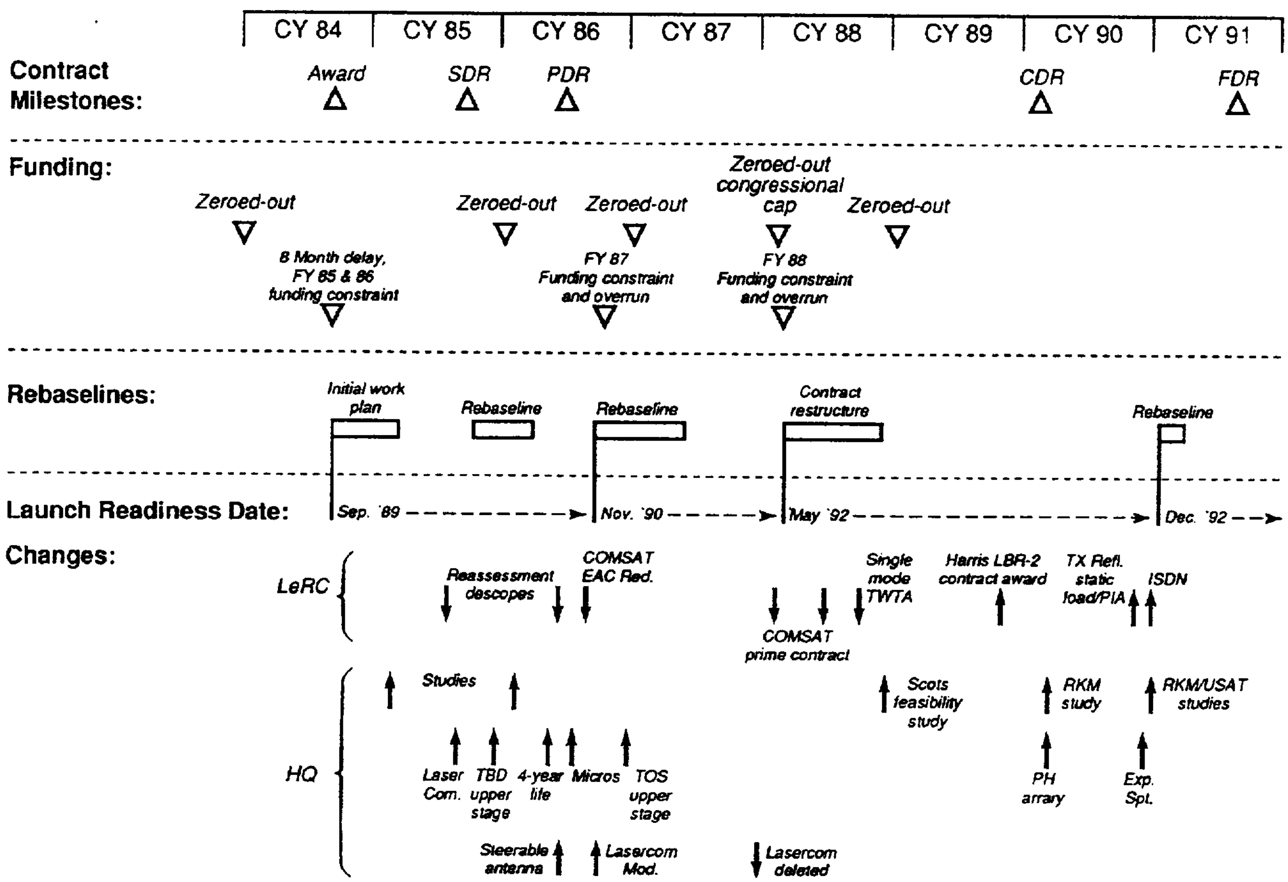
The GE approach for completing the payload was to use the completed portions of the TRW design making only those changes necessary to accommodate the GE manufacturing processes and test procedures. In addition GE decided to use all the parts and material TRW had received. As far as completing the design of the MBA, GE felt that it was well within the capabilities of its engineers. Using this approach, GE forecasted that they could complete the payload for almost $14M less than TRW ($58 versus $72M).

Indeed this was how the communications payload was completed. It is TRW's initial design that was completed and manufactured by GE . To TRW's credit, they completely cooperated in the transition of all design documents and received material to GE. There were many skeptics who thought GE's plan would not be successful. But Charles Schmidt, head of GE AstroSpace, had confidence that his people could pull it off!

MAJOR INCREASES IN SCOPE

At the start of the development in August 1984, the spacecraft weight on-orbit at beginning of life (BOL) was estimated to be 1,970 pounds with 1,008 pounds of that total being for the communications payload. In addition, only enough station keeping fuel for two years of operations was included. With this spacecraft weight, a Payload Assist Module (PAM – A) could be used to place the ACTS in the proper transfer orbit from Shuttle altitude to geostationary altitude.

ACTS Project History – Rebaseline/Change Overview

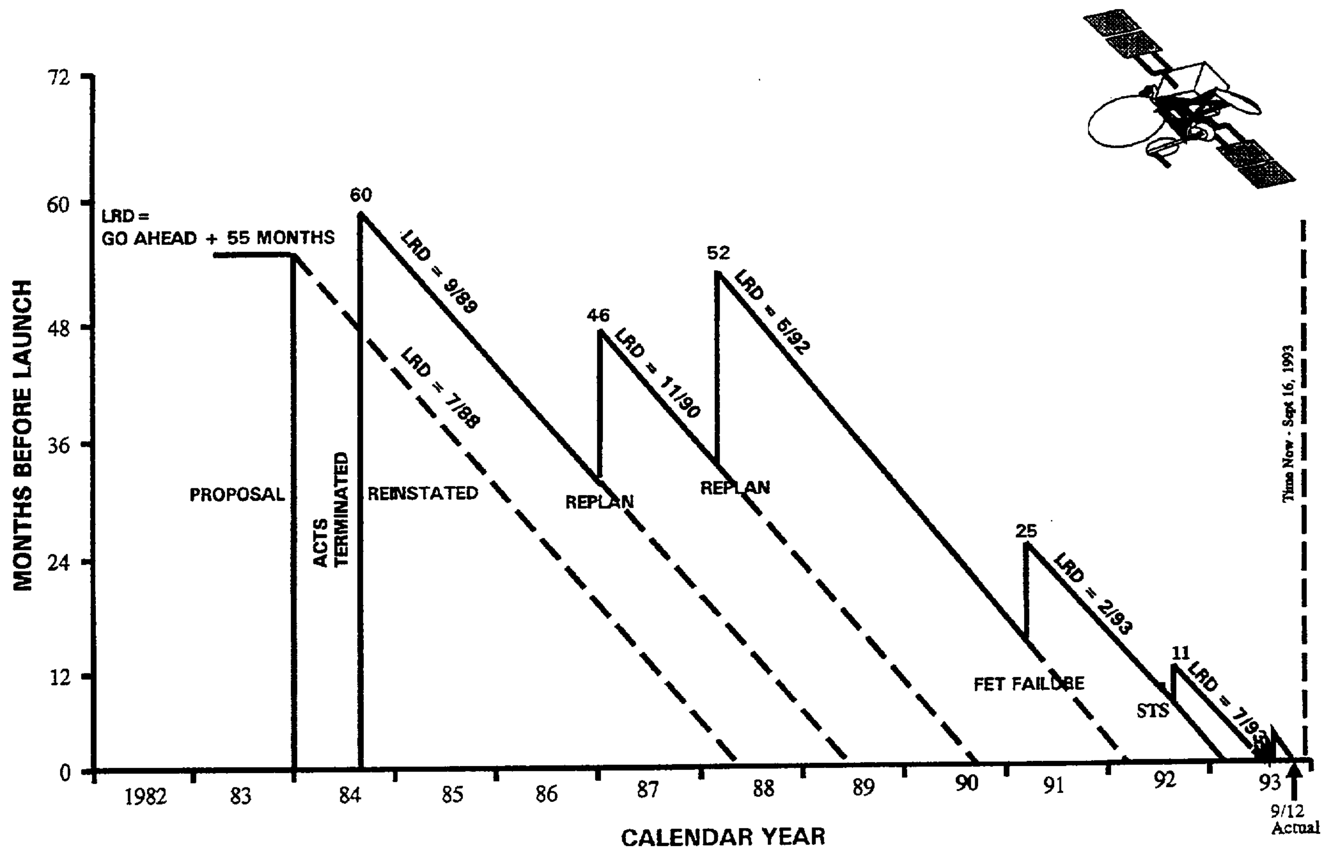


At launch the final spacecraft BOL weight was approximately 3250 pounds with five years of station keeping fuel and 116 pounds of excess margin. Of this total, the communications payload weight was 1295 pounds including a 33-pound Steerable Antenna, which was added in 1986. To accommodate this larger weight, the Orbital Sciences' Transfer Orbit Stage (TOS) was used in place of the PAM-A.

