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X-751-73-178

PREPRINT

NASA TM X- 70435

NASA COMPENDIUM OF SATELLITE COMMUNICATIONS PROGRAMS

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(NASA-TM-X-70435)  NASA COMPENDIUM OF                    N73-30834
SATELLITE COMMUNICATIONS PROGRAMS (NASA)
482 p HC $26.25                       CSCL 22A
                                                         Unclas
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JUNE 1973

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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PREFACE

During the decade of the 1960s a new industry, satellite communications, was born as one of the products of the space program conducted by the United States of America. As of mid-1971, this new industry has evolved to the point where it serves a major portion of the world's population. The most dramatic illustration of this service is real-time television coverage of major international events, allowing millions to literally be "on-the-spot" to view such activities as the Olympic games and official state visits of world political and religious leaders.

Numerous programs have contributed toward the evolution of satellite communications over the past 10 years and much has been written about them. The primary objectives of this compendium are to summarize the major contributions of each program and to compile an extensive bibliography of the publicly available writings on them. The compendium has been assembled by the Computer Science Corporation (Contract Number NAS 5-21522) under the direction of the Communications and Navigation Division, Goddard Space Flight Center. The information is current through August 1971 and was initially submitted as a Contractor's Report. The Compendium is reproduced here as NASA Report X-751-73-178, without up-dating. However it incorporates some editorial changes in Section 10 suggested by the Communications Satellite Corporation (COMSAT), on behalf of Intelsat (International Telecommunications Satellite Consortium).

Charles P. Smith, Jr.
Technical Officer
June 1973

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SECTION 1 - INTRODUCTION

1.1 SCOPE AND ORGANIZATION

This document presents a comprehensive review of worldwide satellite communication programs that range in time from the inception of satellite communications to mid-1971. Particular emphasis is placed on program results, including experiments conducted, communications system operational performance, and technology employed. The background for understanding these results is established through brief summaries of the program organization, system configuration, and satellite and ground terminal characteristics. Major consideration is given to the communications system aspects of each program, but general spacecraft technology and other experiments conducted as part of the same program are, for the most part, at least mentioned summarily. Each program review attempts to be thorough and objective to the maximum extent possible from publicly available literature. In some cases, such literature was not adequate to allow complete reporting to the level of descriptive detail desired. This is particularly true for programs involving foreign, international, or military sponsorship. Program difficulties encountered are viewed as positive contributions towards advancing the state-of-the-art in satellite communications and are presented in that light.

The project reviews presented include all significant past programs in which satellites having some operational capability were successfully launched into orbit and all active programs, as of mid-1971, wherein development and procurement of the necessary space hardware had been approved. Some of the programs described span a considerable period of time and an evolutionary development of several configurations of ground and space assets. In most such cases, separate discussions of the different segments of the program, each segment of which may encompass several spacecraft, are provided. The approach to program segmentation has, in all cases, been guided by the results-oriented objective of this document. The organizational grouping this provides may not in all cases coincide exactly with the chronological sequence of events or the official program organization based on administrative considerations and initially expected results.

The document is organized and formatted to provide the user with easy access to needed information. It features a chronological ordering of program descriptions, brief concise summaries of each program, including extensive use of tabular presentations, adherence to a consistent format from description to description, and extensive bibliographies of cited and related references from which the reader can do more detailed research on a particular aspect of a program. The consistent format provides consideration of the same items of information in the same order on each program and extends this philosophy from the defining and ordering of major subtopics to the defining and ordering of the tables employed. The bibliographies are incorporated directly following the particular program to which they are pertinent and are composed, in general, of references readily available within the public domain.

The basic format for each description encompasses the following major subtopics: (1) Program Description, (2) System Description, (3) Spacecraft, (4) Ground Terminals, (5) Experiments, and (6) Operational Results. In a few instances, the nature and extent of available information dictated that the "Program" and "System Description" subtopics be replaced by a "General Description" or "Introduction" subtopic. In such cases, information of the type normally included in the first two subtopics is distributed over the introductory, spacecraft, and ground terminal subtopics.

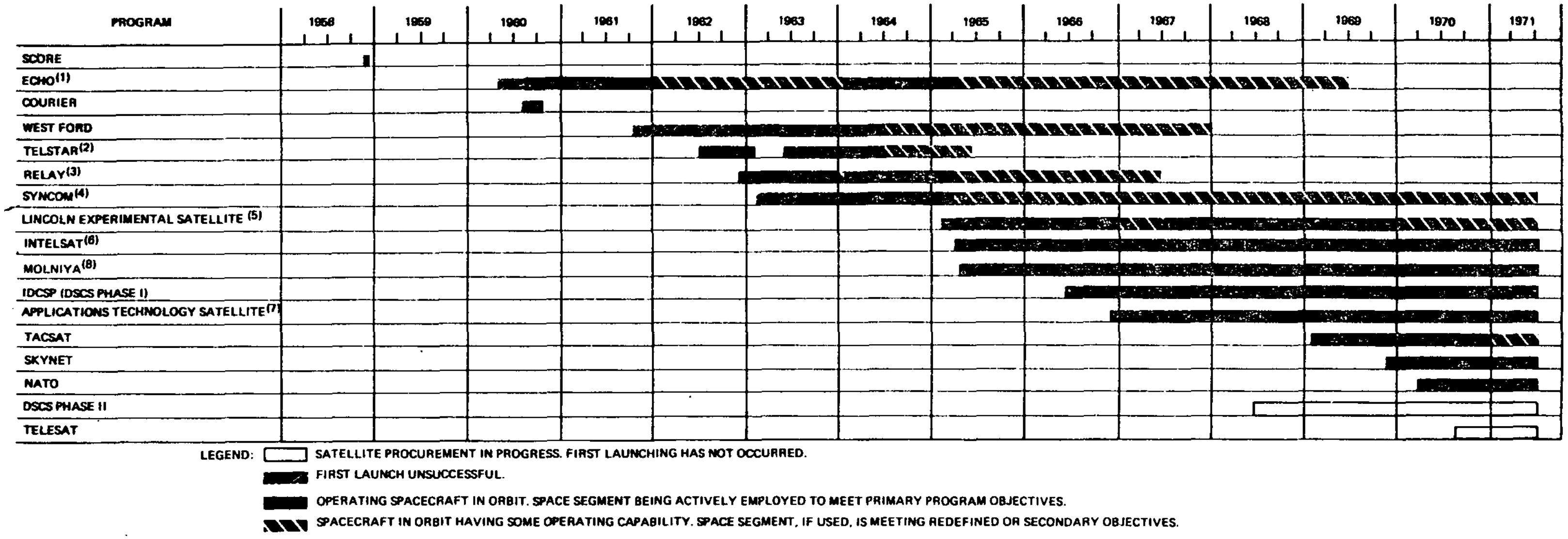
Information, typically, included within each major subtopic is as follows:

- Program Description - Project origin and objectives; spacecraft launch dates, orbital data, and status; extent to which program objectives were accomplished; participating ground terminals; sponsoring organizations; and significant results advancing the state-of-the-art in satellite communications.

- System Description - Ground terminal linking, extent of spacecraft visibilities, operating frequencies, signal processing including modulation and multiple access, system control, and calculated link performance.
- Spacecraft - Major characteristics of antennas and communications repeaters; general satellite features including stabilization, prime power, size and weight; and communications repeater block diagram. Major onboard experiments not directly communications-related are listed but not described in detail.
- Ground Terminals - Major characteristics of antennas, receive system, transmitter, tracking system and physical installation; block diagram of principal subsystems; and any unique aspects.
- Experiments - Definition of major types of experiments, summary of primary experimental results, and descriptions of significant demonstrations and public relations highlights.
- Operational Results - Summary of operational traffic handled, plus operational performance and reliability of the satellites and ground terminals.

1.2 OVERVIEW OF PROGRAMS

Major events, in each of the programs reviewed in this document, are summarized as a function of time in Figure 1-1. The programs illustrated encompass all significant satellite communication activities involving orbiting hardware since the launching of the Score satellite, with the possible exception of Project Oscar. Several active repeater satellites, nicknamed "Oscar," have been launched, starting as far back as late 1961 by the U.S. Air Force, to provide amateur radio communications satellites for use by "Ham radio" operators throughout the world. Some of these satellites were very short-lived and they, by intent, did not push the state-of-the-art in satellite communications.



NOTES:
(1) TWO SPACECRAFT OF DIFFERENT STRUCTURAL DESIGN EVALUATED AT SEPARATE TIMES. SAME TYPE EXPERIMENTS CONDUCTED IN BOTH CASES.
(2) TWO VERY SIMILAR SPACECRAFT EVALUATED AT SEPARATE TIMES USING SIMILAR TESTS. FIRST SATELLITE FAILED PRIOR TO SECOND LAUNCHING.
(3) TWO VERY SIMILAR SPACECRAFT EVALUATED AT SEPARATE TIMES USING SIMILAR TESTS.
(4) SPACECRAFT TURNED OVER TO DOD IN EARLY 1965 AND HANDLED OPERATIONAL TRAFFIC UNTIL ABOUT 1969.
(5) SPACECRAFT OPERATING AT SHF FREQUENCIES EVALUATED DURING FIRST PERIOD OF ACTIVITY AND UHF SATELLITES DURING SECOND.
(6) FOUR GENERATIONS OF SPACECRAFT EVOLVED DURING THE OPERATIONAL PERIOD SHOWN.
(7) SPIN STABILIZED SPACECRAFT EVALUATED DURING FIRST PERIOD OF ACTIVITY AND EXPERIMENTS ON SPACECRAFT DESIGNED FOR GRAVITY GRADIENT STABILIZATION CONDUCTED DURING SECOND.
(8) HISTORY OF SATELLITE FAILURES AND RESULTANT PERIODS WHEN SYSTEM WAS INOPERATIVE ARE UNCERTAIN.

Figure 1-1. Historical Summary of Program Activities as of Mid-1971

The figure dramatically displays the very short duration of the Score and Courier programs conducted during the early history of satellite communications. These programs represented the initial attempts to employ active satellites for communications. During this early era, the Echo and West Ford programs also displayed the long life times attainable through employing passive satellites to establish a communications system. However, the Telstar, Relay, and Syncom programs soon proved that highly reliable active satellites were feasible and, in view of the higher system capacities provided, all subsequent programs have followed their lead. Some modest interest in passive satellite technology has been retained by the National Aeronautics and Space Administration (NASA) but no technology developments or future satellite launchings are presently planned.

The technology demonstrated in the Telstar, Relay and Syncom programs led, in a relatively short time, to the development of operational systems. Subsequent programs providing these systems have included Intelsat, Initial Defense Communications Satellite Program (IDCSP), Skynet, and the North Atlantic Treaty Organization (NATO) program. Additionally, the Defense Satellite Communications System (DSCS) Phase II and Telesat programs have satellite procurements underway that should lead to operational systems by mid-1972 and early 1973, respectively. Satellite experimentation has been continued by the Lincoln Experimental Satellite (LES), Applications Technology Satellite (ATS), and Tacsatcom programs.

A more detailed summary of the programs reviewed in this document is provided in Table 1-1. The table includes an indication of individual program sponsorship and mission. These have been powerful factors dictating the lines along which programs evolved. Accordingly, the programs can be grouped into U.S. military, purely scientific, international commercial, foreign military, and domestic commercial categories.

The U.S. military programs have involved a considerable amount of scientific investigation of their own but it has, for the most part, been channeled towards the specific goals of developing strategic and tactical military communications systems.

Table 1-1. Summary of Program Scope and Status as of Mid-1971

Program	Satellites Launched	Sponsor	Mission	Status
Score	One active store and forward	DOD/Army	Experimentation	Communications failed due to battery failure after 12 days in orbit. Orbit decayed after 35 days.
Echo	Three passive	NASA	Experimentation	Two satellites successfully employed. Experiments completed by early 1965. Orbit of last satellite decayed in 1969.
Courier	Two active store and forward	DOD/Army	Experimentation	One satellite sucessfully supplied communications for 17 days. Command receiver failure caused satellite to become inactive.
West Ford	Two dispensers of dipole needles	DOD/Air Force	Experimentation	One dispenser successfully dispersed dipoles in passive reflecting belt. Major experiments completed in first year in orbit. Estimated that orbit of last dipoles decayed by early 1968.
Telstar	Two active	AT&T	Experimentation	Both satellites successfully employed. Last satellite turned off in 1967. Experimentation essentially completed by early 1965.
Relay	Two active	NASA	Experimentation	Both satellites successfully employed. Last satellite failed in 1967. Experimentation essentially completed by early 1965.
Syncom	Three active	NASA	Experimentation	Two satellites attained synchronous orbit and successfully supplied communications. Both satellites still active with no stationkeeping capability. Experimentation completed by early 1965. Extensively used for DOD operational traffic from 1965 through 1969. No longer employed.
LES	Three active operating at X-Band & three active operating at UHF all in 5 launches	DOD/Air Force	Experimentation	Two X-Band satellites successfully employed. Last satellite became unusable when its orbit decayed in 1968. X-Band experiments were completed by early 1967. All three UHF satellites successfully employed Last satellite remains usable. UHF experiments were essentially complete by early 1970. Plans exist for two additional spacecraft to be launched by late 1974.
Intelsat	One Intelsat I, four Intelsat IIs, eight Intelsat IIIs, & one Intelsat IV. All active operating at C-Band.	Intelsat	Commercial International Communications	One Intelsat I successfully employed. Satellite retired from service in early 1969, reactivated in mid 1969, and finally retired in late 1969. Three Intelsat IIs successfully employed. All three retain some operational capability and have been placed in reserve. Five Intelsat IIIs successfully employed. One has been placed in reserve, one is operational over Indian Ocean, one is operational over Pacific Ocean, and two are operational over the Atlantic Ocean. One Intelsat IV has been successfully placed into operation over the Atlantic Ocean. Plans exist for additional Intelsat IVs and an Intelsat V series of satellites.
Molniya	Eighteen active	Soviet Government	Civilian and military communications internal to USSR	Orbits of five satellites have decayed. Exact status of remaining spacecraft uncertain but at least four are thought to be active. Plans exist for a second series of Molniya spacecraft (Molniya II) operating at C-Band but employing the same highly elliptical orbit as Molniya I. Plans also exist for C-Band spacecraft to be deployed into geostationary orbits.
IDCSP (DSCS Phase I)	Thirty-four IDCSP, One GGTS 1, One DODGE, & one DATS 1 all in 5 launches	DOD/DCA	Experimentation and strategic military communications for U.S.	Twenty-six IDCSP satellites successfully employed. Twenty-one remain usable. Experimentation for most part terminated six months after first launch of 7 and IDCSP satellites and system declared operational. Automatic satellite turn-offs to start in 1972 and be completed by mid 1974. GGTS 1 and DODGE were employed for a time to evaluate gravity gradient stabilization. DATS 1 provided data on electronically despun phased array antennas.
ATS	Two spin stabilized, and three gravity gradient stabilized	NASA	Technical & User Experimentation	Two spin stabilized satellites successfully employed. Both remain usable. Communications experiments essentially completed by early 1969. One satellite designed for gravity gradient stabilization successfully employed. It remains usable. Most experiments that appear likely to be conducted completed by early 1971. Development of two satellites providing 30-foot parabolic antennas underway. Launches expected in 1973 and 1975.
Tacsat	One active	DOD/Air Force	Preoperational Experimentation	One satellite successfully employed. It remains active with periods of 10° coning and degraded EIRP. Major experiments essentially completed by early 1971. Plans exist for follow-on military tactical system.
Skynet	Two active	British Government	Military Communications for U.K.	One satellite successfully employed and remains active. Second series of satellites (Skynet II) being procured and first launching expected in late 1972.
NATO	Two active	NATO	Military Communications for NATO	Two satellites successfully employed to form NATO Phase II system and both remain active. Plans exist for a Phase III system.
DSCS Phase II	None	DOD/DCA	Strategic military communications for U.S.	Six satellites being procured. First launch of two satellites planned for late 1971.
Telesat	None	Canadian Government	Commercial Domestic communiications for Canada	Three satellites being procured. First to be launched in last quarter of 1972. Second to be launched about four months later as in-orbit spare.

The evolution of the strategic systems began with the Score and Courier, experimental store-and-forward satellites. It was continued almost 6 years later with the first IDCSP launching. In the interim period, the military attempted to develop three axis-stabilized satellites for launch into synchronous orbits (i. e., Project Advent), developed the system concepts, and designed the space segment for a medium altitude random polar orbit system, and extensively considered the possibility of employing Intelsat for service. Project Advent was terminated in 1962 when the launch vehicle and stabilization technology required proved to be beyond the state-of-the-art at that time. The medium altitude development was suspended when the potential economies of Intelsat service emerged. The latter was dropped for a number of reasons with the principal factor being the military requirement for a high degree of independent system control. The IDCSP concept effected some of the desired system economies by injecting a reduced number of the previously designed medium altitude satellites into random near synchronous orbits, using independently programmed and funded Titan IIIC developmental launches. Between the termination of Project Advent and the first IDCSP launching, the military gained operational satellite communications experience by supplying the ground complex and conducting the communication experiments on NASA's Project Syncom. Operational strategic military systems will be advanced a step further when the first two DSCS Phase II satellites are launched in late 1971.

Developing tactical systems did not become a formally announced goal of the U.S. military until 1965 when the Tacsatcom program was established. The experimental UHF satellites of the LES program and the Tacsat satellite followed in direct response to that goal. However, some of the major system concepts, and in particular the modulation concepts evaluated in these experiments, began to evolve in the West Ford program and the SHF portion of the LES program. The latter two evaluations also contributed data of general scientific interest and information applicable to the development of strategic military systems but in a larger sense they represented the beginning of tactical military system experimentation.

NASA has been responsible for the purely scientific programs conducted to date. These programs have investigated technology applicable in all types of satellite communications systems. NASA became active in satellite communications at a very early date through the Echo passive satellite program. As the general interest in active satellites intensified in the early 1960s, the Relay and Syncom programs came into being to investigate these types of satellites in medium and synchronous altitude orbits, respectively. Towards the mid-1960s the questions on the type of satellite and orbit to employ had been resolved and approaches to realizing high gain satellite antennas, spacecraft stabilization, and multiple access became the vital issues. An Advanced Syncom program was initially conceived by NASA to study these problems. However, this soon evolved into the ATS program, which added a multitude of other space experiments to those designed to advance communications technology.

The programs oriented toward realizing a system capable of supporting international commercial communications include Telstar and Intelsat. Telstar was an experimental program that contributed to general scientific knowledge. However, it was initiated by the American Telephone and Telegraph (AT&T) Company primarily to demonstrate the feasibility of employing active satellites for commercial communications. Before the program was completed, AT&T was legislated out of international commercial satellite ownership by the Communications Satellite Act of 1962, creating the Communications Satellite Corporation (Comsat). This was followed in 1964 by international interim agreements establishing Intelsat and including Comsat as the U.S. representative in this consortium of international partners. The Intelsat program was initiated immediately based on technology developed in NASA's Project Syncom.

Foreign programs producing systems whose primary objective has been military communications include Molniya, Skynet, and NATO. The experimental beginnings upon which the Russian Molniya program was based are not publicly known. These spacecraft began to be placed in orbit in the mid-1960s and an operational system was soon established to provide military and some civilian communications. This system has been maintained since that time through replacement launches of similar, if not identical, spacecraft. The Skynet and NATO programs evolved in the late 1960s and early 1970s from technology developed in the U.S. military's IDCSP program. Skynet provides military communications for the United Kingdom (U.K.) and NATO does the same for the NATO countries.

Systems designed strictly to provide internal domestic communications for a particular country are still in their infancy. The first such system is expected to be provided by Canada's Telesat program by early 1973.

Looking into the future, a number of potential new programs and continuations of old programs can be discerned which are not extensively reviewed in this document. Plans exist for two additional LES experimental satellites, and it is expected that a follow-on U.S. military tactical satellite program will evolve soon. The LES experiments are still classified and the exact nature and extent of the tactical program have yet to be defined. A Cooperative Applications Satellite (CAS-C), also known as a Communications Technology Satellite (CTS), sponsored jointly by Canada's Department of Communications (DOC) and NASA, should soon start to attract public attention. CAS-C will be jointly developed by Canada and NASA and integrated in Canada. Spacecraft launch is expected by early 1975. The U.S. and Canada will conduct experiments on a time-shared basis. Intelsat has plans for an Intelsat V series of spacecraft to advance their international commercial system into its fifth generation of hardware. The technology upon which these satellites will be based may be developed by a prototype or experimental satellite flown before the operational satellites are launched in the late 1970s. Some competition for future Intelsat systems is likely to emerge in the form of a Soviet Stationar program. The U.S.S.R. has been granted allocations by the International Telecommunications Union (ITU) for a geostationary satellite system operating at C-Band. In the area of foreign military programs, the U.S.S.R. plans a Molniya II series of spacecraft; the U.K. is developing Skynet II satellites; and NATO is designing a Phase III system to replace the existing Phase II system. Molniya II will employ the same highly elliptical orbit as Molniya I but operate at C-Band. Skynet II will be similar in design to Skynet I but will have considerably higher EIRP. NATO Phase III is still in the early planning stages. Two new domestic commercial satellite systems should also begin to emerge soon. Development of a U.S. System will proceed as soon as the Federal Communications Commission (FCC) approves one or more of the numerous filings it has received. Additionally, experimental Franco-German Symphonie and Italian Sirio programs are underway that will provide much of the basis for the intra-European system being developed by the European Space Research Organization (ESRO). Launches of experimental Symphonie and Sirio spacecraft should occur by late 1973 or early 1974. Finally, a completely new use for satellite communications technology has recently become apparent. This is in the area of air and marine traffic management.

1.3 EVOLUTION OF TECHNOLOGY

The low altitude Score satellite employed simple off-the-shelf VHF hardware to dramatize the potential of satellite communications by broadcasting a prerecorded Christmas message from President Eisenhower in 1958. From this beginning, the interest in satellite communications began to mount in the early 1960s.

Major initial areas of concern centered upon the type of satellite to select, type of orbit to employ, frequencies to utilize, and the development of ground terminal technology compatible with satellite communications. The basic satellite question was whether active or passive satellites should be employed. Either store and forward or real time active satellite repeaters were feasible. Passive reflector systems could be composed of a relatively small number of large single point reflecting structures or belts of multiple dispersed reflective elements. To resolve the orbit selection issue, low, medium and synchronous altitudes had to be considered, as did orbit inclination and degree of ellipticity. Frequencies appropriate for consideration were determined to be in the band from 1 to 10 GHz. Ground terminal technology of particular interest included low noise receive systems, demodulator thresholds allowing detection down to low values of signal-to-noise ratio, accurate satellite tracking so that high gain antennas could be employed, and high reliability operational performance.

Outside of these areas the programs of the early 1960s, including Echo, Courier, West Ford, Telstar, and Relay, employed similar technology that was well within the state-of-the-art at that time. Briefly, the active satellites provided almost omnidirectional antennas with essentially zero gain, low transmitter output power, no stabilization or spin stabilization relative to the sun, and solar cell arrays encircling the outside of the spacecraft to generate prime power. The ground terminals supplied large parabolic reflector or horn antennas, high power klystron or TWT transmitters, and fixed installations. Modulation was conventional analog frequency modulation and multiple access was by frequency division when employed. The active satellites were, in general, expected to support no more than two simultaneous accesses. Communication services handled included analog voice, TTY, low resolution facsimile, and television.

By late 1963, with the aid of data from these initial programs, the questions of type satellite, frequency band, and ground terminal technology had been resolved. Relay and Telstar had proven that reliable active real time repeaters were feasible and they had become the preferred choice. These repeaters were of the double conversion type with either hard limiting or AGC to ensure a constant input to the output power amplifier operating near saturation. Active repeaters were preferred over the passive systems of Echo or West Ford due to the higher system communication capacities afforded. Real time repeaters were the choice over the store and forward system of Courier because they resulted in simpler more reliable repeaters, and launch vehicle technology had progressed to the point that reasonably sized satellites could be injected into orbits high enough to provide wide areas and relatively lengthy periods of mutual ground terminal visibility.

Satellite communication frequencies had been reserved at 4 and 6 GHz for commercial operations and at 7 and 8 GHz for government operations. The former were the frequencies demonstrated in the Telstar program while the latter were employed on West Ford.

Basic ground terminal technology had been developed on the Echo program including: Cooled maser and uncooled parametric amplifier low noise receive systems; FM feedback demodulators for threshold extension; and accurate tracking using programmed inputs, manual steering from optical settings or radar autotracking. This technology was upgraded on Project Telstar to display reliabilities compatible with commercial operations and precision autotracking of beacon or communications signals radiated from active satellites. By late 1963, cooled parametric amplifier low noise receive systems had also begun to appear in Projects Telstar and Relay.

In 1963 and 1964, the orbit question was finally, for the most part, resolved by the results of the Syncom program, in favor of geostationary orbits. This completed the early experimental phase of satellite communications wherein the fundamental system concepts that have continued to apply were established.

Syncom demonstrated launch vehicle and satellite positioning and stabilization technologies to precisely inject spacecraft into synchronous equatorial orbits, to position in longitude and to maintain a satellite's longitudinal position (i.e., stationkeep). It further gave a preliminary indication that the long propagation time delay (i.e., 260 ms one way) and the associated echo problems that it introduces into 2-wire terrestrial telephone facilities were surmountable and, therefore, posed no drawbacks to this approach to satellite communications. With synchronous technology proven, the facts that only three or four satellites were required to provide a system giving worldwide earth coverage between ±75° of latitude, that earth terminal tracking requirements were significantly relaxed though not entirely eliminated, and that the problem of handover from one moving satellite to another no longer existed, made geostationary orbits the preferred choice for point-to-point communication via satellite.

Syncom further refined the state-of-the-art by providing advancements in satellite stabilization techniques and antennas. Syncom was spin-stabilized, as were Telstar and Relay, but in this case the spin axis was aligned at a 90° angle to the orbital plane and precisely maintained in this orientation by H_2O_2 gas jets. This allowed antennas providing pancake-shaped beams only slightly wider than required to cover the earth from synchronous altitude (i.e., 17°) to be employed. These antennas provided gains of about 6 dB.

With the feasibility of satellite communications demonstrated and the basic system concepts defined, interest turned in the mid-1960s to implementing operational systems, further refinements of spacecraft and ground terminal technologies, and developing advanced modulation and multiple-access techniques, including those designed specifically for handling digital communications traffic. In 1965 and into late 1966, the Intelsat and Molniya programs provided the beginnings of what was later to develop into extensive operational systems. During this same period, the X-Band portion of the LES program began to investigate technology refinements and advanced techniques.

In early 1965, Intelsat I (Early Bird) was launched into a geostationary orbit with the spacecraft located over the Atlantic Ocean and after a short checkout period introduced the first continuous commercial communications services provided by satellite. Early Bird employed satellite technology developed in Project Syncom to provide communications between terminals that were, for the most part, upgraded and modified versions of installations developed during Projects Telstar and Relay. Early Bird provided a duplex high capacity trunk between the United States and Europe. Its main technological contribution was to demonstrate, finally and conclusively, through extensive subjective user evaluations, that time delay and echo are not serious problems in synchronous satellite communications.

Shortly after the Early Bird launch, the first of the Molniya satellites, developed by the U.S.S.R., began to appear in orbit. These spacecraft employed orbits uniquely suited to provide service to regions lying entirely in the Earth's northern hemisphere. The orbits selected are highly elliptical, with 12-hour periods and apogees occurring over the northern hemisphere. These satellites provided the Soviet Union with a long-haul, cross-continent, Moscow-to-Vladivostok communications trunk. Major spacecraft technological innovations included flywheel stabilization, fully sun-oriented solar panels, and antennas that tracked the earth independent of the main body of the satellite.

The X-Band LES Satellites of this period investigated despun satellite antennas, automatic on-board spacecraft attitude control, fully solid state transponders operating at X-Band, and ground terminal digital equipment providing random multiple access. Antenna despinning was of interest as a means of obtaining high gain earth coverage pencil beams on spin-stabilized spacecraft. The X-Band LES satellites provided an initial indication of the feasibility of despinning by switching between elements of a multi-element array encircling the spacecraft spin axis. However, since these satellites were not at synchronous altitudes, the full gain potential of the technique was not demonstrated. Autonomous on-board attitude control to reduce ground control requirements was initially demonstrated on a satellite stabilized relative to the sun. Accurate on-board control of earth-oriented satellites remained to be proven. Solid-state X-Band transponders were shown to be feasible, but their low efficiencies and power outputs made them relatively unattractive as compared to the TWT output amplifiers being employed on operational systems. Frequency hopping of the center frequency of an MFSK channel was demonstrated to be a satisfactory approach to random multiple access among users handling digital traffic. Frequency hopping was first considered on Project West Ford and was of interest as a means to combat jamming in military systems, resist radio frequency interference, and allow common occupancy of the same frequency/time spectrum by users having low duty cycle random requirements for service. Error correcting sequential decoding of convolutionally encoded messages was also shown to be a powerful means for improving performance in digital systems operating at low signal-to-noise ratios.

By mid-1966, the initial interests of the mid-1960s in operational systems and advanced technology and techniques were supplemented by an interest in new applications. Up to this time, satellite communications had been looked upon, principally, as just another means of providing the kind of communication services commonly available in the military and commercial long-haul telecommunications networks (i.e., analog voice, TTY, low resolution facsimile, and television). It now began to be apparent that powers and bandwidths were available to support wideband digital traffic such as might be produced by high resolution facsimile and computer-to-computer applications. Additionally, the high satellite EIRP made available by advanced TWTs and earth coverage pencil beams made it possible to provide communications and position location for small aircraft, shipborne, remote data platform, and mobile land terminals. Between mid-1966 and late 1968, the Intelsat and Molniya operational systems continued to evolve, and the military IDCSP system was placed into operation. During this same period, a significant portion of the UHF LES testing was conducted, and the ATS program was initiated to investigate new technology, techniques, and applications.

In early 1967, the first successful launching of a second generation of Intelsat spacecraft was accomplished. By late 1967, three Intelsat IIs had been successfully launched, and commercial communications service was being provided over both the Atlantic and Pacific Oceans. The advent of reliable tunnel diode amplifiers to serve as relatively low-noise, high-gain satellite input preamplifiers allowed single RF conversion transponders to be provided on these satellites. Allowable satellite weight and prime power in combination with new high performance earth terminals permitted these transponders to be designed for linear input/output power transfer characteristics. These wideband satellites and an expanded ground complex resulted in extensive satellite multiple access in an operational system for the first time. Conventional FM-FDMA was employed, and system control techniques were developed to provide a high reliability operational system.

Concurrent with these Intelsat activities, continued launches of the Molniya I spacecraft maintained an operational Russian system. With the addition of new ground terminals, service in this system was considerably expanded in 1967 when the U.S.S.R. inaugurated a space television distribution system, allowing people in Siberia, the Far East, and the Far North to view broadcasts from Moscow.

In late 1966, the first group of 7 IDCSP satellites were successfully injected into near synchronous orbits, using a single launch vehicle, and by mid-1968 three more successful launches had established a system including more than 20 satellites.

This military system began to meet emergency operational requirements in December, 1966, and by mid-1967 it was declared completely operational. In this system of multiple, near synchronous satellites, outage periods due to no spacecraft being visible and during satellite handovers were overcome by scheduling around these events. The type of system realized was the result of economic considerations dictating that a space segment, initially designed and developed before synchronous technology was proven feasible, be implemented. The system employed conventional modulation and multiple-access techniques, except for high data rate (1Mbps) MFSK modems for facsimile transmission and an operational pseudonoise antijam capability.

Extensive evaluations of approaches to realizing high gain, pencil beam, earth coverage antennas were conducted during this period. Techniques for realizing despun antennas on spin-stabilized spacecraft were exhaustively considered, and gravity gradient stabilization, such that rigidly mounted spacecraft antennas were continuously pointed towards the earth, was seriously investigated for the first time.

Electronically despun phased arrays were flown on a synchronous ATS satellite in late 1966, and on a near synchronous test spacecraft launched as part of the IDCSP program in mid-1967. These tests demonstrated that this type of antenna system was feasible, and gains of up to 14 dB were realized. Electronic switching as a means to realize a despun antenna was given further consideration in the synchronous UHF LES satellite launched in late 1968. The feasibility of this approach was again demonstrated, and a gain of about 10 dB realized. However, questions on the optimum approach to antenna despinning were laid to rest when an ATS spacecraft launched in late 1967 demonstrated the feasibility of mechanically despun antennas. By late 1968, it was apparent that the latter approach provided reliable performance and antenna gains of about 16 dB. Additionally, weight and prime power consumption were competitive with or superior to that realized by other approaches.

Gravity gradient stabilization was of interest because of the potentially high reliabilities available from such a passive system. Launches of medium and synchronous altitude ATS spacecraft, designed for this type of stabilization, were attempted in early 1967 and late 1968, respectively. Additionally, special near synchronous test satellites, included as part of the IDCSP program, were launched in mid-1966 and mid-1967. The ATS evaluations could not be conducted due to launch vehicle failures. The IDCSP tests demonstrated a limited degree of success in initially establishing and maintaining gravity gradient stabilization, but numerous unexplained difficulties were encountered. As a result, by late 1968, the jury was still out on gravity gradient stabilization, but the initial findings were not favorable.

The mid-1966 to late 1968 time period also saw considerable experimentation, at VHF and the lower UHF frequencies, with providing communications to small mobile or remote terminals or both. The existence of extensive conventional small terminal facilities was the primary driving force behind the initial interest in this frequency band. A preliminary evaluation of propagation characteristics had been carried out with the aid of a simple UHF beacon radiating satellite launched as part of the LES program in late 1965. Additionally, a few simple demonstrations had been conducted, using the telemetry and command system on a Syncom satellite.

More extensive experiments were made possible with the inclusion of a VHF transponder on the first spin-stabilized ATS spacecraft launched in late 1966. These experiments were extended further when a UHF LES satellite was launched in mid-1967, and the second spin-stabilized ATS spacecraft, also including a VHF transponder, was launched in late 1967. The emphasis in the LES experiments was on developing a tactical military capability, while the interest in ATS was in demonstrating position location and communications for application to commercial and private aircraft and ships and to remote data platforms. The experiments performed considerably advanced the state of knowledge of propagation and noise at these frequencies while proving that such systems were feasible. In the LES program, the first experimental tactical terminals designed for specific military applications began to emerge.

During this period, the spin-stabilized ATS satellites also demonstrated the feasibility of a signal-processing satellite repeater that provided multiple access through frequency-division multiplexing of independent single sideband uplink signals and down converting the composite received signal for phase modulation of a single radiated carrier. This system was of interest because it supplied frequency spectrum conservation on the uplink and efficient utilization of available spacecraft power on the downlink. Additionally, a UHF LES satellite displayed that an autonomous control system could accurately maintain a spin-stabilized spacecraft's spin axis at a 90° orientation relative to the orbital plane.

Between late 1968 and early 1971, the areas of concern that existed in the years spanning the mid and late 1960s had to be further expanded to include consideration of higher frequencies for providing the same types of services. Interest began to develop in employing L-Band frequencies (i.e., a higher portion of the UHF band) for aircraft and maritime position location and communications in the private and commercial sectors. These frequencies are attractive because of the wider bandwidths and more accurate position location afforded. Further, millimeter wave frequencies started to be considered for commercial telecommunication services. The wider bandwidths available and visions of overuse of the allocated C-Band spectrum were the driving forces behind this interest. During this period, the operational Intelsat system continued to evolve, the Molniya and IDCSP systems continued to supply satisfactory operational service, the Skynet and NATO military systems initiated operational service, the exploration of tactical military communications was continued by the LES program and supplemented by a Tacsat satellite, and the ATS program conducted initial evaluations of L-Band and millimeter wave communications.

In late 1968, Intelsat began to establish a third generation satellite system. By early 1970, five successful launches had been completed, and a truly worldwide system providing service over the Atlantic, Pacific, and Indian Oceans had been completed. These satellites took advantage of the technology developed in the ATS program by employing mechanically despun antennas. The transponders were again linear, single conversion repeaters and FM-FDMA was the main mode of operation. However, experimentation was conducted on a PCM-PSK-TDMA system designed for 12- to 120-channel links and PCM-PSK-FDMA, SPADE, designed for links ranging from fractional requirements to 12 and 24 channels. Both systems were demonstrated to be feasible.

The TDMA development extended and confirmed earlier TDMA demonstrations conducted as part of the ATS program.

Between late 1968 and early 1971, two new operational systems came into being. A Skynet satellite was placed into a geostationary orbit providing visibility from Europe and much of Africa, in late 1969, and an operational military system for the United Kingdom was established. The satellite was based on technology developed in the IDCSP program but pseudonoise PSK was used to provide multiple access in the first all-digital operational system. NATO satellites were launched into geostationary orbits in early 1970 and early 1971. They were positioned over the Atlantic to provide operational service for the North Atlantic Treaty Organization countries and employed conventional technology developed in the IDCSP and Skynet programs.

On the LES program, testing of the UHF satellite launched in late 1968 continued. In addition to displaying the switched antenna, this satellite demonstrated the feasibility of high-efficiency, solid-state UHF transmitters operating directly from the unregulated primary power source, autonomous satellite stationkeeping and stationchanging, and reliable pulsed plasma microthrusters. The demonstrated autonomous stationkeeping capability, together with the previously displayed autonomous attitude control system, provided the potential for significantly reducing future ground tracking and command requirements. The spacecraft microthrusters were of interest as a means towards attaining highly precise attitude control and stationkeeping systems. Microthrusters were first considered in the ATS program as a means of providing stationkeeping and stationchanging on gravity gradient stabilized satellites where the attitude correction torques were quite low.

In early 1969, a Tacsat spacecraft was placed into a geostationary orbit and used along with the latest LES satellite to further demonstrate and develop a tactical military satellite communications capability. Tacsat included both UHF and SHF transponders, an input/output switching capability, and an ability to vary transponder bandwidth that afforded multiple commandable modes of operation, including cross-band configurations. By early 1971, prototype operational tactical terminals, at both

UHF and SHF, had been demonstrated for aircraft, ship or land mobile use. In addition, operational frequency-hopping MFSK modems had been displayed. This approach was selected over pseudonoise PSK due to shorter acquisition times in a random-access environment, relaxed synchronization requirements, and a greater resistance to the multipath likely to occur in many tactical situations (e.g., as for aircraft communication at elevation angles below 20°).