The switch to the TOS upper stage was made in 1985 with addition of the Laser Communications Package . This package, which was being developed by MIT Lincoln Laboratories for the Air Force, definitely placed the ACTS weight outside the capability of the PAM-A booster. As it turned out, after the addition of the Lasercom and the switch to the TOS was contractually completed, the Lasercom funding was cancelled by the Air

Force and the package was deleted in 1987. The combined Lasercom Package and TOS change was the largest single scope increase to the contract amounting to almost $9M. By holding the scope increases to a minimum, NASA helped to contain the project cost and risk.

History of Launch Readiness Date (Courtesy of Rod Knight, NASA)



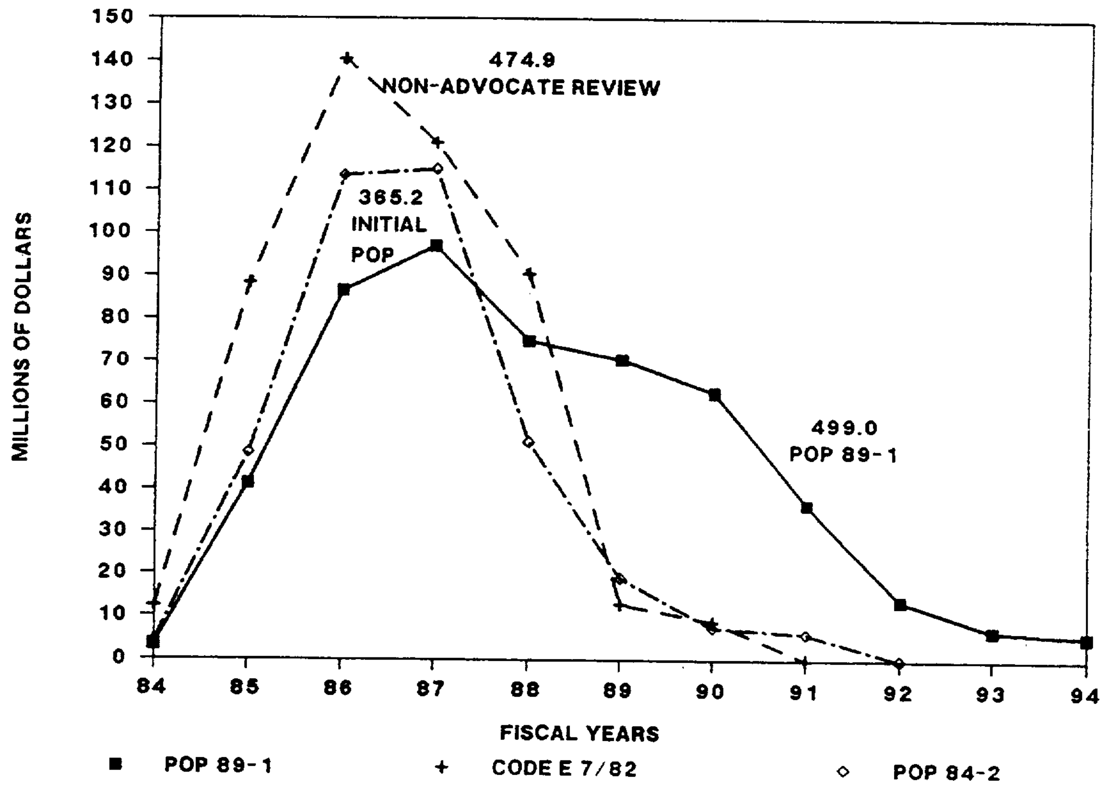
ELEMENTS OF ACTS SCHEDULE SLIPS

The ACTS contract award was originally planned for December 1983 with a launch in July 1988. The actual launch occurred more than five years later on September 12, 1993. The combined schedule impacts due to program approval delays, funding constraints, cost overruns, technical difficulties and launch vehicle availability were gigantic. The effects of some of these factors will be discussed in more detail in this section.

FUNDING CONSTRAINTS AND OVERRUNS

A non-advocate review headed by Dave Pine of NASA Headquarters reviewed the ACTS Program plan in July 1982 and concluded that a peak year funding of approximately $140M was required to complete the 55 month development. When the ACTS development was finally started in August 1984, the peak year funding was planned to occur for two subsequent years at approximately $110M each year with a launch 60 months later. The maximum funds actually allocated to ACTS in any one year were months later. The maximum funds actually allocated to ACTS in any one year were $85M. With the yearly funding authorized for ACTS always being less than required and cost overruns increasing the total amount of funds required, it was impossible to meet the original 60-month development schedule.

ACTS Cost Projections



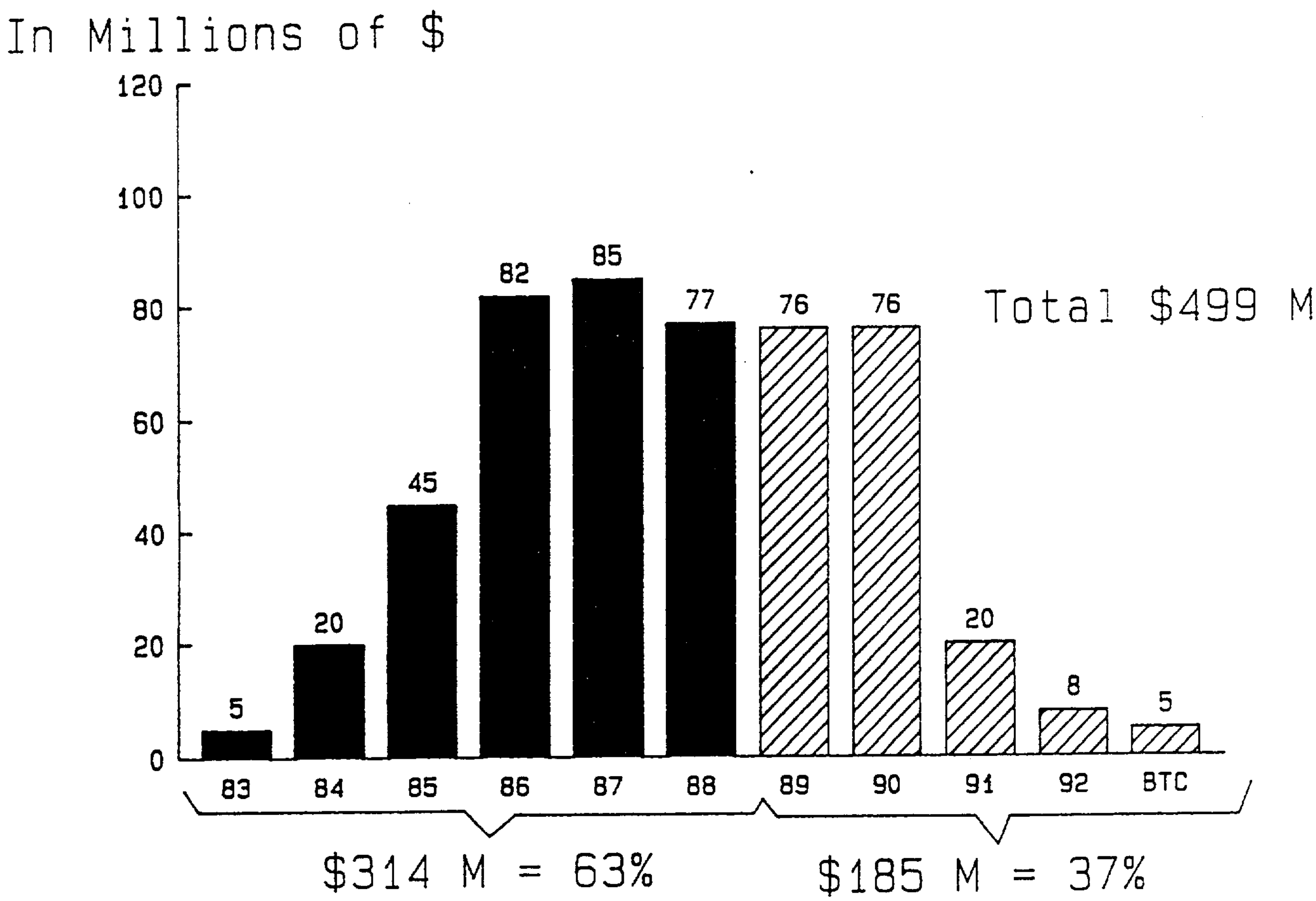
In 1986 and 1987 the launch date was slipped, respectively, 14 and 18 months. Part of the slip that occurred at the end of 1987 was due to the program 'capping' process that took considerable time to accomplish. Therefore, the funding constraints and the cost overruns were responsible for 32 months of slippage (projected launch date now May 1992.)

TECHNICAL DIFFICULTIES

When the contractor team was restructured in January 1988, schedule margins were put in place to ensure meeting the new launch date of May 1992. As it turned out, the margins were not large enough to accommodate several technical problems and a procurement difficulty.

One of the most unexpected impacts that occurred was related to the ordering of parts by AstroSpace for both the spacecraft bus and communications payload. For a spacecraft, part procurements represent a major activity. First, NASA required, for quality reasons, that all electronic parts that had ***not been flown before*** be procured under Class S equivalent standards. For each new part, the procedure required the generation of a requirements document that specified a high degree of inspection and testing by the manufacturer to ensure that the part would be reliable for space. The requirements document for ***each*** new part had to be approved by NASA, which added time before the part could be procured.

ACTS Appropriations by Fiscal Year (January 1988)



Second, the incorporation of the GE parts ordering system into use at RCA AstroSpace (merger of the RCA and GE aerospace units was initiated in 1986) was still taking place and drastically slowed the process. Thirdly, due to management mistakes, the parts ordering process for many components was not initiated on time. Even though extra people were assigned to speed up the process, the end result was that the assembly of parts kits for the manufacturing of electronic boxes and sub-assemblies was significantly delayed. It took months to resolve this problem which completely eroded schedule contingency.

A second major schedule hit was due to a problem with one critical electronic part. In any spacecraft program, one of the worst things that can happen is to find a defective part after it has been installed in boxes that have completed the lengthy manufacturing/test cycle. This 'disaster' happened to ACTS!

Throughout many electronic boxes in the communication payload, a Field Effect Transistor (FET) was used in many hermetically sealed amplifier modules. The laser welded hermetic seal prevented unwanted atmospheric gas from entering the modules and causing damage by corrosion. After the many boxes that contain this FET had completed their manufacture/test cycle, it was found that the FET's expected life fell well short of the ACTS requirement. Resolving this problem meant procuring new FETs, disassembling the affected boxes, breaking the laser-welded seal, installing the new FETs, reassembling and retesting the boxes.

The delays with the parts ordering and the FET lengthy refurbishment coupled with manufacturing problems encountered with the Multibeam Antenna were the major contributors to an additional 9-month slip in the launch date. This slip, which occurred in early 1991, extended the launch from May 1992 to February 1993 and was the fourth one to occur.

The final launch schedule slips were related to the unavailability of the Shuttle. In September 1992, NASA decided to expand the Atlantis Shuttle refurbishment activities at Palmdale, CA to include the incorporation of a docking capability with the Russian MIR space station. Although ACTS was manifested on Discovery, this caused a ripple effect in the entire Shuttle manifest and the rescheduling of the ACTS launch from May 1993 to July 1993.

The spacecraft was delivered to the NASA Kennedy Space Center in February 1993 to be mated with the TOS upper stage and begin final preparations for launch aboard the shuttle. The first launch attempt was made on July 17, 1993. It was scrubbed, less than an hour before the planned lift-off, due to a faulty transistor in the launch system, which armed a set of explosive bolts prematurely. On July 24, a second attempt was made. It was aborted within 19 seconds of launch when a turbine in a Shuttle Auxiliary Power Unit (APU) didn't come up to speed properly. All further launch attempts were delayed until the APU was changed and the Perseid meteor showers had passed. During the August 12th third launch attempt, a faulty sensor failed to indicate that propellant was flowing and the Shuttle's engines were automatically shut down 3 seconds before liftoff. **On September 12, 1993, at 7:45 AM EDT, ACTS was finally launched aboard the Shuttle Discovery on mission STS-51.** ACTS arrived at its permanent location in geostationary orbit at 100- degree west longitude on September 28, 1993.

A QUALITY PRODUCT

Poor quality certainly costs money. This was vividly illustrated by the FET episode described in the previous section. Had a quality product been produced by the FET manufacturer, it would have saved a lot money and potentially another embarrassing launch slip.

To successfully produce a spacecraft, experienced people are needed who have learned from previous failures, know how to build it right the first time, and know how important it is to train and mentor the inexperienced members of the team. It also takes a total team commitment to many, many small details. The relationship between the customer and the contractor team building the system needs to be complementary and not adversarial. With adversarial relations, decisions can be made that sacrifice quality. Just as important, adequate testing must be done to demonstrate that the design is functional and the spacecraft will work in space.

The lack of attention to details and a total team commitment is illustrated by the Hubble Space Telescope failure, which launched a flawed telescope into space. According to the NASA Failure Report [117],

> *"The most unfortunate aspect of this HST optical system failure, however, is that the data revealing these errors were available from time to time in the fabrication process, but were not recognized and fully investigated at the time. Reviews were inadequate, both internally and externally, and the engineers and scientists who were qualified to analyze the test data did not do so in sufficient detail. Competitive, organizational, cost, and schedule pressures were all factors in limiting full exposure of all the test information to qualified reviewers."*

Notice the lack of team commitment and the presence of adversarial relations in this finding.

With all the controversy surrounding ACTS, the yearly funding gyrations, the low priority placed upon the project by some segments of the contractor team and NASA upper management, the many inexperienced people on the project and the pressures to contain costs, **quality became a *major concern*** for the Project Manager at NASA LeRC.

A deliberate philosophy was taken not to decrease the test program and quality requirements. In fact, the net amount of testing was increased as the LeRC project team learned more about the potential weaknesses in the design. Much credit is deserved by the Quality Assurance Managers at NASA, Karl Reader, and at Astro Space, Al Little, for ensuring quality in the electronic parts. They and their teams of parts engineers carefully reviewed, in a cooperative manner the more than 400 requirements documents for Class S electronic parts. Any schedule pressures to circumvent the process during the manufacturing phase were resisted by these two managers.