In late 1969, the final ATS spacecraft designed for gravity gradient stabilization was launched. The launch vehicle performed properly but control of the satellite was lost during an initial spin stabilized period before location on-station in a geostationary orbit. As a result, the spacecraft was left spinning about a longitudinal axis such that it could not be despun and the gravity gradient booms deployed. By early 1971, this final failure to demonstrate reliable gravity gradient stabilization at synchronous altitude, along with the successful development of despun antennas, had caused interest in this technique to wane. In spite of the improper stabilization, L-Band and millimeter wave experiments included on this satellite were performed, and valuable data was obtained that will contribute towards opening these frequencies for future use. The millimeter wave frequencies evaluated were at 15.3 and 31.65 GHz.

Finally, in early 1971, Intelsat successfully launched the first of what will be a fourth generation Intelsat space system. This satellite features earth coverage and fixed narrow coverage antennas on a mechanically despun platform. Additionally, it provides 12 transponders of moderate bandwidth such that separate types of services can be provided in separate channels (e.g., television distribution in one channel, high capacity telephone trunks in another, and low duty cycle individual voice links in still another). Major contributions of the satellite communication programs completed or in progress as of mid-1971 are summarized in Table 1-2.

Looking into the immediate future, it can be seen that two new programs, Telesat and DSCS Phase II, are on the horizon, as is a third basic configuration of ATS spacecraft. Gazing even deeper into the years ahead, the CTS and US domestic satellite (Domsat) programs are among the emerging satellite communications activities.

Table 1-2. Summary of Major Contributions

Program	Primary Results
Score	(1) Demonstrated feasibility of employing active orbiting satellites to relay messages over intercontinental distances.
Echo	(1) Displayed feasibility of erecting and maintaining large lightweight structures adequate to serve as passive reflectors in space. (2) Verified that conventional microwave theories for determining path loss could be applied to satellite links. (3) Fostered development of ground terminal technology including low noise receiver preamplifiers, FMFB receivers, accurate tracking techniques and terminal operating procedures.
Courier	(1) Displayed feasibility of high capacity high rate digital store & forward satellite system. (2) Demonstrated difficulty of attaining lifetime & reliability need for operational systems.
West Ford	(1) Showed that X-Band dipoles can be dispersed into a passive reflecting belt. (2) Displayed that belt is predictably affected by solar radiation pressure & does not interfere with radio astronomy. (3) Demonstrated that communications are feasible and multipath time delay & frequency smear are predictable.
Telstar	(1) Demonstrated performance and reliability, adequate for commercial operations, can be attained with active satellites. (2) Verified that multipath fading was not significant for operation at 4-6 GHz and elevation angles above few degrees. (3) Displayed accurate and reliable acquisition and auto-tracking of active satellites.
Relay	(1) N-on-P solar cells shown to be more resistant to radiation than P-on-N cells. (2) Displayed that dew point criteria and leakage tests should be included in power transistor specifications. (3) Indicated that relatively complex command signals are necessary to avoid spurious responses.
Syncom	(1) Demonstrated feasibility of placing & accurately positioning satellites in synchronous orbit. (2) Provided first, in orbit, demonstration that time delay and echo are not serious problems in synchronous satellite communications.
LES	(1) Displayed feasibility of all solid state X-Band satellite transponsers even though power out & efficiency were relatively low. (2) Demonstrated feasibility of X-Band & UHF electronically switched despun antennas. (3) Advanced state of knowledge of UHF propagation & noise including RFI. (4) Displayed workable experimental tactical ground terminals. (5) Demonstrated feasibility of high efficiency UHF satellite transmitters operating from unregulated solar array power supply (6) Accurate autonomous spin axis attitude control was exhibited. (7) Performance potential of sequential decoding as applied to satellite links was displayed. (8) Frequency hopping was shown to provide satisfactory random access & resistance to multipath & RFI. (9) Demonstrated feasibility of autonomous stationkeeping and station changing.
Intelsat	(1) Demonstrated that time delay & echo are not serious problems in commercial communications through synchronous satellites. (2) Displayed single conversion linear satellite repeaters. (3) Employed first satellite antennas having beamwidths considerably narrower than required for earth coverage. (4) Developed techniques for control & operation of a high reliability operational system. (5) Developed and demonstrated PCM-PSK-TDMA trunking systems. (6) Developed PCM-PSK-FDMA single voice channel system (i.e., SPADE).
Molniya	(1) Demonstrated feasibility of operational system in northern hemisphere using 12 hour highly elliptical orbits. (2) Displayed electric motor driven, flywheel stabilized spacecraft with earth tracking antennas & capability of orienting solar panels towards sun.
IDCSP (DSCS Phase I)	(1) Demonstrated operational system composed of large number of simple random orbit satellites can be established & maintained. (2) Displayed feasibility of wide band high data rate (1Mbps) satellite transmissions of high resolution imagery. (3) Demonstrated a limited degree of success in initially establishing & maintaining gravity gradient stabilization but encounted numerous unexplained difficulties. (4) Displayed operational jam resistant psuedonoise modems.
ATS	(1) Demonstrated feasibility & potential of electronic despinning using phased arrays. (2) Displayed feasibility & attractiveness of mechanically despun antennas. (3) Showed that single-sideband frequency division multiplexing on uplink & phase modulation by the composite received signal on downlink is practical means of multiple access. (4) Demonstrated feasibility of VHF satellite communications among small mobile terminals. (5) Provided data on millimeter wave propagation. (6) Gave initial indication of potential L-Band holds for aircraft and maritime communications (7) Displayed the difficulties that can be encountered in attempting to deploy & initially stabilize gravity gradient stabilized satellites.
Tacsat	(1) Demonstrated operational UHF and SHF mobile earth terminals. (2) Displayed feasibility of channelized satellite repeater capable of switched input/output connections. (3) Provided gyrostat satellite stabilization. (4) Demonstrated operational frequency hopping modem.
Skynet	(1) Provided first operational all digital satellite system using spread spectrum multiple access.
NATO	(1) Employed conventional FM-FDMA technology to minimize system risk.

These programs will continue to advance spacecraft and ground terminal technology, investigate new applications for satellite communications technology, and evaluate the potential for opening new frequency bands for utilization. The Telesat program will provide Canada with a commercial domestic satellite communications system. The ground complex will include small simple terminals for unattended remote operation in far northern and arctic locations, as well as more conventional terminals. The DSCS Phase II will provide the U.S. military with an operational second generation system to replace the IDCSP. The satellites will demonstrate accurately steerable narrow coverage antennas.

The new ATS spacecraft will include a 30-foot diameter parabolic antenna, highly accurate 3-axis stabilization using gas jets and error signals derived from a monopulse receive tracking system, and input/output switching among multiple transponders receiving and transmitting in different frequency bands. The first of these satellites will investigate the feasibility of employing a synchronous communications satellite as a relay for tracking other satellites and transferring digital signals between them and a ground station, of aircraft position location and air-to-ground communications using a synchronous satellite, and of supplying FM TV reception to small UHF ground terminals with the benefit of a 30-foot satellite antenna. Additionally, this spacecraft will investigate uplink RFI at 6 GHz, millimeter wave propagation at 20 and 30 GHz, and signal attenuation at 13 and 18 GHz caused by atmospheric hydrometeors.

The CTS satellite will include a super-efficiency power transmitting tube, providing a 200-watt minimum output at 12 GHz, unfurlable solar power arrays of approximately 1.5-kilowatt initial capability, liquid metal slip rings, and electric propulsion for accurate stationkeeping and stabilization using flexible appendages. High power RF transmitters at frequencies above 10 GHz and prime power sources of kilowatt size or greater represent technology that will be needed for educational and community TV satellite broadcast systems, interplanetary space probes, and large earth-orbiting platforms. The liquid metal slip ring experiment should demonstrate a means of alleviating many of the problems characteristic of transferring high power across rotating interfaces. Electric propulsion provides the potential for reducing one of the constraints on narrowing the spacing between satellites in synchronous orbit. Excessive drift and instability could result in major interference problems and degraded communication capabilities. In addition to the advanced technology experiments, CTS will provide the vehicle for investigating numerous user applications. These may include educational TV, biomedical networks, law enforcement networks, and service for the handicapped applications.

The U.S. Domsat program provides the potential for supplying point-to-point trunk and multipoint message telephony; telegraphic and wideband data; and network, educational, and community antenna television services that complement and improve the services presently provided by terrestrial facilities. Eight applicants filed for permits from the Federal Communications Commission (FCC) to construct U.S. domestic satellite systems by the March 15, 1971 filing deadline. The Commission's invitation to file covered systems "for multiple or specialized common carrier services, for lease to other common carriers, for private use, joint cooperative use, or any combination of such services." The applications filed propose widely varying types and levels of service for a diverse group of potential users. The FCC has a goal of ruling on applications by mid-1972.

A whole new industry was brought into being in the 1960s built on technology demonstrated by experimental satellites such as Relay, Telstar, and Syncom. Similarly, rapid growth of existing capabilities and initiation of new space communications applications, such as high rate information transfer, data collection, educational broadcast, and traffic management, are sure to occur during the 70s, based on the results of experiments described in this document.

SECTION 2 - SCORE

2.1 PROGRAM DESCRIPTION

The objective of Project SCORE (Signal Communication by Orbiting Relay Equipment) was to place in orbit an 80-foot Atlas missile and to use this as a platform for a communication system capable of spanning intercontinental distances. The ultimate goal was to demonstrate the feasibility of such a system and to explore some of the technical and operational problems that would attend a military satellite communication system. The communications portion of the project was assigned to the U.S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, late in July 1958. SCORE was successfully launched by the Air Force on December 18, 1958, thus becoming the first communications satellite. The orbital parameters are given in Table 2-1.

Table 2-1. Participating Spacecraft

	Satellite	SCORE
	Manufacturer/Sponsor	U. S. Army, ARPA
	Launch Date	December 18, 1958
	Launch Vehicle	Atlas 10-B
Orbital Data	Apogee (mi.)	928
	Perigee (mi.)	115
	Inclin. (deg.)	30
	Period (min.)	101
	Status	Expected Life of Orbit: 20 Days; Actual life of orbit: 35 days, Communications failed December 30, 1958, due to battery failure

This first satellite communications system functioned for approximately 12 days, achieving its desired goals - to demonstrate the feasibility of an orbital relay that could span intercontinental distances. Among the achievements attained during the experiment were:

1. The first successful relay of teletype signals through an orbiting station.
2. The first successful delayed repeater communication from earth to satellite to another point on earth at a later time.
3. The first successful multichannel teletype transmission by a delayed repeater.

2.2 SYSTEM DESCRIPTION

Two complete communications packages were installed in what are normally the guidance pods on the sides of the Atlas missile. Ground equipment installed in army vans with associated support vehicles was located at Fort MacArthur, California; Fort Huachuca, Arizona; Fort Sam Houston, Texas; and Fort Stewart, Georgia. All ground stations were linked by both telephone and HF radio to the system control center at the Signal Corps Laboratory in Fort Monmouth, New Jersey.

The design of the system was based on providing two modes of operation – as a delayed repeater and as a real time active repeater. In the delayed repeater mode, the satellite would record information transmitted to it upon reception of a suitable command signal from a ground station. Upon reception of a different command signal, the satellite would transmit the previously stored information back to the originating ground station. The second mode of operation, that of a real time repeater, was obtained by the use of yet another command signal which activated the satellite as a radio relay repeater station with the recording mechanism bypassed. The capacity of the system was one voice channel or seven 60-wpm teletype channels, frequency division multiplexed.

The satellite receiver was an FM "paging" receiver - the type often used by doctors and salesmen to receive telephone calls when away from their offices. A commercial transistor model was modified extensively through the addition of an RF stage using selected transistors to increase its sensitivity. A vacuum tube transmitter from an FM handie-talkie was repackaged and modified through the addition of a high power (8 watts) output stage. A continuous loop magnetic tape recorder developed at the Signal Corps Laboratory was used as the message storing device. Seventy-five feet of magnetic tape was used to provide 4 minutes of audio recording. The control unit responded to command signals from the ground and activated the receiver, the transmitter, or the magnetic tape recorder. Three modes of operation were commanded - record, playback, and real time. Since the satellite was expected to orbit for only 20 days, a non-rechargeable high capacity zinc-silver oxide battery was employed rather than heavier and more costly solar and nickel cadmium cells.

The Atlas missile itself was used as the antenna and was excited by slots located in the two pod covers. The resulting radiation pattern was similar to a long wire doublet with associated nulls.

Spacecraft characteristics for the SCORE satellite are displayed in Table 2-4. A system diagram of the satellite is shown in Figure 2-1.

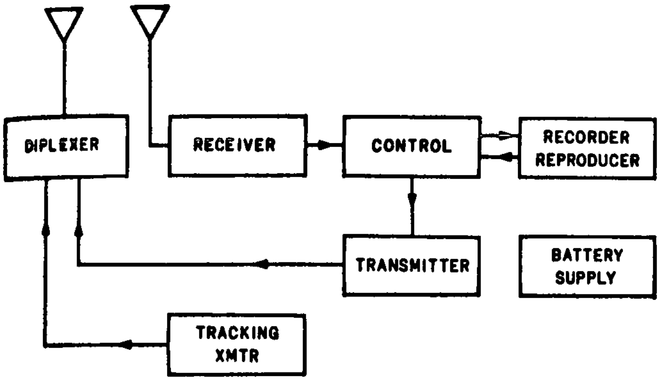


Figure 2-1. SCORE Satellite Interconnection Diagram

VHF frequencies were used to minimize the effects of cosmic noise and ionospheric propagation while still permitting the use of sensitive, transistorized receiving equipment in the satellite. The operating frequencies employed in Project SCORE are given in Table 2-2. The IF bandwidth chosen was as narrow as possible consistent with frequency stability, Doppler shift, maximum audio frequency, and carrier frequency deviation.

Table 2-2. Frequencies Employed in Project SCORE

Uplink	Downlink	Beacon
150 mHz	132 mHz	108 mHz

Narrowband FM was selected as the modulation technique with a deviation ratio limited to 1.0 at 5 kHz. Additional data on the modulation technique is shown in Table 2-3.

Table 2-3. Signal Processing Employed in Project SCORE

Single Access	One Voice Channel or Seven 60-wpm teletype
RF Modulation	Narrowband FM, Deviation = ±5 kHz
Demod. Performance (FM Threshold)	10 dB
Link Margin (Up/Down)	39/19 dB*

*At a slant range of 1000 miles.

2.3 SPACECRAFT

The 142-lb payload consisted of two complete repeater terminals installed in what are normally the guidance pods on the sides of the Atlas missile. Each package contained a receiver, transmitter, magnetic tape recorder, control unit, beacon transmitter, dc to dc converter, and battery. Communications characteristics of the satellite are summarized in Table 2-4.

Table 2-4. Satellite Characteristics

Antennas		Type	Slot Antenna
		Number	Two receiving, two transmitting
		Xmit. Beamwidth	No Data
		Gain	-1 dB
Repeaters		Frequency Band	VHF
		Type	Store-and-forward/real-time repeater
		Bandwidth	40 kHz
		Number	Two
	RCVR	Type Front End	Transistor
		Front End Gain	No Data
		System Noise Fig.	10 dB
	XMTR	Type	Vacuum Tube
		Gain	No Data
		Power Out	8 Watts
General Features		EIRP	8 dBW*
	Stabilization	Type	None
		Capability	None
	Power Source	Primary	Zinc-silver oxide battery
		Supplement	None
		Comm. Power Needs	53 Watts
		Size	Mounted on Atlas Missile of dimensions of 85 ft. long by 10 ft. diameter
		Weight	142 lbs.

*Derived value based on available data.

2.4 GROUND TERMINALS

Each of the communication ground terminals noted in Paragraph 2.2 included two transmitters and receivers for communication, each capable of operating on two frequencies; two beacon receivers for tracking and temperature recording; and two control units. The equipment configuration is shown schematically in Figure 2-2; it was housed in a 35-foot semitrailer.

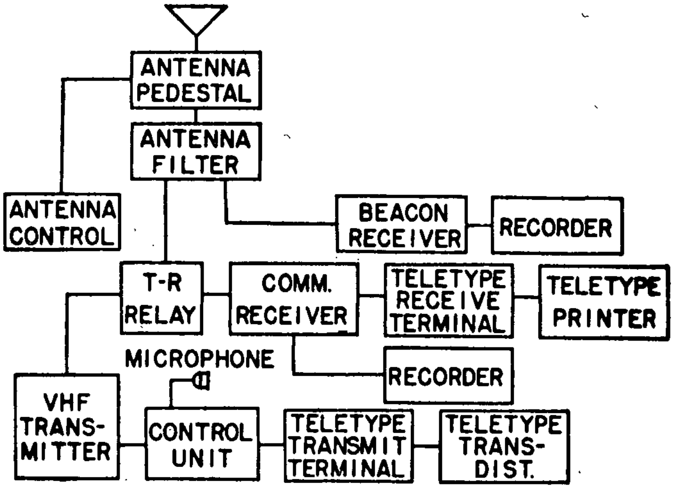


Figure 2-2. SCORE Ground Station Interconnection Diagram

The VHF communications receivers and transmitters in the ground station were commercial FM equipment adapted for use in the SCORE Project. For monitoring the satellite's tracking beacons, receiving equipment was provided which enabled reception of the tracking frequency near 108 MHz. In all but the California station, the ground antenna was positioned by an operator maximizing the 108-MHz signal reception with the antenna positioning controls. At the California station, the azimuth control was slaved to the alidade of an experimental direction-finding equipment while the elevation control was manually varied. The communication characteristics of the ground stations are tabulated in Table 2-5.

2.5 EXPERIMENTS

On the first orbit, attempts were made by the California ground station to interrogate the communication package designated No. 1. An excellent carrier was

Table 2-5. Earth Terminal Characteristics

	Terminal Feature	
Antenna	Type	Quad-helices Array
	Aperture	13-ft-square
	Gain (108/132/ 150 MHz)	9/14/16 dB
	Efficiency	No Data
	Rec. Beamwidth	Approximately 30° @ 3 dB Pts*
Receive System	Type Preamplifier	No Data
	Bandwidth	40 kHz
	Noise Temp	6 dB
Transmit System	Type Amplifier	No Data
	Bandwidth	No Data
	Power Output	250 or 1000 Watts
Tracking	Type	Manual**
	Accuracy	No Data
Total Perfom.	G/T	-17 dB/°K*
	EIRP	75 dBm*
Polar-ization	Transmit Feed	Circular
	Receive Feed	Circular
Installa-tion	Random	None
	Type Facility	Transportable

Notes: *Derived value based on available data.

**Except for azimuth control from experimental direction-finding equipment at California station.

received from the communication transmitter, but no modulation. Since no other orbit that day was close enough to the ground station, no further attempts were made to interrogate the communication equipment. On the following day, package No. 2 was interrogated by a temporary site established at Cape Canaveral (now Cape Kennedy) for prelaunch checkout. It responded and the ground crew received the following prerecorded message from President Eisenhower:

> This is the President of the United States speaking. Through the marvel of scientific advance, my voice is coming to you from a satellite circling in outer space. My message is a simple one. Through this unique means, I convey to you and to all mankind America's wish for peace on earth and good will towards men everywhere.

On each of the subsequent days, each function for which the equipment was designed was tested and successfully demonstrated. Among the experiments performed were the following:

1. Initially, transmission of President Eisenhower's prerecorded voice message followed by one channel of teletype code.
2. Direct relay of California's communication site identification in voice, followed by the President's message in teletype code. The Texas site received these signals with two short fades and the Arizona and Georgia sites received portions of the transmission.
3. While clearing the tape recorder, California transmitted in voice to the satellite for storage. Texas interrogated the satellite, and both Texas and Georgia received the voice loud and clear. Then Georgia reinterrogated the satellite and received the message again.

The above tests were performed in other variations using voice and one channel of teletype until the fortieth pass, when the Georgia site sent seven simultaneous multiplexed teletype messages in a single transmission to the satellite for storage. The satellite was then interrogated and good teletypewriter copy was received.

In summary, the communications package was interrogated 78 times, loaded with new material 28 times, and operated as a real time relay for a total of 117 deliberate operations. Until battery exhaustion on December 30, 1958, the satellite demonstrated conclusively the practical operation of a satellite radio relay system capable of spanning intercontinental distances.

2.6 OPERATIONAL RESULTS

Since Project SCORE was an experimental program, no operational traffic was passed. Further, the operational reliabilities of the satellite and ground terminals were generally good and in agreement with prelaunch expectations. This performance reflected the exclusive usage of state-of-the-art hardware that characterized this system's implementation.

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SECTION 3 - ECHO

3.1 PROGRAM DESCRIPTION

R&D efforts that led to the Echo satellites descended from an IGY program that the National Aeronautics and Space Administration, NASA, had inherited from its predecessor organization, the National Advisory Committee for Aeronautics. The IGY balloon satellite had been conceived and designed primarily for air density experiments. NASA took charge of this activity and reformulated it as Project Echo in late 1958. Major objectives for the Echo program were as indicated in Table 3-1.(1)(2)

Table 3-1. Echo Program Objectives

Number	Description
1	To evaluate the communications capability available from large spherical passive satellite reflectors.
2	To study the feasibility of erecting and maintaining large lightweight structures in the space environment.
3	To gather data on solar pressure and the outer limits of the earth's atmosphere as well as evaluating their effects on satellite orbits.

Of three attempts to orbit passive reflecting balloons during this program, two of these efforts were successful. The launches and satellite status are reviewed in Table 3-2. (1)(3)(4)

Prior to the initial Echo launch, extensive ground, vacuum chamber, and space ballistic tests were conducted.(1)(2)(5) The ground tests employed prototype spheres to confirm sphericity and structural integrity of basic balloon design. The vacuum chamber tests evaluated balloon release from its containing canister, unfolding, and inflation during free fall at NASA's Langley Research Center. The balloon deployment system was refined and space-qualified during four launches into a ballistic trajectory by modified Sargent rockets from NASA's Wallops Island, Virginia, launch site. These launches were code-named Shotput I through IV. The first launch on 28 October 1959 resulted in the sphere rupturing into a thousand pieces. After two more tests on 16 January 1960 and 27 February 1960 and changing the folding pattern, inflation system, and prelaunch payload conditioning cycle, a successful vertical test was conducted on 4 January 1960.

Table 3-2. Participating Satellites

Satellite		Echo A-10	Echo I	Echo II
Manufacturer & Sponsor		G. T. Schieldahl(1) & NASA		
Launch Date		5/13/60	8/12/60	1/25/64
Launch Vehicle		Delta(2)		Thor-Agena B
Orbital Data(3)	Apogee (mi.)	No Orbit Attained	1051	816
	Perigee (mi.)		941	642
	Inclination		47.2°	81.5°
	Period (min.)		118.2	108.8
Status		Satellite lost due to second stage attitude control malfunction	Orbit decayed 5/24/68 resulting in satellite destruction	Orbit decayed 6/7/69 resulting in satellite destruction

Notes: (1) Balloon manufacturer. Beacons on Echo I and II supplied by Radio Corporation of America.

(2) Thor-Delta with the Delta being the improved second and third stages of Vanguard.

(3) At initial injection. Solar pressure and atmospheric drag substantially altered parameters

Subsequent to the failure of the initial launch, a fifth Shotput test was conducted on 31 May 1960 to qualify the sphere with radio tracking beacons attached. These beacons were left off the payload during the initial orbital launch attempt, since they had not been previously qualified by a vertical test. Following these activities, Echo I was successfully launched from Cape Kennedy, Florida, into a near circular low altitude inclined orbit. It was an immediate resounding success, being large and reflective enough to be seen against the nighttime sky with the naked eye. During its lifetime, valuable information was contributed towards meeting all the program objectives listed in Table 3-1. In particular, the feasibility of passive satellite communications was demonstrated.

The one drawback of the Echo I balloon was that it was not rigid enough to remain smooth and spherical under the deforming forces of atmospheric drag and solar pressure after its pressurizing gas leaked out.(1)(2)(6) Its shape deteriorated significantly within a few weeks after launch. In recognition of this, efforts were inititated in late 1960 to develop a second generation Echo balloon that was rigid enough to withstand the deforming forces.

Once again, static ground tests, vacuum chamber drop tests, and vertical space tests were conducted. The first two groups of tests were again conducted in the dirigible hanger at Weeksville, North Carolina, and at Langley Research Center, respectively. The two vertical launch tests occurred 15 January 1962 and 18 July 1962, employing a Thor rocket from Cape Kennedy. TV and movie cameras mounted in the Thor followed and photographed the payload from ejection through reentry. In the first test, the balloon blew up due to excessive inflation pressure. During the second test, a different balloon inflatant resulted in successful balloon deployment, but pressurization was not great enough to provide a good reflecting surface.

As a result of the suborbital tests, it was concluded that a thorough evaluation of inflation characteristics was necessary by means of full-scale balloon statics ground tests. These were conducted in the dirigible hanger at the Naval Air Station, Lakehurst, New Jersey. Following further refinement of the pressurization system during these tests, Echo II was successfully launched from the Western Test Range (i.e., Vandenberg Air Force Base, California) into a near polar low altitude orbit.

Immediately after the first pass, it was determined that internal pressurization reached no more than 1000 psi as compared to the 5000-6000 psi expected, and the balloon was rotating about an inertial axis with a spin period of about 100 seconds.(7) These occurrences produced forces within the satellite shell that caused the surface to wrinkle somewhat. As a result, unexpectedly high scintillations of the reflected RF signals were encountered. In spite of this, the balloon remained an effective passive communications reflector and demonstrated that a lightweight spherical balloon could maintain its shape and surface characteristics, even after the loss of inflatant pressure. Valuable information was contributed towards meeting all the program objectives listed in Table 3-1.

Numerous terminals from various countries conducted communications operations with the Echo satellites in response to an open invitation by NASA for worldwide utilization. Some of the major participating terminals are listed in Table 3-3. (See references 1, 5, and 8 through 12.) Additionally, innumerable terminals distributed over the entire world, at one time or another, conducted radar or optical tracking operations with these satellites. NASA's minitrack network supplied the data from which Goddard Space Flight Center derived orbital tracking information for all interested parties. Satellite launchings were provided by NASA.

The Echo program, which through Echo I provided the first extended satellite communications experiment, made a host of significant contributions to satellite communications technology. First, in reaching its major objective, it demonstrated the feasibility of using passive satellite reflectors for communication purposes and verified the theoretical limitations of such a system. Additionally, it verified the conventional theories for determining path loss on satellite links. Further, it fostered the development of much of the ground terminal technology that continues to be employed. Specific ground terminal items first demonstrated in the Echo project included a large-scale horn reflector antenna at Holmdel, low-noise receiver preamplifiers using solid state masers, frequency modulation feedback receivers, and satellite tracking of sufficient accuracy to allow real-time operational communications. Satellite tracking by radar, telescope, and computer predictions all proved to be quite reliable. Radar tracking operations included successful autotracking.

3.2 SYSTEM DESCRIPTION

The system configuration for the major participants involved in the evaluation of communications via Echo I is depicted in Figure 3-1.(5) Separate transmitting and receiving antennas, each operating at different frequencies, were employed at both Goldstone and Holmdel to provide full duplex operations. A single antenna capable

Table 3-3. Participating Terminals

LOCATION	SPONSOR	ANTENNA DIAMETER (ft)	SATELLITE EMPLOYED
Goldstone, California	Jet Propulsion Laboratory	8.5 (2 dishes)	Echo I
Holmdel, New Jersey	Bell Telephone Laboratories	60 & 20	Echo I
Stump Neck, Maryland	Naval Research Laboratories	60	Echo I & II
Paris, France	Centre Nationale d'Etudes des Telecommunications	30	Echo I
Jodrell Bank, England	University of Manchester	250	Echo I & II
Schenectady, New York	General Electric Laboratories	28	Echo I
Cedar Rapids, Iowa	Collins Radio Corporation	28	Echo I
Dallas, Texas	Collins Radio Corporation	60 & 28	Echo I & II
Columbus, Ohio	Ohio State University	30 (4 dishes)*	Echo II
Gorky, Russia	Zimenki Observatory	49	Echo II
Trinidad	United States Air Force	84	Echo II
Rome, New York	United States Air Force	33	Echo II

*Operated as phased array

of alternate transmit or receive operation at the same frequency was utilized at Stump Neck. The Goldstone terminal employed a third frequency and its separate transmit and receive antennas to provide a radar tracking capability.(13) Ordinarily, both Holmdel and Stump Neck received from Goldstone during the first part of a satellite pass. After the balloon set for Goldstone, Stump Neck then transmitted to Holmdel. On a few passes, both Goldstone and Stump Neck simultaneously transmitted to Holmdel, using circular polarizations of opposite sense and slightly different transmit frequencies. Echo I provided periods of mutual visibility up to about 15 minutes for Holmdel and Goldstone and 25 minutes for Holmdel and Stump Neck.

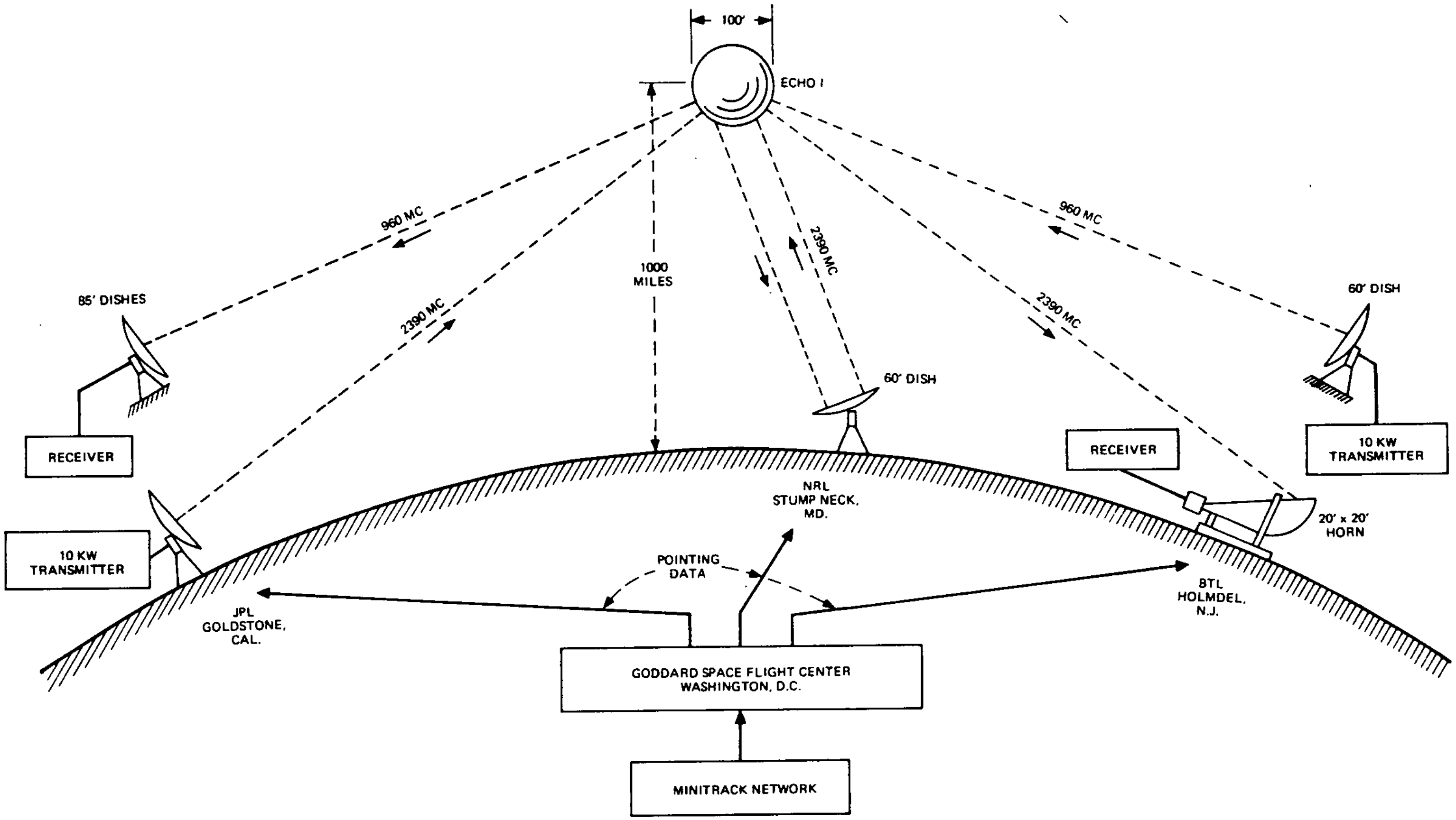

Figure 3-1. General Features of the Echo I Experiment

For the Echo II communication experiments, the system configuration for the principal participants was as illustrated in Figure 3-2.(10) The configuration was such as to provide half duplex communications as the primary mode of operation. Normally, Dallas transmitted while Stump Neck or Columbus or both received. Dallas could transmit on either of two frequencies and Stump Neck could receive either of these frequencies. However, Columbus received on only one of the Dallas transmit frequencies.

The Dallas site included a second transmit antenna used in radar tracking operations to a receiver operating off the communications transmitting antenna. Radar tracking was performed at a separate frequency from the communication frequencies, and Stump Neck included a receive capability at that frequency. Stump Neck also included a communications transmit capability for use in special cases. East Coast to West Coast mutual visibilities were increased over those for Echo I by the higher orbital inclination of Echo II.

Frequencies employed for communications and radar tracking operations with the Echo satellites spanned a wide range extending from VHF to S-band. This was a result of performance as a function of frequency, being, in general, unaffected by these passive reflectors. Strictly speaking, fading, due to scattering from the wrinkled skin of these reflectors, did become more of a problem at the higher frequencies. Operating frequencies for the major participants involved in experiments with Echo I and II are summarized in Tables 3-4 and 3-5, (5)(10) respectively. The two GHz frequencies were chosen because they were available for allocation by the Federal Communications Commission and because they were the correct frequencies for future satellite and deep space communications activities. The 960-MHz frequency was chosen because equipment on this frequency existed at Goldstone from an earlier program.

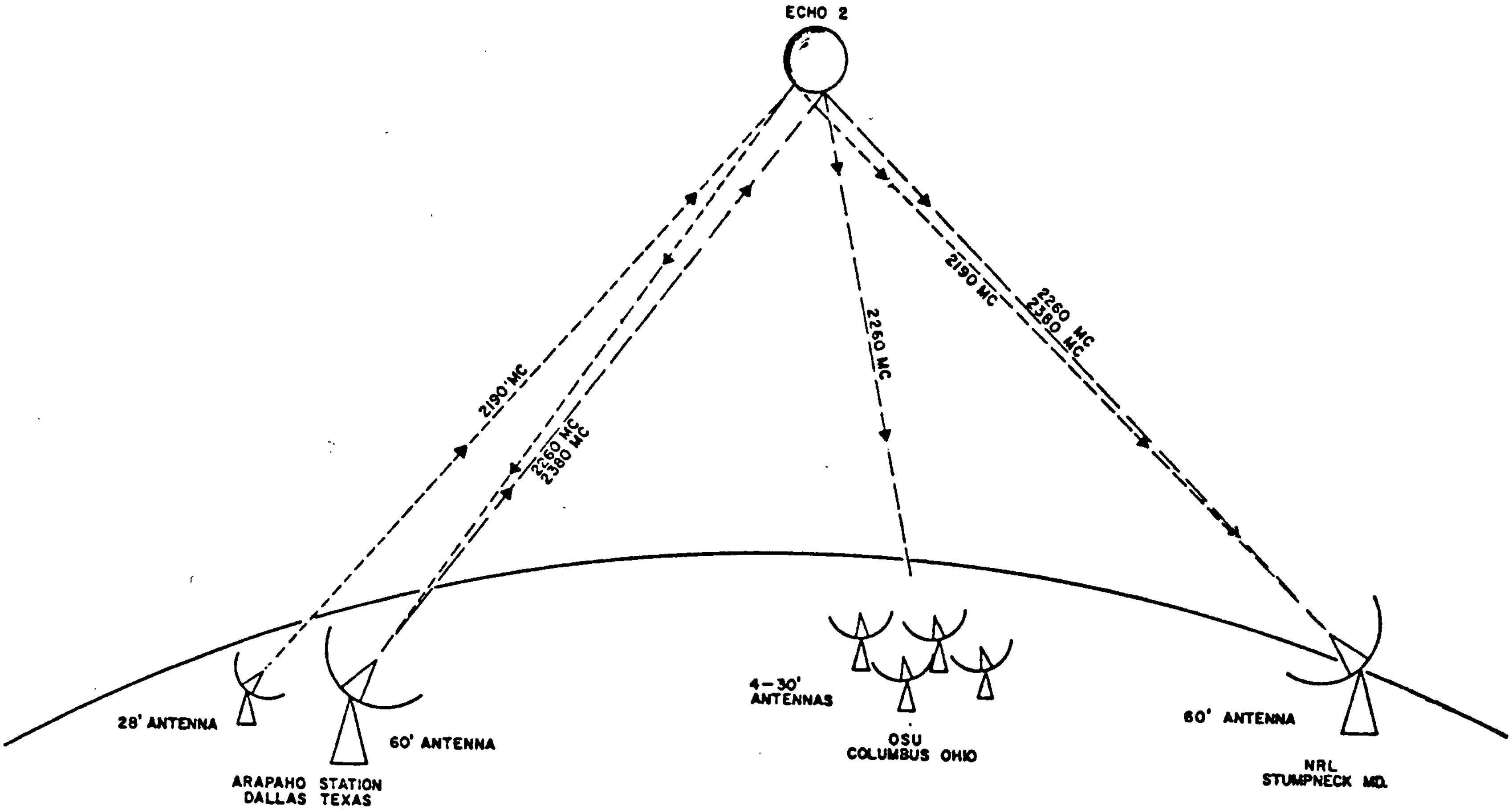

Figure 3-2. Circuit Configuration, Echo II Communications Experiments

Table 3-4. Echo I Operating Frequencies

Goldstone to Holmdel or Stump Neck	Goldstone to Goldstone	Holmdel to Goldstone	Stump Neck to Holmdel
2390 MHz	2388 MHz	960 MHz	2390 MHz

Table 3-5. Echo II Operating Frequencies

Dallas to Stump Neck	Dallas to Columbus	Dallas to Dallas
2260 MHz or 2380 MHz	2260 MHz	2190 Mhz

The basic signal processing techniques employed for the Echo I tests are summarized in Table 3-6.(5)(14)(15) There were no multiple-access restrictions except the normal requirements for signal orthogonality, since the satellite was simply a passive reflector. Therefore, any of the commonly conceived multiple-access techniques (e.g., time, frequency, and code-division multiple access) could have been employed. Frequency division was used because of its ready compatibility with common existing earth terminal technology. For a perfectly spherical reflector with a smooth skin, there are likewise no satellite-imposed restrictions on the RF modulation technique employed. However, for a deformed reflector with a wrinkled skin, both fading and limitations on the coherent bandwidth are imposed. Frequency modulation (FM) is normally effective in the face of fading as long as the coherent bandwidth of the channel isn't exceeded. Large margins are required for an operational system of this sort.