TEST PROGRAM

The traditional spacecraft testing philosophy encompasses three levels of testing at the electronic box/mechanical component, at the subsystem (e.g. multibeam antenna and baseband processor), and finally at the spacecraft. The overall approach for ACTS was to 'protoflight test' where the flight system was subjected to stress levels that were increased beyond mission requirements to demonstrate design margins.

Because of the complexity of the ACTS payload, additional tests were also carried out to verify the design of this new switching and processing technology. Engineering models of critical boxes were built, tested, and integrated into a partial payload. This engineering model of the payload proved extremely valuable in verifying the complete payload design and its interfaces. It was also used with the master control station (MCS) as an early check on the MCS design including the network control software.

The ACTS testing program, however, did not end there. At the completion of the spacecraft level testing, a fourth level of testing was implemented to test the ACTS spacecraft and MCS in an end-to-end series of communications tests with three of the ground stations types that would be used in the on-orbit operations. This comprehensive system test lasted nearly three months and proved extremely valuable because it revealed a number of software problems that had not been uncovered during previous testing with the payload engineering model. Additional anomalies were uncovered in the high-speed command link to the Baseband Processor. These software problems and anomalies would have been very difficult to diagnose on-orbit. After these communication tests, a special test was conducted to verify the RF continuity and switching for each of the forty eight hopping spot beam locations. This spacecraft/ground system test was extremely valuable in further retiring technical risk and providing the confidence that ACTS was indeed ready to launch. Evidence of this fact is that on-demand digital services using the Baseband Processor were successfully established the very <u>first time</u> they were attempted on orbit.

One of the more difficult items to test was the RF performance of the multibeam antenna. A completely new measurement capability, called a RF near-field facility, had to be built at Lockheed Martin to verify that the gain properties for fifty one 0.3-degree spot beams met their requirements. Approximately two weeks was allocated for these measurements. In the end it took over three months to work out the test bugs in the new facility before the NASA and Lockheed Martin engineers were satisfied with the results. There were many, many more such stories where quality was not sacrificed.

In any spacecraft program, there isn't enough time or money to verify every aspect of the design by test. Therefore, the review process is a critical element in producing a quality product. During design reviews of all assemblies, subsystems and the total system it is necessary to make sure that there is adequate redundancy in case of equipment failure and that there are no single point failures of significance. After the design and manufacturing is complete, a complete as-built review of those aspects that are not verified by test should be made. One area, which always falls into this category, is verification of the correct polarity for electrical signals. This is extremely important for the attitude control system. For example, it may not be able to verify by direct test that when a command is given to pitch the spacecraft down that some incorrect wiring will cause the spacecraft to rotate up.

On ACTS a critical part of the attitude control for maintaining the pointing of the spot beams within an accuracy of +/- 0.025 degrees was the autotrack subsystem. Using phasing information derived from RF signals transmitted to the spacecraft, the autotrack sent error signals to the spacecraft attitude control system that were used to maintain the correct pointing. There was no complete end-to-end test to determine whether or not the autotrack would provide the correct error signals, and as it turned out the normal review process had missed a design error in the autotrack that rendered its error signals useless. During one of these reviews, Charles Profera, questioned the correctness of the Autotrack signal polarity. Since no end-to-end test verification was being made for this critical element, Mike Kavka, the Lockheed Martin Program Manager, instituted a late independent review of this subsystem. John Graebner, a senior and very experienced Lockheed Martin engineer, performed the review and conducted a special test which confirmed the design error which necessitated a spacecraft change at the launch base. This illustrates the critical importance of reviews and that they be performed by experienced engineers. Inexperienced engineers who have not experienced failures may not be motivated to perform a thorough-enough check. Also, shame on the manager who presses his engineers to cut short the review process to save costs or schedule.

Checks and more checks are the recipe for producing a quality spacecraft. On-orbit, the only significant ACTS problem has been the wandering of the spot beams during a two-hour period each day. This deficiency, which is caused by a thermal distortion of the antenna subreflector surface (see Chapter 2 for description of problem), was missed because of an inadequate thermal distortion analysis! Because of its complexity, no direct thermal test had been performed to verify the thermal analysis. A better check on the thermal analysis should have been performed.

THE ACTS SYSTEM HAS PROVEN ITSELF

ACTS has met all its objectives, has had no failures that reduced its capability to perform and has exceeded its two-year operation requirement by over three years with all redundant systems fully operational, except for a 20 GHz beacon transmitter, which exhibited low power output and was turned off soon after launch. Much of the credit for this success must be given to NASA, Lockheed Martin, COMSAT and their subcontractors working as a committed team during the last few years before launch.

During that time, in fact, the government/contractor team cooperated and focused on success. When a test revealed a problem (and there were many of them), not only was the problem identified and fixed but the team strove to understand why the deficiency wasn't discovered sooner. Additional checks or reviews were then conducted to make sure the same type of deficiency did not occur elsewhere. A lot of credit for the success must go to Mike Kavka who, as the ACTS Program Manager at Lockheed Martin during this period, provided a lot of the necessary ingredients needed to form and maintain this committed government/contractor team.

CHAPTER 7

Market Forecast in Shaping ACTS Technology Investment

In 1978, NASA awarded two contracts to common carriers, Western Union (WU) Telegraph Company and US Telephone and Telegraph Company, a subsidiary of International Telephone and Telegraph (ITT), for market studies [14, 15]. The emphasis of these studies was to provide estimates of future satellite addressable traffic; that is, forecast telecommunications traffic, which could be competitively carried by satellite. The satellite addressable traffic took into consideration economic competition with terrestrial delivery systems.

These initial market studies predicted that the demand for telecommunications in general, and for satellite communications in particular, would increase substantially over the next two decades. The rapid growth taking place in the US domestic voice, data, and video traffic was forecast to lead to a **five-fold increase** in traffic capable of being carried by satellites in the early 1990's. A combination of these market projections as well as communication satellite license filings with the FCC portended saturation in capacity of the North American orbital arc using the C- and Ku-frequency bands by the early 1990's.

Two years later in 1980, these market studies were updated. The point of saturation was found to be approaching even more rapidly than envisioned just two years earlier. In these two years, the demand estimate had virtually doubled, and the date of exhaustion on the conventional C- and Ku-band US domestic communication satellites moved nearer by five years [118].

1983 MARKET ASSESSMENT UPDATE

After 1980, significant changes took place in the satellite communications industry. These changes included: technology advances, a wave of new satellite service providers, a rapid increase in the demand for cable TV channels and the development of fiber optics. In response to these and other changes, NASA again updated the satellite traffic forecasts.

Three fixed service telecommunications demand assessment studies were completed in 1983 [119, 120, 121]. The studies provided forecasts of the total US domestic demand from 1980 to the year 2000, for voice, data, and video services. That portion that is technically and economically suitable for transmissions by satellite systems, both large trunking systems and customer premises services (CPS) systems was also estimated. This portion was termed "satellite–addressable traffic." It is important to emphasize that the satellite-addressable traffic is not an estimate of what will be captured by satellite systems, but is an estimate of what could be captured by satellite system operators. It is the amount of traffic that is potentially viable for transmission over satellite systems.

Each study contractor (WU & USITT) conducted its study entirely independently of the other. Independent approaches to the forecasts were taken and different ground rules and assumptions were employed. These studies focused on identifying the potential demand for customer-premises-type satellite communications systems providing services to terminals on the user's premises, possibly shared with other local users.

The third study (by WU) quantified the demand potential for large trunk-type satellite system applications suitable for carrying traffic among the 313 Standard Metropolitan Statistical Areas (SMSA). At the time of the studies, satellites were beginning to provide considerable trunking services.

In order to provide a single set of forecasts for use in the ACTS program, a NASA synthesis of the above studies was conducted and reported [22]. Thirty-five services were considered; 9 voice, 17 data and 9 video services (see accompanying table).