Margins, for a perfectly reflecting sphere, must account for variations in range, atmospheric and ionospheric attenuation and noise, antenna tracking and polarization losses, and ground terminal performance. For an imperfect sphere such as Echo I, margins must be further increased to account for signal fading due to scattering off the balloon surface and changes in the instantaneous reflective cross sectional area.

Signal processing techniques were basically the same for Echo II as for Echo I. Performance was improved somewhat primarily due to an average reflective cross sectional area that was 3 dB larger, slightly shorter ranges to the satellite, and the fact that the balloon shape did not deteriorate as a function of time. Additionally, both frequency and space diversity were tried as means of combating coherent fading.

Table 3-6. Signal Processing for Echo I

Multiple Access	FDMA for an Unlimited Number of Users
RF Modulation	FM,(1) single sideband, narrow-band phase modulation, and conventional amplitude modification.
Ground Demodulator Performance	FMFB receivers employed giving threshold at about 13 dB C/N in 6-kHz bandwidths.(2)
Holmdel Receive Carrier-to-Noise	34.2 dB for Goldstone transmit, satellite midway between terminals, and 6-kHz noise bandwidth.
Holmdel Receive Margin	About 21 dB.(3)

Notes: (1) Frequency modulation was normally used.

(2) In normal 60-MHz RF bandwidth, threshold occurs at 3-dB C/N.

(3) High margin allows successful operation in spite of significant signal fluctuations. Also allows good quality communications employing modulation techniques with considerably less processing gain than FM.

3.3 SPACECRAFT

Echo I was a hollow sphere constructed from gores of 0.0005-inch thick Mylar with the external surfaces coated with vapor-deposited aluminum to provide efficient radio-wave reflectivity.(1) In this design, long cigar-shaped pieces are cut out of sheet material and joined together with "butt" seams. Where the "gores" come together at the two poles of the structure, a reinforcing "pole cap" was used. The sphere was designed to have a 100-foot diameter when inflated and weighed approximately 135 pounds.(3)

Before launch, the satellite was evacuated and accordion-pleat folded for packing in the spherical launch container. The launch container, measuring 26 inches in diameter, was also evacuated to a rather low vacuum prior to launch.

When the container was placed in orbit, it was explosively separated at its equator and the satellite was initially inflated by the small amount of residual air entrapped within its interior.(16) Inflation was completed and the shape of the inflated satellite was temporarily maintained by the small gas pressure created by sublimating solids (i.e., 20 pounds of anthraquinone and 10 pounds of benzoic acid) contained within the satellite.(2) These inflatants could produce a skin stress of about 150 psi in Echo I and the pressurized life of the satellite was approximately 14 days.

Initial tracking of the satellite was greatly aided by two radio beacon transmitters attached to the sphere's external surface. Each of the two assemblies, located diametrically opposite on the equator of the satellite, include one transmitter, its associated antenna, a group of solar cells and one-half of the satellite's storage-batteries.(16) Each of the continuous wave transmitters was designed to provide about 10.5 milliwatts of power at a frequency of 107.94 MHz. Crystals were chosen to provide a frequency separation of 500 to 1000 Hz between the two transmitted signals. The quarter-wave monopole antenna for each beacon transmitter was erected normal to the satellite surface. The radiation pattern provided was somewhat similar to that of a monopole antenna above an infinite plane.

In Echo II, the basic type of gore construction developed in Echo I was retained.(1) It was made up of 106 gores with each gore measuring 4 x 215 feet.(2) The gores were butt-jointed together, using 1-inch wide tapes made of the same material as the gores. The gores terminated at the polar areas of the sphere where 54-inch diameter pole caps were attached, using a 1-inch overlapping joint. The material used was a 3-layer sandwich of .00020-inch sheets of aluminum on each side of a .00036-inch mylar polyester film. The total skin thickness was .00075 inch, which was only 50 percent greater than that of Echo I but it produced a rigidity about 100 times greater. This construction resulted in an inflated sphere measuring 135 feet in diameter and weighing 550 pounds.

The structure was folded and packed inside a launch canister having an elliptical vertical cross section and a circular horizontal cross section as mounted for launching.(6) The canister had a 30-inch vertical diameter and a 44-inch horizontal diameter. The container, as well as the satellite, was evacuated to prevent excessively rapid inflation by expansion of residual air inside. The canister was separated in orbit in the same manner as for Echo I and residual air again provided the initial inflation. However, continued inflation and full pressurization were accomplished in a much more controlled manner. In this system, the inflatant, now pyrozole, was sealed in numerous small packets that were attached to the inside surface of the satellite.(1) The packets were sealed with an adhesive wax that melted just below the equilibrium temperature of the sphere in orbit. The bags, therefore, were not opened to start sublimation and the buildup to higher pressurization until the sun's energy elevated the temperature of the satellite. This occurred long after initial inflation and the danger of rupture due to dynamic loads had passed.

Initial pressurization was designed to be higher than for Echo I. The theory behind the use of the three-layer laminated material and this higher pressurization was that the different moduli of elasticity of mylar and aluminum would result in the aluminum stretching in a nonelastic fashion while the mylar sheet was still within its elastic limit.(1) Thus, after the pressurization escaped, the mylar would tend to return to its original dimensions, placing the aluminum cemented to it under a compressive load. This results in a material that behaves like a prestressed beam and is quite rigid.

Echo II also supported two radio telemetry beacons mounted diametrically opposite one another at the sphere's equator. These beacons served as a tracking aid as well as a means of telemetering data on satellite temperature and pressure. The pressure monitoring capability extended from a minimum of 10^{-5} mm to a maximum of 0.5 mm of mercury.(17) The temperature measurements extended from minus 120° to plus 160° C. The beacon system included two battery packs, four solar cell panels, and interconnecting cables to give a total weight of approximately 6 pounds. The carrier frequencies were at 136.020 and 136.170 MHz, and each carrier was amplitude-modulated with three sinusoidal subcarriers bearing the telemetry information. The antenna, supplied with each transmitter, was a quarter-wave monopole made of spring wire. Upon satellite inflation, the antenna erected to a position normal to the surface of the satellite. The effective radiated power of each transmitter was greater than 34 milliwatts under continuous operation. The beacons were designed to operate for 1 year, at which time a mercury cell cutoff circuit terminated radiations.

3.4 GROUND TERMINALS

Characteristics of three of the terminals listed in Table 3-3 as participants in Project Echo are provided in Table 3-7.(5)(10)(18)(19)(20) Holmdel and Goldstone were the two major experimenters involved in Echo I testing, while the Stump Neck terminal participated in Echo I tests and was a principal evaluator of communications via Echo II. Major subsystems of the Holmdel and Stump Neck terminals are depicted in Figures 3-3(5) and 3-4(10), respectively.

The configuration of each of these three terminals reflects the considerable concern that existed over the feasibility of accurately acquiring and tracking the passive Echo spacecraft. None of the terminals relied on the satellite beacon for tracking. Beacon tracking was performed by the NASA Minitrack network, and the data contributed towards the generation of program track information by Goddard Space Flight Center. Radar techniques were employed by the communications terminals to give an active tracking capability. However, optical tracking was the preferred method of tracking when the satellite was visible (i.e., at night).

Circular polarization was employed to eliminate the need for polarization tracking. The direction of rotation (i.e., left- or right-hand circular) was selected at each transmit and corresponding receive antenna to account for the direction reversal that occurs upon reflection from the spacecraft.

Table 3-7. Characteristics of Major Project Echo Ground Terminals

TERMINAL FEATURE			Terminal		
			Holmdel	Goldstone	Stump Neck
Antenna	Type		Parabolic Transmit & Horn Receive	Separate Parabolic Transmit & Receive	Single Parabolic Reflector
	Aperture Size		60 ft. Diameter Xmit & 20x20 ft. Receive	85 ft. Diameter Xmit & 85 ft. Diameter Rec.	60 ft. Diameter
	Gain	Receive	43.3 dB @ 2390 MHz	45.5 dB @ 960 MHz	49.7 @ 2380 MHz
		Transmit	43.1 dB @ 960 MHz	52.5 dB @ 2390 MHz	----(4)
	Efficiency	Receive	72%(1)	52%(1)	44%(1)
		Transmit	60%(1)	42%(1)	------(4)
	Beamwidth	Receive	1.2° @ 3 dB Pts.	0.9° @ 3 dB Pts.	0.5 @ 3 dB Pts.
		Transmit	1.2° @ 3 dB Pts.	0.33° @ 3 dB Pts.	-------(4)
Receive System	Type Preamplifier		Maser	Uncooler Parametric Amplifier	Traveling Wave Amplifier
	Bandwidth		7 MHz(2)	5 MHz(2)	200 MHz RF(3)
	Noise Temperature		45° K @ 7.5° El.	300° K	550° K
Transmit System	Type Amplifier		Klystron	Klystron	Klystron(4)
	Bandwidth		1.5 MHz	No Data	No Data
	Amp. Power Out		10 KW	10 KW	10 KW
Tracking	Type		Program track, optical track, manually controlled radar track	Program track, optical track, or monopulse radar autotrack	Program track or optical track
	Accuracy		Program track ±0.2° Optical track ±0.05° Radar track ±0.1°	Program track ±0.15° Optical track ±0.1° Radar track ±0.03° for receive & ±0.1° xmit.	Program track ±0.4° Optical ±0.3°
Total Performance	G/T		26.5 dB/°K(1)	20.5 dB/K°	22 dB/°K
	EIRP		112.5 dBM(1)	122.5 dBM	---(4)
Polarization	Transmit Feed		Left Hand Circular	Right Hand Circular	---(4)
	Receive Feed		Left Hand Circular	Right Hand Circular	Circular
Installation	Radome		None	None	None
	Type Facility		Fixed	Fixed	Fixed

Notes: (1) Derived value based on data available

(2) Front end bandwidth. Predetection demodulator bandwidth was 6 kHz

(3) Predetection demodulator bandwidth was 50 kHz

(4) Terminal did not normally transmit

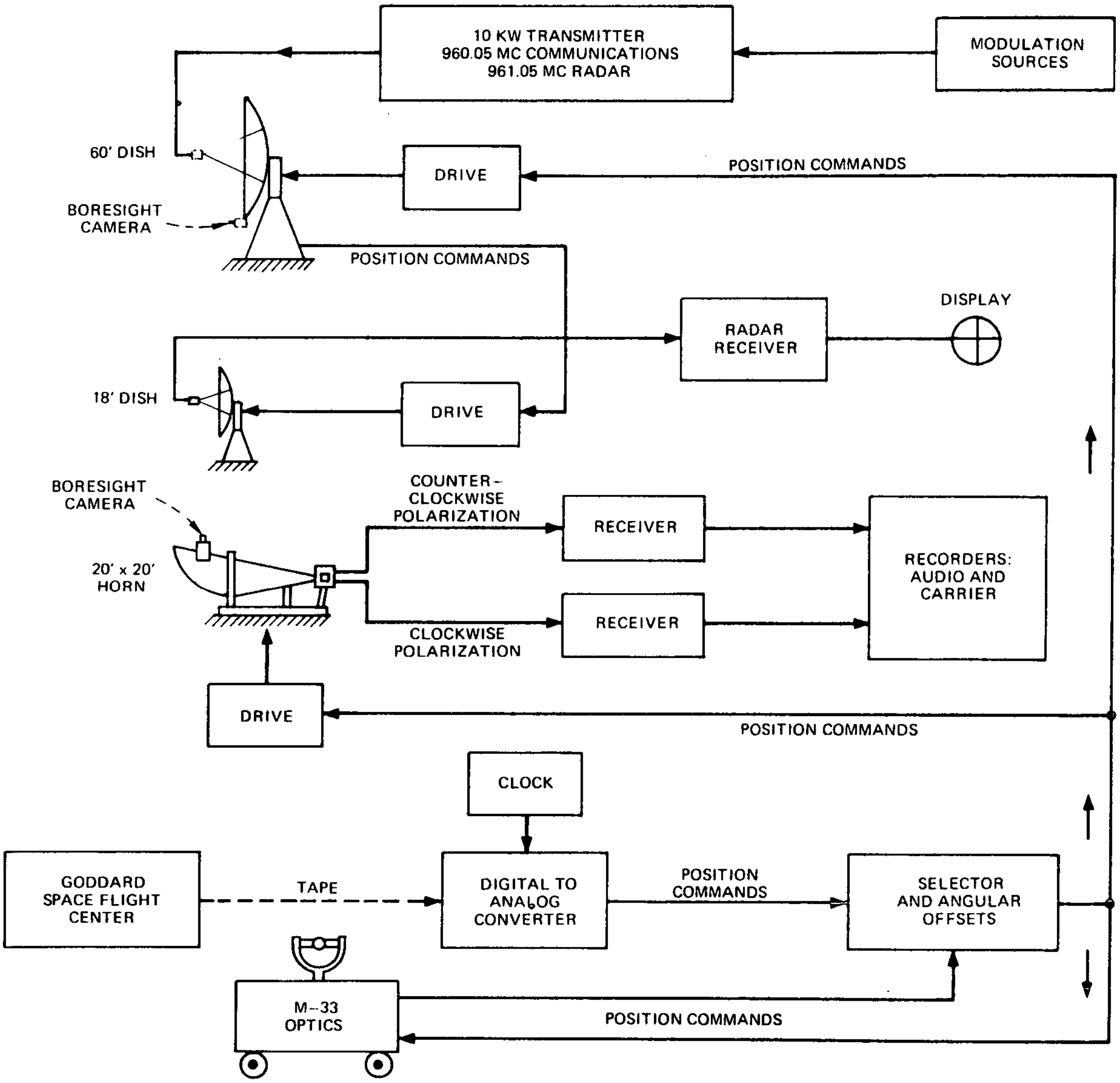

Figure 3-3. Block Diagram of the Holmdel Facilities

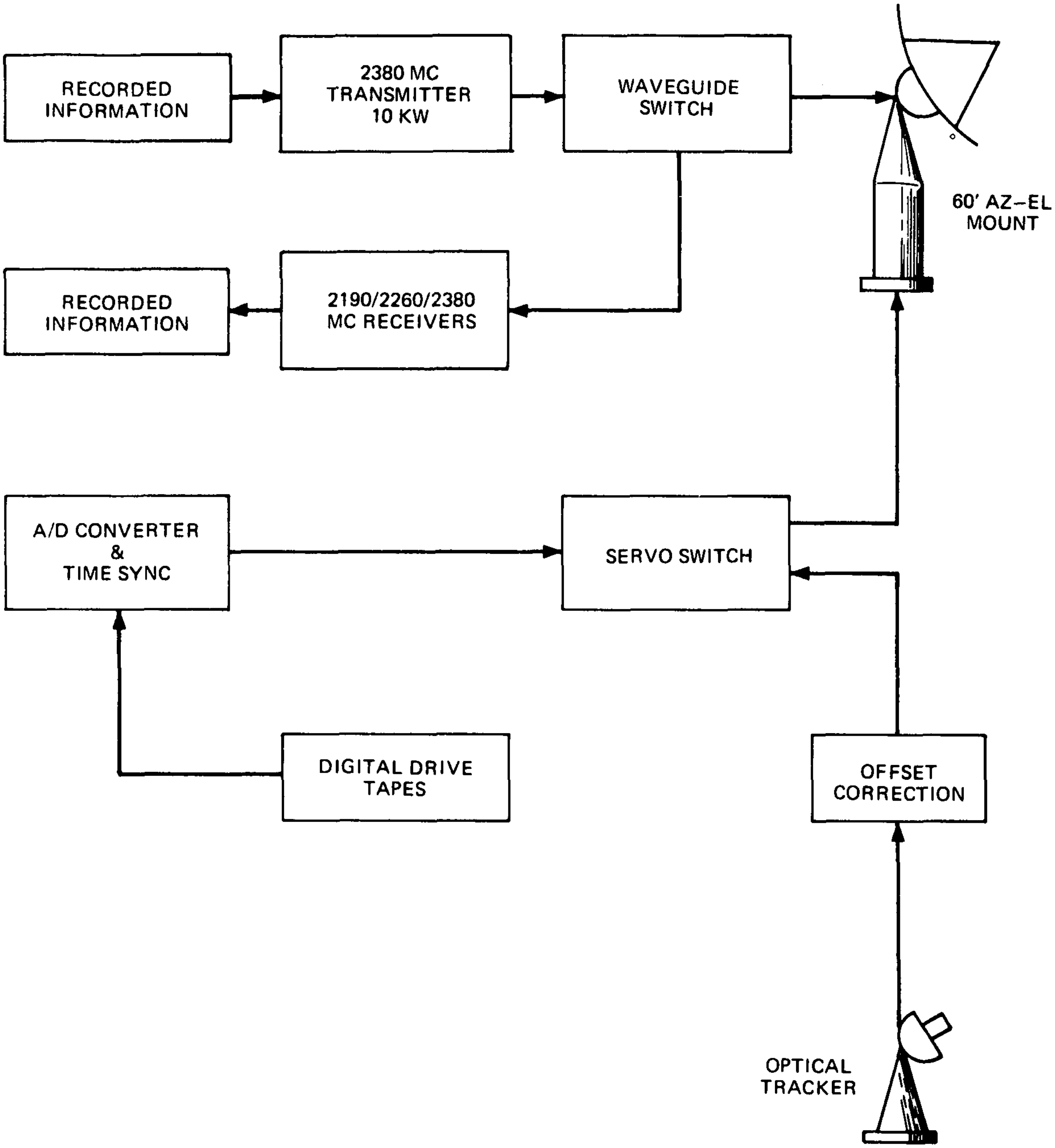

Figure 3-4. NRL Space Communications Facility, Stump Neck, Maryland

3.5 EXPERIMENTS

The premier objective of the Echo program was to evaluate the feasibility of employing satellite reflectors for global communications, and most of the planned experiments were directed towards that end. The second objective listed in Table 3-1 was accomplished through preflight statics tests, ballistic space tests, the TV system on the booster that monitored the deployment of Echo II, optical observations of both spheres over a period of time, and monitoring of reflected received signal levels over a period of time. Received signal level data was obtained in the planned communications tests as well as in independent radar tracking operations. References 21 through 24 provide examples of the type of information analyses completed to verify that large lightweight structures of the Echo type can be successfully deployed and maintained in orbit.

Accurate tracking of the Echo balloons was maintained throughout their lifetime. This gave the basis for accomplishing the third objective in Table 3-1, as well as allowing the balloons to serve as accurate position location measurement references for remote geographic points. References 25 through 28 are examples of the types of analyses and conclusions that have been made possible by the extensive data on the Echo orbits.

The major communications tests performed on Project Echo and a summary of their results are given in Table 3-8.(5)(8)(10)(22)(29)(30) Items 1 through 4 in the table were tests or analyses employed extensively on both Echo I and II, while the remaining listed tests were conducted mainly with Echo II alone. Results of the first three items, as well as optical data, indicated that Echo I was relatively smooth and spherical during its pressurized lifetime but developed wrinkles and flat areas during the first month in orbit, which tended to become more extensive and severe as time passed. Similar data indicated that Echo II developed a wrinkled skin very quickly after deployment and maintained its shape as a function of time.

Table 3-8. Communications Experiments

TYPE EXPERIMENT	NATURE OF RESULTS OBTAINED
1. Received Signal Level	Levels, in general, agreed with expectations verifying effective balloon cross sectional areas and path loss.
2. Average Scattering Cross Section(1)	Indications were that Echo I was within 1 dB of theoretical(2) during pressurized life of satellite,(3) dropped to about 3 dB down within first month in orbit and gradually decayed to 6 dB down over 3 years. Echo II was 1 dB down from theoretical(2) shortly after launch and held constant as a function of time.
3. Fading Characteristics(1)	On Echo I, 10 to 90 percent fade range(4) was 2 to 4 dB during first month in orbit and gradually increased to 6 dB to 8 dB over 3 years. Echo II range was 11 to 13 dB and held constant as a function of time. On both Echo I after 3 years and Echo II, a Rayleigh probability density function and an amplitude spectrum indicating nearly all power fluctuations occurred at frequencies below 3 or 4 Hz were observed.
4. Voice Transmission	Received quality judged excellent on both Echo I and II for voice. Music also excellent on Echo II. Echo I employed 200-Hz to 3-kHz baseband and frequency deviation of ±30 MHz. Echo II employed 30-Hz to 15-kHz baseband and frequency deviation of ±15 MHz. Capability of reasonable quality on up to 4 voice channels also demonstrated on Echo II.
5. Facsimile Transmission	Standard military machine that normally used 3-kHz voice channel was prerecorded and played back at 4 times normal speed to give 12-kHz baseband. 1000-Hz tone was simultaneously prerecorded for speed control and doppler correction. Using ±15-kHz frequency deviation, good quality with some streaking and distortion due to signal fluctuating below threshold observed.
6. Coherent Bandwidth	Appeared to be greater than 12 MHz but less than 70 MHz. Indications were that frequency diversity became effective at about 190-MHz frequency spacing. Both amplitude and phase correlation analyses applied to tones at separate frequencies to make these determinations.
7. Space Diversity	Little diversity improvement observed for antenna spacings of 2378 feet.
8. Digital Data Transmission	Alternate ones and zeros transmitted by FM or carrier and conventional detection. Decisions on received signal employed a matched filter (i.e., integrate and dump). Error rates for transmission at 1.2 kbps rate typically ranged between 10^{-2} and 10^{-3} bits/bit.

Notes: (1) Determined from analysis of received communications signals and radar returns.

(2) For Echo I, 729.64 square meter or 28.63 dB relative 1 square meter. For Echo II, 1329.81 square meter or 31.23 dB.

(3) One to two weeks.

(4) Difference between value exceeded 10 percent of time and value exceeded 90 percent of time.

In addition to the experiments listed in the table, several tests of perhaps somewhat lesser importance were conducted employing primarily Echo 1. Voice transmission evaluations were extended by utilizing single-sideband, narrow-band phase, and amplitude-modulation techniques for comparison with frequency modulation.(5) The performance did not equal that with FM, indicating that the coherent bandwidth of the channel had not been exceeded in the tests; therefore, conventional theories for comparing modulation techniques applied. Measured doppler shift was compared with theory and found to be in good agreement. Performance of FM with feedback receivers was evaluated and found to agree well with previous laboratory measurements and theory. Performance of the ground terminal tracking systems was closely watched. All performed well, and the potential of automatic tracking was demonstrated. In addition, a television signal was transmitted and limited quality reception obtained, using facilities developed for Project West Ford.(31)

Numerous notable demonstrations were also conducted.(5)(30) Most of these occurred during the early days of Echo I and tended to dramatize the potential of this type of communications. Included were a tape-recorded voice message by President Eisenhower during the first satellite pass on August 12, 1960; prerecorded 2-way messages by President Eisenhower and Senator L. B. Johnson on August 13, 1960; and the first 2-way live voice transfer between Mr. W. C. Jakes of Bell Telephone Laboratories and Mr. P. Tardani of Jet Propulsion Labs also on August 13, 1960.

Finally, Echo II provided a first in international communications, when Russia agreed to participate in a cooperative experiment with NASA and to supply NASA with tracking data during the early orbits after launch.(11)(32)(33) The tests were conducted in accordance with the Bilateral Space Agreement between the USSR (Academy of Sciences) and the USA (NASA) reached at Geneva on June 8, 1962. The tracking data consisted of photographs and optical observations that helped to determine that the balloon had been successfully deployed and to establish initial orbital parameters.

The communications experiments were performed between the Jodrell Bank Radio Observatory of the University of Manchester, England, operating on NASA's behalf and the Zimenki Observatory of the Gorki State University northeast of Moscow. The Jodrell Bank facility provided a 250-foot diameter steerable antenna and a 1-kW transmitter to radiate signals at a frequency of 164.2 MHz. The Zimenki facility received both this signal and the 136-MHz satellite beacon, using a 49-foot diameter antenna. Transmissions included unmodulated carrier, 400-Hz tone modulation, Morse telegraphy, teletype, telephone and facsimile.

Theoretical link calculations showed that performance could only be marginal, but the results obtained were even poorer than expected. This was attributed to inaccurate pointing of the antenna at the transmitting site, refractive and reflective effects on the signal at the low elevation angles and wide beamwidths used, and polarization mismatches between the transmitting and receiving antennas. In spite of this, 34 experiments were conducted between 21 February and 8 March 1964, and the international cooperation displayed made the entire operation a significant diplomatic success.

3.6 OPERATIONAL RESULTS

Project Echo was an experimental program; therefore no operational traffic was carried. Operation of the experimental ground stations was entirely satisfactory as expected. The only difficulty of any significance was caused by occasional errors in the prepass tracking predictions. These errors were of sufficient magnitude to make ground terminal program tracking unsatisfactory. They were a result of the manner in which the orbits of the large lightweight Echo structures were being perturbed from pass-to-pass by solar pressure and atmospheric drag. The tracking difficulties encountered could have been overcome by obtaining more extensive tracking data and updating computed orbital elements more often.

No unexpected operational difficulties of importance were encountered with the Echo I balloon. At the end of a week of operation, a malfunction occurred in the beacon battery supply such that the beacons transmitted only when a solar cell pack was illuminated by the sun. However, the beacons were not designed for a long lifetime, since their primary mission was to assist the tracking operations during the early orbits of the satellite so that accurate initial orbital elements could be generated. This mission was fulfilled.

The only anomalous operation that developed during operations with Echo II was scintillation of the reflected received signal due to wrinkling of the satellite skin. This was caused by the unexpected satellite spin that developed during the first orbit after launch and lower than expected initial inflation pressure. The exact cause of these unusual occurrences was not determined. The beacons on this spacecraft operated for 1 year as planned.

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SECTION 4 - COURIER

4.1 PROGRAM DESCRIPTION

In September 1958, the U. S. Army Signal Research and Development Laboratory (USASRL) submitted a technical proposal for a delayed repeater satellite communication system to the Advanced Research and Development Agency of the Defense Department. In October 1958, USASRL received approval to proceed with Project Courier. The program was undertaken to demonstrate the feasibility and operational capabilities of a store-and-forward (information storage for future retrieval) satellite communications system with potential military application. (1)

Two active delayed repeater satellites, Courier Ia and Ib, were launched before this program was completed, as indicated in Table 4-1. (2) After Courier Ia failed to reach orbit due to a missile malfunction, Courier Ib was successfully injected into a low altitude eliptical orbit. Testing during the 17-day operational lifetime of Courier Ib fulfilled the program objectives. The operational usefulness of Courier Ib came to an end when it ceased to respond to attempts at "turn on."

Table 4-1. Participating Spacecraft

Satellite		Courier Ia	Courier Ib
Manufacturer & Sponsor		Philco Corp. & U.S. Army Signal Corp	
Launch Date		8/18/60	10/4/60
Launch Vehicle		Thor-Able-Star	
Orbital Data	Apogee(Mi.)	No Orbit Attained	755
	Perigee (Mi.)		600
	Inclination		28.3°
	Period (Min.)		107
Status		Spacecraft lost due to missile failure	Satellite ceased to respond to "turn on" commands on 10/21/60 leaving VHF beacon as only radiation

The two earth terminals employed in Project Courier are listed in Table 4-2. (3) Satellite launchings were supplied by the U.S. Air Force.

Table 4-2. Participating Earth Terminals

Location	Sponsor	Antenna Diameter (Ft.)	Date Installed
Fort Monmouth, New Jersey	USASRDL	28	1960
Camp Salinas, Puerto Rico	USASRDL	28	1960

The major contribution of Project Courier to satellite communications technology was to demonstrate the technical feasibility of a delayed repeater high capacity digital satellite communications system. However, the satellite's early failure clearly demonstrated the need for additional care and effort in designing and testing components and systems intended for operational satellite applications.

4.2 SYSTEM DESCRIPTION

Tests were conducted with Courier Ib on a loop-back or push-to-talk basis by the two terminals indicated in Table 4-2. Both real time and store-and-forward operation was possible. During store-and-forward operation, an earth terminal could load traffic into the spacecraft's tape recorders at the same time it received previously stored messages from the satellite.

The altitude and inclination of the satellite orbit made an average of five workable orbits at the Fort Monmouth station and an average of seven at the Puerto Rico station possible out of approximately 14 orbits per day. (3) The satellite was in view of the ground station during each orbit for a maximum of 19 minutes at Fort Monmouth and 22 minutes at Puerto Rico. (2) Mutual visibilities as long as 15 minutes were available.

Operating frequencies for the Courier satellites were as indicated in Table 4-3.(2) The UHF communications frequencies were chosen for the wide bandwidth and simplicity of equipment design provided in addition to the noise and propagation advantages at these frequencies.(4)

Table 4-3. Courier Frequencies (MHz)

Communications		TT&C	
Uplink	Downlink	Command	Telemetry
1750	1800 to 1900*	135	108**

* Two transmitters, modulated with same information and operating about 20 MHz apart, utilized for frequency diversity.

** Separate acquisition beacon, disabled upon satellite "turn on," operated at same frequency.

The basic signal processing techniques utilized on Project Courier were as indicated in Table 4-4.(2) (5) The modulated uplink signal was detected in the satellite. The detected baseband was recorded in the satellite or retransmitted in real time. During transmission over the downlink, the detected signal modulated the satellite transmitter's radiated carrier. The uplink performance was, in general, superior to the downlink performance indicated in the table. Margins had to be adequate to account for variations in range, rain losses, satellite antenna gain as the aspect angle to the ground terminal changed, and other link parameters that varied to a smaller extent.

Table 4-4. Signal Processing Employed

Multiple Access	None
RF Modulation	FM*
Ground Demodulator Performance	Estimated** threshold at about 10 dB C/N
Ground Terminal Receive Carrier-to-Noise	16 dB for maximum range*** and 100 kHz noise bandwidth
Ground Receive Margin	6 dB at maximum range

* Employed on both the up and down link
** Estimate based on fact that conventional discriminators were employed
*** 3300 statute miles

4.3 SPACECRAFT

Spacecraft characteristics for the Courier satellites are displayed in Table 4-5.(2) (3) (6) A block diagram depicting the basic electrical configuration of the satellite is shown in Figure 4-1.(3) The considerable redundancy incorporated reflected the concern over spacecraft reliability that existed at that time. The design expectation was for a 1 year in orbit lifetime. A special acquisition transmitter, separate from the telemetry transmitter, was supplied. While in the acquistion mode, the two VHF receivers were alternately activated to "listen" for ground terminal signals, on a part-time basis. The cycling of the receivers was such that an active receiver was listening only about 10 percent of the time.

Table 4-5. Satellite Characteristics

Antennas		Type	UHF - Pair of slotted fin antennas located 180° apart on satellite equatorial band. *	VHF - 4 whip turnstile for TT&C
		Number	One	One
		Beamwidth	Essentially Omnidirectional	Essentially Omnidirectional
		Gain	0 dB	0 dB
Repeaters		Frequency Band	UHF	
		Type	Demodulating/remodulating with capability for real time or delayed operation. **	
		3 dB BW	550 kHz	
		Number	One with considerable built in redundancy	
	Receiver	Type Front End	Four receivers, each with a down conversion mixer first stage. Discriminator outputs of receivers combined in baseband combiner.	
		Front End Gain	100 dB IF following down conversion mixer in each receiver.	
		Sys. Noise Fig.	14 dB	
	Xmitter	Type	2 planar triodes, each modulated with the detected uplink signal and operating 20 MHz apart to supply frequency diversity. Redundant pair of transmitters available at ground command.	
		Gain	No data available	
		Power Out	33 dBm	
		EIRP-UHF Ant.	29 dBm***	
General Features	Stabilization	Type	Spin with no active correction capability	
		Capability	Unoriented relative to earth. Initially approximately 90° spin axis aspect to sun.	
	Power Source	Primary	Solar array with 65 watts average output. ****	
		Supplement	2 nickel cadmium batteries - about 12 amp. hr. capacity per battery****	
		Comm. Power Needs	Approximately 200 watts	
		Size	Spherical with 52 in. diameter	
		Weight	500 lbs.	

* Two receivers and a redundant transmitter connected to each slotted fin. Transmitters on one fin operate at different frequency from those on other. All receivers at same frequency.

** 1 analog and 4 digital tape recorders allow delayed operation.

*** Transmitter to antenna losses are 4 dB including a diplexer and hybrid.

**** At launch.

When one of the receivers detected a ground terminal signal, it came on in full-time operation and the remaining satellite systems could be activated on command.

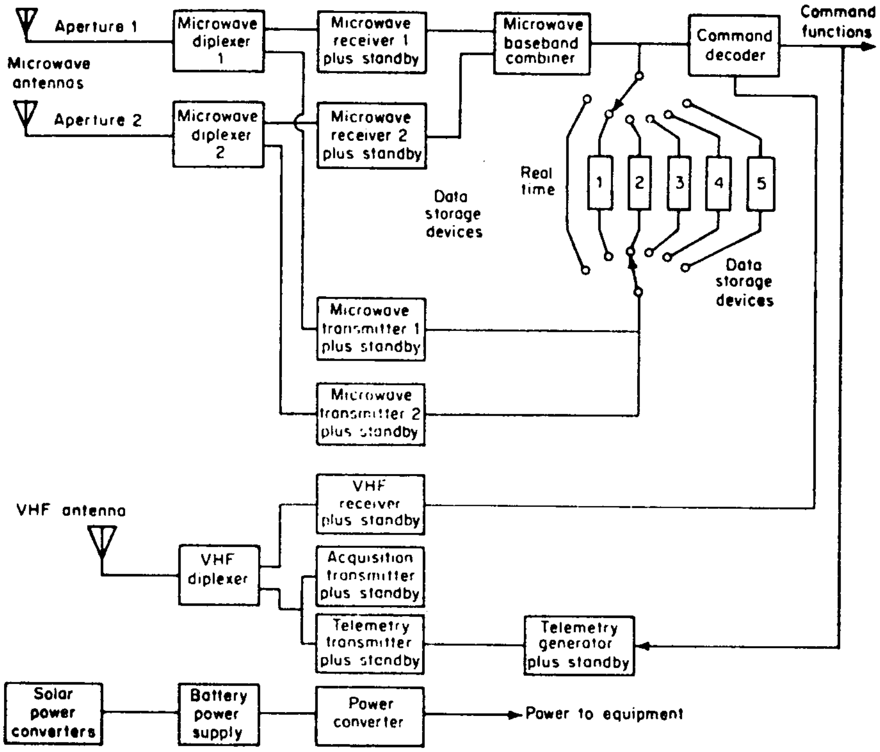

Figure 4-1. Satellite Electrical Subsystems

4.4 GROUND TERMINALS

The ground terminals employed at Fort Monmouth and Camp Salinas were essentially identical. Major characteristics of these terminals are displayed in Table 4-6.(1) (2) (3) Major subsystems are illustrated in the block diagram of Figure 4-2.(3)

Table 4-6. Characteristics of Earth Terminals

Antenna	Type	Parabolic Reflector
	Aperture Size	28 Ft. Diameter
	Receive Gain	41 dB
	Efficiency	50%*
	Rec. Beamwidth	1.35 at 3 dB pts.
Receive Sys.	Type Preamplifier	Four receivers each with uncooled parametric amplifier front end. Two receivers operate in linear polarization diversity at each satellite transmit frequency.**
	Bandwidth	500 kHz***
	Noise Temp.	640°K
Transmi System	Type Amplifier	Klystron
	Bandwidth	4 MHz****
	Amp. Pwr. Out	1 kW
Tracking	Type	Conical Scan Auto track
	Accuracy	0.5° at maximum slewing rate of 15°/second
Total Perf.	G/T	13 dB/°K*
	EIRP	99 dBm*
Polarization	Transmit Feed	Circular
	Receive Feed	Linear Diversity Reception[†]
Installation	Radome	None
	Type Facility	Fixed because of antenna installation[† †]

* Derived value based on data available.

** Receivers operating on same frequency combined at RF. Composite signals at separate receive frequencies combined at baseband.

*** 100 and 200-kHz bandwidths also selectable.

**** RF bandwidth. Effective bandwidth of signal from modulator was a maximum of about 200 kHz.

† Crossed dipoles at 45° to horizontal and vertical employed.

† † Terminal included antenna, 3 semitrailers, and a maintenance van plus power generators.

As the figure indicates, the system was primarily designed to handle teletype traffic since digital messages are normally more compatible with store-and-forward operation than analog messages. The terminals included a record and playback speed changing capability in their data storage system such that stored teletype messages could be transferred to and from the satellite at a 55-kbps rate.