VOICE CATEGORY

Besides the normal long distance terrestrial telephone calls, this category included the following:

- The long distance component of mobile radio traffic carried by the switched network. As we now know this is important today because of the large increase in cellular phones;
- The distribution of programming for National Public Radio, Commercial Radio Networks and Special Events; and
- The distribution of high quality music for cable TV.

DATA CATEGORY

Data transmissions were organized into two computer type services (low speed terminal/CPU interactions and high speed CPU/CPU interactions) and message-type services.

The low -speed Terminal/CPU services were all envisioned to occur at speeds of 56 Kbps or less. The Inquiry/Response service was for "terminal operations of a more urgent nature such as airline reservation systems and stock quotations." The Videotex/Teletext subcategory was thought to be an "umbrella service covering a variety of interactive and non-interactive consumer information services displayed on the home video screen." Today we would relate these services to being performed by the Internet.

The CPU/CPU services were mostly thought to be low data rate with some transmission speeds in the range of 56 Kbps to 1.544 Mbps (T1). It is interesting to quote from the report the description of some of these service subcategories to demonstrate how the market forecasters were 'right on the money.'

- Data Transfer – "The transfer of information from one storage bank to another."
- US Postal Service Electronic Mail switching System (USPS EMSS) – "The volume of mail transferred electronically over the USPS systems."
- Mailbox – "In Mailbox service, messages are stored in a central computer which the recipient accesses at his convenience to obtain his messages."
- Administrative Message Traffic – "Generally short person-to-person messages usually of an intracompany nature."
- Mailgram – "Similar to the USPS EMSS service only performed by companies."

Telecommunications Services Forecast In 1983

VOICE	DATA	VIDEO
MTS, Residential MTS, Business and WATS Private Line Other Mobile Public Radio Commercial and Religious Occasional CATV Music Recording	**COMPUTER** Terminal-To-CPU Data Entry Remote Job Entry Inquiry/response Timesharing Point of Sale Videotex Telemonitoring CPU-To-CPU Data Transfer Batch Processing	**BROADCAST VIDEO** Network, Commercial Network, Non-Commercial (PBS) CATV Occasional Educational Public Service (Telemedicine) Recording Channel
	MESSAGE USPS EMSS Mailbox Administrative TWX/Telex Facsimile Mailgram Communicating Word Processing Secure Voice	**VIDEOCONFERENCING** One-Way Two-Way –Full Motion –Limited Motion –Fixed Frame

- Communicating Word Processors – "A communicating word processor adds communication capability to a printer/keyboard or CRT-based word processing system. This allows the input to be prepared on one system and sent via communication links to another system for output, editing, or manipulation. The advantage to the user is the ability to transmit original-quality documents with format control similar to letter and memo correspondence."

We refer to these services today as either e-mail or ftp (file transfer protocol) performed using the Internet, Intranets or Virtual Private Networks (VPN). Surprisingly ***these studies were quite visionary considering that the PC, ATM and the Internet were at most only concepts at that time.***

VIDEO CATEGORY

The nine-video services used in the study are quite familiar. It should be noted that the CATV subcategory included "low to medium powered direct broadcast satellites (DBS) operating in the fixed services frequency bands." This of course is being done today. The Recording Channel was "a pay service providing video material for home recording, generally in the off-peak hours." This service has been superseded by the local video rental store. Most significantly, the forecasting did not envision the amount of image, video and audio information that are, or soon will be, provided over the Internet today.

METHODOLOGY

The prime objective of the WU and USIT&T studies was to quantify the amount of communications traffic that potentially could be transmitted over satellite systems. This is that portion of the total U.S.-generated communications traffic that, due to its system economics and technical and user characteristics, would cause satellite systems to be the preferred transmission means. The satellite-addressable traffic was derived by first estimating the total domestic U.S. traffic for 1980, excluding local non-toll traffic. This total traffic was then forecast for the years 1990 and 2000 using the contractor's proven methodologies which included interview with the IT managers of many corporations. The intra-SMSA toll traffic component was then removed (the assumption being that this is too short a distance for potential satellite traffic) to define the "Net Long Haul" (NLH) traffic. The NLH traffic forecast then formed the basis for deriving the satellite-addressable market. A certain amount of traffic is not suitable for satellite transmission due to time delay, somewhat lower availability levels, and other factors. These factors were taken into account.

In developing the forecasts, the voice, data, and video traffic estimates were derived first in their natural source units such as number of messages for voice, bits/year for data, and channels for video. Service usage statistics such as message length, overhead, peak-hour factors, and transmission efficiencies were then considered to give an estimate of the equivalent transmission capacity required to carry the traffic; voice in peak-hour half circuits, data in peak-hour megabits/second, and video in numbers of peak-hour channels.

To convert these capacity requirements to transponder requirements, estimates were first made of factors expected to influence transponder throughput capabilities. These included the likely coding advancements permitting the reduction of required bit rate/digital voice channel, multiplexing advancements permitting greater data rates/unit bandwidth, and video compression improvements. For the CPS service, the transmissions were considered to be all digital.

FIBER OPTICS IMPACT

Although fiber optic transmission technology was considered by both WU and USIT&T as a terrestrial competitor with satellite systems, rapid advances in this field after the studies were completed made fiber optic systems more competitive with satellite systems than accounted for in the studies. The first major long-haul fiber cable was installed between New York and Washington, DC in 1983. In 1986 the US interexchange carriers installed 34,000 miles of fiber cable followed by 64,000 miles in 1987.

Because of fiber optics, the satellite transmission companies saw a large reduction in demand. For instance, in the early 1980's trunking of bundled analog voice circuits using companded single sideband techniques was being carried over satellites. By the latter part of the 1980's, no voice trunking traffic was being carried by satellites. In fact, the large amount of trunking traffic that was forecasted by these 1983 studies to be provided by satellites has never materialized because of fiber optics. For this very reason, many thought that the ACTS technologies would not be needed.

ON-DEMAND, INTEGRATED SERVICES

One very important finding of the forecast studies was that business users desired on-demand, integrated services (as opposed to permanently leased lines) even though these type of services were not being offered at the time by any means. As a result of this forecast, the ACTS system was configured to provide such services, and when the satellite was launched in 1993, it could provide the type of new services that users expected.

VERY SMALL APERTURE TERMINALS (VSAT)

In late 1980, Satellite Business Systems (SBS) launched the first, commercial Ku-band satellite to provide a full spectrum of communication services aimed primarily at business users. The SBS system employed large 18 and 25 feet earth stations, located directly on the customer's premises, providing all-digital, fully integrated voice, data, and image transmission capacity. These earth stations proved to be too costly to manufacture and install because of their size. Generally, only the larger corporate users could afford their installation. In the mid-1980's, the emergence of a small class of earth stations, at or less than 8 feet in diameter, called Very Small Aperture Terminals (VSAT), took place. Such terminals were better suited for location at a customer's business site. It was then recognized that the future development of earth stations to be used with the ACTS BBP should be of the VSAT type with antenna apertures of 4 feet. At this size, installation costs are greatly reduced.

FORECASTS

The table presents the forecast for the total US domestic (excluding non-toll) peak-hour demand or capacity requirement for voice, video and data.

VOICE CATEGORY

The business-oriented voice services appear to exceed the residential requirement by an order of magnitude; but this merely reflects the fact that the busy hour (peak) for each service type occurs at a different time of day, with the business busy hour dominating. The total voice demand, as measured in half circuits, grows by a factor of 6.75 from 1980 to 2000 or an average annual growth rate of 10 percent over the 20-year period.

DATA CATEGORY

The data forecasts are presented for each of the 17 data services in terms of peak-hour megabits/second. Two factors influencing the forecasted data traffic growth with time are the underlying growth in demand and improvements in efficiency of transmission. Although the basic demand grows by a factor of 15 (about 14% per year) over the period from 1980 to 2000, the dominating influence of transmission efficiency improvements causes the transmission capacity requirement, expressed in peak-hour megabits/second, to exhibit a peak and then decline somewhat beyond 1990. Remember that in 1980 most data traffic was transmitted over the circuit-switched terrestrial telephony system. The forecaster correctly assumed that by 2000, high-speed digital data links would exist where multiplexing advancements would permit greater data rates per unit bandwidth.