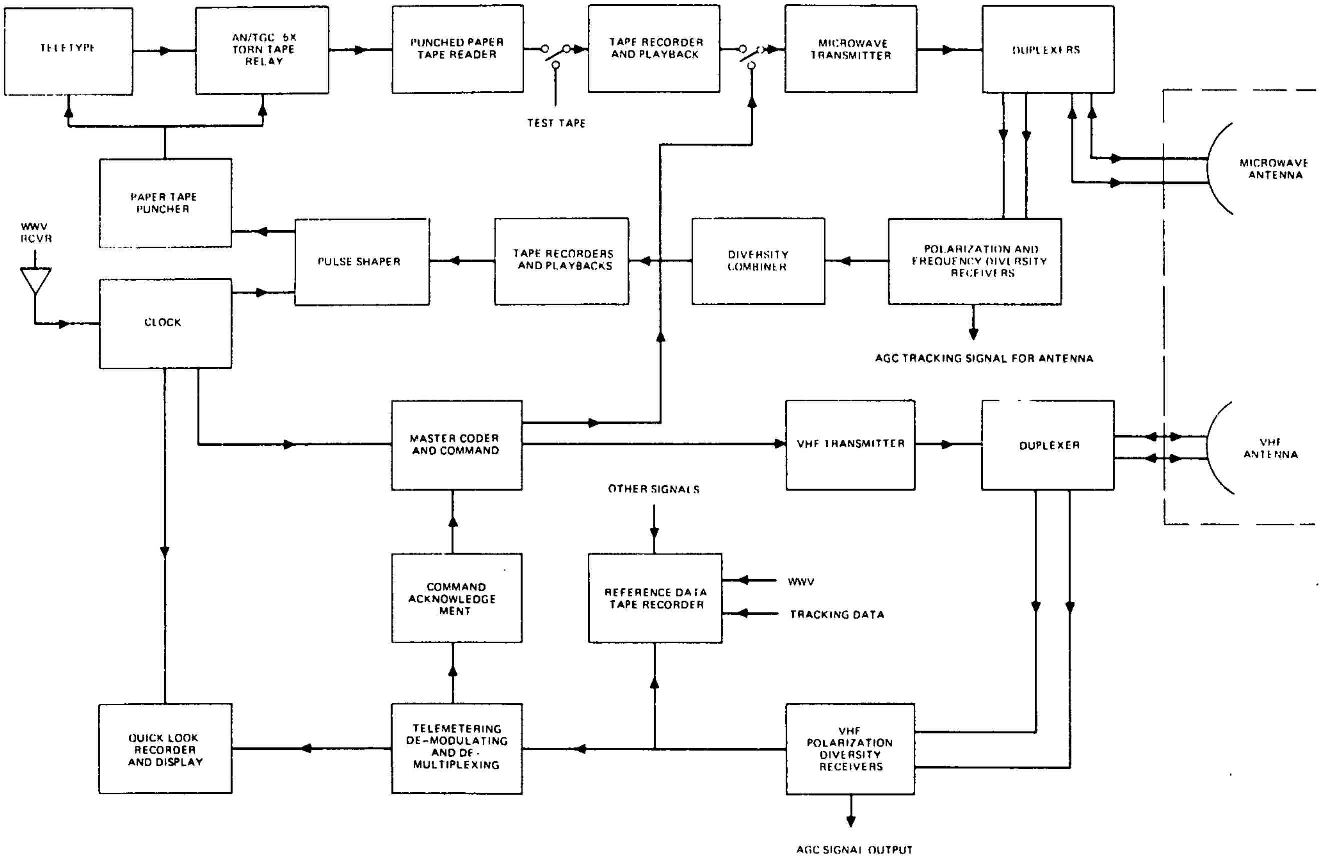

Figure 4-2. Ground Terminal Block Diagram

The choice of circular polarization for the transmit feed resulted in a 3-dB uplink polarization loss since the satellite antenna's transmit and receive polarization was linear. This loss was avoided on the downlink without resorting to a polarization tracking system by employing crossed dipoles and dual receivers at each downlink frequency to give polarization diversity reception.

4.5 EXPERIMENTS

Experiments conducted on Project Courier can be grouped into the three major categories listed and defined in Table 4-7.(2) Each of these groups of tests contributed to accomplishing the program objectives.

Table 4-7. Summary of Program Experiments

Type	Description
1. Communications Performance	Evaluate link parameters and communications traffic handling capabilities of a delayed repeater satellite.
2. Satellite Performance	Determine capability and reliability of various subsystems of complex signal processing repeater.
3. Jamming Resistance	Measure satellite and communications performance under interference conditions on VHF or UHF uplinks to satellite.

The spacecraft performance tests monitored items such as satellite tape recorder operation, temperature, spin axis attitude, spin rate, solar power supply, and command system performance.(2) During the short operational lifetime of Courier Ib the satellite performance was (in general) good and in agreement with expectations. Spin rate was observed to decay at the rate of about 1 rpm per month. Performance exceptions involved the tape recorders and command system. One of the five tape recorders became stuck at an endstop and further recording or playback was impossible. Command system malfunctions resulted in an operational effectivity of only about 95 to 97 percent. Malfunctions included failure to respond to commands, improper command acknowledgements, response to improper access codes, and in one case improper execution of the command sent.

Jamming resistance tests involved CW interference to the VHF link and both CW and pulse interference with the UHF message link. (2) The system was found to be readily susceptible to jamming of either the UHF or VHF links, as might be expected since no antijamming features were incorporated. UHF link signal-to-jamming ratios of 5 to 7 dB had to be maintained to preserve system operation in the presence of CW jamming. With pulse jamming, the signal-to-jamming ratio required appeared to be somewhat higher.

The communications performance tests described in Table 4-7 are defined in Table 4-8. (2) The table also includes primary results obtained. A precise evaluation of link parameters was not obtained, since spin axis attitude could be determined only from surface temperature sensors and received signal level, and spin rate was determined from the received signal level alone. As a result, highly accurate real time satellite antenna gain data was not available. In both the record and playback modes, delayed repeater operation required 5-second lags before initiating signal transfers to allow tape recorders to reach operational speed. In addition to the tests listed in Table 4-8, Courier Ib was employed in radar range measurement experiments. (7) These experiments contributed the development of techniques for employing ranging data to develop satellite tracking information.

4.6 OPERATIONAL RESULTS

Project Courier was an experimental program; therefore, no operational traffic was carried. Satellite operational results during the 17-day lifetime of Courier Ib were described in the discussion of experiments (Paragraph 4.5). Ground terminal tracking reliability and accuracy were quite good. Communications equipment performance and reliability was easily adequate for the limited duration

Table 4-8. Communications Performance Experiments

Type Experiment	Nature of Results Obtained
1. Received Signal Level	VHF and UHF uplink and downlink levels, in general, appeared to agree with expectations with level variations for most part due to Faraday rotation, satellite spin and changes in spin axis aspect to earth. *
2. Teletype	Delayed repeater and real time performance was the same. Average corrected error rate* was 3.33×10^{-4} bits per bit.
3. Voice	Delayed repeater and real time performance appeared the same. Single channel voice subjectively evaluated to be of commercial quality. Estimated that four or more multiplexed voice could have reasonably been accommodated.
4. Facsimile	Real time performance subjectively evaluated as excellent. Some synchronization difficulties encountered in delayed repeater operation due inadequate speed stability of tape recorders. ***

* Exact real time effects of spin rate and spin axis aspect were difficult to ascertain since satellite did not incorporate sensors for their measurement. However, fades did not correlate with atmospheric disturbances that affect more conventional types of long distance radio propagation such as HF.

** Nulls in pattern from two-element satellite antenna caused error bursts twice per satellite spin cycle due to signal level dropping below threshold. Corrected error counts eliminated these bursts from consideration.

*** Synchronization difficulties could be overcome by multiplexing a separate synchronization signal with facsimile signal. However, this resulted in noticeable intermodulation.

experiment conducted. However, reliabilities of the klystron power amplifiers and low noise parametric amplifier receiver front ends employed were not adequate for an operational system.

The major operational difficulty encountered with the Courier system occurred on October 21, 1960, when the satellite ceased to respond to ground terminal "turn on" commands. This left the satellite in an acquisition mode with the UHF communications system and telemetry transmitter deactivated, and only the VHF beacon transmitter remained active. The exact cause of failure was never determined. Erratic command system in-orbit performance on Courier Ib and subsequent life testing of a duplicate satellite model pointed toward a failure of command system circuitry. The circuitry for cycling the VHF acquisition receivers "on" and "off" (i.e., battery saver circuit) was hypothesized as the most likely point of failure. (2)

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SECTION 5 - WEST FORD

5.1 PROGRAM DESCRIPTION

Project West Ford (earlier, Project Needles) was a scientific and technical investigation, sponsored and supported by the U.S. Air Force, into the feasibility of using an orbital array of dipoles as passive reflectors in a global communication system. The communications concept investigated under Project West Ford could, in principle, provide the following:

1. Immediately accessible, continuous, worldwide communication coverage linking widely separated transmitting and receiving terminals without intermediate relay stations.
2. High dependability by virtue of very low vulnerability to disruption by natural or manmade influences.
3. Capability of resisting electronic jamming and compatibility with techniques for providing cryptographic security.
4. Reliability and ease of maintenance and repair, since the space subsystem is passive and the active electronic equipment is on earth, and since relay stations in remote and possibly politically unstable locations are not required.
5. Ability to carry simultaneously a large number of circuits between transmitters and receivers located in widely separated geographical regions.
6. Relative ease of operation, since ground antennas are not required to track the satellite relay medium at high rates over large angles.
7. Relative economy of establishment, since only two successful rocket launches could establish the entire satellite portion of a system to provide the performance indicated.

The principal advantage of the West Ford concept is its great inherent resistance to any damage (natural or other) that could significantly reduce its capability, so worldwide communications could be maintained under any foreseeable circumstances.

The question of possible interference to radio astronomy, optical astronomy, and space travel was under discussion from the outset of Project West Ford. Because of this concern, an ad hoc committee of the National Academy of Sciences was established which subsequently recommended that the project be declassified and disclosed to the scientific community at large. Opposition to the West Ford project was especially concerned with leaving material that might prove to be considerably harmful in the above-mentioned respects dispersed in space.

Late in September 1961, a special panel of the President's Science Advisory Committee concluded that "the United States can proceed with the West Ford communications experiment without danger to science." As a result, a satellite carrying the West Ford dipole dispenser package was launched on October 21, 1961. The attempt failed because of a mechanical malfunction in the dispenser. The dipoles did not disperse; fragments of the package were observed in orbit by a VHF radar but they could serve no useful communications function.

A year and a half elapsed before a second attempt was made on May 10, 1963. The dipole dispenser was carried into orbit as a piggyback payload on a large parent satellite, and the parent satellite was placed in an approximately polar orbit of about 3700-km altitude. The inclination and altitude were selected to ensure that the dipole belt lifetime would be limited by solar radiation pressure. A radio command signal was employed to release the dipole dispenser. However, due to a 30-minute ejection delay imposed by the mission of the parent vehicle, the dipole dispenser was heated unevenly by the sun. This caused imperfect dispensing which resulted in somewhat less than half the dipoles being dispensed individually. Nevertheless, a sufficient number of dipoles were successfully dispensed into orbit to allow experimental investigation.

The subsequent West Ford space experiment demonstrated that the orbiting dipole technique can provide reliable radio communication over large distances. More specifically, this program demonstrated that:

1. Large quantities of fine microwave dipoles can be fabricated, compactly packaged, launched into orbit about the earth, and dispensed.
2. Large quantities of fine dipoles can be made to form a compact belt around the earth of predictable dimensions and within a predictable time period.
3. The orbital perturbations caused by solar radiation pressure and the earth's gravitational field are essentially as predicted by theories developed at Lincoln Laboratory. The spreading of a dipole belt similar to that deployed, over 7 months' time, is no more than about 200 km in a radial direction from the earth and about 60 km in a direction normal to the orbit plane.
4. Solar radiation pressure will limit the lifetime of a dipole belt similar to that deployed to about 3 to 5 years.
5. Propagation effects of the dipole scatter medium are as predicted: a multipath time delay spread of about 100 microseconds and a doppler frequency smear of 1 to 2 kHz were observed several months after dispensing.
6. The various modulation-demodulation techniques operate with a dipole belt at close to their predicted performance; communication rates of several tens of thousands of bits per second were achieved soon after dispensing.
7. The interference of a dipole belt similar to that deployed, with radio astronomy measurements, is negligible as might be theoretically predicted.

5.2 SYSTEM DESCRIPTION

The major experiments performed using the dipole belt were conducted with sites in Massachusetts and California operating as monostatic radars, as a bistatic west-to-east radar, and for west-to-east communications. The eastern site was more heavily instrumented as a receiving station and the western site more as a transmitting station. Propagation measurements and communications experiments including high-speed data, teletype, and voice were performed. Belt-scattering cross-section and dimension measurements were made by both monostatic and bistatic radar experiments. The results of these experiments are discussed in Paragraph 5.5.

The choice of frequency range for Project West Ford was a compromise among many factors. In the upper UHF and SHF region, atmospheric noise is negligible. Galactic noise is not of great concern at frequencies above about 1000 MHz, nor is the influence of the ionosphere, in either a quiet or disturbed state. At frequencies of some 3000 MHz and higher, the noise contributed by atmospheric attenuation is noticeable in sensitive receivers, and precipitation-induced attenuation begins to be important along long slant paths at frequencies above 6000 MHz.

The use of lower frequencies will yield higher values of radiowave cross-section per unit mass for a given dipole thickness; at very low frequencies, however, the dipole thickness must be increased to preserve its shape and the greater mass would increase any possible spacecraft collision hazard. In addition, there are greater numbers of more powerful radio equipments operating at the lower frequencies. Signals scattered from a low frequency belt by these powerful equipments may cause interference.

Consideration of these factors led to the choice of a band of frequencies near 8000 MHz for a test of the orbital scatter technique. The operating frequencies employed in Project West Ford are given in Table 5-1.

Table 5-1. Project West Ford Frequencies

	Millstone		Camp Parks	
	Radar	Communications	Radar	Communications
Transmit Frequency (MHz)	7750	7750	8350	8350
Receive Frequency (MHz)	7750	8350	8350	7750

The experimental program for determining the properties of the dipole belt as a communications medium had two major goals. The first of these was the measurement of the propagation characteristics of the belt in sufficient detail to permit the design of possible future communications systems. The second goal was the achievement of digital data transmission at high rates consistent with the density of the dipoles in orbit. The fact that these two goals were to be achieved at the same point in time required the use of two receivers.

The receiver employed for measuring the propagation characteristics of the dipole belt was essentially of the RAKE-type and is shown in the block diagram of Figure 5-1. The tap unit (tapped delay line) outputs are used to form real-time displays of multipath envelope and doppler spectra and to derive error. signals for frequency and delay tracking and for gain control. The communication receiver is essentially of the correlation type using quadrature, full wave, square law detection. The block diagram for this receiver is shown in Figure 5-2.

5.3 SPACECRAFT

Early in May 1963 a package containing 4.8×10^8 copper dipoles, each 0.00178 cm in diameter and 1.78 cm in length, was placed into a nearly circular, nearly polar orbit at a mean altitude of 3650 km. A radio command signal from the ground initiated the release of the dipoles from the package. At first the dipoles formed a rather compact cloud which, due to differential linear velocity increments imparted to each dipole, gradually spread around the orbit. After several months,

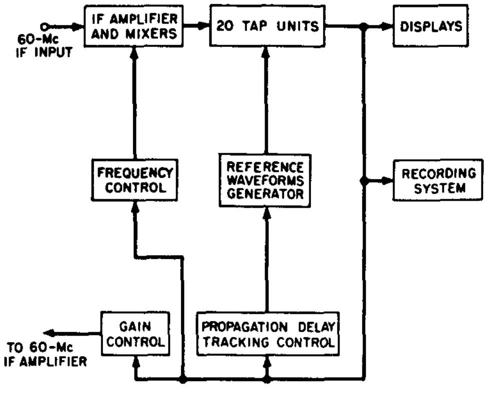


Figure 5-1. Block Diagram of Propagation Experiment Receiver

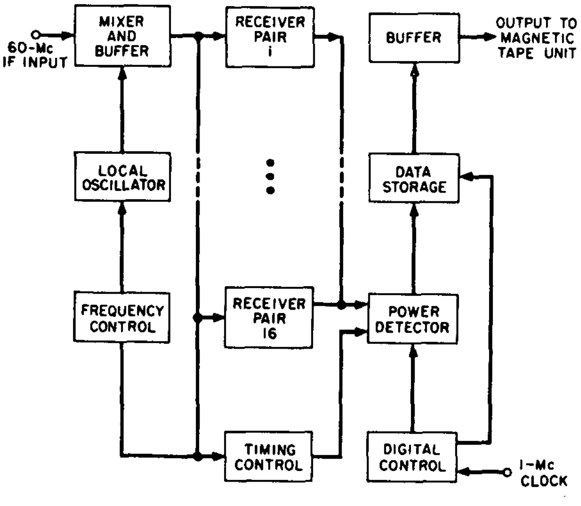


Figure 5-2. Block Diagram of Communications Receiver

the dipole distribution assumed an approximately toroidal configuration with a circumference of 63,000 km and cross-section that varied along the orbit, with a mean width of about 15 km and a mean depth (in the orbital plane) of about 30 km. In this condition each dipole was separated from its nearest neighbor by an average distance of about 400 m. This tenuous distribution of orbital dipoles is known as the Project West Ford Dipole Belt.

The above description of the dipole belt suggests that it may be considered as a large number of approximately coorbital passive satellite reflectors. Each passive reflector spacecraft takes the form of a short-circuited dipole half-wave resonant at a frequency of 8000 MHz The half-wave dipole was selected as the elemental reflector because it achieves a large gain in scattering cross-section per unit mass (due to resonance effects). In addition, the scattering from a large number of randomly oriented dipoles is essentially nondirectional. Other passive reflectors which also achieve large gain per unit mass are available (e.g., a flat circular plate), but most are extremely directional, a severe limitation for use in a system of worldwide coverage.

As a consequence of the concern that the dipole belt might result in interference to other scientific endeavors, limiting the lifetime of the belt became an important goal of the West Ford program. As a result of extensive studies on the orbital properties of the dipole belt, it was determined that the major influence on the perigee height would be solar radiation pressure. The effect of the solar radiation pressure would be to drive down the perigee height until the orbit pierced the dense portions of the earth's atmosphere where air drag would exert an additional force to drive down the perigee height still further until the orbit intersected the earth's surface.

From an extrapolation of the time behavior of the physical cross-section of the actual belt, it was concluded that 25 percent of the individually orbiting dipoles would cease to orbit after about 2-1/2 years, 50 percent after 3 years, and 100 percent after 5 years Thus it was expected that the orbits of all separated dipoles would decay by early 1968.

5.4 GROUND STATIONS

Two ground stations were constructed, one in Massachusetts (at Millstone Hill in West Ford) and one in California (at Camp Parks in Pleasanton) to use the dipole belt and to measure its characteristics. The ground stations can transmit and receive CW X-band communications signals simultaneously. In addition, each station can be changed within minutes to a radar capable of tracking and measuring the characteristics of the dipole belt and other satellites. The characteristics of the ground stations are presented in Table 5-2.

5.5 EXPERIMENTS

Two broad investigative programs were established for determining the feasibility of using the orbital dipole belt as a medium for global communications. The first was a measurements program for estimating the belt orbit parameters over an extended period of time, studying dispersion of the belt with time, determining the variation of dipole density along the orbit with time, and estimating the total number of dipoles. The second program, determining the properties of the dipole belt as a communications medium, had two major goals: the first was the measurement of the propagation characteristics of the belt; the second goal was the achievement of digital data transmission at high rates consistent with the density of the dipoles in orbit.

Physical measurements of the dipole belt were obtained by three distinct approaches. The first approach involved monostatic pulse radar operations to measure range, angles, and scattering cross-section. The second approach involved direct measurement of path loss for bistatic CW transmissions from one side to the other via belt scattering. The third approach involved inference concerning belt dimensions which may be made from bistatic measurements of doppler spread.

Table 5-2. Earth Terminal Characteristics

	Terminal Feature	Terminal	
		Millstone	Camp Parks
Antenna	Type	Parabolic Reflection	Parabolic Reflection
	Aperture Size	60' dia.	60' dia.
	Receive Gain	60 dB	60 dB
	Efficiency	40%*	45%*
	Receive Beamwidth	0.15° at 3 dB Pts.	0.15° at 3 dB Pts.
Receive System	Type Preamplifier	Maser	Paramp
	Beamwidth	30 kHz	No Data
	Noise Temp.	60°K	200° K
Transmit System	Type Amplifier	Klystron	Klystron
	Bandwidth	30 MHz	30 MHz/30 MHz
	Amplifier Power Out	20 kW	20 kW/40kW
Track-ing	Type	Computer Predicted	Computer Predicted
	Accuracy	0.01°	0.01°
Total Perfor-mance	G/T	42dB/°K*	37dB/°K*
	EIRP	132 dBm*	133 dBm *
Polar-iza-tion	Transmit Feed	Circular	Circular
	Receive Feed	Circular	Circular
Installa-tion	Radome	None	None
	Type Facility	Fixed Terminal	Fixed Terminal

*Derived value based on available data.

C-2

Measurements of the orbit parameters verified the important predictions about orbital vehavior, as, for example, the smoothing of the distribution of the dipoles around the orbit from the initial high-peaked cluster at the dispenser. In measuring orbital parameters, rms deviations normal to the orbital plane averaging 7.5 km and rms deviations in geocentric radius averaging 9.5 km were observed. The average nodal period during the first 720 revolutions (the first 80 days of belt life) was found to be 166.455 minutes. From this nodal period the average semimajor axis during this interval was computed to be 1.57 earth radii.

All three physical measurement approaches were employed in determining belt dimensions. Typical results of these measurements are summarized in Figure 5-3. In this figure, perigee and semi-latus-rectum points are marked and each point on the chart indicates the data sources, the 3-dB in-plane dimension and, except for the inferences from doppler measurements, the 3-dB out-of-plane dimension. Experimental estimates of the number of dipoles in orbit indicated that between 16 and 39 percent of the ejected dipoles were properly dispensed. It also appeared that occasionally more than one center of density developed, so that two closely spaced dipole belts were present. This situation is depicted in Figure 5-4.

Measurement of the propagation characteristics of the belt was one of the goals of the second experimental program. The dipole belt provided a channel in which signals were communicated from one point to another by scattering from a large number of dipoles in a volume of space defined by the intersection of two antenna beam patterns with the belt. Each dipole behaves like an independent scatterer, and consequently the received signal at any given time is the sum of the signals scattered by a large number of dipoles. The fact that the dipole scatters are not concentrated at a single point influences the performance of the system in detail. Specification of the received signal-to-noise ratio is not sufficient to characterize a spread channel such as the orbital dipole belt. The minimum additional information that is required to give an adequate description of the communications performance is knowledge of two parameters - multipath spread (L) and doppler spread (B) - which are measures of

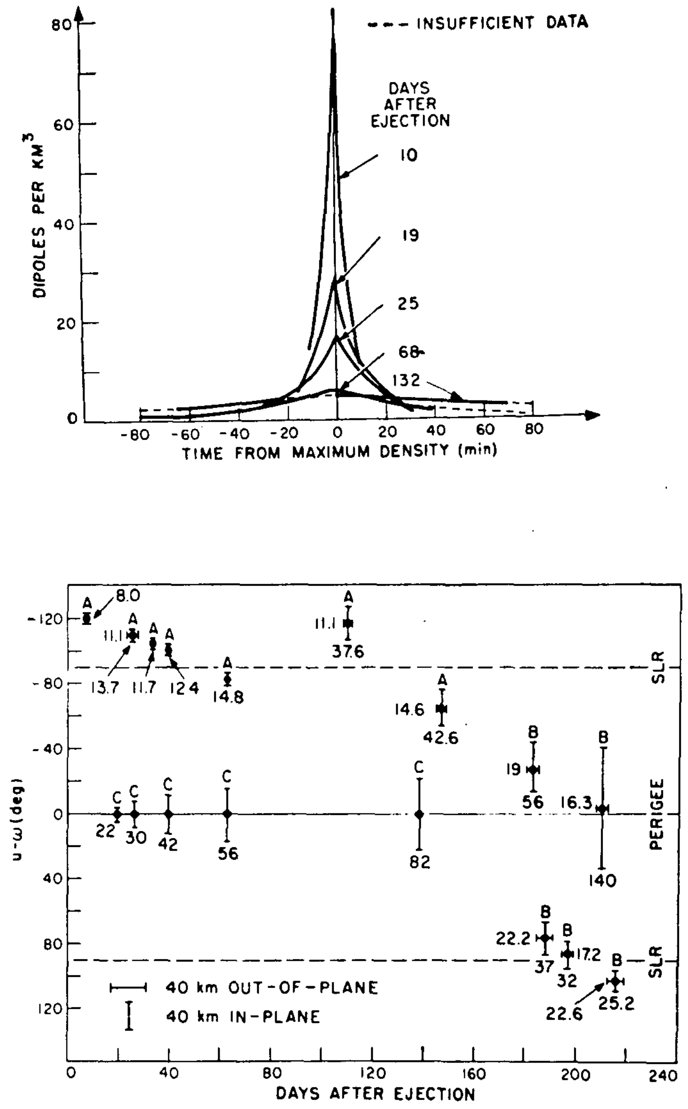
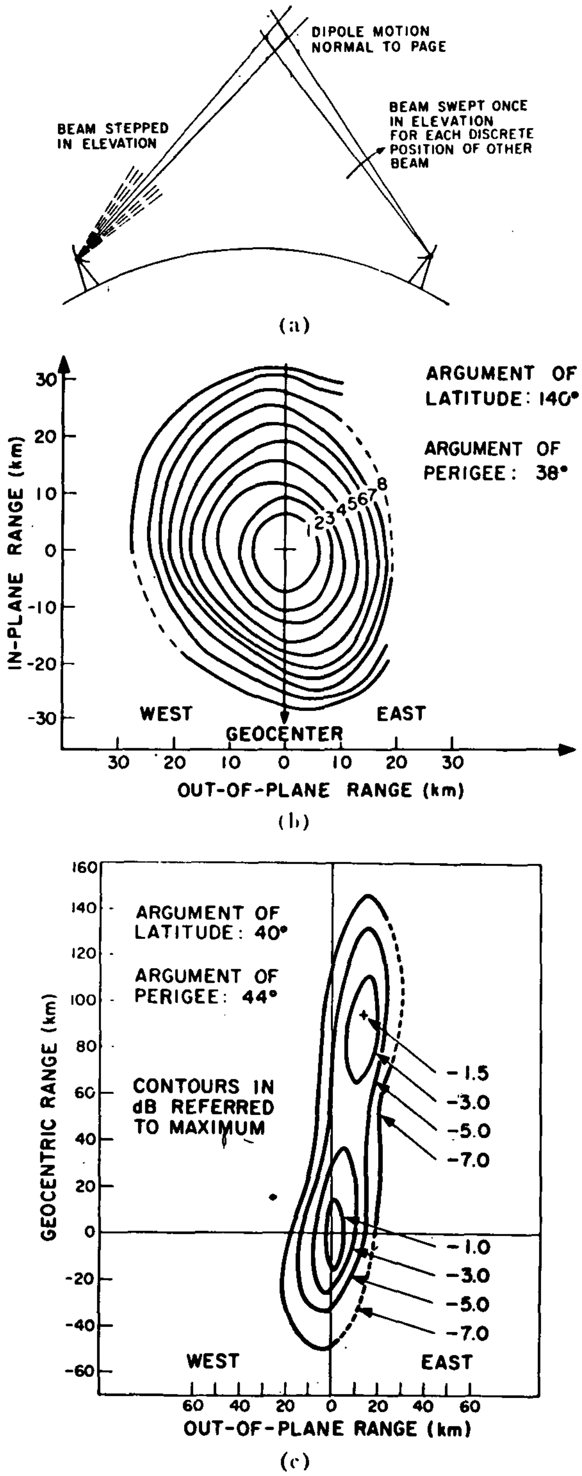


Figure 5-3. In-Plane and Out-of-Plane Belt Demensions vs Time. A = Monostatic Radar Data. B = Bistatic Radiometric Data. C = Inference from Bistatic Doppler Data. u-w = Angle from Perigee.



(a)

(b)

(c)

Figure 5-4. (a) Bistatic Belt Mapping. (b) Constant Density Contours (1-dB Increments) 215 Days after Ejection. (c) Contours of Constant Density 209 Days after Ejection the channel spreading in the time and frequency domains, respectively. If the time and frequency behavior of a dispersive medium is sufficiently well-behaved, the two parameters B and L are an adequate description for the purpose of signal design. A more complete description of the dipole belt is furnished by the so-called scattering function of the medium. This is a function σ of the two variables, time τ and frequency f, and designates the scattering cross-section of the medium at propagation delay τ and doppler shift f. The scattering function of a dispersive channel, together with the spectrum of the additive noise component, constitutes a model of the channel that is sufficiently detailed to allow synthesis of optimum signals and detections and to permit comparative performance of signaling schemes.

The multipath and doppler spreads and path losses as measured by these techniques are summarized in Table 5-3. The strongest overall conclusion of the propagation experiment is that the scattering function is generally well-behaved.

Table 5-3. West Ford Dipole Belt: Channel Characterization

Date of Experiment*	Doppler Spread B (cps)	B X L†	Path Loss (dB)	Angle re Perigee (deg)
May 20	630	.031	203	138
May 29	680	.034	207	115
June 19	1600	.080	209	100
July 12	1800	.090	212	82
Sept. 24	2300	.11	215	77
Nov. 13	1200	.060	221	69
Nov 8	960	.048	221	27
Dec. 5	1070	.054	222	2

*Date of ejection,
†L = 50 sec (3-db width)

The second objective in the study of the dipole belt as a communications medium was the achievement of actual communication in the absence of detailed knowledge of the scattering function. Thus, the purposes of the communications experiment were the transmission of digital data, the measurement of the performance of the system, and the comparison of these results with theory. The basic communications technique employed was binary frequency shift keying (FSK) with quadrature, full-wave, square-law detection as indicated in Paragraph 5.2. In order to cope with intersymbol interference due to the dispersive nature of the channel, successive transmissions used different frequency pairs and were detected in separate receivers operating in parallel. Two message sources were available to the transmitter: a fixed word repetition and a standard 60-wpm teletype. In addition, a digitized PCM system was constructed to provide voice communication in the early stages of the experiment.

On May 14 and 15, speech was transmitted using the PCM system. The received speech was intelligible and its general quality varied as the P_R/N_o ratio fluctuated about a mean of about 53 dB. Between May 14 and June 18, eight communications experiments were performed. This covered the period of time from shortly after initial dispensing to roughly closure time. During all the experiments, therefore, the belt was incomplete and in each run that portion of the belt spanning the central densest spot was employed. The experimental results were generally in fairly good agreement with the theory. For the most part, the theory overbounded the actual error probability at most by a factor of 2. In summary, the performance of the data communications system was found to be in substantial agreement with a theory which assumed the use of an optimum receiver. This is consistent with the above result that the scattering function was adequately described by the two parameters B and L, since the signals were designed under that assumption.

5.6 OPERATIONAL RESULTS

No operational traffic was carried by this experimental system. The operational reliability of the space subsystem was quite high due to its passive nature. Finally, the operational performance of the earth terminals employed in the experiments was good, as expected.

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SECTION 6 - TELSTAR

6.1 PROGRAM DESCRIPTION

The Telstar program was conceived by Bell Telephone Laboratories for the primary purpose of demonstrating the feasibility of employing orbiting satellites for commercial communication purposes. Specifc objectives were as indicated in Table 6-1.(1)(2)(3)

Table 6-1. Telstar Program Objectives

Number	Description
1	Demonstrate broadband transmission through communication satellites.
2	Test operational communications satellite reliabilities.
3	Obtain operational experience with satellite ground terminals.
4	Increase knowledge of satellite tracking techniques.
5	Provide scientific measurements of radiation in space.

Two active spacecraft, Telstar I and Telstar II, were successfully launched into medium altitude elliptical orbits during the course of the program as indicated by Table 6-2.(1)(2) Numerous communication demonstrations and detailed experiments were successfully conducted with Telstar I during its 7-month lifetime and considerable data on radiation in the inner Van Allen belt obtained. Before Telstar I finally failed from higher than expected radiation (which had resulted from the high altitude nuclear tests), an initial malfunction of the command circuit was successfully diagnosed from the ground and the satellite was commanded back "on." This ground diagnosis represented a first in satellite communications. Program objectives were for the most part met in the Telstar I experiments. Telstar II, launched after the failure of Telstar I, extended the previous experiments and demonstrations.

Table 6-2. Participating Spacecraft

Satellite		Telstar I	Telstar II
Manufacturer & Sponsor		Bell Labs and AT&T	
Launch Date		7/10/62	5/7/63
Launch Vehicle		Delta	
Orbital Data	Apogee (Mi.)	3514	6713
	Perigee (Mi.)	592	604
	Inclination	44.8°	42.7°
	Period (Min.)	158	225
Status		Failed 2/63 due to radiation damage to command decoders.	Transmitted until 6/65

Major earth terminals participating in the program are shown in Table 6-3.(1) (2) (4-7) Satellite launchings and the collection of tracking and telemetry data through a worldwide network of Minitrack stations were provided by the National Aeronautics and Space Administration (NASA).

Probably the most important contribution of Project Telstar, to satellite communications technology, was to publicize, through numerous television demonstrations, that orbiting satellites were feasible for use in commercial communication systems. From a purely technical viewpoint, one of the most important achievements was to confirm (in basic agreement with Echo I experience) that standard transmission parameters could be employed to predict performance with no concern about multipath fading for frequencies approaching 4 to 6 GHz and ground antenna elevation angles greater than a few degrees. A second technical achievement of major importance was to demonstrate further that acquiring and tracking a moving satellite was not an overly demanding assignment for a narrow-beam communications antenna equipped with an autotrack system.

Table 6-3. Participating Earth Terminals

Location	Sponsor	Antenna Diameter (Ft.)	Date of Installation
1. Andover, Maine	AT&T	67.7	1962
2. Holmdel, N. J.*	AT&T	20 ft. x 20 ft.	1962
3. Pleumeur Bodou, France	French Nat'l. Center for Telecommunications Studies (CNET)	67.7	1962
4. Goonhilly Downs, England	British General Post Office	85	1962
5. Fucino, Italy	Telespazio	30	1962
6. Raisting, Germany	Deutsch Bundespost	30/82	1963/1964

*Existing terminal with receiver modified for use with Telstar. Terminal employed a pyramidal horn reflector.

6.2 SYSTEM DESCRIPTION

The Andover terminal was the principal terminal involved in the experiments performed, with many of them being conducted on a loop-back basis. Major demonstrations were performed over a link between Andover and terminals in Europe or at Holmdel.

The satellite orbits, described in Table 6-2, were in agreement with plans to provide the maximum realizable visibility per day and per pass while employing a Delta rocket launched from Cape Kennedy. The higher apogee given to Telstar II was to reduce the amount of time spent in the most intense regions of the radiation environment, thereby minimizing damage to radiation sensitive components.

Operating frequencies in the Telstar program were as displayed in Table 6-4.(8) The communication frequencies selected were based on considerations of propagation, link noise, bandwidth, hardware available, and the feasibility of frequency sharing between commercial satellite communications and existing terrestrial services.(3) The bands selected share spectrum occupancy with common carrier line-of-site radio relay systems. The lower frequency band was selected for the downlink because of the reduced effects of precipitation and atmospheric absorption.

Table 6-4. Telstar Frequencies Employed (MHz)

Communications			TT&C		
Uplink	Downlink	Beacon	Command	Telemetry	Beacon
6389.58	4169.72	4079.72	122.9	136.05	Telemetry Carrier Used

Basic signal processing techniques utilized in the Telstar system were as indicated in Table 6-5.(8-11) Power control for multiple access was greatly improved at Andover by employing computer-derived slant range signals to vary the power amplifier output to compensate for changes in the range to the satellite. Power balancing was accomplished manually by coordinating between terminals. Margins provided had to account for variations in satellite antenna gain as a function of satellite aspect angle to the terminal and rain losses as well as various miscellaneous losses.

Table 6-5. Signal Processing Employed

Multiple Access	Frequency division for up to two carriers to support duplex operation
RF Modulation	FM
Demodulator Performance	Conventional Discriminator - Threshold at about 10 dB C/N FMFB Receiver - Threshold at about 5 dB C/N
Andover Receive Carrier-to-Noise (C/N)	13.6 dB* for maximum slant range, ** 7.5° antenna elevation angle, 1 satellite access, and 25-MHz noise bandwidth
Andover Receiver Margin	Conventional Discriminator - 3.6 dB FMFB Receiver - 8.6 dB

*Includes 0.4-dB radome loss.
**Approximately 5,700 mi.

6.3 SPACECRAFT

Satellite characteristics for Telstar I and II are displayed in Table 6-6.(12-15) The communications repeater in both satellites was as illustrated in Figure 6-1. The basic repeater design reflects the desire to employ established technology to ensure reliability. Most of the repeater is in broad principle similar to equipment used earlier in land-based microwave systems. Storage batteries and a capability to command equipment "on" and "off" allowed utilizing a solar array too small to meet real-time power demands but within weight limitations. Spin stabilizing relative to the sun reduced temperature equalization and solar array illumination problems. However, it made the selection of an essentially omnidirectional antenna necessary.