However, as these figures show, the data market was underestimated. In recent years, due to the Internet and business needs, data traffic has increased at a rate of 20 to 30% per year. Probably one of the biggest categories of data, not included in the forecast that exists today, is the large amount of Web pages downloaded to Internet users.

VIDEO CATEGORY

The demand for broadcast video channels was forecasted to grow at a rate of about 11 percent per year during the 1980's and then level off to about 4 percent per year during the 1990's. The forecast included some broadcast of TV channels by satellites directly to home receivers. This was correct since PrimeStar had a service in the 1990's that used the FSS Ku-band with a 30-inch terminal for this purpose. In 1999, PrimeStar was purchased by Hughes with the plan that all the PrimeStar subscribers (2,300,000 in February 1999) be eventually converted to the Ku-band, DBS frequency band using a 18-inch terminal by the year 2000.

Total US Domestic Telecommunications Demand

Traffic Type	1980	1990	2000
Voice (Peak Hour, 103 Half Circuits)			
MTS Residential	89	215	473
MTS Business and WATS	1616	4223	9842
Private Line	870	2765	7000
Other	4	43	129
Total Voice	**2575**	**7246**	**17444**
Data (Peak Hour Mbps)			
Data Entry	35446	37525	30918
Remote Job Entry	5668	5794	2863
Inquiry/Response	7526	7959	5083
Timesharing	4307	1507	736
Point-of-Sale	355	2975	2398
Videotex	3	969	931
Telemonitoring	1	4	16
Data Transfer	108	165	590
Batch Processing	1263	324	306
USPS EMSS	31	143	244
Mailbox	12	121	150
Administrative	4630	11575	17895
TWX/Telex	6	1	1
Facsimile	443	945	1120
Mailgram	1	1	1
Comm. Word Processor	35	115	227
Secure Voice	1	35	201
Total Data	**59836**	**70158**	**63679**
Video (Peak Hour, No. Of Channels)			
Broadcast	57	158	233
One Way Videoconferencing	1	112	225
Two Way Videoconferencing	2	1859	8000
Total Video	**60**	**2129**	**8458**

Note: Videoconferencing contains a wide mix of channel speeds.

SATELLITE ADDRESSABLE TRAFFIC

Service pricing was developed for both satellite and terrestrial transmissions to arrive at the volume of traffic that could potentially be captured by satellite system operators as shown in the table. The Customer Premises Service was assumed to be for business traffic only because of the ground terminal cost. Today 'VSAT' is the current nomenclature use for CPS terminals.

In *hindsight*, the Year 2000 forecast can be compared to the actual US domestic satellite traffic in the year 1998. This comparison shows that essentially no voice trunking traffic is carried by satellite; significantly less data traffic is carried and significantly more video is broadcasted. In terms of equivalent 36 MHz transponders the broadcast video in the year 2000 was projected to be 92 while the videoconferencing was estimated at 220. This estimate for broadcast video was ***underestimated by more than a factor of*** **four** while the demand for videoconferencing was over estimated.

Summary Of Voice, Data And Video Satellite Addressable Demand (Equivalent 36 MHz Transponders)

Segment	Traffic Type	1980	1990	2000
Overall				
	Voice	310	641	1594
	Data	33	254	518
	Video	60	250	312
	Total	**403**	**1145**	**2424**
Trunking Segment				
	Voice	310	638	1578
	Data	0	17	41
	Video	60	240	295
	Total	**370**	**895**	**1914**
CPS Segment				
	Voice	0	3	16
	Data	33	237	477
	Video	0	10	17
	Total	**33**	**250**	**510**

Despite these large discrepancies, the forecast was accurate in predicting saturation of the C- and Ku-band frequencies in the early 1990's. In order for satellites to carry a much larger portion of the ever-expanding data and video market, it is certain that spot-beam satellites will be needed.

FINAL ASSESSMENT of 1983 MARKET PROJECTIONS

The market forecast conducted in 1983 to predict the satellite addressable communications market 17 years later was visionary in that it:

- Identified many new services that are similar to those provided by the Internet;
- Included an impact of all digital transmissions with statistical multiplexing, low rate voice and efficient video compression;
- Realized the importance of integrating voice, video and data onto a common channel and providing that service on-demand; and
- Understood the increasing importance of video and high-speed data links.

These visions were incorporated into ACTS, which made it a modern communications test bed when it was launched in 1993. Any communications traffic market study has difficulty quantitatively estimating the impact of technology (fiber optics, high capacity personal computers, Internet, Intranets, and digital signal processing), and this market study was no exception. The significant under and over predictions were identified in the previous section. However, the forecast fairly accurately predicted the approximate time the C- and Ku-band frequencies would become saturated for US domestic FSS communications.

CHAPTER 8

ACTS Successors

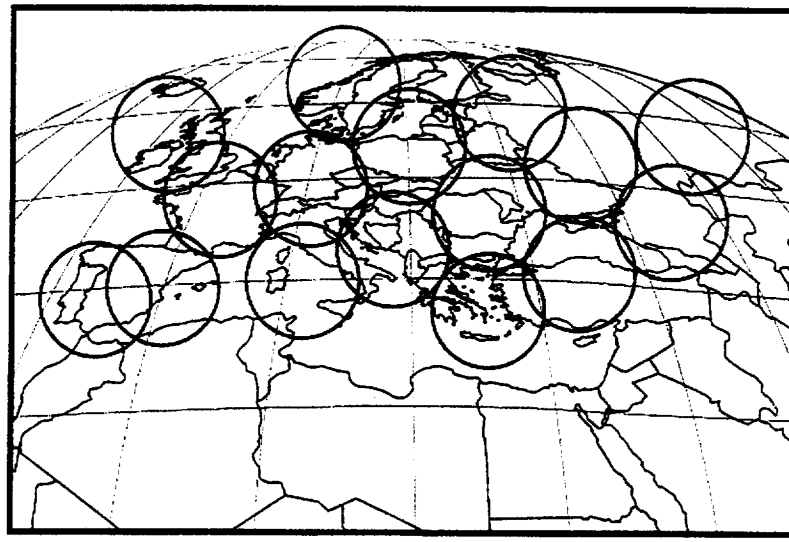
Satellites are emerging as an ideal medium for a host of new global communication services. NASA's Advanced Communications Technology Satellite has provided an on-orbit test bed for pioneering, evaluating, and validating some of the cutting edge communications technologies needed for these new services for the 21st century. The development and on-orbit testing of ACTS has helped to herald a new advance for the role of satellites in the information revolution. ACTS pioneered four key technology breakthroughs: on-board circuit switching and processing, dynamic hopping spot beams, very wideband transponders, and use of the Ka-band portion of the frequency spectrum. The advanced switching technologies provided ACTS users with bit rates on-demand. The multiple spot-beam technology permitted a high degree of frequency re-use and small terminals for direct user-to-user (mesh) interconnectivity. With a high degree of frequency reuse, the capacity for a single satellite in orbit can be much greater with a resultant reduction in service cost. Trials with the ACTS test network have validated on-demand, high-bandwidth, integrated voice, video and data applications that potentially can be provided at a service price that is competitive with terrestrial communications. In today's deregulated environment, the reduction in service cost is crucial if satellites are to remain competitive.