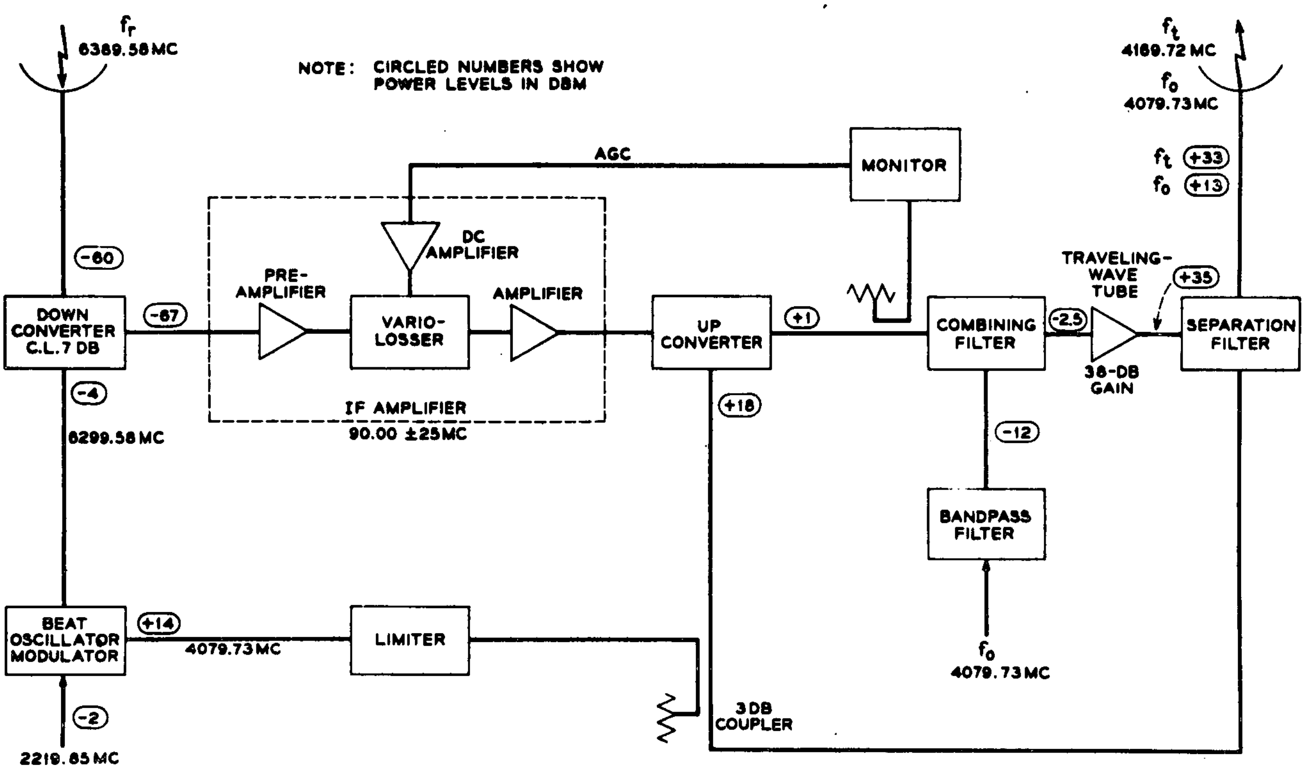

Figure 6-1. Satellite Repeater

Table 6-6. Telstar I and II Characteristics

Antennas		Type	C Band with separate multi-port xmit. & rec. girding S/C equator	VHF quadrafiler Helix for TT&C
		Number	One	One
		Beamwidth	About 120° centered on S/C equator *	Essentially Omni-directional
		Gain	0 dB	0 dB
Repeaters		Frequency Band	C Band	
		Type	IF translating with AGC of IF stage	
		Bandwidth	50 MHz at 1-dB points	
		Number	One	
	Receiver	Type Front End	Down Conversion Mixer	
		Front End Gain	7-dB conversion loss into 87 dB ** IF	
		Sys. Noise Fig.	Overall - 12.5 dB. 20 MHz centered on carrier - 16.5 ± 2 dB	
	Xmiter	Type	Single 6-watt TWT	
		Gain	37.5 dB as operated	
		Power Out	3.5 watt as operated	
		EIRP - C Band Ant.	33 dBm for 1 carrier	
General Features	Stabilization	Type	Spin with magnetic torquing coil	
		Capability	Unoriented relative to earth Normal 90° spin axis aspect to sun	
	Power Source	Primary	Solar array with 14 watts*** average output	
		Supplement****	Nickel cadmium batteries giving about 35 watts***	
		Comm. Power Needs	19 watts maximum including beacon	
		Size	Spherical with 34.5 in. diameter	
		Weight	175 lbs	

* Pattern reasonably uniform with smooth dropoff to 6 dB down over ± 60° from spacecraft (S/C) equator. Deep nulls beyond this.

** Nominal gain varied by AGC.

*** At launch.

**** Furnishes power during peak loads and eclipses.

6.4 GROUND TERMINALS

Primary earth terminals participating in Project Telstar were listed in Table 6-3. Major characteristics of the predominant participating terminals are described in Table 6-7.(4-7) (17-26) For communication purposes, circular polarization, corresponding to that of the satellite, was employed at all terminals. This choice avoids the difficulties that Faraday rotation in the ionosphere could present. All of the terminal designs reflect an intense prevailing interest in reducing receive system noise to the very minimum and accurately tracking a moving satellite.

The Andover terminal included three separate tracking antennas with their individual associated autotrack systems in addition to a capability for computer-derived programmed tracking. The autotracking systems were all, broadly speaking, of the monopulse type. Major subsystems of the Andover terminal are shown in the block diagram of Figure 6-2.

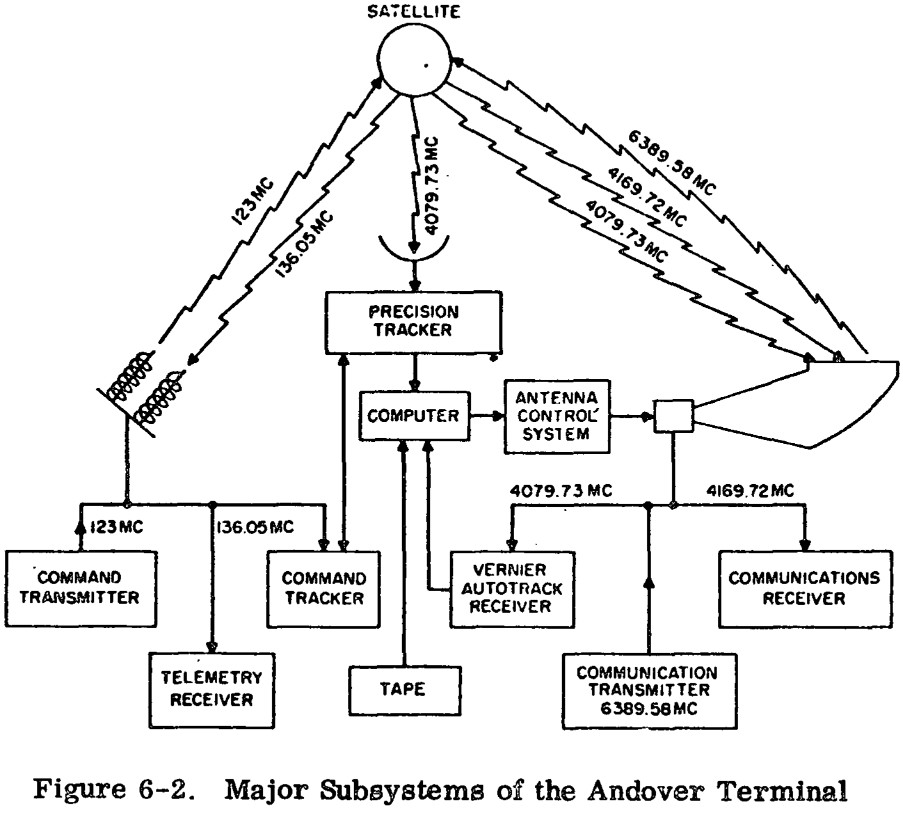

Figure 6-2. Major Subsystems of the Andover Terminal

Table 6-7. Characteristics of Major Earth Terminals

	TERMINAL FEATURE	TERMINAL		
		ANDOVER*	HOLMDEL	GOONHILLY DOWNS
ANTENNA	Type	Conical Horn Reflector	Pyramidal Horn Reflector	Parabolic Reflector
	Aperture Size	67.7 ft. Dia.	20 ft. x 20 ft.	85–ft. Dia.
	Receive Gain	58 dB	48 dB	55.6 dB
	Efficiency	70 – 75%	70 – 75%	Approx. 30%
	Rec. Beamwidth	0.23° @ 3 dB Pts.	0.78° @ 3 dB Pts.	0.2° @ 3 dB Pts.
RECEIVE SYSTEM	Type Preamplifier	Traveling Wave Ruby Maser	Maser	Traveling Wave Maser
	Bandwidth	25 MHz @ 3 dB Pts.	20 MHz @ 1 dB Pts.	25 MHz @ 3 dB Pts.
	Noise Temp.	32°K** @ 90° El.	17°K @ 90° El.	55°K @ 90° El.
TRANSMIT SYSTEM	Type Amplifier	Traveling Wave Tube	No Transmissions Employed	Traveling Wave Tube
	Bandwidth	32 MHz @ 1 dB Pts.		100 MHz @ 3 dB Pts.
	Amp. Pwr. Out	2 kW		5 kW
TRACKING	Type	Autotrack by Command Tracker, Precision Tracker, or Vernier Tracker by Separate Antenna.	Predicted Look Angles plus Manual Correction of Errors Detected on Separate 18–ft. Dish Tracker.	Programming Tracking
	Accuracy	Command Track ±1° Precision Track ±.01° Vernier Track ±.005°	As good as ±0.05° can be obtained.	Approximately 0.1°
TOTAL PERFORMANCE	G/T	40.7 dB/°K	36 dB/°K	38 dB/°K
	EIRP	123 dBm	None	Approx. 123 dBm
POLARIZATION	Transmit Feed	Circular	Circular	Circular
	Receive Feed	Circular	Circular	Circular
INSTALLATION	Radome	210–ft. Diameter Pressurized to 0.175 lb/in.^{2}	None	None
	Type Facility	Fixed Terminal	Fixed Terminal	Fixed Terminal

*The terminal at Pleumeur Bodou has essentially the same characteristics.
**The noise temperature at a 7.5° elevation angle is about 50°K.

The Holmdel terminal, originally built for Project Echo, included a glint telescope to determine the orientation of the satellite's spin axis and the spin rate. Determinations were made by observing the flashes of sunlight reflected from the three mirrors mounted on the satellite's surface.

6.5 EXPERIMENTS

The experiments conducted on the Telstar project can be grouped into four major categories as displayed and defined in Table 6-8. The radiation experiments, described in the table, contributed considerable data towards characterizing the particles within the inner and outer Van Allen belts. Additionally, valuable knowledge of the effects of radiation upon solid-state devices (i.e., upon solar cells and transistors) was gained. The most spectacular radiation experiment result, however, was the discovery, from the data on Telstar I, that high altitude nuclear testing dramatically intensified the radiation environment in the Van Allen belts.(2)(27)

The space experiments, defined in Table 6-8, monitored such items as attitude of the spacecraft spin axis in inertial space, spin rate, temperatures at the spacecraft surface and of critical internal components, satellite RF power levels, and variations in spacecraft circuitry and components. Changes in spin axis attitude, due to the residual magnetic moment of the spacecraft, were recorded. Spin rate decay, resulting from eddy currents generated in the satellite as it rotates in the earth's magnetic field, was observed. The decay was greater on Telstar I because of its lower orbit. Skin temperatures varied between about -15°F and 40°F.

Table 6-8. Summary of Program Activities

Type Activity	Program Objective Satisfied *	Nature of Activity
1. Radiation Experiments	5	Measure electron and proton spectrums** and spatial distributions as a function of time. Evaluate radiation damage to solid state devices as a function of shielding.
2. Space Experiments	2	Measure spacecraft performance under launch and space stresses.
3. Communication Demonstrations	1	Display broadband transmissions by satellite comparable to conventional commercial transmissions.
4. Communication Experiments	1	Evaluate technical performance of broadband satellite communications.

* Program objectives are numbered and defined in Table 6-1.

** Radiation spectrums characterize the number of particles per unit volume as a function of particle energy level.

Internal temperatures varied between about 60°F and 80°F. The radiated RF power was observed to remain constant as a function of time. The only significant changes observed in circuitry or components were a degradation of solar cell output and the failure of several transistors within the command decoder of Telstar I. Both of these changes were a result of the radiation encountered.

The communication demonstrations, mentioned in Table 6-8, included a variety of tests whose descriptions and results are indicated in Table 6-9.(29)(30) More than 400 demonstrations were conducted in the Telstar program.(31)

Table 6-9. Telstar I and II Communication Demonstrations

Type Demonstration	Nature of Results Obtained
1. One-way monochrome TV	Highly successful. Some loss of picture definition due to baseband bandwidth limitations[*] in ground terminals. At maximum range, weighted signal-to-noise somewhat less than for normal Bell System commercial service. Transients from camera switching at originating studios caused noise bursts in received signals.
2. One-way color TV[**]	With no audio transmitted[***] and spacecraft at short to moderate ranges, high quality pictures were obtained.
3. Two-way monochrome TV	Audio signals transmitted in both directions with definite reduction in quality. Picture quality about 20 dB[****] poorer than for one-way transmissions.
4. One-way 600 telephone channels	Amount of noise in poorest telephone channel about 6 dB more[†] than for CCIR commercial grade circuits.
5. Two-way 12-channel telephony	Poorest channel typically had noise performance about equal to that for 600 telephone channel transmissions. Crosstalk between carriers was no problem.
6. High- and low-speed data including facsimile	Data rates from those for 60-wpm teletypewriter signals to 875 kbps were tried. Test results satisfactory to excellent compared to results obtainable on a 4000-mile microwave radio relay system. Changes in absolute time delay caused some timing problems for high-speed data and facsimile. Doppler shift caused some distortion in low-speed data signals.

Notes:

[*] Filtered to about 2 MHz to allow audio signal to frequency modulate a 4.5-MHz aural subcarrier.

[**] A color program demonstration with audio was conducted in early January 1963 in which the audio modulation was inserted during the time interval reserved for horizontal blanking.

[***] No baseband filter employed.

[****] About 16 dB of degradation due to reducing peak frequency deviations from 7 MHz to 1 MHz. Remaining degradation from reduced satellite transmitter power per carrier.

[†] When satellite is at maximum range.

The communication experiments, noted in Table 6-8, are defined in detail in Table 6-10.(29)(30)(8) This table includes the general results obtained. In considering received carrier power fading measurements, note that the horizons at Andover and Goonhilly are at about 2° and 0.5° in elevation, respectively. Most of the impairments to signal transmission were determined to be caused by the ground terminals. In addition to the tests mentioned in Table 6-10, a time synchronization test was conducted.(29) Precision atomic clocks in the USA and UK were compared by transmitting pulses simultaneously in both directions. The accuracy of the method was believed to be about 20 μs and a difference in clock time of 2 milliseconds was found.

6.6 OPERATIONAL RESULTS

No operational traffic was handled during this program due to its experimental nature. However, the operational performance of the system, as the various experiments were conducted, was of considerable interest as indicated by Program Objectives 3 and 4 listed in Table 6-1. Operational performance of the two satellites was as discussed in the description of program experiments in Paragraph 6.5. The ground complex operations displayed that satellite communications ground terminals of satisfactory reliability to provide continuous commercial service were feasible. The performance demonstration included showing a capability for dependable satellite acquisitions and accurately tracking moving satellites. Satellite tracking turned out to be less difficult than expected and special purpose tracking antennas were determined not necessary. Perhaps the most spectacular ground operational result was produced by the malfunction of the command circuit on Telstar I on November 24, 1962.(32) Subsequent ground diagnosis and attempts to revive the spacecraft resulted in its being successfully commanded "on" again on January 3, 1963. This was a first in satellite communications. The ability to devise revised command signals to bypass radiation damaged transistors in the command decoder were instrumental in the successful results obtained.

Table 6-10. Telstar I and II Communication Experiments

Type Experiment	Nature of Results Obtained
1. Received Carrier Power	Measured values, in general, agreed with predicted values when range and spin axis aspect angle of satellite are taken into account. Variations in received power clearly showed satellite rotation, changes in aspect angle and changes in range. No noticeable multipath fading observed at Andover for elevation angles above about 4° or at Goonhilly for elevation angles above about 3°.
2. Frequency Responses	Baseband response essentially flat up to 5 MHz when conventional FM receiver was used. For FMFB receiver response flat up to 3 MHz. All of response limitations appeared to be due to ground terminal equipment employed.
3. Noise	Baseband noise performance, for various signals employed, defined in Table 6-9. Measurements for impulse noise indicated only random thermal noise present. Satellite repeater noise spectrum on Telstar I observed to display considerable peaking around communications carrier frequency. This gives effective noise figure over 20 MHz of about 16.5 dB ±2 dB.
4. Amplitude and Phase Distortion	Measurements of envelope delay, differential gain and phase, and intermodulation noise taken. Performance measured for television and 600-channel telephony indicate objectives* for these measurements met. Additionally, no audio to video crossmodulation interference observed and video to audio crossmodulation not significant.
5. Doppler Shift	Measured and calculated curves of Doppler shift agreed within 1 kHz over period of about 45 mins.
6. Absolute Delay	Measured and calculated delay agreed within about 20 μsec.

*Objective for intermodulation noise is maximum 36 dBrn total at 0-dB transmission level divided among various sources. Delay distortion objective corresponds to a differential phase of 4.2°, which is within 5° requirement for N.T.S.C. color television.

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SECTION 7 - RELAY

7.1 PROGRAM DESCRIPTION

The Relay Program was conceived and implemented under the auspices of NASA/Goddard Space Flight Center (GSFC), beginning in 1960. The objectives of the program were:

1. To demonstrate the feasibility of relaying wideband communication signals between ground stations via satellite relays in low altitude orbits
2. To evaluate spacecraft performance and to test the life of communication satellite system components in the orbital environment, and
3. To measure the amount of radiation encountered, its effect on solar cells and diodes, and the effectiveness of various amounts of shielding.

The spacecraft for this program were designed and manufactured by Astro-Electronics Division of the Radio Corporation of America, based on system engineering studies by Thompson-Ramo-Wooldridge Systems Group. The Relay program was directed by NASA (GSFC).

Two active satellites, Relay I and Relay II, were successfully launched into medium altitude elliptical orbits. Relay I was launched on December 13, 1962, and Relay II on January 21, 1964. The orbital parameters for both spacecraft are shown in Table 7-1. Relay I and II were basically of the same design, although certain modifications were introduced into Relay II based on operating experiences with Relay I. These modifications included the use of n-on-p instead of p-on-n solar cells and changes in the wideband repeater high-power regulator circuitry.

The primary earth terminals participating in the Relay Program are listed in Table 7-2. Tracking and telemetry data were provided by the NASA worldwide network of Minitrack stations.

Table 7-1. Participating Spacecraft

Satellite		Relay I	Relay II
Manufacturer & Sponsor		Radio Corporation of America/NASA	
Launch Date		12/13/62	1/21/64
Launch Vehicle		Thor-Delta	Thor-Delta
Orbital Data	Apogee (mi.)	4612	4606
	Perigee (mi.)	819	1298
	Inclination	47.5°	46.3°
	Period (min.)	185	195
Status		Last Useful Operation of Transponder: 2/10/65	Last Useful Operation of Transponder: 6/9/67

Perhaps the most significant contributions to space communications from the Relay Program were due to the observed malfunctions of the spacecraft. Major difficulties included the power regulator failure on Relay I and a satellite command receiver susceptibility to spurious signals. As a result of the power regulator failure, it was recognized that dew point criteria and leakage tests had to be included in all future power transistor procurement specifications and that equipment should be tested throughout the temperature range, rather than at specific maximum, minimum, and typical values. The command receives spurious responses resulted in a recommendation that more complex command signals be designed for all future spacecraft.

7.2 SYSTEM DESCRIPTION

The Relay system consisted of the orbiting satellite, the complex of participating ground and test stations, the Operations Center, and GSFC supporting activities. The satellite itself was basically a microwave repeater which received frequency modulated communication signals on 1725 MHz for translation to 4170 MHz

Table 7-2. Primary Earth Terminals Participating in the Relay Program

Location	Sponsor	Date of Installation	Antenna Diameter (ft.)
Andover (Maine)	AT&T	1962	67.7
Nutley (N.J.)	IT&T	1963	40.
Goonhilly Downs (England)	General Post Office	1962	85.
Fucino (Italy)	Telespazio	1962/1965	30./44.
Rio de Janeiro (Brazil)	Radio International de Brazil	1963	30.
Raisting (Ger.)	Deutsche Bundespost	1963/1964	30./85.
Ibaraki (Japan)	Kokusai Denshin Denwa Co.	1963	65.
Kashima (Japan)	Radio Research Laboratories		100.
Pleumeur Bodou (France)	Centre National d'Etudes des Telecommunications (CNET)	1962	67.7
Rao (Sweden)	Scandinavian Committee for Satellite Telecommunications (STSK)	1966	85.
Griñon (Spain)	Compania Telofonica Nacional de España	1964	85.
Mojave (Calif.)	NASA	1960	40.

and retransmission. In the translating process the modulation index was tripled to compensate for the bandwidth limitations of the earth terminal klystron transmitters. The repeater transmitted one-way television signals, when operated in the wideband mode, and 12 simultaneous two-way telephone conversations when operated in the narrow-band mode. In addition to a redundant wideband communication system, the spacecraft had a radiation experiment package, electrical power system, command and telemetry system, and supporting structure. Satellite operating frequencies are given in Table 7-3. The characteristics of the spacecraft and the ground stations are described in Sections 7.3 and 7.4, respectively.

Table 7-3. Project Relay Frequencies (MHz)

Communications			TT&C		
Xmit. Mode	Uplink	Downlink	Beacon	Command	Telemetry
Wideband	1725.0± 7.0	4169.7± 11.5			
Narrowband	1723.3± 0.5 1726.7± 0.5	4164.7± 1.5 4174.7± 1.5	4080	148	136

The orbital parameters for both Relay I and II are described in Table 7-1. The orbit was selected to meet the following requirements:

1. To maximize satellite mutual visibility above a 5-degree horizon between U.S. and Europe. A minimum of 100 minutes per day during the first 30 days was the achieved design objective
2. To provide acceptable mutual visibility times for the test stations and smaller ground stations
3. To traverse a radiation environment suitable for evaluation by the on-board radiation experiments
4. To minimize the simultaneous occurrence of mutual visibility times and eclipses

5. The sun look angle was to lie between 90 ± 15 degrees for the first 30 days in orbit with a maximum deviation of ± 31 degrees for a year's orbit

6. The launch trajectory was to be consistent with the range safety requirements at the Atlantic Missile Range.

Relay II was launched into a slightly higher orbit because of improved launch vehicle performance.

7.3 SPACECRAFT

Except as noted, the Relay I and Relay II spacecraft exhibited no essential differences. The principal characteristics of the spacecraft are presented in Table 7-4. Two completely independent microwave transponders were provided for increased reliability; their configuration is shown in Figure 7-1. Two modes of operation were available with the transponder. The wideband mode was utilized for one-way wideband communications such as television or 300 channels of telephony. The narrowband mode was utilized for two-way communications such as 12-channel two-way telephony. In the narrow-band mode, two ground stations could communicate with each other, one transmitting on 1723.33 MHz, the other transmitting on 1726.67 MHz. The spacecraft transponder converted these frequencies to 4165 MHz and 4175 MHz, respectively. As noted previously, the modulation index was tripled to compensate for the bandwidth limitations imposed by the earth terminal klystron transmitters.

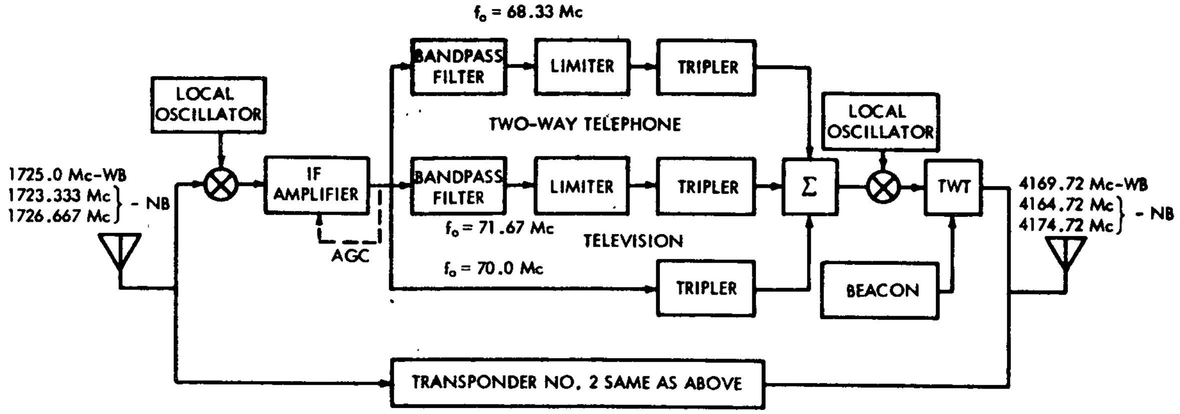

Figure 7-1 - Relay Satellite Transponder Configuration

Table 7-4. Satellite Characteristics

Antennas		Type	L,C-Band slotted waveguide, separate transmit and receive	VHF 4 Monopole Array for TT&C
		Number	One	One
		Beamwidth	75° in any place thru the spin axis	Essentially Omnidirectional
		Gain	-1 dB (transmit and receive)	Approximately -1dB
		Polarization	Circular: RHP (receive), LHP (transmit)	Linear in plane parallel to spin axis
Repeaters		Frequency Band	L,C-Band	
		Type	IF Translating	
		Bandwidth	34 MHz @-1 dB Points (Wideband Mode); 2 MHz @-3 dB Points (Narrowband Mode)	
		Number	Two (Including one spare)	
	RCVR	Type Front End	Down Conversion Crystal Mixer	
		Front End Gain	6 dB Conversion Loss into IF followed by a limiter	
		System Noise Figure	Overall: 13 dB	
	XMTR	Type	Single 11 watt TWT	
		Gain	36 dB	
		Power Out	10 watt	
General Features		EIRP - Microwave	9dBW*	
	Stabilizator	Type	Spin with Magnetic Torquing Coil, 160 RPM	
		Capability	Unoriented relative to Earth, nominal 90° spin axis aspect to sun	
	Power Source	Primary	Solar Array with 61 watts average output.	
		Supplement	Nickel Cadmium Batteries, each cell having about 3-ampere hour capacity.	
		Comm Power Needs	87 watts	
		Size	Basically Cylindrical, 30" diameter, 52" height	
		Weight	175 lbs.	

*Derived value based on antenna gain and transmitter output power.

The microwave antennas were circularly polarized biconical horns with nominally omnidirectional patterns about the spin axis to prevent amplitude modulation. Vertical coverage (in the plans of the spin axis) extended from 40 to 115 degrees (-1 dB points). In addition, this particular antenna system provided decoupling between the two transmitters and receiver of the spacecraft without any switches, thereby reducing losses and increasing reliability. Further details on the microwave antenna can be found in Appendix 7-A.

The VHF antenna consisted of 4 monopoles extending out from the bottom mounting ring face of the spacecraft. For command reception the antenna elements were fed in phase to produce a dipole-like pattern; while for telemetry and tracking transmission they were fed pairwise in phase quadrature to produce a circularly polarized wave in the plane perpendicular to the spin axis. In any planes parallel to the spin axis the wave was linearly polarized.

All spacecraft power was generated by solar cells. Storage batteries charged by the solar cells were used to supply the peak power necessary for repeater operation. On Relay I the solar cells were boron-doped silicon cells, p-on-n, gridded and covered with 60-mil thick fused sheets. To decrease solar cell degradation due to radiation, n-on-p cells were used on the solar array of Relay II.

In addition to the communications repeaters, and other subsystems needed to support the principal mission of Relay, the spacecraft carried a group of components to obtain data on particle radiation in space. These consisted of six radiation detectors and a collection of isolated solar cells and semiconductor diodes. The latter were accumulated on a "radiation-damage-effects" panel.

7.4 EARTH STATIONS

Some of the major earth stations participating in Project Relay are described in Table 7-5 in terms of their basic characteristics. In the Relay system, the stations at Nutley and Mojave were designated as Test Stations and, as such, had prime responsibility to command the satellite and monitor telemetry. Other stations participating in the program under agreements with NASA were designated as Ground

Table 7-5. Earth Terminal Characteristics

	Terminal Feature	TERMINAL			
		Andover	Nutley/Mojave	Fucino No. 1	Raisting No. 2
Antenna	Type	Conical Horn Refl.	Parabolic Refl.	Parabolic Refl.	Parabolic Refl.
	Aperture Dia.	67.7'	40'	30'	85'
	Receive Gain	58 dB	49.1 dB	48.7 dB	57.5 dB
	Rec. Beamwidth (3 dB)	0.23°	0.45°	0.55°	0.20°
	Efficiency	70-75%	30%*	45%*	45%*
Receiver System	Type Preamplifier	TW Ruby Maser	Uncooled Paramp	Cooled Paramp	T.W. Maser
	Bandwidth	25 MHz	25 MHz	25 MHz	25 MHz
	Noise Temp.	32°K/Zenith	360°K	220°K/Zenith	54°K/7.5° elev.
Transmit System	Amplifier Type	Klystron	Klystron	TWT	TWT
	Bandwidth	No Data	No Data	25 MHz	25 MHz
	Power Output	10 kW	10 kW	2 kW	2 kW
Tracking	Type	Autotrack by Command Tracker, Precision (Beacon Tracker, or Communicator Antenna	Programmed Tracking, Monopulse	Programmed Tracking, plus Monopulse	Computer Tracking Monopulse
	Accuracy	Command Tr. ± 1° Precision Tr. ±0.02° Comm. Ant. ± .005°	Prog.Tr. ± 0.1° Monopulse ± 0.1°	No Data	Computer Tracking ± 0.01° Monopulse ± 0.003°
Total Performance	G/T	41dB/°K*	23.5dB/°K*	25.3 dB/°K*	40 dB/°K*
	EIRP	120 dBm*	111 dBm*	104 dBm*	112 dBm*
Polarization	Transmit Feed	Circular	Circular	Circular	Circular
	Receive Feed	Circular	Circular	Circular	Circular
Installation	Radome	210' Diameter, Rubberized Dacron	None	None	160' Diameter Rubberized Dacron None
	Type Facility	Fixed Terminal	Transportable	Fixed Terminal	Fixed Terminal

*Derived value based on data available.

Stations. It should be noted that although the Nutley Test Station employed the same communications antenna, they were separate operations.

The Communications Satellite Operations Center was established to handle experimental scheduling, daily operations planning, and data processing. This center also provided a centralized command post to exercise control over the satellite. Supporting activities included telemetry data processing, orbital prediction, and satellite tracking information.

7.5 EXPERIMENTS

Each of the participating stations was asked to submit a detailed experiment plan concerning those tests in which that particular station would participate. The communications experiments were divided into three classifications: wideband performance experiments, narrowband performance experiments, and system demonstration experiments. System performance experiments - wideband and narrowband - were intended as objective tests to obtain quantitative and statistical data on the electrical parameters of the system by analyzing the response to carefully controlled executions. The various major types of experiments prepared for the Relay program are outlined in Table 7-6. Details of the experiments were given in the Relay Communications Experiment Plan (RI-0521A). This plan gave the general purpose and description of the individual experiments, and the test procedures for each of the stations.

In order to make the most effective use of the entire Relay system, which included the complex of participating earth stations as well as the satellite, it was necessary to schedule the communications experiments with some care. Experiment schedules were initially planned over a 1-month period. It was found useful early in the program to assign operational days during each week to designated stations, with the days assigned arbitrarily. Examination of orbital data would then indicate which passes on each day were usable for the station designated for that day.

For detailed experimental results the reader is referred to the bibliography. General conclusions were as follows:

Table 7-6. Major Relay Communication Experiments

I. Wideband Performance Experiments
   - A. Received Carrier Power
   - B. Insertion Gain Stability
   - C. Noise Measurements: Continuous random, impulsive, periodic, baseband, ground terminal IF, and satellite noise
   - D. Linear Distortion: Field-time, line-time, and short-time distortion plus amplitude-frequency and phase-frequendy characteristic at both baseband and RF.
   - E. Nonlinear Distortion: Differential gain, envelope delay, synchronization nonlinearity, audio distortion, and intermodulation noise
   - F. Interference
   - G. Special Transmission Tests: Doppler shift, absolute delay, and tracking accuracy
   - H. Television Test Patterns: Monochrome and color.

II. Narrowband Performance Experiments
   - A. Received Carrier Power
   - B. Insertion Gain Stability
   - C. Noise Measurements: Continuous random, impulsive, periodic and satellite noise
   - D. Linear Distortion: Amplitude-frequency and phase-frequency at baseband
   - E. Nonlinear Distortion: Envelope delay, intermodulation noise, and intelligible crosstalk
   - F. Interference
   - G. Special Transmission Tests: Doppler shift, absolute delay, tracking, clock pulse synchronization, and multiple loop.

III. System Demonstration Experiments
   - A. Television: Monochrome, color, and narrowband
   - B. Telephony: One-way and two-way
   - C. Digital Data Transmission: High and medium rate
   - D. Program Material: Music
   - E. Satellite vs. Conventional Communications Comparison: Teletype, facsimile, and high-rate teletype
   - F. Multiple Satellite Tests.

1. Television - No appreciable degradation of the signal could be attributed to the satellite except for the expected noticeable increase in noise. The received pictures at Pleumeur Bodou were always of excellent quality and were often transmitted over the European network. At Goonhilly Downs good quality of the satellite video channel was obtained; multipath and echo signals were imperceptible. Further, doppler frequency shifts are observed to have no effect on the quality of the received monochrome video signal.

2. Telephony - Links were always excellent with respect to the contact established and noise in the telephone channels.

3. Facsimile - Some deformation (skew) caused by the variation in propagation time during the transmission could be seen. For photographs lacking in fine detail the effect was tolerable; for newspaper pages or drawings the effect could be sufficiently large to be troublesome.

4. Radiation Experiment - The n-on-p solar cells were shown to be more resistant to radiation than p-on-n cells. Some mapping of the electron and proton fields in the Relay orbit was also accomplished.

7.6 OPERATIONAL RESULTS

The objectives of the Relay program were entirely experimental in nature; therefore, no operational traffic was handled. The program was extraordinarily successful with malfunctions in either the satellites or ground complex being infrequent. However, it was not entirely free of operational difficulties. Most troublesome was an inability to turn off one of the high power regulators and its associated wideband repeater on Relay I. Analysis indicated that excessive reverse leakage current in the high power regulator series pass transistors prevented the regulator from being shut off. The cause of this excessive reverse leakage current was apparently moisture precipitating on the active surface of the transistor as the junction temperature passed through the transistor's dew point temperature. After about 12 months operation the problem seemed to disappear, perhaps due to the evaporation of the condensation into the vacuum of space. In addition, spurious responses by the spacecraft were observed rather frequently by noting the satellite equipment being turned on and off in the absence of ground commands.

APPENDIX 7-A. THE RELAY MICROWAVE ANTENNA

The microwave antenna requirement for the Relay spacecraft included:

1. Omnidirectional pattern about the spin-axis
2. Coverage from near 35° to 120° in zenith angle as measured from the spin axis
3. Circular Polarization
4. Sufficient decoupling between the two Relay transmitters to prevent the inactive one from loading the active one
5. Sufficient decoupling between transmitters and receiver.

These requirements were met in a unique slotted waveguide antenna designed by O. M. Woodward of RCA. The transmitting portion of the antenna was comprised of five parts: the mode transducer, the coaxial wavequide transmission line, the quarter-wave plate, the inclined-slot exciters, and the radial waveguide. The mode transducer consists of two de-coupled input ports near the base of the antenna. With this the input coaxial TEM mode line can feed the coaxial TE_{11}-mode waveguide transmission line. The two input ports were oriented at right angles so that the TE_{11} modes excited in the coaxial waveguide would be orthogonal. In addition, the transmitter ports were one guide wavelength apart to reduce direct cross-coupling between them. To provide still further isolation, a quarter-wave plate consisting of two longitudinal metal ridges attached on opposite sides of the coaxial waveguide inner conductor was employed to convert the linearly polarized waves from the separate input ports to circularly polarized waves of opposite rotational sense. The radiator itself consisted of eight slots inclined at an angle of 55° and equally spaced about the outer conductor. Because the radial and tangential components of the field radiated by these slots were observed to be inphase, a radial waveguide, constructed from two parallel metal discs, was employed to obtain the quadrature phasing required for circularly polarized radiation. The phase velocity of the axial component was unaffected by these discs. The phase velocity of the tangential component, however, was a function of the spacing. Hence, by proper choice of spacing and diameter, a differential phase-shift of 90° between these two components was obtained, to produce circular polarization of the plane normal to the spin axis.

The receiving portion of the antenna consisted of three parts: the transmission line, the inclined radiating slots, and the radial waveguide. Only a single port antenna was needed for reception as the two receivers were joined in parallel. The receiving antenna was mounted above the transmitting antenna and connected to the receiving port by a coaxial transmission line residing interior to the coaxial line of the transmitting antenna. The receiving radial waveguide acts similarly to that of the transmitter in causing a 90° phase shift between the orthogonal, axial and tangential, electric-field components. The slots are oppositely inclined to those of the transmitter, resulting in opposite sense, circular polarization.

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SECTION 8 - SYNCOM

8.1 PROGRAM DESCRIPTION

A spin-stabilized synchronous communications satellite was first proposed by Hughes Aircraft Company in the autumn of 1959.*(1) Project Syncom was initiated as a joint NASA/DOD development in August, 1961. The major objectives of this program were to develop the capability of launching satellites into earth synchronous orbits and to demonstrate the utility of this type of orbit for satellite communications. (2)

Three spacecraft were launched during the course of completing Project Syncom, as indicated in Table 8-1: (4) (5) (6) Syncom I went totally silent during the firing of its apogee motor in an attempt to complete injection into a synchronous inclined orbit. Subsequent optical sitings revealed that the desired orbit was attained to partially satisfy the program objectives. Syncom II was successfully launched into a synchronous inclined orbit and initially positioned over Brazil at 55° W. longitude. It was later moved to a final location over the Indian Ocean. Numerous experiments and demonstrations were conducted to satisfy all program objectives. Subsequent to the initial successful operations with Syncom II, the Thrust Augmented Delta rocket became available, making possible further improvements in the synchronous orbit injection technology. This launch vehicle allowed Syncom III to be successfully placed into a synchronous equatorial orbit (i. e., a geostationary orbit). The satellite was positioned over the Pacific International Date Line and additional communications measurements and demonstrations were conducted. With all of the Syncom programs' experimental objectives attained, Syncoms II and III were turned over to DOD in early 1965 to provide an operational communications capability serving the Far East, Pacific Ocean and Western United States. This continued until the first worldwide military satellite communications system became operational and was able to assume the communications load (see Section 12).

The principal earth terminals involved in the program were supplied by the U.S. Department of Defense and are indicated in Table 8-2. (3) (4) (6-11) Satellite

Table 8-1. Participating Spacecraft

Satellite	Syncom I	Syncom II	Syncom III
Manufacturer & Sponsor	Hughes Aircraft & NASA		
Launch Date	2/14/63	7/26/63	8/19/64
Launch Vehicle	Delta		Thrust Augmented Data
Orbital Data*			
Apogee (Mi.)	22,978	22,760	22,590
Perigee (Mi.)	21,205	22,072	21,578
Inclination	33.5°	33.1°	0.31°
Period (Min.)	1,426.6	1,454	1,423
Status	Spacecraft became inactive during apogee motor firing to attain synchronous orbit.	Spacecraft active. Stationkeeping capability exhausted. Left at about 77° E. longitude.**	Spacecraft active. Stationkeeping capability exhausted. Left drifting West. Circles earth in about 18 months.

NOTES: *At initial injection. Attitude control and stationkeeping produced changes.
**Stable equalibrium point in earth's gravitational field.

Table 8-2. Participating Earth Terminals

Location	Sponsor	Antenna Diameter (Ft.)	Date Installed
Ft. Dix, N.J. *	U.S. Army	60	1962
Camp Roberts, Calif. *	U.S. Army	60	1962
Lakehurst, N.J. **	U.S. Army	30	1962
Greenbelt, Maryland **	U.S. Army	30	1963
Republic of Viet Nam ***	U.S. Army	30	1964
Thailand ****	U.S. Army	15	1964
Asmara ****	U.S. Army	15	1964
Kingsport†	U.S. Navy	30	1962
USS Canberra†	U.S. Navy	6	1965
USS Midway†	U.S. Navy	6	1965
Kashima, Japan††	Japan's Radio Research Lab	32.8	1964
Point Mugu, Calif.†††	U.S. Navy	85	1964

* Fixed AN/FSC-9 terminals.

** Transportable AN/MSC-44 terminals later relocated to Hawaii and Philippines.

*** Transportable AN/MSC-45 terminal.

**** Transportable MK-IV terminals.

†U.S. Navy ships.

††Transmitting terminal only.

†††Receiving terminal only.

launchings were provided by the National Aeronautics and Space Administration (NASA). The NASA Worldwide Minitrack network collected tracking and telemetry data. Selected newly procured tracking, telemetry, and command (TT&C) terminals were also provided by NASA. One of the most important of these was located on the Kingsport.

The great contribution of Project Syncom to satellite communications technology was to display the feasibility of placing satellites into synchronous equatorial orbits and maintaining precision stationkeeping and attitude control. The synchronous equatorial orbit significantly reduced the ground terminal tracking requirements and made it possible to establish an essentially worldwide communications system with as few as three or four satellites. The only earth areas without satellite visibility in such a system are the regions immediately around the North and South Poles. The high altitude of the synchronous orbit and the capability to precisely maintain the satellite's spin axis at a 90^o attitude relative to the orbital plane made it possible to employ antennas providing pancake-shaped radiation patterns of significantly higher gain than the previous essentially omnidirectional satellite antennas. Finally, the communications experiments verified the link propagation parameters and provided the first indication that round trip time delay and return echo due to two-wire user terminations are not insurmountable obstacles to the use of synchronous satellites in commercial communications applications.

8.2 SYSTEM DESCRIPTION

Initial tests performed while Syncom II was stationed over Brazil involved the Fort Dix, Camp Roberts, Lakehurst, and Kingsport terminals. After the satellite was repositioned over the Indian Ocean, tests were conducted employing principally the Asmara, Philippines, and Thailand terminals. Tests involving Syncom III included the Camp Roberts, Hawaii, Viet Nam, Kingsport, USS Canberra, USS Midway, Kashima, and Point Mugu terminals, among others. Practically all transmissions over either satellite were conducted on a loop-back basis or over a single link between two terminals. Both half and full duplex links were established.

Typical earth coverages supplied by the synchronous orbits of Syncoms II and III are illustrated in Figure 8-1. (9) The significantly smaller area of 24-hour earth coverage provided by Syncom II is due to its inclined orbit resulting in a daily figure eight earth trace of the subsatellite point.

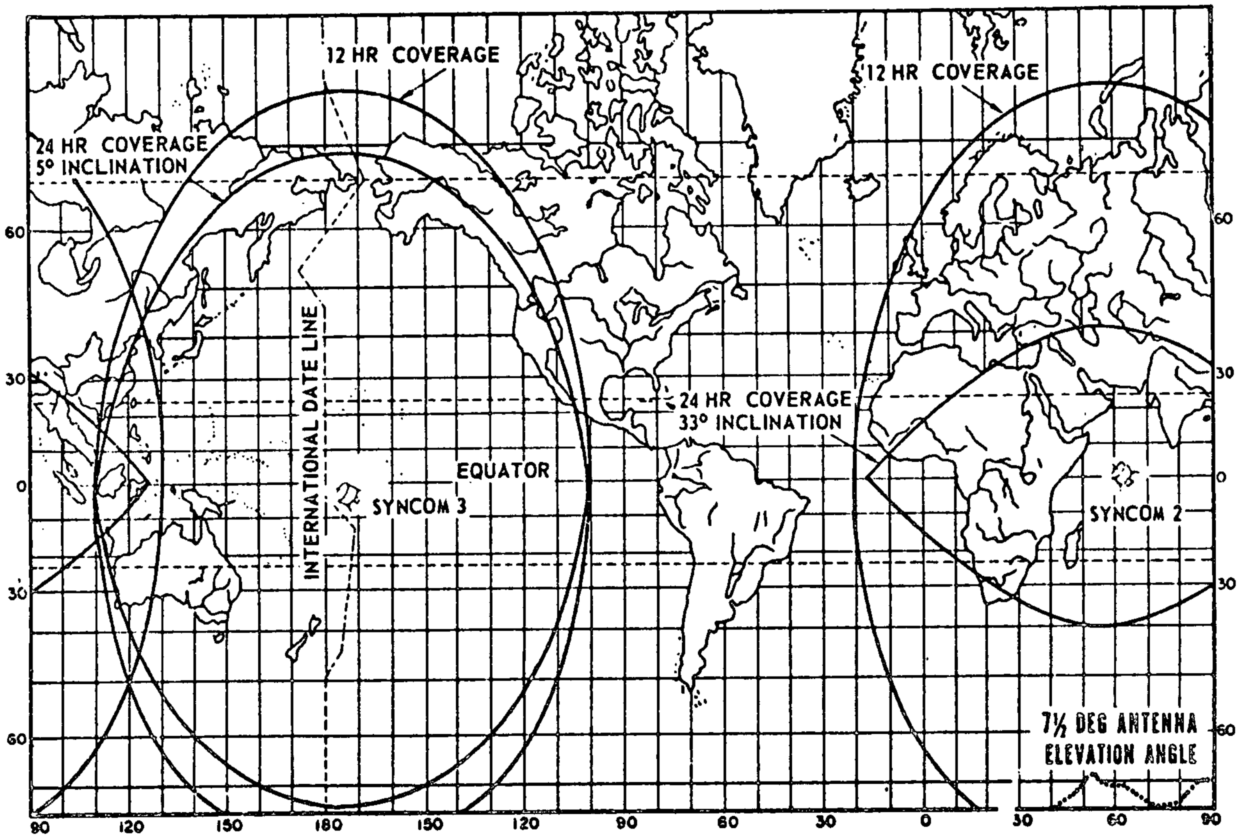

Figure 8-1. Syncom Earth Coverage

Operating frequencies for the Syncom satellites were as indicated in Table 8-3. (5) The communications frequencies were selected to be compatible with the ground complex under development at that time for the Army's Project Advent. (7) Upon termination of this synchronous satellite project, the Fort Dix, Camp Roberts, and Kingsport terminals required only relatively minor modifications to become part of the Syncom program.

Basic signal processing techniques used in the Syncom program were as indicated in Table 8-4. (3) (4) Power balancing for duplex operation was accomplished manually by coordinating between terminals via leased conventional circuits. Margins for duplex operation were quite narrow but had to account only for rain losses, inaccurate

Table 8-3. Syncom Frequencies (MHz)

COMMUNICATIONS				TT&C	
SATELLITE	UPLINK	DOWNLINK	BEACON	COMMAND	TELEMETRY
Syncom II	7361.275*	1814.969			
	7363.000*				136.470**
	7362.582	1815.794	1820.117	148.260	
Syncom III	7363.000	1815.794			
	7362.138	1814.931			136.980**

*Dual channel narrow band repeater
**Redundant transmitters

Table 8-4. Signal Processing Employed

Multiple Access	Frequency Division* for up to two carriers to support duplex operation
RF Modulation	FM and PSK**
Demodulator Performance	Conventional Discriminator – Threshold at about 10 dB C/N FMFB Receiver – Threshold at about 6 dB C/N
Lakehurst Receive Carrier–to–Noise (C/N)	12 dB for 43.2° antenna elevation, one satellite access, and 188–kHz noise bandwidth
Lakehurst Receive Margin	Conventional Discriminator – 2 dB FMFB Receiver – 6 dB

*Spread Spectrum modulation and more than two accesses were displayed in special tests.
**The Advent modem employed in a limited number of tests.

power balancing, and various miscellaneous variations in link parameters of lesser magnitude.

8.3 SPACECRAFT

Spacecraft characteristics for the Syncom satellites are displayed in Table 8-5.(3) (4) (5) (13) All three satellites contained identical apogee motors for final orbit circularization. The basic configuration for the communications subsystem on the Syncom satellites is displayed in Figure 8-2.(4) Each receive channel consists of a mixer, a local oscillator, an IF amplifier, a limiter amplifier, and a mixer connected through a hybrid to the redundant TWTs.

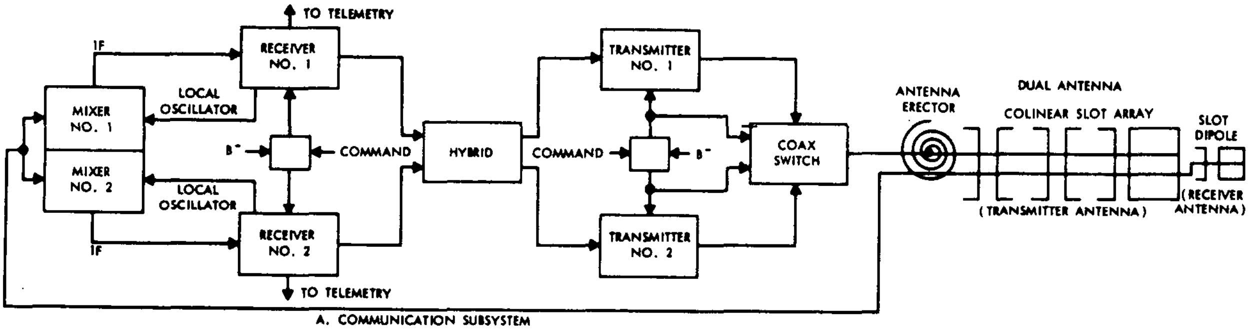

Figure 8-2. Satellite Communications Subsystem

Syncom II differed from Syncom I only in nitrogen tank mounting and internal operating pressure, the wiring harness, and the addition of a standby battery to provide 40 minutes of telemetry should the main power supply fail. These changes resulted from the conclusion that a high-pressure nitrogen tank failure caused the loss of Syncom I.

Based on Syncom II experience, several modifications were also made to Syncom III. N-on-P solar cells with 12-mil fuzed silica covers replaced the more radiation sensitive P-on-N solar cells with their 6-mil glass covers. A redundant hydrogen peroxide (H_2O_2) system replaced the high pressure nitrogen (N_2) system. The standby battery and apogee motor timer were deleted. Two temperature sensors were

Table 8-5. Satellite Characteristics

SATELLITE		SYNCOM I & II		SYNCOM III	
ANTENNAS	Type	UHF Xmit. – collinear array of slot dipoles SHF Recv. – slot dipole	VHF–4 whip turnstile for TT&C	Essentially the same as for Syncom I & II	
	Number	One	One		
	Beamwidth	Pancake beam about 25° wide at 3–dB pts. for Xmit.	Essentially Omnidirectional		
	Gain	Xmit. – 6 dB Recv. – 2 dB	0 dB		
REPEATERS	Frequency Band	SHF Recv. and UHF Xmit.		Same as for Syncom I & II	
	Type	IF Translation Hard Limiting			
	3 dB BW	5 MHz	0.5 MHz*	4.5 MHz	13 MHz or 50.kHz**
	Number	Redundant Xponders of different BW selectable on ground command		Essentially the same as for Syncom I & II	
	Receiver				
	Type Front End	Down Conversion Mixer			
	Front End Gain	90 dB IF following down converter			
	Sys. Noise Fig.	10 dB			
	Transmitter				
	Type	Redundant TWTs***			
	Gain	33 dB			
	Power Out	2 watt (nominal)			
	EIRP – UHF Ant.	6 dBW			
GENERAL FEATURES	Stabilization				
	Type	Spin with H_2O_2 and N_2 reaction control****		Spin with H_2O_2 reaction control****	
	Capability	Spin axis could be maneuvered to within 1° of normal to orbital plane.			
	Power Source				
	Primary	Solar Array – 29 watt output at launch			
	Supplement	2 Nickel Cadmium Batteries – about 0.8 amp. hr. per battery at launch			
	Comm. Power Needs	About 15 watt		Essentially the same as for Syncom I & II	
	Size	Cylindrical – 15.5 in. high & 28 in. diameter			
	Weight	78.8 lbs. initially in orbit		73.8 lbs. initially in orbit	

*Bandwidth for each of two channels provided for more convenient full duplex narrowband operation.

**Either wideband or narrowband mode can be selected.

***Either TWT can operate with either transponder. Interlocks prohibit parallel operation.

****Gas jets provide both attitude corrections and stationkeeping.

added. The transponder containing two 0.5-MHz bandwidth IF sections was replaced by a 10-MHz bandwidth channel for television tests with a 50-kHz option for small station testing.

8.4 GROUND TERMINALS

Among the participating earth terminals listed in Table 8-2, the AN/FSC-9, the AN/MSC-44, and the Kingsport terminals were the principal stations involved in the early testing on both Syncoms II and III. Characteristics of these terminals are presented in Table 8-6. (3) (6) (9) (11) (14) (15) Major subsystems of the ground facilities placed aboard the Kingsport are shown in Figure 8-3. (3) The AN/FSC-9 and AN/MSC-44 terminal installations did not, in general, include the TT&C antenna and system.

The transmit and receive polarizations available at the AN/MSC-44 and Kingsport terminals were compatible with those of the Syncom sattellites. In contrast, the receive polarization of the AN/FSC-9 terminals was such that a 3-dB polarization loss was suffered. By choosing circular polarization, however, it was no longer necessary to track variations in the linear polarization received from the satellite.

The AN/FSC-9 and AN/MSC-44 terminals employed two axis (i.e., azimuth and elevation) tracking and control of the antenna. The Kingsport terminal was provided with a three-axis antenna, however, to ensure a capability for near zenith operation from the rolling and pitching ship.

8.5 EXPERIMENTS

Experiments conducted on project Syncom are grouped in five major categories and defined in Table 8-7. Synchronous orbit injection was successfully completed on Syncoms I, II and III. In the latter case, a synchronous equatorial orbit was realized. Spacecraft stationkeeping and attitude control were successfully maintained on Syncoms II and III. In the process of stationkeeping, considerable data on the triaxial nature of the earth and the drift of synchronous satellites was generated. (16) (17) (18)

Table 8-6. Characteristics of Major Earth Terminals

TERMINAL FEATURE		TERMINAL		
		AN/FSC-9	AN/MSC-44	KINGSPORT
ANTENNA	Type	Parabolic Reflector	Parabolic Reflector	Parabolic Reflector
	Aperture Size	60 Ft. Diameter	30 Ft. Diameter	30 Ft. Diameter
	Receive Gain	48 dB	42 dB	40 dB
	Efficiency	50%	50%*	35%*
	Rec. Beamwidth	0.65° at 3 dB Pts.*	1.3° at 3 dB Pts.	1.6° at 3 dB Pts.*
RECEIVE SYSTEM	Type Preamplifier	Temperature Controlled Parametric Amplifier	Temperature Controlled Parametric Amplifier	Temperature Controlled Parametric Amplifier
	Bandwidth	100 kHz**	100 kHz**	100 kHz**
	Noise Temp.	230°K at 7.5° El.	200°K at 7.5° El.	200°K at 7.5° El.
TRANSMIT SYSTEM	Type Amplifier	Klystron	Klystron	Klystron
	Bandwidth	100 kHz***	100 kHz***	100 kHz***
	Amp. Pwr. Out	20 kW****	20 kW****	20 kW****
TRACKING	Type	Conical Scan Autotrack	Conical Scan Autotrack	Spiral Scan Autotrack
	Accuracy	±0.024	±0.05°	±0.05°
TOTAL PERF.	G/T	24.4 dB/°K*	19 dB/°K*	17 dB/°K*
	EIRP	128 dBm*,****	123.4 dBm*,****	125.3 dBm*,****
POLARIZATION	Transmit Feed	Circular	Circular	Circular
	Receive Feed	Circular	Linear	Circular or Linear (Interchangeable)
INSTALLATION	Radome	None	None	53 Ft. Diameter Pressurized
	Type Facility	Fixed Terminal	Transportable†	Ship

*Derived value based on data available

**IF bandwidth variable to 10 and 40 kHz. RF bandwidth is 10 MHz at 3–dB pts.

***Radiated signal bandwidth. RF bandwidth is 15 MHz at 3–dB pts.

****Peak possible. Operationally the practical limit is 3 dB less.

†Included eight vans, all air–transportable in C124 and C133 aircraft. Total weight about 65,000 lbs.

TABLE 8-7. SUMMARY OF PROGRAM EXPERIMENTS

Type Activity	Nature of Activity
1. Synchronous Orbit Injection	Demonstrate launch and synchronous orbit injection of spin stabilized satellite.
2. Stationkeeping and Attitude Control	Demonstrate precision control of spin axis attitude and central longitude of earth subsatellite point.
3. Communications Demonstrations	Display feasibility of synchronous satellite communications to live audiences.
4. Communications Performance	Measure overall communications performance of synchronous satellite system.
5. Communications Technical Characteristics	Measure detailed link and communications parameters in synchronous satellite system.

Thousands of successful special tests and demonstrations were performed over the Syncom satellites. These include numerous demonstrations of teletype, telephony, and facsimile. Special demonstrations displayed vocoder operation, multiple access using spread spectrum, real time relaying of satellite telemetry, transmission of oceanographic data, continuous 24-hour auto-tracking, 28 hours of continuous communications with the Kingsport while underway at sea, and direct teletype communications with an aircraft in flight. The latter employed the VHF command receiver and telemetry transmitter on Syncom III. (19).

Special occurrences among the demonstrations included President J. F. Kennedy speaking from the White House to the Prime Minister of Nigeria; President Kennedy's address to the United Nations; conversations between participants in the 1963 Extraordinary Administrative Radio Conference of the ITU in Geneva, Switzerland, and members of the U.N. in New York; and international TV coverage of the Olympics from Japan in October, 1964. The demonstrations also displayed that satellite time delay and echo could be overcome. However, to accomplish the latter it was found necessary to maintain incoming conventional phone line levels at -15 dBm or above with the equipment employed. The time delay presented few psychological problems even with unexpectant speakers.

The communications performance experiments described in Table 8-7 are defined and their basic results presented in Table 8-8. (3) (4) (15) (19) Results indicated are for half duplex operation. The Syncom II television transmissions involved a wideband FM modulator at Fort Dix. At the receive end, the Bell Telephone Laboratory's Andover terminal was outfitted with a maser preamplifier operating at the Syncom frequencies. The Syncom III Japan to California television test was the 1964 TV coverage of the Olympics. Television p-p signal to weighted rms noise ratios would be about 8 dB better than the unweighted values indicated in the table. This means signals were quite viewable but not of high quality.

The communications technical characteristic measurements noted in Table 8-7 are described in Table 8-9. (3) (4) In addition to the tests mentioned, the frequency response of the 50-kHz transponder on Syncom III was measured. It displayed an 87-kHz bandwidth at the 3-dB points. Further, measurements of the Faraday rotation of the 137-MHz telemetry signal from Syncom III provided considerable data on the electron content of the ionosphere. (20) (21)

8.6 OPERATIONAL RESULTS

The communications system operations on Project Syncom displayed that highly reliable synchornous satellite communications systems were feasible. During the initial experimental period of the program, operational responsibility for the Syncom satellites rested with NASA while DOD operated and maintained the ground communications terminals. In early 1965, DOD added the satellites to its operational responsibilities and employed them to provide operational military communications for the Far East, Pacific Ocean area, and Western United States. During all of the time the Syncom satellites were actively employed, no significant operational difficulties were encountered. Minor difficulties included a slight gas leak, a buildup of H_2O_2 pressure, and one receiver occasionally going into oscillation upon turn on under high spacecraft temperature conditions. Ground terminal operation and tracking was, in general, routine.

Table 8-8. Communications Performance Experiments

TYPE EXPERIMENT	NATURE OF RESULTS OBTAINED
1. Telephony	Single channel S+N/N of 35 dB* readily attained with maximum FM deviation** ratio employed. Multichannel*** operation demonstrated on Syncom III at reduction in per channel performance.
2. Data Transmission	Using vestigial sideband modems operating into 4–kHz baseband input to normal FM terminal equipment, 3–kbps rates at low error rates**** were possible. Using PSK RF modulation, data rates as high as 50 kbps were possible.
3. Teletype	For single channel operation into 4–kHz baseband input to normal FM terminal equipment, error rates of 0.1% were readily attained. For 1 of 16 channels into 4–kHz baseband, error rates less than 1% were attained.
4. Facsimile	Operating into standard FM terminal equipment, overall picture quality numerically rated at 7 on a 0 to 10 scale was commonly obtained. Factors degrading quality included bandwidth limitations,† phase delay distortion,† and satellite spin rate modulation.
5. Television	Fort Dix to Andover through Syncom II realized 26–dB p–p signal to rms noise ratio.†† Kashima to Point Mugu through Syncom III realized 34–dB p–p signal to rms noise ratio.†††
6. Direct Aircraft TTY	Pan American scheduled aircraft to Camp Roberts through Syncom III VHF command receiver and telemetry transmitter realized under proper conditions, up to 60–wpm TTY.††††

NOTES:
*Signal was 1–kHz tone; 35 dB provided better than 99% sentence intelligibility.
**Maximum was 10; lower ratios were also selectable.
***Four channel AN/TCC–3 multiplex employed on Syncom III.
****On order of 10^{-5} bits/bit.
†Ground terminal equipment imposed limitations.
††Video baseband bandwidth –2.5 MHz, p–p FM frequency deviation –4.5 MHz, preemphasis –14 dB, and audio signal transmitted separately.
†††Video baseband bandwidth –2.5 MHz, p–p FM frequency deviation –7 MHz, preemphasis –14 dB, sync pulses removed and regenerated at receiver, and audio handled separately.
††††Aircraft had vertically and horizontally polarized Yagi antennas. Roberts used TT&C Yagi antenna.

Table 8-9. Communications Technical Characteristics Measurement

TECHNICAL CHARACTERISTICS	NATURE OF RESULTS OBTAINED
1. Spacecraft Transfer Function	Beacon receives total output power for no communications signal present. Communications input must be varied over several dB to completely suppress beacon and capture TWT.
2. Ground Terminal UHF/SHF Beam Alignment	Determined from point of maximum suppression of beacon signal. Good alignment found.
3. Received Carrier Power at Ground	Measured values, in general, agreed with predicted values. For antenna elevation angles above 7.5°, no selective fading due to multipath existed.
4. Received Signal Level at Satellite	Agreed well with predicted values.
5. Frequency Response	For 4–kHz channel, baseband response exceeded the requirements of MIL STD 188B for a 6000–n.mi. reference circuit.*
6. Envelope Delay	For 4–kHz channel, baseband response exceeded the requirements of MIL STD 188B for a 6000–n.mi. reference circuit.*
7. Spacecraft Antenna Pattern	Performed with satellite spin axis in plane of orbit. Pattern shapes agreed well with prelaunch measurements and indicated about 1.5° error in measured satellite orientation parameters.
8. Intermodulation	Not performed on Syncom II. Nearly all measured degradation was due to AN/TCC–3 and FM modulation/demodulation.
9. Spacecraft Oscillator Frequency	Measured frequency agreed with prelaunch measurements.

*Ground terminal equipment imposed limitations.

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SECTION 9 - LINCOLN EXPERIMENTAL SATELLITES

9.1 INTRODUCTION

From its inception, the Lincoln Laboratory of the Massachusetts Institute of Technology has had an interest in long-range military communications systems. Early work was with ionospheric and tropospheric scatter systems. The scatter concept was extended, under U. S. Air Force sponsorship, to the West Ford Program. Upon successfully concluding Project West Ford, the Laboratory's program aims were recast, in 1963, towards developing active communications satellite techniques.(1) This program, also under Air Force sponsorship, has made use of the original West Ford ground terminals as well as small mobile ground terminals to communicate through a series of Laboratory-developed satellites designated the Lincoln Experimental Satellites (LES).

Lincoln Laboratory's active communications satellite program has been concerned with the development and testing of new spacecraft and ground terminal techniques having application to military command and control.(2) The objective of the spacecraft techniques investigations has centered on obtaining the maximum satellite effective radiated power for a given satellite mass. In agreement with this objective, research has been conducted on improved spacecraft power-generation systems, high efficiency spacecraft transmitters, high-gain spacecraft antennas, and spacecraft attitude stabilization and stationkeeping systems. The surface terminal techniques investigation has focused on developing methods of more effectively utilizing a given radio signal strength generated by a communications satellite. Areas of interest have included the development of efficient modulation-demodulation systems, random multiple access techniques having no stringent synchronization and control requirements, source signal encoding techniques that reduce required user data rates, low noise receiving systems, and simple antenna systems suitable for small terminals.

In the first phase of the program, particular attention was given to X-band frequencies in the vicinity of the microwave bands allocated for military communications. This emphasis was a natural extension of the X-band capabilities developed during the Project West Ford experiment.(3) In the second phase of the program, attention has been focused on frequencies in the 225 to 400 MHz UHF communications band. This band is used for a wide variety of United States government communications services.

To date, six satellites, LES-1 through -6, have been launched as part of this program and employed in experiments. LES-7 was conceived as a high ERP, three axis stabilized, 300 to 500 pound satellite using a lens antenna and a 19 horn feed cluster to provide a composite beam whose shape could be carried by ground command to fit the earth coverage requirements of a particular link. This satellite would have operated at X-band but funding considerations plus a greater interest in experiments at the UHF frequencies resulted in its cancellation. Presently, plans exist for a LES-8 and LES-9 to be launched by late 1974 but these experiments are still in the concept formulation stage.

9.2 X-BAND SATELLITES

9.2.1 General Description

Specific objectives of the satellites and earth terminals included in this portion of the LES program are listed in Table 9-1.

Table 9-1. X-Band Experiment Objectives

Number	Description
1	Investigate X-Band Satellite Communications Performance
2	Display Operation of Solid-State X-Band Transponders
3	Investigate Despun Antennas
4	Evaluate Autonomous Satellite Attitude Control
5	Study Space Radiation Environment
6	Demonstrate Efficient Error Correcting Coding-Decoding Techniques
7	Investigate Minimum Data Rates for Voice Signal Transmission
8	Study Multiple Access Techniques with no Stringent Synchronization Requirements

Three X-band satellites have been launched during the LES program as indicated in Table 9-2(4) (5). LES-1 was correctly injected, by its launch vehicle, into an inclined medium altitude circular orbit. However, a design flaw in the satellite's ordnance circuity prevented ignition and separation of the rocket motor supplied for final orbit injection. This left the combination in the medium altitude circular orbit instead of a 1500 by 8000 nautical mile inclined elliptical orbit as planned. At separation from the launch vehicle, the satellite-rocket motor combination was spun up about the axis of least inertia to 180 rpm. When the rocket motor failed to separate, spin axis conversion immediately started to occur. Before it was completed, a few initial communications tests were conducted. The X-band repeater and antenna switching system functioned properly but the tumbling mode that was assumed destroyed LES-1's usefulness.

LES-2 was successfully launched along with the Lincoln Calibration Sphere (LCS)-1 later in 1965. This satellite was almost identical to LES-1. With the benefit of a revision of the satellite's ordnance circuitry, it was placed into the type of orbit that had been planned for LES-1. Numerous communications experiments were conducted with this satellite and all objectives listed in Table 9-1, with the exception of Item 5, were accomplished. The satellite contained no experiment measuring the space radiation environment.

LES-4 was launched along with LES-3, Oscar 4, and OV2-3 as a secondary payload aboard the third flight test of the Titan IIIC. LES-3 was a UHF Lincoln Experimental Satellite operating as a radio signal generator. Oscar 4 was an amateur radio communications satellite for use by "Hams" throughout the world. OV2-3 was a scientific satellite to gather data on solar and geomagnetic activity by measuring changes in cosmic ray and trapped particle fluxes. The objective was to place LES-3 and LES-4 into near synchronous (i.e., 18,200 nautical mile), circular orbits having a 0° inclination. After a near perfect injection into parking and transfer orbits, the Titan III C third stage failed to ignite and LES-3 and LES-4 were ejected into highly elliptical inclined orbits.

Table 9-2. X-Band Spacecraft

Satellite		LES - 1	LES - 2	LES - 4
Manufacturer & Sponsor		Lincoln Laboratories & U. S. Air Force		
Launch Date		2/11/65	5/6/65	12/21/65
Launch Vehicle		Titan III A		Titan III C
Orbital Data (1)	Apogee (mi.)	1744	9384	20,890
	Perigee (mi.)	1726	1757	124
	Inclination	32.2°	31.4°	26.6°
	Period (min.)	145.7	315.2	589.6
Status		In orbit, solar array degraded, and tumbling with satellite rocket motor still attached.	In orbit but was shut down automatically by its internal clock in 1967.	Transmission ceased in October 1968. Orbit subsequently decayed and satellite was destroyed. elliptical orbit.

NOTE: (1) At initial injection. Parameters of LES-4 were altered by atmospheric drag due to the low perigee.

LES-4's initial spin axis orientation was such that solar panel illumination provided telemetry power only. By late 1965, a residual magnetic moment along the spin axis had precessed the spin vector until the sun was only 47° below the satellite equator. This provided sufficient solar power to allow operation of all systems. As a result of the unplanned orbit, one of the two onboard antenna switching control systems and the magnetic spin axis orientation system could not be operated. However, one of the two antenna switching control systems did operate properly and all of the objectives listed in Table 9-1, with the exception of Item 4, were for the most part successfully accomplished.

The principal satellite communications terminals participating in experiments with the X-Band LES satellites are listed in Table 9-3(6) (7). The terminal at Camp Parks and one of the terminals at Millstone Hill were the facilities originally developed for Project West Ford. Lincoln Experimental Terminal-1 (LET-1) was a transportable ground terminal housed in two vehicles capable of being towed as trailers. One vehicle contained the antenna and RF equipments. The second vehicle continued the signal conditioning and processing equipment necessary for signal generation, modulation and up conversation to IF. The LET-1 terminal was located adjacent to the Lincoln Laboratory's Facilities in Lexington. The other two LET terminals consisted of a LET-1 type signal processing van utilized with existing antennas and RF equipment. LET-2 employed the 60-foot West Ford antenna and X-band RF equipment at Millstone Hill. LET-3 employed the 30-foot antenna and X-band RF equipment of the Army's transportable Mark 1A terminal.

The LET-3/Mark 1A combination was initially deployed to Camp Roberts, California for LES tests. After a few months it was moved to Ft. Monmouth, New Jersey for a limited number of LES experiments and subsequent modification for tests with the IDCSP satellites.

Table 9-3. Participating Earth Terminals

Location	Sponsor	Antenna Diameter (Ft)	Date Installed
Camp Parks, California	U.S. Air Force	60	1961
Millstone Hill, Mass. (West Ford)	U.S. Air Force	60	1961
Lexington, Mass. (LET-1)	U.S. Air Force	15	1965
Millstone Hill, Mass. (LET-2)	U.S. Air Force	60	1965
Camp Roberts, California (LET-3)	U.S. Army Satellite Communications Agency	30	1966

Tracking and VHF telemetry data was obtained primarily by the Camp Parks and Millstone Hill (West Ford) terminals. The satellite launchings were provided by the U.S. Air Force.

The X-Band LES program was responsible for a number of significant contributions to satellite communications technology. It proved the feasibility of building solid state X-band transponders for operation in a communications satellite. A useful communications capability was supplied even though satellite dc to RF power conversion efficiency and RF power output were relatively low. The feasibility and performance capabilities of electronically switched despun antennas were demonstrated. A workable automatic magnetic spin axis torquing system for attitude correction was exhibited. The performance potential available through the application of convolution encoding and sequential decoding to satellite links was displayed. Frequency hopping was shown to be a satisfactory means of multiple access having no stringent synchronization requirements and giving considerable protection against interfering signals. Finally, the capabilities of both pitch-excited and voice-excited vocoders, when used over a satellite link, were demonstrated. The former handled speakers at the satellite ground terminal while the latter allowed remote speakers, connected through the normal switched telephone network, to use low rate digital satellite voice circuits.

9.2.2 System Description

The West Ford terminals contained conventional analog voice signal processing and frequency modulation equipment while the newly developed LET terminals were equipped for digital signal processing. As a result, the three LET terminals interoperated independent of the West Ford terminals. Individual terminal loop back tests plus half and full duplex two-terminal operations were conducted. Extensive multiple access tests were not performed due to the limited number of participating terminals having compatible modulation and signal processing systems. However, the LET terminal approach to modulation made multiple access a real possibility even for operation with hard limiting satellites.

Operating frequencies for the X-band Lincoln Experimental Satellites are shown in Table 9-4(8). By choosing the X-band frequencies for communications experiments, it was possible to make use of ground terminal facilities previously developed for Project West Ford. More important, however, it afforded the opportunity in accordance with the program objectives, to conduct tests and develop experimental hardware operating at frequencies internationally allocated for military satellite communications.

Table 9-4. X-Band LES Operating Frequencies (MHz)

Communications			Telemetry*
Up Link	Downlink	Beacon	
8350	7750	7740	237

*VHF tracking was also performed on this signal. A command system was not employed.

The two West Ford terminals used conventional FM for their RF modulation and frequency division multiple access when full duplex operations were conducted. Signal processing and link performance for LET operations with LES are summarized in Table 9-5(7) (9) (10). The signal structure except for the frequency hopping feature is sketched in Figure 9-1(9).

In the LET system, the elementary channel symbol used was a sinusoidal pulse 200 μs in duration on one of 16 frequencies. The received pulse was detected by a bank of 16 matched filters. This modulation-demodulation system was preceded by a convolutional encoder and followed by a sequential decoder. Information rates of approximately 200 bps, 5 kbps, and 10 kbps were achieved.

At the 5-kbps rate, an information bit was fed to the encoder every 200 μs. The encoder generated three parity check bits based on the 60 preceding information bits. These four bits were employed to select one of 16 channel frequencies every 200 μs. At the receiver the match filter outputs were sampled every 200 μs and ordered according to magnitude. The seven samples of largest magnitude were fed to the sequential decoder which recovered the original information bits.

Analogous operation occurred at the 10 kbps rate. In this case, one parity check bit was generated for each input information bit and two information and two check bits were used to select 1 of 16 channel frequencies. At the 200 bps rate, 24 successive 200 μs pulses carried the same information while the 25th pulse was a synchronization pulse. At the receiver, the matched filter outputs were integrated over 24 successive pulses before ordering the samples and decoding.

This signalling system guaranteed accurate transmission at low values of E_b/N_o. To convert this into multiple-access, or anti-interference operation, the block of 16 channel frequencies employed in any 200 μs symbol interval was, itself, pseudorandomly hopped over the 20 MHz bandwidth of the terminal and satellite RF systems. Since the frequency hopping occurred only every 200 μs, the signal acquisition and synchronization requirements were modest as compared to a pseudonoise spectrum spreading system. Acquisition was achieved automatically using time and frequency predictions obtained from a station clock and the satellite ephemeris. The desired synchronization was achieved by transmission of a synchronizing pulse (i.e., a 200-μ s pulse that is frequency hopped but carries no information) every 5 ms. A tracking loop integrated over many of these pulses in sequency to achieve the desired timing and frequency accuracies of 5 μs and 625-Hz, respectively.

Table 9-5. Signal Processing for LET Operation with LES-4

Multiple Access	Code Division through pseudorandom frequency hopping of channel center frequency
RF Modulation	MFSK employing 16 channel frequencies
Ground Demodulator Performance	E_b/N_o(1) of 6 dB required(2) corresponding to 43 dB/Hz signal-to-noise density ratio for a 4.8-kbps voice channel
LET-1 Receive Carrier-to-Noise Density	58 dB/Hz based on operation at synchronous altitude, 2 watt satellite EIRP, & 100°K(3) receive system noise temperature.
Margin Required for Link Degradation	5 dB
Margin Available for Multiple Access	10 dB corresponding to 10 potential users of the same type

Notes: (1) Energy per bit to noise density ratio

(2) Gives probability of error of 10^{-3} when matched filter detection and sequential decoding of convolution encoded signal is employed.

(3) Represents LET receiver thermal noise alone. For code division multiple access when almost entire satellite output represents interference, receive system noise temperature was raised a maximum of 12.7°K.

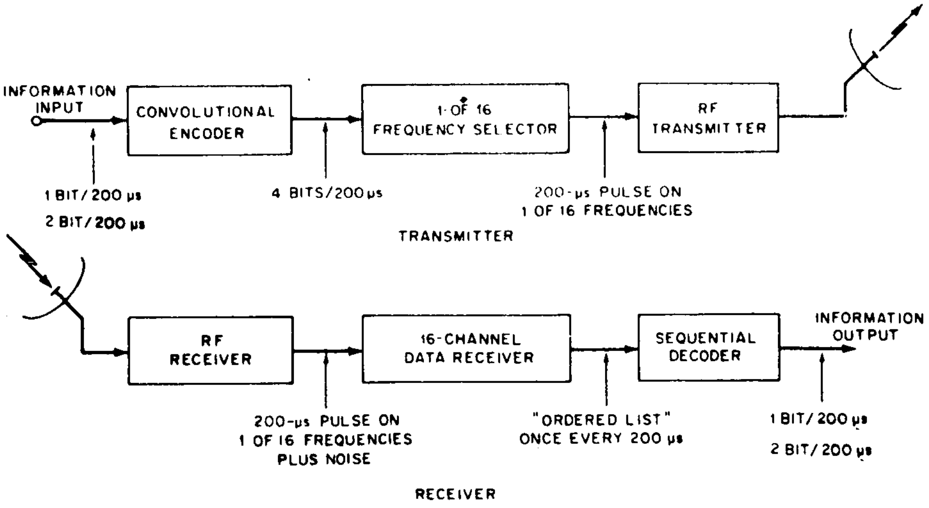

Figure 9-1. Simplified Terminal (without Frequency Hopping)

The three alternate information rates provided corresponded, in order of ascending rate, to transmission of two 100-wpm teletype channels, a pitch-excited vocoder output (4.8 kbps) plus the two teletype channels, or a voice-excited vocoder output (9.6 kbps) plus two teletype channels, respectively. The two vocoder systems were provided in one unit capable of two modes of operation. Both modes provided a high degree of intelligibility and speaker recognizability. In the pitch-excited mode, a high fidelity input was required as provided by the high quality microphone at the LET terminal. When operated at the higher data rate, the vocoder was used in the voice-excited mode, allowing the use of a degraded input, including a "phone patch" connection to the commercial telephone plant.