EXPLOSION IN KA-BAND FILINGS

In the mid-1990's, it was clear that the existing C and Ku frequency bands being used by satellite operators had insufficient spectrum to provide for the projected new interactive, high data rate services. To satisfy this demand, satellite manufactures and service providers began to turn to Ka-band, multiple spot-beam, switching and processing satellites using some or all the elements of the technology pioneered by ACTS. As a result, there was a "land rush" for Ka-band spectrum. In 1995, US Satellite developers laid claim to Ka-band spectrum in response to the FCC's deadline for accepting the 1st round satellite filings. Filings to the ITU from other countries around the world soon followed the US initiatives. As a result, a whole new generation of sophisticated global communication satellite systems has been proposed. Developers plan to invest well over $30B to make Ka-band the home of a wide range of high speed, two-way, digital communication services within the next 10 years [122]. Most of these systems will be global in scope and provide services directly to businesses and consumers on their premises.

The accompanying table details the various geostationary Ka-band satellite systems that have been proposed and filed with the ITU and/or the FCC [134] through mid 1997. The ACTS technologies of on-board switching and processing, hopping spot beams, and wide bandwidth transponders, are being used by a large number of these proposed system. This list has been prepared by Walt Morgan and updated in 1997. It should be noted that since the original filings some systems have been withdrawn (most notably AT&T VoiceSpan System, not included in the list), while others have been modified.

SES ASTRA 1K Coverage. The 16 Ka-band, Spot-Beams Are Used For Interactive Services Using 60 Centimeter Terminal With 0.5 Watt 30 GHz Uplink HPA.



In the United States alone, seventeen different communication satellite systems have filed with the Federal Communications Commission (FCC) to provide both domestic and international services from GEO for a total of 92 Ka-band communication satellites. The use of multiple spot beams and on-board switching and processing is not confined to Ka-band geosynchronous satellites only. Additional filings have been made to the FCC for use of Ka-band for non-geostationary fixed services and feeder links for big LEO systems. The most notable of these non-geostationary systems include Motorola's 66 satellite Iridium system featuring Ka-band cross and feeder links and now operational, and Teledesic's 288-satellite system.

Of course, not every proposed system will be funded, built, and supported by the market. Historically, not all filings have turned into reality. For example, of the 1984 filings for C- and Ku-band satellites, more than half were abandoned. In 1984 the market for C- and Ku-band satellites was better understood than that for Ka-band today. However, financing is probably more readily obtainable today. ***Even if only a small fraction of these proposed systems obtains orbit, it is clear that there is an enormous growth ahead in satellite communications.***

As of February 1999, only three commercial satellites with Ka-band transponders are being constructed; these being KoreaSat-3, and Societe Europeenne des Satellites (SES) – Astra 1H and 1K. SES's 1H and 1K satellites provide Ka-band, bent-pipe, spot-beams uplinks from the user and a forward link back using Ku-band DTH transmissions. They recently ordered the first Ka-band, two-way user terminals (actually a hybrid Ka/Ku terminal) for commercial services from Nortel, a major milestone. For two-way interactive services, the cost of the terminal determines the feasibility of the service since the satellite transmission costs are very small.

As discussed in the previous chapter, the Internet/Multimedia service revenues for 1998 and 1999 grew at approximately 100% rate. Intelsat is currently providing Internet services into 80 countries and expects the revenues from these services to be 20% of its business in 1999. So far the initial satellite broadband business has been satisfied by current assets of the service providers. As the satellite market continues to grow, there will be a natural evolution into the Ka-band arena. The initial approach was to take the multiple spot-beam and on-board processing technology and try to apply it to all broadband markets in general. This has turned out to be a mistake. The natural evolution will be to analyze the market segments and determine the best ways that satellites can respond. With the large broadband market growth, the new ACTS type technologies will certainly have a role to play.

GLOBAL GEOSTATIONARY ORBIT Ka-BAND FILINGS

SATELLITE SYSTEM	COUNTRY OF ORIGIN	SPONSORS	ORBITAL SLOTS REQUESTED
AFRISAT	UNITED KINGDOM(HK)	....	4
ARABSAT Ka	ARAB LEAGUE	ARABSAT	12
ASIASAT-AKA	UNITED KINGDOM(HK)	....	5
ASTROLINK	USA	LOCKHEED MARTIN	5
BIFROST	NORWAY	TELENOR	1
CANSAT Ka	CANADA	TELESAT CANADA	5
CHINASAT 41-47	CHINA	CHINESE GOVT.	7
COMETS	JAPAN	NASDA	1
CYBERSTAR	USA	LORAL SPACE	3
DACOMSAT	SOUTH KOREA	DACOM	1
DB-SAT	GERMANY	....	1
DRTS	JAPAN	....	5
EAST	UNITED KINGDOM	....	5
EASTSAT	KOREA	....	1
ECHOSTAR-Ka	USA	ECHOSTAR	2
EDRSS	ESA	ESA	4
ETS-8	JAPAN	NASDA	3
EUROSKYWAY	ITALY	ALENIA SPAZIO	7
EUROPESTAR K	GERMANY	....	3
EUTELSAT-Ka	REGIONAL, EUROPE	EUTELSAT	22
GENESIS	GERMANY	DT	1
GE STAR	USA	GE AMERICOM	5
GLOBALSAT	KOREA	....	1
HISPASAT-2AKa	SPAIN	HISPASAT	1
INFOSAT	KOREA	....	3
INMARSAT-GSO-2	INTERNATIONAL	PTT'S	5
INSAT, INSAT-Ka	INDIA	INSAT/ISRO	15
INTELSAT-Ka	INTERNATIONAL	PTT'S	12
JBS	USA	....	17
KaSATCOM	USA	....	6
KaSTAR	USA	KaSTAR	2
KOREASAT	SOUTH KOREA	KOREASAT	1

SATELLITE SYS-TEM	COUNTRY OF ORIGIN	SPONSORS	ORBITAL SLOTS RE-QUESTED
KYPROS-SAT-Ka	CYPRUS	....	5
KYPROS-SAT-L	CYPRUS	....	4
LUX-Ka(ASTRA)	LUXEMBOURG	SES	20
MALTASAT-1	MALTA	....	4
MEASAT	MALAYSIA	SHINAWATRA	5
MEASAT LA&SA	MALAYSIA	SHINAWATRA	5
MEDSAT	MEDITERRANEAN	AEROSPATIALE, etc.	1
MEGASAT	MEXICO	....	10
MILLENIUM	USA	MOTOROLA	4
MORNING STAR	USA	....	4
MTSAT	JAPAN	....	3
NETSTAR-28	USA	....	1
ORION	USA	ORION	6
PAKSAT	PAKISTAN	....	5
PANAMSAT	USA	PANAMSAT(HUGHES)	2
ROSCOM	RUSSIA	....	4
SAMSAT	SINGAPORE	PACIFIC CENTURY	3
SARIT	ITALY	TELESPAZIO	1
SICRAL-2	ITALY	....	2
SIRIUS-4	SWEDEN	NSAB	1
SKYSAT	UNITED KINDOM	AFRO-ASIAN	12
SPACEWAY	USA	HUGHES	14
STENTOR	FRANCE	....	1
SUPERBIRD	JAPAN	SCC	2
SYRACUSE	FRANCE	....	9
THAICOM Ka	THAILAND	BINARIANG	5
TONGASAT Ka-1	TONGA	TONGASAT	9
TOR-M	RUSSIA	....	18
TURKSAT-Ka	TURKEY	TURKSAT	6
USCSID	USA	....	12
USGBS	USA	....	5
USGCB	USA	....	5
VIDEOSAT Ka	FRANCE	FRANCE TELECOM	3
VINASAT-A	REGIONAL	VIETNAM	4
VISIONSTAR	USA	....	1
WEST-GEO	FRANCE	MATRA MARCONI	12
YAMAL	RUSSIA	GAZPROM	5

ACRONYM LIST

ACTS	Advanced Communications Technology Satellite
AGC	Automatic Gain Control
AIAA	American Institute of Aeronautics and Astronautics
AKM	Apogee Kick Motor
AM	Amplitude Modulation
AMT	ACTS Mobile Terminal
APT	ACTS Propagation Terminal
APU	Auxiliary Power Unit
APW	ACTS Propagation Workshop
ARIES	ATM Research and Industrial Enterprise Study
ARPANET	Advanced Research Project Agency's Network
ASIC	Application Specific Integrated Circuit
ATM	Asynchronous Transfer Mode
ATS	Application Technology Satellite
AWGN	Additive White Gaussian Noise
B	Billion
BBP	Baseband Processor
BER	Bit Error Rate
BFN	Beam Forming Network
B-ISDN	Broadband Integrated Services Digital Network
BOL	Beginning of Life
Bps	Bits Per Second
BPSK	Binary Phase-Shift Keying
BSS	Broadcast Satellite Service
BTC	Budget to Completion
CATN	Common Antenna Television Network
CRD	Critical Design Review
CD-ROM	Compact Disk-Read Only Memory
CML	Current Mode Logic
CMDS	Commands
CMOS	Complementary Metal Oxide Semiconductor
CODEC	Code-Decode
CONUS	Continental United States
CPS	Customer Premises Services
CPU	Computer Power Unit
CRT	Cathode Ray Tube
CR&T	Command Ranging & Telemetry
CT	Computed Tomograghies
CTS	Communication Technology Satellite
CW	Continuous Wave
CWG	Carrier Working Group
CY	Calendar Year

DAMA	Demand Assigned Multiple Access
DARPA	Defense Advance Research Projects Agency
dB	Decibel
dBi	Decibel, Isotropic
DBS	Direct Broadcast Service
dBW	Decibel, Watt
DC	Direct Current
D/C	Downconverter
DCU	Digital Control Unit
DCTN	Defense Communication Telecommunications Network
DOD	Department of Defense
DPSK	Differential Phase Shift Key
DTH	Direct to Home
Eb/No	Energy per bit per Noise Density
ECL	Emitter Controlled Logic
EDT	Eastern Daylight Time
EIA	Electronic Industries Association
EIRP	Effective Isotropic Radiative Power
EOA	Experiment Opportunity Announcement
ESA	Earth Sensor Assembly, European Space Agency
FAX	Facsimile
FCC	Federal Communications Commission
FCS	Fixed Communication Service
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FDR	Final Deign Review
FEC	Forward Error Correction
FET	Field Effect Transistor
G/T	Gain/Temperature, Ground Terminal
GaAs	Gallium Arsenide
GEO	Geostationary Earth Orbit
GES	Gigabit Earth Station
GHz	Gigahertz
GPS	Global Positioning System
GSFC	NASA Goddard Space Flight Center
GSO	Geostationary Orbit
GTO	Geostationary Transfer Orbit
GII	Global Information Infrastructure
HDR	High Date Rate
HDV	High Definition Video
HEMT	High Electron Mobility Transistor
HMMWV	Highly Mobile Maneuverable Wheeled Vehicle
HV EPC	High Voltage Electronic Power Conditioner
Hz	Hertz (cycles per second)
I&T	Integration and Test
IBOW	In Bound Order Wire

IF	Intermediate Frequency
IMPATT	Impact Ionization Avalanche Transit Time
INS	Inertial Navigation System
IP	Internet Protocol
IR&D	Internal Research and Development
IRP	Initial Response to Proposal
ISDN	Integrated Services Digital Network
ITU	International Telecommunication Union
JPL	Jet Propulsion Laboratory
JSC	NASA Johnson Space Center
JWID	Joint Warrior Interoperability Demonstration
KAO	Kuiper Airborne Observatory
Kbps	Kilobits Per Second
KHz	Kilohertz
LAN	Local Area Network
LeRC	NASA Lewis Research Center
LEO	Low Earth Orbit
LET	Link Evaluation Terminal
LLNL	Lawrence Livermore National Laboratory
LNA	Low Noise Amplifier
LNR	Low Noise Receiver
LRD	Launch Readiness Date
LSI	Large Scale Integration
mm	Millimeters
ms	millisecond
M	Million
M/V	Motor Vessel
MAN	Metropolitan Area Network
MBA	Multiple Beam Antenna
Mbps	Megabits Per Second
MCS	Master Control Station
MHz	Megahertz
MMIC	Monolithic Microwave Integrated Circuit
MOSAIC	Motorola Oxide Self-Aligned Implanted Circuit
MR	Magnetic Resonance
MSM	Microwave Switch Matrix
MSP	Modular Switching Peripheral
MTS	Metered Telephone Service
ns	Nanosecond
NAPEX	NASA Propagation Experiment
NASA	National Aeronautics & Space Administration
NASDA	Japanese Space Agency
NCAR	National Center for Atmospheric Research
NCS	National Communication Systems
NGS	NASA Ground Station
NGSO	Non Geostationary Orbit

NII	National Information Infrastructure
NLH	Net Long Haul
NMT	Network Management Terminal
NOI	Notice of Intent
NRC	National Research Council
OBOW	Out Bound Order Wire
OC	Optical Character
OMB	Office of Management and Budget
PAM	Payload Assist Module
PBS	Public Broadcast System
PC	Personal Computer
PD	Presidential Directive
PDR	Preliminary Design Review
PHEMT	Pseudomorphic High Electron Mobility Transistor
PM	Phase Modulation
POC	Proof of Concept
PSN	Public Switched Network
QPSK	Quaternary Phase Shift Keying
rms.	Root Mean Squared
R&D	Research and Development
RCSA	Receive Coax Switch Assembly
RF	Radio Frequency
RFT	Radio Frequency Terminal
RFP	Request for Proposals
SBA	Steerable Beam Antenna
SBPSK	Staggered Binary Phase-Shift Keying
SCADA	Supervisory Control and Data Access
SDR	System Design Review
SITF	Satellite Industry Task Force
SMSK	Serial Minimum Shift Keying
SNMP	Simple Network Management Protocol
SONET	Synchronous Optical Network
SQPSK	Staggered Quaternary Phase Shift Keying
SSI	Small Scale Integration
SS-TDMA	Satellite Switched Time Division Multiple Access
STS	Space Transportation System
STU	Secure Telephone Unit
T1	1.544 Mbps Bell Standard Digital Data Rate
TCP	Transport Control Protocol
TCSA	Transmit Coax Switch Assembly
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TDRSS	Tracking & Data Relay Satellite System
TEW	Tracking Error Word
TIP	Telemedicine Instrument Package
TLM	Telemetry

TOS	Transfer Orbit Stage
TT&C	Telemetry, Tracking & Command
TWT	Traveling Wave Tube
TWTA	Traveling Wave Tube Amplifier
TV	Television
TWX	
U/C	Upconverter
UDP	User Datagram Protocol
UHF	Ultra High Frequency
USAT	Ultra Small Aperture Terminal
VHF	Very High Frequency
VPN	Virtual Private Network
VSAT	Very Small Aperture Terminal
WATS	Wide Area Telephone System
WIRS	Waveguide Input Redundancy Switch
WORS	Waveguide Output Redundancy Switch
Z	Zulu time
3D	Three Dimensions
°K	Degrees Kelvin

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13. ABSTRACT ***(Maximum 200 words)***

The ACTS Project was originated at NASA Glenn Research Center in the early 1980's to sponsor the development and application of technology that was intended to be used by the private sector. The program was formulated with the underlying philosophy of maintaining U.S. leadership in satellite communications while focusing technology development for efficient use of the frequency spectrum. This report chronicles the execution and results of the program from the perspective of its technology managers, from inception through hardware and system development to on-orbit experiments and demonstrations of the technology. The first eight sections of the report discuss programmatic background, the specific satellite and ground terminal technology and the results generated by the program including industry relevance. A federally funded program of this type attracted strong advocates and adversaries and the resulting impact on the project schedule is also discussed. The last two sections are a list of useful acronyms and extensive references.

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