9.2.3 Spacecraft

Characteristics of the communications-related subsystems of the LES-1, 2 & 4 spacecraft are given in Table 9-6(1) (8) (11). The LES-1 and 2 satellites were nearly identical in all respects and the transponder, aboard all three spacecraft, was basically the same. A simplified block diagram of the transponder is shown in Figure 9-2. A 60-MHz IF was employed which made double up conversion necessary to avoid the need for narrow sideband separation filters at the 7.8-GHz output frequency.

LES-1 and 2 were designed to operate with their spin axis normal to the earth-sun line. As a result, the spacecraft orientation relative to the earth varied making a broad range of coverage by the satellite antenna pattern necessary. This was solved through the 8-element switched array of antenna elements arranged in two rings. The two 4-element rings girded the upper and lower hemispheres of the satellite, respectively. Sensors operating at the wavelengths of visible light served as inputs to the logic system determining spacecraft spin rate and earth direction. The logic controlled antenna switching. A 2-throw switch selected the ring to be activated while a 4-throw switch performed the despinning within an individual ring. The automatic magnetic torquing system employed solar cells on the upper

Table 9-6. Satellite Characteristics

SATELLITE		LES 1 AND 2		LES 4	
ANTENNAS	Type	X–Band – Switched array of 8 horn elements* in 2 rings about spin axis	UHF Telem. – Four 1/8–wavelength monopoles	X–Band Xmit. – Switched single ring array of 8 horn elements. X–Band Rec. – Biconical horn.	UHF Telem. – Circumferential gap between X–Band xmit. and receive antennas.
	Number	One	One	One	One
	Xmit. Beamwidth (3 dB)	Pencil Beam a minimum of about 60° wide including switched beam pointing errors.	Omnidirectional	Pencil Beam 23° wide at minimum dimension	Toroidal pattern of greater than earth coverage width.
	Gain	Xmit. – 3.1 dB Rec. – 3.7 dB	0 dB	Xmit. – 10.6 dB Rec. – 4.4 dB	1.4 dB in equatorial plane of satellite
REPEATERS	Frequency Band	X–band		X–band	
	Type	IF translation hard limiting		IF translation hard limiting	
	Bandwidth (1 dB)	20 MHz		20 MHz	
	Number	One		One	
	Receiver				
	Type front end	Down conversion mixer		Down conversion mixer	
	Front end gain	No Data		No Data	
	System Noise Figure	16 dB		9 dB	
	Transmitter				
	Type	Up converter output radiated		Up converter output radiated	
	Gain	No Data		No Data	
	Power out	115 mW		230 mW	
	EIRP	–7 dBW		3 dBW	
GENERAL FEATURES	Stabilization				
	Type	Spin with autonomous magnetic torquing of spin axis		Spin with autonomous magnetic torquing of spin axis	
	Capability	LES–2 settled to 12° ± 7° from perpendicularity to satellite–sun line		Torquing inoperable due to unplanned orbit	
	Power Source				
	Primary	Silicon solar cell array providing at least 27 watts at launch		Silicon solar cell array providing at least 40 watts at launch	
	Supplement	None		None	
	Comm. Pwr. Needs	No Data		No Data	
	Size	Polyhedron 24 in. wide between opposite square faces		10–sided cylinder approximately 25 in. high and 31 in. across	
	Weight	69 lbs. for LES–1 and 82 lbs. for LES–2		116 lbs.	

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*Each horn was terminated in a diverging lens.

and lower halves of the satellite to excite aluminum windings on four torquing rods mounted parallel to the spin axis. The onboard telemetry system utilized direct binary phase shift keying of a UHF carrier. No command system was provided.

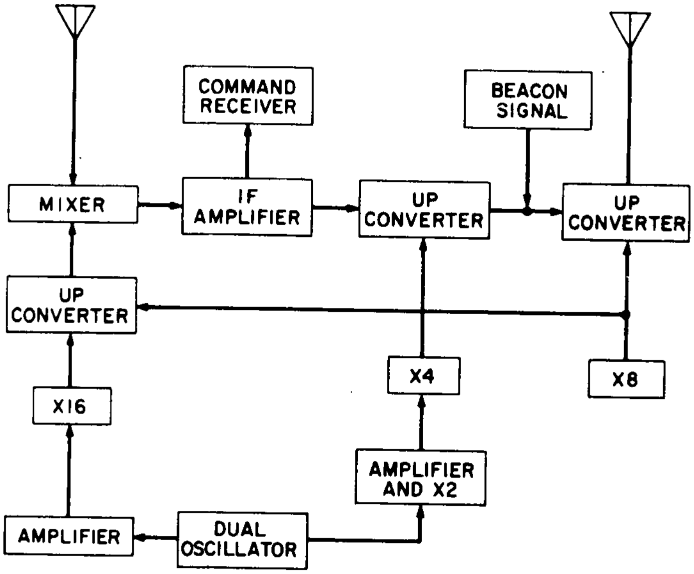


Figure 9-2. LES X-Band Transponder

LES-4 was designed to maintain its spin axis perpendicular to the orbital plane. This allowed all antenna elements to be arranged in one switched ring providing a higher gain. Visual sensors served as inputs to two different antenna-pointing logic systems. One system operated much as that on LES-1 and 2 measuring spin rate and determining direction of the earth center once per revolution. The second measured earth direction at one point in the orbit and time to travel to a second known point in the orbit. Assuming a circular orbit, this allowed predictions of earth direction to be derived as a function of orbital position.

The transponder was the same as that on LES-2 except for changes in the crystal mixer, IF amplifier, directional couplers, and power monitoring circuits. An isolator was eliminated, line lengths reduced, and connectors matched at operating frequencies. These changes increased transmitter power by 3 dB and suppressed spurious frequencies. The autonomous magnetic torquing system generated two orthogonal axes in inertial space and measured spin axis orientation relative to these axes once per orbit at points, 90° apart, where the satellite orbit intersected these fixed axes. LES-4 also included a radiation experiment to measure spatial and temporal variations of the energy spectrum of trapped electrons. The spectrum was measured in five energy ranges from 130 keV to 4 MeV.

9.2.4 Ground Terminals

Among the terminals listed in Table 9-3, the Lincoln Experimental Terminals were the major stations involved in experiments with the X-band Lincoln Experimental Satellites. LET-1 and LET-2 performed most of these tests. The characteristics of LET-1 are summarized in Table 9-7(9) (12). Characteristics of the existing Millstone Hill antenna and RF equipment employed in LET-2 were discussed in the description of Project West Ford ground stations in Section 5.4. A block diagram of the LET-1 system is shown in Figure 9-3(9).

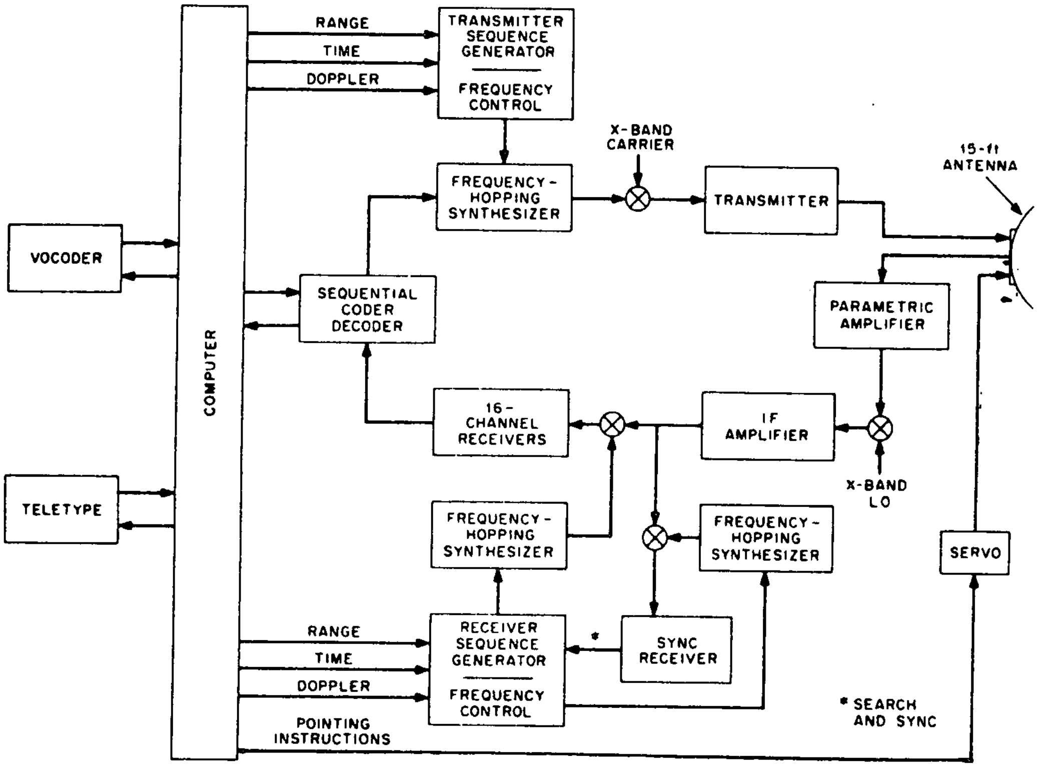


Figure 9-3. LET System

Table 9-7. Characteristics of LET-1 Ground Terminal

Antenna	Type	Cassegrain
	Aperture Size	15 ft. diameter
	Receive Gain	48 dB
	Efficiency	50 percent
	Rec. Beamwidth	0.58° at 3 dB pts.
Receive System	Type Preamplifier	cooled parametric amplifier
	Bandwidth	20 MHz
	Noise Temperature	100°K at 90° elev. in clear weather
Transmit System	Type Amplifier	Klystron
	Bandwidth	20 MHz
	Amp. Pwr. Out	10 kW
Tracking	Type	computer-aided monopulse autotrack
	Accuracy	no data
Total Performance	G/T	28 dB/°K *
	EIRP	118 dBm *
Polarization	Transmit Feed	right hand circular
	Receive Feed	left hand circular
Installation	Radome	none
	Type Facility	transportable in two trailers **

Notes: * A derived value based on data available.

** An electronics vehicle and an antenna vehicle.

As has been indicated, LET-1 was contained in two vehicles. The electronics vehicle was a modified low-bed commercial van which contained the signal processing equipment, a communications and antenna control console, a prime power generator and its fuel, an air conditioner, and storage for the antenna panels. The second trailer, called the antenna vehicle, contained the transmitter and its heat exchanger, a refrigerated parametric-amplifier receiver, low-level microwave equipment, the antenna backup structure, feeds, and servo-mechanism equipment. The use of circularly polarized antenna feeds made the terminal compatible with the circular polarization employed by the X-band antennas on LES-1, -2, and -4.

In addition to its signal processing, the LET system included another novel innovation. It incorporated a small general purpose digital computer (UNIVAC 1218) as an integral part of the communications terminal. The computer system was assigned four major tasks. It derived pointing angle inputs to the antenna servo system. This computation also produced range and Doppler estimates for use in time and frequency synchronization. The computer generated displays for terminal operators and provided flexible operating controls. Further, it handled vocoder and teletype message traffic multiplexing/demultiplexing.

9.2.5 Experiments

Experiments conducted during the X-band portion of the LES program may be grouped into six major categories as indicated in Table 9-8(1) (4) (9). The automatic magnetic torquing experiment was a success on LES-2 where, after several months, the spin axis settled into an average 12° position away from perpendicular to the satellite-sun line. The spin axis oscillated ±7° about this position with a period of 135 days(1). Automatic magnetic torquing of the spin axis could not be accomplished on LES-1 and -4, however, due to the tumbling mode assumed and improper orbit respectively.

The space radiation experiment was conducted on LES-4 exclusively. With the highly elliptical orbit attained, LES-4 supplied extensive data on the energy spectrum of trapped electrons in five energy ranges from 130 keV to 4 MeV and at altitudes from 100 to 18,200 nautical miles(1). Five solid state detectors were employed. A sixth detector was continually exposed to a source of known intensity and served as a calibration sensor such that the degradation of the five detectors due to the space radiation environment could be determined. Three of the five detectors were shielded silicon cells while the other two were CdTe thin film cells. Results on the CdTe cells, as constructed, indicated they could not satisfactorily withstand a space environment(13). Earth albedo measurements were also made as an additional experiment on the earth environment(14) (15).

Table 9-8. Summary of X-Band LES Experiments

Experiment	Program Objective Satisfied*	Nature of Activity
1. LET Terminal & Signal Processing	6,7&8	Evaluate performance of antenna, RF components, & signal processing system.
2. Satellite X-Band Transponder	1 & 2	Demonstrate feasibility of solid state satellite transponders for operation at X-Band
3. System Performance	1,2,6,7&8	Measure LES/LET capability when operated as a communication system
4. Despun Antenna	3	Study antenna switching as a method of antenna despinning in spin stabilized satellites
5. Space Radiation Environment	5	Determine temporal and spatial characteristics of near earth space radiation
6. Automatic Magnetic Torquing of Spin Axis	4	Evaluate feasibility of magnetic torquing for automatic attitude alignment of spin stabilized satellites.

*Program objectives are numbered and defined in Table 9-1.

The despun antenna experiment was carried on all three X-band satellites. On LES-1, the switched antenna functioned as expected during most of the first 10 orbital revolutions until conversion to the 60-rpm tumbling mode was completed(16). On LES-2 operation was satisfactory and in agreement with expectations. The use of conventional optics at visible wavelengths in conjunction with logic initially designed for IR sensors resulted in some anomalous operation(1). Near satellite sunrise and sunset, the logic tended to lock on the sun rather than the earth. Moreover, the logic tended to point antennas toward the middle of the illuminated crescent rather than at the middle of the earth. These difficulties were not crucial as the ground sites operated with daylight at both transmitter and receiver. On LES-4 the antenna system which measured earth direction during every satellite rotation also operated essentially correct. Operation occasionally broke up for typically tens of minutes in a 8-hour pass due to a defective circuit(14). The second switching logic system on LES-4 could not operate properly at all since the satellite was not in a circular orbit.

Measurements on the LET system included evaluations of the performance of RF equipment, antenna system, and signal processing system. In the two former areas, transmitter output power, receiver noise temperature, system bandwidth, and antenna autotrack capability were particular parameters of interest(17). These measurements demonstrated performance in agreement with specified values. Performance of the signal processing system was demonstrated in "back-to-back" testing. Both the voice-excited vocoder mode using remote speakers connected to the terminal through the commercial switched telephone network and the pitch-excited vocoder mode using local speakers displayed satisfactory operation. In both modes, familiar speakers could easily be detected. The frequency hopping, MFSK, and convolution encoder-sequential decoder combined signal processing system displayed a threshold in close agreement with the 6 dB E_b/N_o expected (18). Theory and practice were in almost perfect agreement when 0.3 dB of loss due to non-ideal matched filters and another 0.3 dB of loss due to non-ideal pulsed signals (i.e., the switching time of the frequency synthesizer was 2-4 μs) were taken into consideration. The one-way delay induced by the sequential decoder was about 200 μs(7).

The satellite X-band transponder received considerable operational evaluation on LES-2 and LES-4. Satellite EIRP, receiver noise figure, bandwidth, frequency stability, and beacon performance were all monitored and found to be the same as measured during prelaunch checkouts(19). LES-1's transponder was operated for a short time until the satellite assumed its tumbling mode and the transponder performed as expected(16).

The satellite system performance tests and their results are summarized in Table 9-9(9) (11) (16) (19) (20). These tests were conducted with LES-2 and LES-4. Specific results mentioned in the table are for operation with LES-2.

9.2.6 Operational Results

Since these were experimental satellites, no operational traffic was carried. The general performance of all spacecraft was good and in agreement with expectations. The solar array output on LES-1 had degraded significantly by September of 1965 due to the satellite being left in a circular orbit within the Van Allen Belt(19). With LES-2 being in an elliptical orbit having an apogee out of the area of severe Van Allen Belt radiation, its solar array did not show significant degradation until mid 1966(6). Even then the difficulties were not severe enough to impair transponder or telemetry operation.

The Lincoln Experimental Terminals provided generally reliable performance. One significant initial difficulty was due to the installation of the general purpose computer. Its inclusion resulted in certain equipment malfunctions being difficult to localize because "everything was so connected."(9) When this became clear, special troubleshooting programs and techniques were designed. With these techniques, the computer became an asset since it could test all interconnecting equipment.

9.3 UHF SATELLITES

9.3.1 General Description

On October 2, 1965 a Deputy Secretary of Defense memorandum titled "Tactical Satellite Communications Research and Development" inagurated the U.S. military's TACSATCOM experimental program. This memorandum instructed the military departments to initiate studies in R&D to hasten the use of satellite repeaters for tactical communications. Experiments with the UHF Lincoln Experimental Satellites

Table 9-9. Satellite System Performance Experiments

TYPE EXPERIMENT	NATURE OF RESULTS OBTAINED
1) FM Voice & Music	Monostatic plus half and full duplex bistatic tests conducted by Camp Parks and Millstone Hill (West Ford). Quality was excellent.
2) Vocoded Voice & TTY (Full duplex)	LET-1 conducted tests. Transmitter power necessary to attain receiver threshold measured as function of satellite range. Measured values generally agreed* with calculated theoretical values. **
3) Vocoded Voice & TTY (Full duplex)	LET-1 & LET-2 conducted tests. LET-2 transmitter adjusted 8 dB below that of LET-1. Measured performance agreed well with theoretical performance based on projected up and down link parameters, hard limited satellite transfer function, and theoretical receiver threshold. **
4) Interference Sensitivity	With either interfering tone or wide-band noise, no interference to normal transmissions detected until interfering signal substantially exceeded communications signal on satellite up link. Communications failed only when interference forced the communications downlink signal to drop below receiver threshold.
5) Frequency Spread vs. Processing Threshold	Spreading from frequency hopping varied over 2.5, 5, 10, and 20 MHz. No change in signal processing threshold occurred except at the 20 MHz rate. At this rate, bandpass limitations of the satellite and terminals caused some degradation.
6) Vocoder Performance	For operation above threshold, both vocoded modes displayed essentially the same performance as found in LET "back-to-back" tests.
7) Vulnerability to Intelligent Hostile Jamming	Performance compared to pseudonoise for a broad class of jammers. Results classified.

Notes: * Deviations caused by: satellite power varying with temperature, age and inexact aiming of satellite antennas; terminal receive noise temperature varying with weather conditions and antenna elevation angle; path loss varying with weather conditions, satellite range, and antenna elevation angle; terminal calibration changing with age; and satellite and terminal bandpass not being entirely flat.

** Theoretical threshold occurs at a received power to noise density ratio (P_r/N_o) of 43 dB based on an E_b/N_o of 6 dB and a 4.8 Kbps vocoder data rate. This compares to a P_r/N_o of 52 dB required to obtain comparable quality on a single FM voice channel.

(LES) constituted the initial phases of this program. The program was continued by the successful launching of TACSAT I in early 1969 (see Section 14). Specific objectives of the satellites and earth terminals included in the LES portion of the TACSATCOM program are listed in Table 9-10(21).

Table 9-10. UHF LES Experiment Objectives

Number	Description
1	Develop and demonstrate space hardware operating in the miliary UHF frequency bands
2	Develop and demonstrate mobile tactical terminals operating at the military UHF frequencies
3	Investigate propagation characteristics of UHF satellite links
4	Determine the extent of RF interference to a UHF tactical satellite communications system
5	Study electronic switching in despun antennas
6	Evaluate high efficiency RF transmitters
7	Demonstrate automatic onboard satellite attitude control
8	Display automatic onboard satellite stationkeeping
9	Study the space radiation environment

Three UHF Lincoln Experimental Satellites were launched as part of the TACSATCOM program as indicated in Table 9-11(22) (23) (24) (25). LES-3 was launched along with LES-4, Oscar 4, and OV2-3 as indicated in the "General Description" of the X-band LES (see Section 9.2.1). When the improper injection into a highly elliptical inclined orbit occurred, LES-3 was left spinning at 140 RPM with its spin axis inclined about 15° to the orbital plane(14). This was in contrast with the planned perpendicular orientation. Despite the unplanned orientation, LES-3 operated as designed and, in accordance with its sole mission objective, provided the signals necessary to carry out UHF propagation measurements. Atmospheric drag, resulting from the low perigee of this satellite's highly elliptical orbit, eventually caused the orbit to decay but not before all desired testing had been successfully completed.

Table 9-11. UHF Spacecraft

Satellite		LES-3	LES-5	LES-6
Manufacturer & Sponsor		Lincoln Laboratories and U. S. Air Force		
Launch Date		12/21/1965	7/1/1967	9/26/1968
Launch Vehicle		Titan III C		
Orbital Data*	Apogee (mi)	20,890	20,894	22,236
	Perigee (mi)	124	20,692	22,119
	Inclination	26.6°	7.2°	3°
	Period (min.)	589.6	1,319	1,431.2
Status		Formal spacecraft observations terminated in late summer 1967. Orbit decayed 4/6/68 and satellite was destroyed.	In orbit but a failure in the final power amplifier driver stage caused radiations to cease in late May 1970.	In orbit and active with output power reduced due to solar array degradation. Stationed at approximately 40° West longitude.

NOTES: *At initial injection. Atmospheric drag, solar pressure, and attitude and stationkeeping maneuvers are among causes of parameter changes.

LES-5 along with its companion satellites, IDCSP 16 through 18, DATS 1 and DODGE, constituted the payloads successfully launched by Titan III-C Vehicle No. 14 into planned near-synchronous, near-equatorial orbits(21) (26). The three essentially identical IDCSP satellites, DATS 1 and DODGE were all part of the Initial Defense Communication Satellite Program (see Section 12). IDCSP 16-18 augmented two earlier successful launches of seven and eight IDCSP satellites respectively and completed the first U. S. global experimental military communication satellite system. DATS 1 was electrically identical to the IDCSP satellites but employed an experimental electronically despun antenna. DODGE was intended to study a number of advanced gravity-gradient stabilization techniques at near-synchronous attitudes and to take color TV pictures.

LES-5 and the ground complex employed with it provided experiments aimed at meeting all of the objectives listed in Table 9-10 with the exception of Items 5, 6 and 8(21). The satellite was utilized, during its 3-year (approximate) active lifetime, by tactical terminals of all the U. S. armed services and NATO forces. In general, the experiments conducted allowed all of the intended objectives to be accomplished. These successes were attained in spite of a number of minor spacecraft failures. Difficulties included predictable daily periods of abnormally high rate receiver timing signals to the command system and Radio Frequency Interference (RFI) Experiment, predictable yearly periods of reduced receiver sensitivity, failure of one of four sun sensors providing inputs to the automatic attitude control system, and a 1.7 kHz frequency shift in one of two transponder local oscillators resulting in a corresponding change in frequency translation.

LES-6, OV2-5, OV5-2, and OV5-4 were successfully launched into planned orbits by Titan III-C Vehicle No. 5(21) (27). The launch vehicle's Transtage left LES-6 in an essentially synchronous equatorial orbit. The satellite's onboard cold ammonia thruster system was used for final adjustment into a stationary orbit with the spacecraft positioned at about 86° West longitude(28). OV2-5 and OV5-2 were launched to collect data on the space radiation environment while OV5-4 provided an experiment on heat transfer in a liquid under zero-g conditions. LES-6 and the ground terminals operating with it provided experiments aimed at meeting all of the objectives listed in Table 9-10.

Shortly after orbital injection it was observed that the satellite was spinning about an axis offset about 2.2° from the axis of symmetry of the cylinder (i.e., nutating). Additionally one solar panel, lying in the plane defined by the actual spin axis and the axis of symmetry, was providing a severly reduced power output(29). The exact cause of these seemingly related difficulties was not determined. It was hypothesized that the satellite unbalance and resultant spin axis offset was produced by about 1.1 pounds of weight added to the outside surface of the cylinder. One theory suggested that an object was caught on a dipole antenna and was shadowing the solar panel. The net effect was to make the automatic attitude control system unusable and produce a spin rate modulation of the solar array dc power output that resulted in a similar modulation of the RF power output.

A further difficulty was encountered about a week after launch when a relay flip flop failed in the Earth Position register of one of the satellite's two antenna switching logic systems(29). However, the second switching logic system remained in good working order and was able to successfully handle antenna switching except during periods of darkness of the subsatellite point. The satellite was allowed to drift from its initial position to about 93°W longitude and was maintained at this location by the automatic stationkeeping system for several months. During these initial months in orbit, the satellite was employed by tactical terminals of all of the U. S. armed services in tri-service tests and all of the objectives listed in Table 9-10, with the exception of Item 7, were successfully accomplished.

On July 23, 1969 a program was initiated to move LES-6 further eastward to about 40°W longitude so that the NATO countries of Europe could view the spacecraft(30). The satellite arrived at its new station in the beginning of December 1969(31). It has been maintained at approximately this location until the present and continues to be employed by the NATO countries and the U. S. armed services.

The major satellite communications ground station involved in testing with all three UHF Lincoln Experimental Satellites was the Lincoln Laboratory's terminal located on the roof of Building B at the Laboratory in Lexington, Massachussetts(29)(32). This terminal employed a 30-foot parabolic antenna and initially came into being in 1965. It was subsequently upgraded in performance capabilities. Lincoln Labs supplemented this terminal in late 1966 with a small truck-based UHF terminal employing a 12-dB gain helix antenna(6). This terminal was designated LET-4 as it was preceded by three transportable SHF Lincoln Experimental terminals (see Section 9.2.1). LET-4 was a major participant in LES-5 and LES-6 testing.

In addition to these terminals, a host of mobile terminals built by the three major U. S. armed services used the satellites. These included fixed wing aircraft, helicopter, surface ship, submarine, van, small truck, jeep, and manually carried terminals(33)(34)(35)(36). The latter included small terminals that can be carried by one man and larger terminals carried by a team of men.

Fixed wing aircraft outfitted with these terminals included B-52s, C-135s, and P-3s. Many of the aircraft tests used airplanes based at Wright Patterson Air Force Base in Ohio. Helicopters provided with terminals included the UH-1F and UH-1D aircraft. Surface ship terminals involved in tests included the USS Providence, USS Guadalcanal, USS Threadfin, USS Picuda, USS Pocono, USCGC Glacier, and USS Leahy. Submarine terminals participating in tests included the USS Tullibee and USS Thornback. Army tests of vehicular and manually transported terminals were conducted at Fort Monmouth, New Jersey and Fort Clayton, Panama Canal Zone among other places. Various fixed or semi-fixed stations making some use of LES-5 and LES- were located at Rome, New York; St. Petersburg, Florida; San Diego, California; New London, Connecticut; Patuzent River, Maryland and St. Inigoes, Maryland.

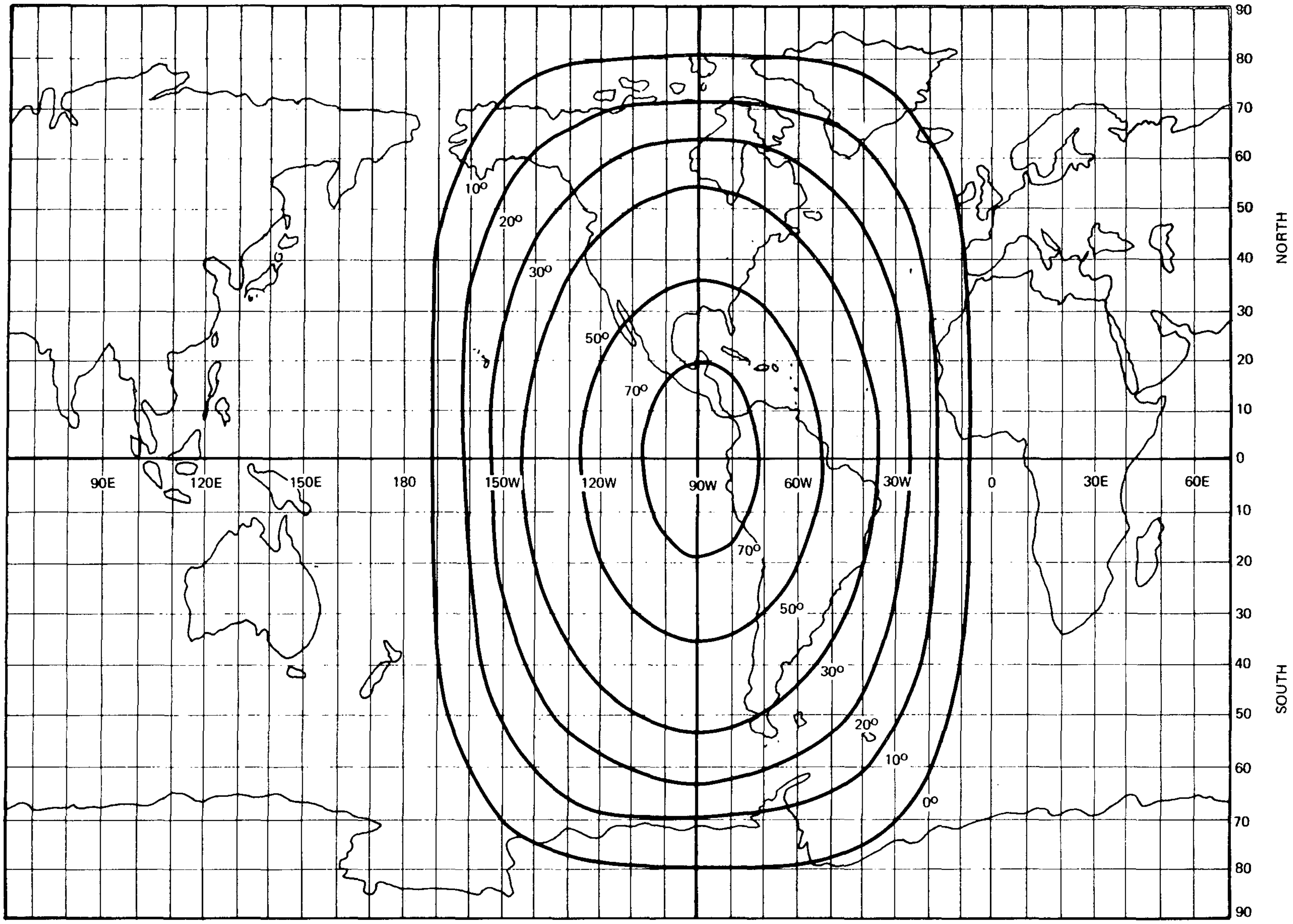
Spacecraft telemetry was obtained by Lincoln Laboratory facilities at Camp Parks, California; Millstone Hill, Massachusetts; and Lexington, Massachusetts. Additional locations receiving special installations of telemetry equipment included

Cape Kennedy, Florida and Guam Island. The main command station was Lexington, Massachusetts. Spacecraft launchings were provided by the U. S. Air Force.

The UHF LES program resulted in numerous advancements in technology available to support the design of satellite communications systems. It significantly advanced the state of knowledge of UHF propagation and the UHF noise environment including RF interference. In particular, the studies characterized propagation and noise pertinent to systems involving small mobile aircraft, ship, vehicular and manpack terminals. Workable experimental tactical communications terminals, including antennas and modems, were developed and demonstrated. The feasibility of high efficiency UHF satellite transmitters operating directly from an unregulated solar array power supply was displayed accurate autonomous attitude control of spin-stabilized near-synchronous satellites was exhibited. The feasibility of autonomous stationkeeping and station changing was demonstrated. These two automatic control concepts could ultimately greatly simplify the need for ground control operations and ground tracking requirements. This may become important as the number of satellites in orbit increases and the separation between them decreases. In addition, an electronically switched despun antenna system successfully operating at UHF frequencies was displayed.

9.3.2 System Description

Numerous linking arrangements were devised among the many terminals participating in tests. The tests included individual terminal loop back, two terminal hald duplex, full duplex, and multiple access tests. Many of these tests centered upon the Lexington terminal. The orbit of the LES-5 spacecraft supplied 5 days of visibility at Lexington out of the 11 required for its slight west-to-east drift to produce one revolution of movement relative to a given spot on the surface of the earth(23). The earth visibility supplied by LES-6 in its initial stationary location is shown in Figure 9-4(33).



10°
20°
30°
50°
70°
70°
50°
30°
20°
10°
0°
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E
60E
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
NORTH
SOUTH

Operating frequencies for the three UHF Lincoln Experimental Satellites are shown in Table 9-12(14)(21)(33). The choice of the UHF frequency band for these studies was governed principally by the antenna problem and the spectrum allocations that were available for military use. In the very constrained physical environment of a small mobile terminal, and in particular in the environment of an aircraft, it is highly desirable to use simple antennas which do not require accurate pointing. Given this requirement, a relatively low frequency is attractive since the receiving cross section of a dipole antenna is proportional to the square of the wavelength(33). The limitations on the lower end of the spectrum are governed by noise background and spectrum availability

Table 9-12. UHF LES Operating Frequencies (MHz)

Satellite	Communications			Telemetry
	Uplink	Downlink	Beacon	
LES-3	--	--	232.9	No data
LES-5	255-280(1) 255.1(2)	228.2	228.43	236.75
LES-6	290-315(1) 302.7(2)	249.1	254.14	236.75

Notes: (1) Frequency band over which RFI measurements were made. Command receiver operated off RFI receiver.

(2) Center frequency of communications transponder.

The major approaches to signal processing centered upon a triple frequency-time diversity technique conceived by Aerospace Corporation and developed by Electronic Communication Inc., and the frequency hopped Tactical Transmission System (TATS) developed by Lincoln Labs. Conventional analog FM and frequency division multiple access were also occasionally employed. Signal processing and link performance when the frequency diversity technique was employed on a channel perturbed by Gaussian additive noise are summarized in Table 9-13(33)(34).

The triple diversity modem handled 60 or 100 word per minute teletype using an asynchronous baudot code. Incoming teletype messages were reclocked to obtain a uniform bit stream which could be split into three chips per bit. The three chips were sequentially transmitted on three different frequencies. There was a constant frequency separation between the three "Mark" and three "Space" frequencies. The data demodulator used a phased lock loop to derive ship timing such that the proper pair of matched filters were sampled at the proper time. The total energy present in the three mark channels was compared with the total energy present in the three space channels for each bit time to decide if a "Mark" or "Space" had been sent. This system was designed specifically for aircraft and with its 100-kHz bandwidth provided good resistance to multipath fading down to an elevation angle of about 4° to the satellite for an airplane flying at about 30, 000 feet. The triple diversity also provided protection against RFI.

Table 9-13. Signal Processing Using Frequency Diversity

Multiple Access	Frequency Division but frequency-time diversity(1) provides some resistance to interference from other users in same frequency band.
RF Modulation	FSK
Ground Demodulator Performance	E_b/N_o(2) of 12 dB required(3) corresponding to 31 dB/Hz signal-to-noise density ratio for 75 bps TTY channel
C-135 Receive Carrier-to-Noise Density	44 dB based on operation with LES-5 at maximum range and utilization of blade aircraft antenna with 1-kW transmitter (4) and receiver having 4.5 dB noise figure
Link Margin	13 dB

NOTES:
(1) Each bit divided into three chips. Each chip transmitted successively at separate frequency.
(2) Energy per bit-to-noise density ratio
(3) Gives probability of error less than 10^{-3} based on matched filter detection and integration over outputs of each of three filters representing "Mark" and "Space" respectively.
(4) Spacecraft transponder operated at 100-kHz bandwidth and marginally saturated by uplink signal.

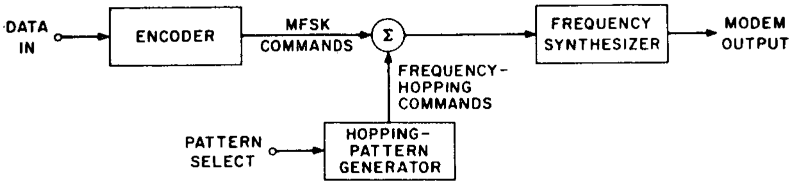
Signal processing and link performance when the TATS modem was employed on a channel perturbed by Gaussian additive noise are summarized in Table 9-14(33)(37)(38). A functional block diagram of a TATS modem is given in Figure 9-5(37). This modem was specifically designed for the military tactical communications environment and continued to be used in extensive testing on TACSAT I (see Section 14.5). It was designed to allow a high level of random multiple access with a minimum of acquisition and synchronization difficulties, provide a high degree of resistance to RFI, and supply good performance in the face of multipath fading. As designed, it provided little resistance to jamming.

Table 9-14. Signal Processing Using TATS

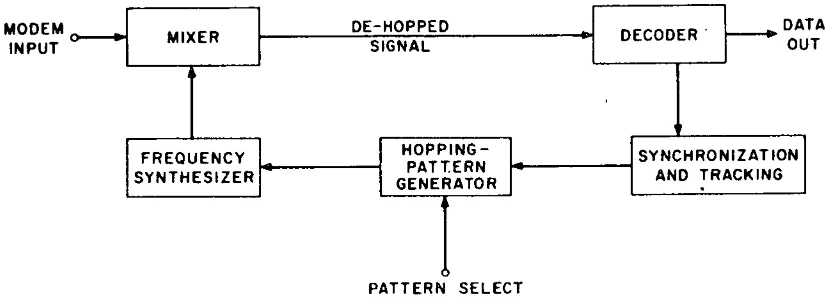
Multiple Access	Code Division through frequency hopping of channel center frequency
TATS Demodulator Performance	E_b/N_o(1) of 11 dB required(2) corresponding to 45 dB/Hz signal-to-noise density ratio for a 2.4 kbps vocoded voice channel
C-135 Receive Carrier-to-Noise Density	55 dB based on operation with LES-6 at maximum range and utilization of blade aircraft antenna with 1 kW transmitter(3) and receiver having 4.5-dB noise figure.
Link Margin	10 dB

Notes: (1) Energy per bit-to-noise density ratio
(2) Gives probability of error less than 10^{-3} based on matched filter detection and Reed-Solomon coding of data
(3) Spacecraft transponder operated at 500-kHz bandwidth and marginally saturated by uplink signal.

The basic signaling waveform was a T_c second sine wave pulse on one of eight frequencies spaced at $1/T_c$-Hz increments. Six bits of information corresponding to sixty-four possible states of the input word were coded into a sequence of seven such pulses using the (7, 2) octal Reed-Solomon code(37). An additional fixed frequency pulse started each seven pulse code word to aid in time and frequency synchronization. Therefore, the time to transmit each code word was 8 T_c seconds. Since each code each word contained six bits of information, the data rate was $0.75/T_c$ bits-per-second. At the two data rates handled by the modem (i.e., 75 or 2400 bits/sec), T_c was 10 msec. or 312.5 μs, respectively.



(a) TRANSMITTER



(b) RECEIVER

Figure 9-5. TATS Functional Block Diagram

At the receiver, the amplitude of the envelope out of each of eight matched filters was sampled and quantized to one of 16 levels at the end of each T_c-sec pulse interval(37). Seven sets of these measurements, corresponding to one code word, were used to generate 64 numbers related to the likelihood that each of the 64 possible code words was the one actually being received. The maximum likelihood 6-bit information word was outputed each 8 T_c seconds.

Bandspreading was accomplished by generating a new base or carrier frequency in each pulse interval to which the frequency selected in that interval by the input code word was added(37). The carrier hopping pattern consisted of a repetitive sequence of seven frequencies chosen from a larger set of possible carrier frequencies. Since the modulation frame contained 8 pulses or chips, the carrier frequency for each chip position within the modulation frame was cycled through the carrier hopping pattern. This guaranteed frequency diversity in the sync measurement in the presence of selective fading.

The hopping patterns were selected such that each pattern used the whole transmitted bandwidth (i.e., 500 kHz or 10 MHz as selected) and the number of pattern overlaps between members of the selected set were small for all possible time shifts. The first property provided the diversity necessary to combat frequency selective fading due to multipath and RFI. The second property minimized the possibility of decoder error due to channel cross-talk.

9.3.3 Spacecraft

Characteristics of the communications related subsystems of the LES-5 and 6 spacecraft are given in Table 9-15. See References 21, 32, and 39 through 42. A block diagram of the transponder on LES-5 is shown in Figure 9-6(39). The LES-6 transponder was basically the same as that shown for LES-5. Transponder frequencies, powers and bandwidths were different. Additionally, the beacon transmitter served as the third input to the antenna triplexer instead of the telemetry transmitter. The latter employed a separate antenna for signal radiations.

The characteristics of LES-3 are not summarized in Table 9-15 since it did not contain a communications repeater. LES-3 was built to provide an orbiting UHF beacon to be used for propagation measurements. It radiated 28.5 watts biphase modulated by a 15-bit pseudorandom sequence clocked at a rate of 100 kHz (11)(14). Such a signal permitted detailed measurements of the multipath and fading characteristics of the propagation medium.

LES-3 was constructed utilizing the frame, power system, and power amplifiers designed for LES-1 and 2 and was similar in appearance to these satellites(1)(19). The most apparent difference was a lack of optical sensors and X-band antennas on the triangular faces and the presence of a UHF monopole antenna projecting from the top and bottom rectangular surfaces of the spin stabilized satellite. These surfaces

Table 9-15. Satellite Characteristics

		Satellite	LES-5	LES-6	
Antennas		Type	UHF-Array of 16 axial cavity backed slots in 2 rings and 8 full-wave deployable dipoles in 1 ring.(1) Triplexer allowed communication xmit and receive plus telem. to use same antenna system	UHF-Switched array of 16 axial cavity backed slots and 16 axial half-wave extended dipoles.(1) Both slots and extended dipoles in 2 rings of 8 elements each.	Telem-Monopole stub extended from one end along line of spin axis.
		Number	One	One	One
		Xmit Beamwidth (3 dB)	Torroidal pattern about 37° wide	Pencil beam 34° x 47°	Omnidirectional
		Gain	Xmit - 2.5 dB; Rec - 2.2 dB	Xmit - 10 dB; Rec - 10 dB	0 dB
Repeaters		Frequency Band	UHF	UHF	
		Type	IF translation hard limiting	IF translation hard limiting	
		Bandwidth (3 dB)	100 or 300 KHz switchable on ground command	100 or 500 KHz switchable on ground command	
		Number	One	One	
	Receiver	Type Front End	Down Conversion Mixer	Down Conversion Mixer	
		Front End Gain	No data	No data	
		System Noise Figure	3.6 dB	3.6 dB	
	Transmitter	Type	Four hybrid summed transister amplifiers in final stage	Eight hybrid summed transistor amplifiers in final stage	
		Gain	About 25 dB for transmitter power amplifier chain	About 10 dB for final stage and 60 dB for total xmit chain	
		Power Out	42 watts	122 watt at launch	
		EIRP	17 dBW	29 dBW at launch	
General Features	Stabilization	Type	Spin with autonomous magnetic attitude control system	Spin with autonomous magnetic or gas thruster attitude control system plus autonomous stationkeeping using cold ammonia gas or pulsed plasma thrusters	
		Capability	Spin axis was kept within 2.6° of orbit normal	Automatic attitude control inoperable because of spin axis misalignment.(2) Stationkeeping displayed capability of keeping satellite within about 2° of desired longitude.	
	Power Source	Primary	Silicon solar cell array providing 136 watts at launch	Silicon solar cell array providing 220 watts at launch	
		Supplement	None	None	
		Communication Power Needs	Approximately 70 watts	Approximately 180 watts	
		Size	Cylindrical approximately 66 inches in length and 48 inches in diameter	Cylindrical approximately 66 inches in length and 48 inches in diameter	
		Weight	225 lbs	360 lbs	

Notes: (1) Elements in 2-ring arrays employed in collinear pairs made up of one element from each ring. Slot arrays driven in phase quadrature with extended dipole arrays. This in combination with the orthogonal polarization of the two types of arrays produced a circularly polarized antenna system.

(2) System was designed to attain an accuracy of ±0.16° using gas thruster system.

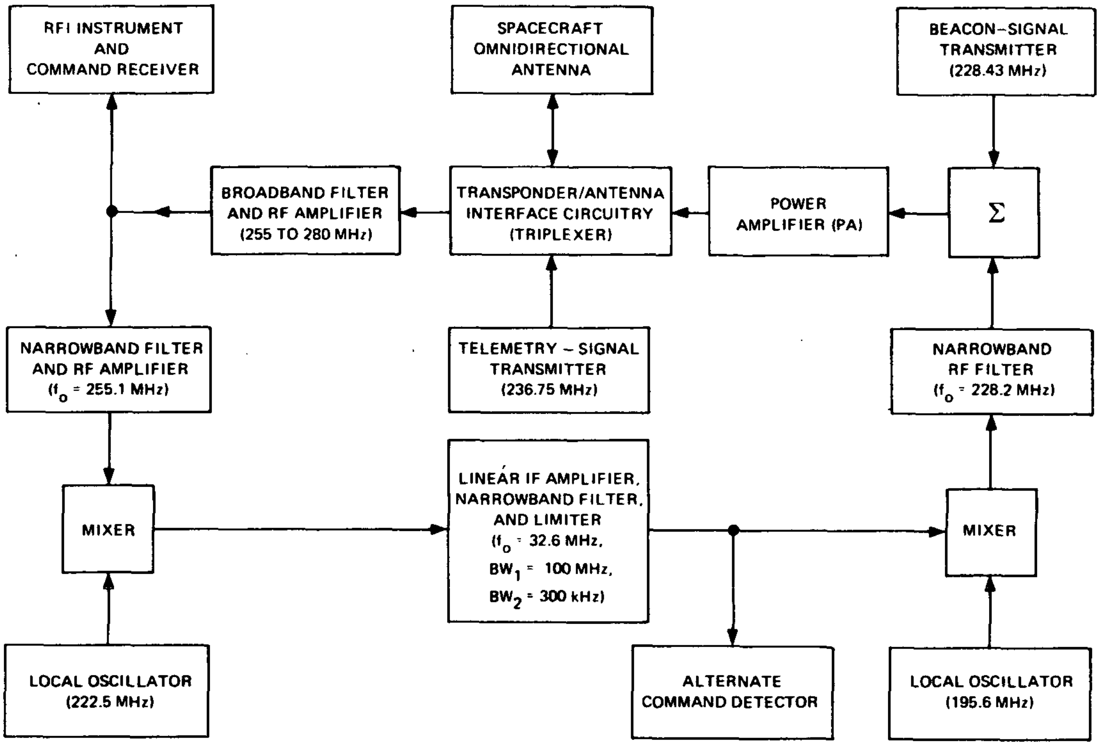


Figure 9-6. LES-5 Transponder Block Diagram

carried no solar cells. The antenna system produced a toroidal pattern with a measured gain of 4-1/4 dB in the direction perpendicular to the spin axis. The spacecraft weighed approximately 32 pounds.

LES-5 provided, in addition to the features indicated in Table 9-15, a solar cell degradation experiment, an RF interference experiment, and experimental switching logic for antenna despinning although no actual antenna switching was performed(21). The solar cell experiment included measurements on two 10-ohm cm. silicon cells with 30-mil. cover slides, one 10-ohm cm. silicon cell with 6-mil. cover slide, and two CdS thin film cells(13). The satellite RFI receiver had a 120-kHz noise bandwidth and was designed to tune from 283 MHz to 253 MHz in 256 steps of approximately 120 kHz each, dwelling at each step for 2.56 seconds(43). The time for a complete frequency scan was approximately 11 minutes. In the fixed frequency modes, the RFI instrument also functioned as the command receiver for the spacecraft. The onboard experimental switching logic was included to obtain data for the design of the despun antenna system flown on LES-6.

LES-6 provided, in addition to the features indicated in Table 9-15, a solar cell degradation experiment, space radiation environment measurements, an earth albedo experiment, an RF interference experiment, precision spin period measurements, and a communications transmitter making highly efficient use of available dc power(21). The solar cell experiment studied radiation effects pertinent to solar power arrays made from the standard silicon cells normally used and effects on experimental cells of various types. The latter included lithium-doped cells made from silicon grown by crucible, float zone and Lopex techniques; cells made from silicon grown by the dendretic support process; cells manufactured by ion implant techniques; CdS thin film cells, and Cd Te thin film cells(44). The space radiation experiment was designed to measure the trapped electron spectrum over the range of 275 keV to 3 MeV(21)(45). The earth albedo experiment measured the reflected optical spectrum from the earth in 6 spectral bands from 0.41 microns to 1.00 microns(21). The RFI experiment was very similar to that on LES-5 except it measured interference in the band from 290 to 315 MHz(43). Precision spin period measurements were a by-product of a special clock rate generator included on LES-6 as part of the automatic stationkeeping system. The high efficiency transmitter operated directly from the solar bus. The power amplifier load line was adjusted to be coincident with the locus of maximum power points as the output from the solar array varied with sun illumination and satellite life(21). There was no dc-dc converter losses in order to obtain proper regulated voltages and no unutilized power for solar array radiation degradation margins.

9.3.4 Ground Terminals

The major station involved in UHF LES testing was Lincoln Laboratory's Lexington terminal. Early military terminals involved in the program were the Electronic Communication, Inc., (ECI) terminals employed by the Air Force(33) and Navy and the Project East vehicular earth terminals(35) developed by the Army. The ECI terminal was an experimental, off-the-shelf, single channel, low data rate, teletype communication system that employed the triple frequency diversity ECI modem. The U. S. Navy version of this terminal was nicknamed a LODUS terminal. The U. S. Air Force version was designated the UHF terminal (ECI 591). The U. S. Army's Project East equipments included two jeep, two 3/4-ton truck, and one 26-foot van terminal. They were assembled from off-the-shelf commercial and military equipment and employed conventional frequency modulation for voice and teletype communications. Block diagrams of typical Air Force ECI and Army 3/4-ton truck terminals are shown in Figures 9-7 and 9-8 respectively.

With the experience gained from operating these early terminals, the U. S. Armed Services went on to develop terminals specially designed for operation in a tactical military communications environment. These terminals employed the TATS modem, developed by Lincoln Laboratories and produced by Sylvania Electronics Products Inc., as a major mode of communications. They are described in the discussion of ground terminals employed with TACSAT I (see Section 14.4). Characteristics of the Lexington fixed terminal and a typical C-135 aircraft ECI terminal are delineated in Table 9-16(6)(33)(34)(36)(39). The linear polarization of the blade aircraft antenna resulted in a 3-dB link polarization loss since all of the UHF Lincoln Experimental Satellites had circularly polarized antennas. The crossed dipole and crossed slot aircraft antennas were circularly polarized.

9.3.5 Experiments

A multitude of small mobile terminals were available for test operations and innumerable measurements, demonstrations, and tests of a wide variety were conducted over the UHF Lincoln Experimental Satellites. Demonstrations even included support of Apollo 9's splashdown by LES-6. Major categories of significant experiments were as indicated in Table 9-17(21)(33).

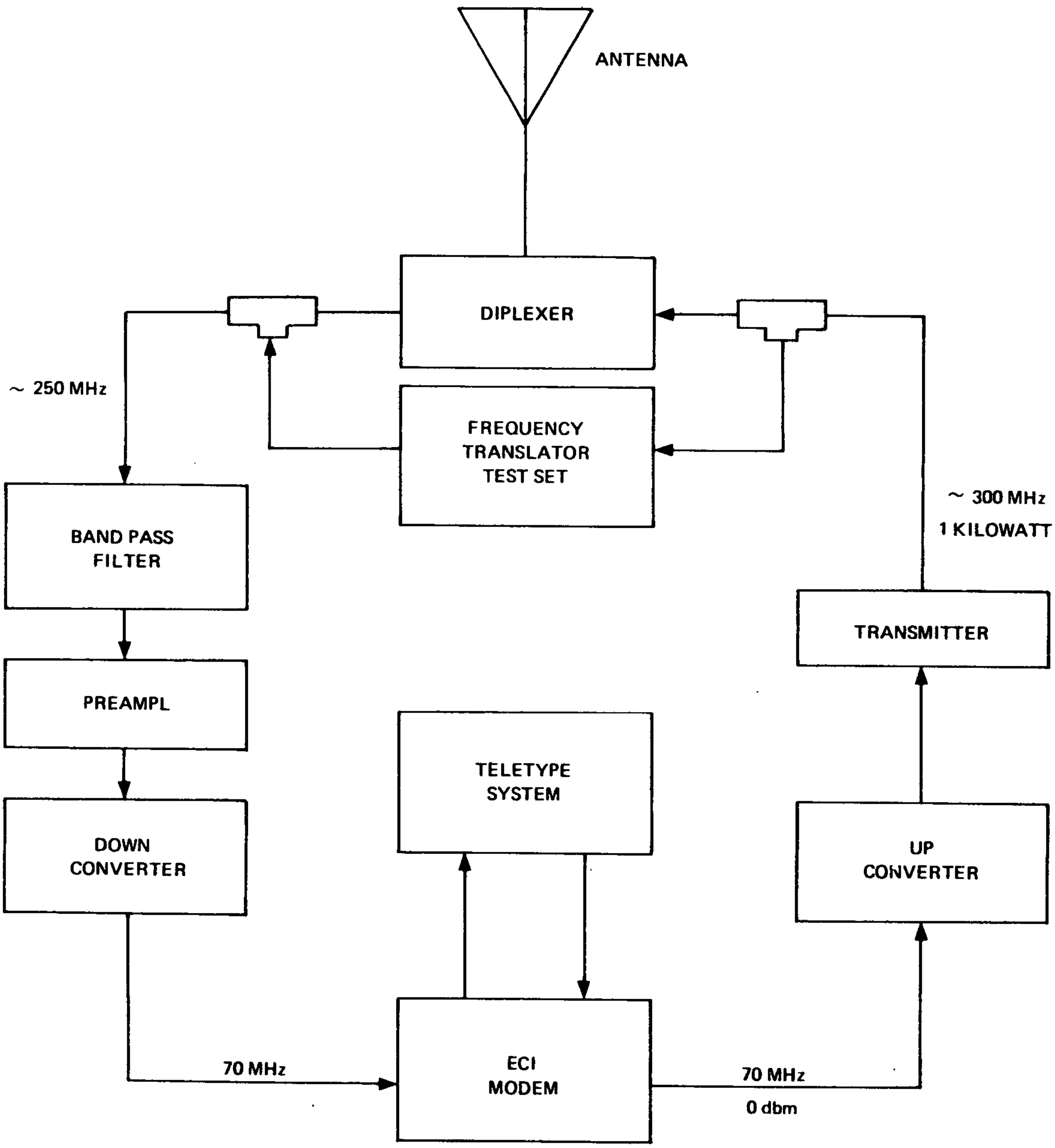


Figure 9-7. ECI UHF Terminal Block Diagram

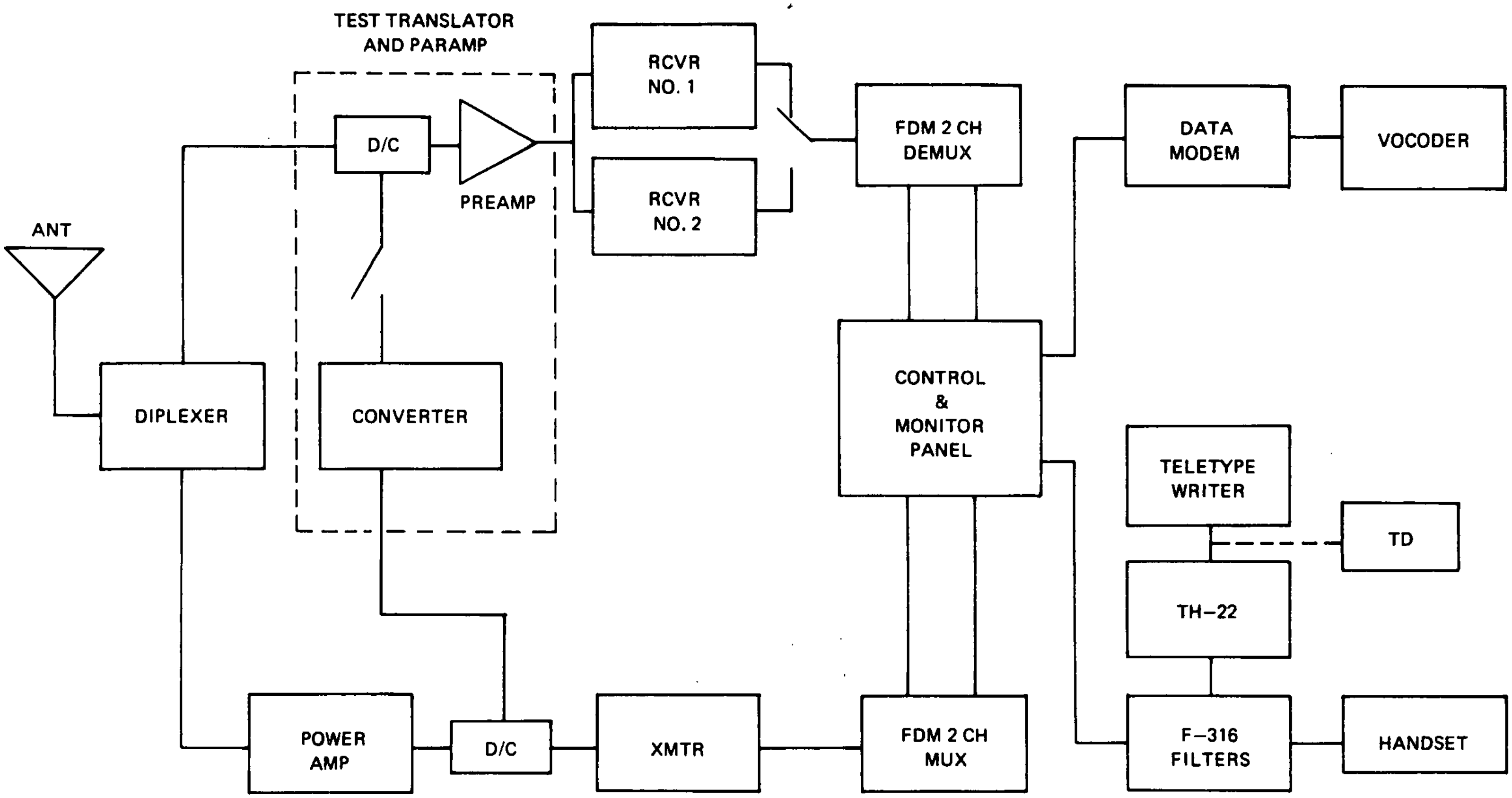


Figure 9-8. Project East 3/4-Ton Terminal Block Diagram

C-3

Table 9-16. Characteristics of Major UHF LES Terminals

Terminal Feature		Lexington	C-135 ECI
Antenna	Type	Parabolic Reflector	Blade(1)
	Size	30-ft Diameter	5½ in. x 1 in x 8½ in.
	Receive Gain	23 dB	4 dB
	Efficiency	42%(2)	No data
	Rec. Bandwidth	10° @ 3 dB Pts.(2)	Approx. 35° width for toroidal pattern
Receive System	Type Preamplifier	No data	No data
	Bandwidth	No data (3)	100 KHz
	Noise Temperature	No data	500-800°K
Transmit System	Type Amplifier	No data	No data
	Bandwidth	No data(3)	100 KHz
	Amp. Power Out	1 kW	1 kW
Tracking	Type	Autotrack	None
	Accuracy	No data	None
Total Performance	G/T	No data	-24 dB/°K (2)
	EIRP	83 dBm(2)	64 dBm(2)
Polarization	Transmit Feed	Circular	Linear
	Receive Feed	Circular	Linear
Installation	Radome	None	None
	Type Facility	Fixed	Aircraft Terminal

Notes: (1) Other antennas such as crossed dipoles and crossed slots were also employed.

(2) Derived value based on data available.

(3) Had to be at least 500 KHz to be compatible with the bandwidth of LES-6.

Table 9-17. Summary of UHF LES Experiments

Experiment	Program Objective Satisfied*	Nature of Activity
1. Aircraft Antennas	2	Evaluate antennas for use on airplane and helicopter satellite communications terminals.
2. Satellite Multiple Access	1, 2&3	Determine system limits and constraining factors for multiple access using tactical terminals.
3. Tactical Modems	2	Measure performance of different tactical terminal modulation/demodulation techniques.
4. Propagation Link Losses	3	Evaluate factors producing variations from link attenuation determined by conventional free space spreading and antenna gain considerations
5. System Noise and Interference	3&4	Measure receive system noise temperatures and RF interference to tactical satellite communications systems.
6. Satellite UHF Transponder	1	Determine performance of solid state satellite repeaters operating at UHF.
7. Solar Cell Degradation	9	Study the effect of the space radiation environment on various experimental solar cells.
8. Earth Albedo	9	Define the spectrum of electromagnetic energy at optical frequencies as reflected by the earth and viewed by a synchronous satellite.
9. Space Radiation Environment	9	Measure temporal and spatial characteristics of near earth, space radiation.
10. Automatic Stationkeeping	8	Evaluate the feasibility of autonomous onboard control employing either cold ammonia gas or pulsed plasma thrusters.
11. Automatic Attitude Control	7	Determine the feasibility of autonomous on board control employing either magnetic torquing or cold ammonia gas thrusters.
12. High Efficiency RF Transmitters	6	Demonstrate the feasibility of satellite transmitters operating directly from a solar array primary power system.
13. Despun Antenna	5	Study use of switching in conjunction with multi-element arrays as a means of realizing a despun antenna on a spin stabilized satellite.

*Program objectives are numbered and defined in Table 9-10.

The despun antenna, indicated in the table, was flown on LES-6 and consisted of an array of 8 elements with each element composed of a pair of collinear axial extended dipoles in combination with a pair of collinear axial slots(21). Two elements were excited at a time and all combinations of successive elements were sequentially activated as the satellite rotated. Each combination was excited in either of two-phase relationships to produce two beam positions per pair of elements and a total of 16 switched overlapping beams in the array. Post launch measurements of antenna gain indicated it was in the region of 8.5 to 9 dB, which agreed with pre-launch measurements. Pattern ripple due to beam switching was ±0.5 dB(29).

Two antenna-switching logic systems were included on LES-6 which could be operated independently or in a combined mode(21). As on LES-4, one system measured the direction to the earth at one point in the orbit and predicted the orbital position of the satellite as a function of time while the second system determined earth direction during every revolution of the spinning satellite. In the combined mode, the earth direction measuring system was employed during the hours of local daylight at the subsatellite point and the orbit storage system was used during the hours of local darkness. All modes of operation worked well for the first week in orbit(29). Subsequently a relay flip-flop failed in the Earth Position register of the orbit storage system causing inaccurate pointing in both that mode and the mixed mode. The earth direction measuring system continued to work as expected. As on LES-4, however, pointing became inaccurate between local sunset and sunrise as the satellite's optical sensors lost track of the exact location of the earth.

Proper operation of LES-6's high efficiency RF transmitter from a varying dc power source was verified immediately after launch when it was discovered that one solar panel was not delivering the expected power. This failure produced a spin variation of about 1 volt in the solar bus voltage which resulted in about a 0.5-dB spin variation in transmitted power(29). This variation was superimposed on the ripple due to beam switching. The transmitter has continued to perform properly as solar array output has varied with the season of the year and satellite lifetime in orbit.

Automatic attitude control systems were included on both LES-5 and LES-6. Their principal of operation was basically the same. They measured latitude, of the satellite-earth line, relative to the satellite's equatorial plane at points 90° apart in the orbit, providing a good view of both the sunlit earth and the sun(21)(46). By positioning the measurements 90° apart, X and Y axes of correction were established. In making a limited number of measurements it was assumed that the satellite attitude did not change greatly between measuring points. Proper orbital measurements points were determined by the coincidence of pulses from specially positioned earth and sun sensors. Knowledge of the satellite spin rate, as determined from sun sensor measurements, and X and Y axis errors allowed corrections to be triggered at the appropriate points during every satellite rotation.

The LES-5 attitude control system employed only magnetic torquing for corrections and operated correctly in spite of the failure of one of its four sun sensors. The effect of the failure was to reduce the rate of attitude correction but not its overall accuracy(21). The system demonstrated a capability of keeping the spin axis within 2.6° of normal to the orbital plane(46). The LES-6 system provided either magnetic or cold ammonia gas thruster corrective torquing and was designed to maintain attitude within 0.16° when the gas thruster system was employed(21). The LES-6 system could not be operated when the satellite spin axis was found (immediately after launch) to be offset 2.2° from the axis of symmetry of the cylinder.

The automatic stationkeeping system on LES-6 used an accurate onboard clock to provide an indication of the time at which the satellite should arrive at a given point in its orbit(21)(28). The time of actual arrival, as determined by the clock and the coincidence of sun and earth sensor observations, was compared with the desired time to generate longitude position errors to be corrected by firing thrusters as appropriate. Thrusters firings were activated at satellite orbital points separated by 180° in order to ensure that orbit eccentricity remained constant. Either cold ammonia gas thrusters or pulsed plasma electric microthrusters, using solid Teflon as the propellant, could be employed for corrections.

Both thruster systems displayed proper and reliable operation although some intermittency of the pulsed plasma thrusters was observed after they had fired for several thousand hours(47). Further, the system displayed a capability of maintaining the spacecraft within about 2° of a desired reference longitude.

The earth albedo and space radiation environment experiments were carried on LES-6 alone. Both experiments have returned considerable data that has been useful in characterizing the space environment. In the case of the radiation experiment, this was accomplished in spite of interference produced when the communication antennas situated closest to the experiment were energized(48). Data taken during periods of interference were unusable. However, there were times defined by a set of earth and sun angles during which valid data could be obtained.

Solar cell experiments on LES-5 and LES-6 returned valuable data that has contributed towards the design of spacecraft solar arrays. LES-5 silicon cells showed an initial 4 percent degradation and an 8 percent yearly degradation. The CdS cells displayed a 5 percent initial degradation and a 20 percent yearly degradation(13). LES-6 experiments revealed, among other things, that low energy proton damage effects at the unshielded edges and contact bars of cells do occur in synchronous orbit and are significant and that lithium doped P-N cells fair quite poorly with an initial year's degradation as high as 42 percent(44).

The UHF transponders carried on LES-5 and LES-6, in general, performed well. Measurements taken included received communications signal level, local oscillator frequency stability and transponder frequency translation, bandwidth, receiver sensitivity, transponder total and differential time delay, transponder transfer characteristics, and beacon performance. The receiver on LES-5 showed a 17-dB seasonal decrease in sensitivity which was attributed to an open circuit in the first RF amplifier that was produced as the average temperature of the satellite decreased(21). The satellite temperature cycle was such that the sensitivity dropped in March and recovered in November of each year. In addition, one of the transponder local oscillators exhibited a sudden 1700-Hz shift in frequency in December

1968. This produced a comparable change in translation frequency. It was hypothesized from ground testing on similar hardware that a capacitor in the LO experienced an abrupt change in value. LES-6 has performed almost exactly as predicted throughout its lifetime except for the output variations due to the spin modulation on the dc power supply. None of the difficulties reviewed significantly handicapped the communications test program.

Results of UHF noise and interference measurements are given in Table 9-18(33)(35)(43). As indicated by the table, receiver composite noise temperature measurements were taken on vehicular, shipborne, and airborne terminals while uplink UHF interference levels at a synchronous satellite were measured on LES-5 and LES-6. LES-5's RFI receiver experienced a timing problem which was hypothesized to be due to cross coupling from one of the onboard logic systems that operated on earth-sun inputs. These inputs disappeared around local midnight at the subsatellite point as did the RFI receiver timing problem. As a result, all of the LES-5 RFI data was centered about local midnight. LES-6's data gave a 24-hour distribution of interference but since the satellite was stationary the information obtained was primarily applicable to the North and South American continents alone. In addition to the measurements indicated in Table 9-18, tests of interference generated by the UHF tactical satellite communications terminals were conducted showing that potential conflicts do exist if adequate distances and frequency separations are not maintained.

Propagation link losses experienced by a UHF tactical satellite communications system as determined from experiments on LES-3, -5, -6 are summarized in Table 9-19 (see References 33 through 35 and 49). In addition to the factors indicated in the table, structural blockage during maneuvers was found to be an occasional problem in aircraft and shipboard terminals.

Performance of the three major types of modems evaluated in the tactical satellite communications environment is summarized in Table 9-20(33)(34). In all cases, the table indicates performance on a channel perturbed by additive white Gaussian noise alone.

Table 9-18. Noise and Interference to UHF Tactical Satellite Communications

Test	Nature of Results
1. Vehicular Terminal Receive System Noise Temperature	Receiver noise temperatures varied between 360°K and 530°K. Contributions by environment were as low as 300° K and occasionally an order of magnitude higher. Total system noise temperatures ranged between about 700°K and 3,700°K. RFI was an occasional problem. Both AN/TRC-24 and AN/ARC-27 terminals were sources of interference.
2. Shipborne Terminal Receive System Noise Temperature	Total receive system noise temperatures varied between about 600°K and 2000°K. RFI was not a serious problem but was occasionally encountered. Shipboard radars such as the AN/SPQ-5A, AN/SPS-29, and AN/SPS-43; communications terminals such as the AN/GRC-27, portable electric generators and arc welders could produce interference.
3. Airborne Terminal Receive System Noise Temperature	Total receive system noise temperature including RFI was about 1000°K over water and lightly populated areas, about 2000°K over fairly heavily populated land areas, and about 10,000°K at low altitudes directly over industrialized towns. Specific high power UHF ground communications transmitters and the Time Division Data Link (TDDL) transmitters located around the perimeter of the U.S. caused interference problems.
4. Uplink Interference to Synchronous Satellites	Measured on LES-5 and LES-6.* Largest signals come from TDDL sites in the air-defense system. Many other signals also detected. There was no piling-up of signals from many small common-channel transmitters. Some portions of the bands scanned showed little activity.

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*Surface EIRPs as low as 50 to 100 watts detected on LES-5. LES-6 responded to EIRPs of 10 to 25 watts.

Table 9-19. UHF Propagation Link Losses

Parameter	Nature of Results
1. Surface Terminal Antenna Gain	Aircraft antenna gain may vary from +9 to -15 dB over a hemisphere with elevation angle to satellite a major factor determining average gain. Surface vehicular or manpack terminal patterns affected by any metal object within 10 meters.
2. Power Imbalance	Can be significant problem for multiple mobile terminals accessing a hard limiting satellite since individual terminal uplink power levels showed about a ±2 dB variation. Ability of individual terminal to effect entire system decreased dramatically as number of total accesses became large (i.e., about 10).
3. Intermodulation	In general, was not a significant problem. In case of FM voice signal and frequency hopping signal, however, intermodulation added a noticeable amount of noise to FM signal.
4. Atmospheric Absorption	Attenuation due to atmospheric moisture may vary between 0.5 to 1.5 dB dependent upon the atmospheric path traversed by the signal. Locally heavy precipitation can add several more dB of loss.
5. Multipath Fading	Encountered by aircraft. Two ray model for the most part valid in predicting results. Circularly polarized signals provide degree of protection since multipath fading on horizontally and vertically polarized components is relatively independent. Fading occurs primarily for elevation angles between 0 & 20°. Over water and ice cyclic fades vary between 1 & 10 dB with 5 dB being most common. Over land cyclic fades decrease to 2 to 3 dB with occasional random fades of 5 to 10 dB. Flights over mountains display no multipath.
6. Polarization Losses	Can be up to 3 dB for operation with circularly polarized satellite. Circularly polarized aircraft antenna losses will, in general, vary with elevation angle to satellite.
7. Fast Fading	Occurred at rate 100 times faster than predictable by 2-ray multipath model. Both enhancement and fading occurred. Was frequency selective. Ocurred only over water at look angles greater than 25° when operating within 30° of equator. Did not appear cyclic.
8. Scintillation	Limited data indicated low probability of occurrence for operation above 10° elevation angle in Temperate Zone (±20° to ± 65° latitude). Can cause fades up to 20 dB. Polar Zone scintillation also observed.
9. Tropical Foliage	4 to 6 dB of loss encountered by vehicular and manpack terminals. Changing moisture content causes variations.
10. Auroral Activity	Limited data indicated little or no effect.

Gaussian noise alone. The TATS performance is about 2.5 dB at 2.4 kbps and 4.5 dB at 75 bps above theoretical. This performance was for production model modems optimized for the 2.4-kbps data rate. Lincoln Laboratory prototype TATS modems achieved much nearer to theoretical performance at both data rates. Production TATS modems also displayed poor operational reliability. The triple diversity modem displayed a significant degree of protection against multipath and RFI as did the TATS modem. The TATS modem also supplied an in-band multiple access capability.

Multiple access tests were successfully conducted employing narrowband FM voice, triple diversity teletype, TATS 2400 bps, and TATS teletype separately and in mixed modes(33). Up to 17 TATS 2400 bps accesses through LES-6 into a C-135 aircraft terminal were demonstrated to be feasible(50). However, TATS, as designed with its short period frequency hopping pattern (i.e., it repeats every 7 symbols) suffered from considerable interference due to related address codes. With even as few as two common frequencies between two hopping patterns the cross correlation was sufficiently high to make false acquisitions so prevalent that acquiring the proper signal was almost impossible. Therefore, the hopping patterns present in a multiple access environment had to be severly constrained. These restrictions, in some cases, limited the number of premissible users below that theoretically indicated by consideration of available power and bandwidth alone.

Table 9-20. Tactical Modem Performance

Modem	Nature of Results
1. TATS	E_b/N_o of 11.5 dB and 13.5 dB required for 10^{-4} probability of error at 2.4 Kbps and 75 bps data rates respectively. At these levels of E_b/N_o acquisition failure rates were less than 10^{-3}.
2. Triple Diversity	E_b/N_o of 12 dB required for probability of error less than 10^{-3} at 75 bps data rate. No acquisition problem existed.
3. FM Voice	Narrowband FM gave acceptable quality at P_r/N_o=50 dB which corresponded to E_b/N_o of about 15 dB for data transmissions over this channel. No acquisition problem existed.

Numerous tests were conducted in attempts to develop aircraft antenna systems providing constant gain and polarization losses over an entire hemisphere. Fixed wing aircraft experiments included evaluations of crossed slot, crossed dipole, and blade antennas(33). The crossed slot antenna supplied relatively good hemispherical coverage with antenna gain for the circularly polarized antenna varying between -1 dB and +5 dB. The crossed dipole and blade antennas provided complementary patterns with the former displaying good gain at elevation angles above 30° to 40° while the latter supplied its peak gain at elevation angles below 30° to 40°. The crossed dipole supplied circularly polarized signals and the blade linearly polarized signals. The complementary patterns indicated that these two antennas should be employed in a combined system having a switching capability for selecting the appropriate antenna.

Helicopter antenna tests included evaluations of crossed dipole and blade antennas individually and in various combinations mounted above and below the rotor(36). As in the case of the fixed wing aircraft tests, results indicated that a crossed dipole and blade antenna should be employed in combination. Locating it above the rotor avoided rotor blade modulation caused primarily by blockage of the antenna aperature.

9.3.6 Operational Results

These were operational spacecraft; therefore, no operational traffic was carried. The experimental tactical ground terminals operated essentially as expected. One difficulty was that production models of the TATS modem displayed poor reliability. The satellites also operated, generally, as expected in spite of a number of minor difficulties, most of which were described in the discussion of "Experiments" in Section 9.3.5.

Problems previously discussed on LES-5 included the sun sensor failure affecting the automatic attitude control system, the high rate timing signal to the RFI and command receiver, the 17-dB degradation in communications receiver sensitivity, and the sudden shift in transponder frequency translation. Additional LES-5 difficulties included intermodulation between the telemetry and commuincations transmitters, an open circuit in one series-connected string on a solar panel, and higher than expected first year degradation of the solar array (i.e., about 22%). The intermodulation was a result of the two signals using the same antenna and was generated in spring finger contacts used at the edges of the slot antenna cavities behind the solar panels. This problem disappeared after the satellite had been in orbit a few months. The solar array power difficulties did not interfere with LES-5 testing.

Problems previously discussed on LES-6 included spinning about an axis 2.2° offset from the axis of symmetry of the cylinder, one solar panel delivering a low power output, a flip flop failure in an Earth Position register of the antenna switching logic, and interference to the radiation environment experiment by radiating communications antenna elements. Additional LES-6 difficulties included intermodulation between the beacon and communications transmitters and the shutter, covering the radiation experiment, operating intermittently. The former was the same problem as experienced on LES-5 and it too disappeared after a brief time of in-orbit operation. The latter was caused by variations in the dc power level and the lack of a power regulator on this spacecraft.

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SECTION 10 - INTELSAT

10.1 PROGRAM DESCRIPTION

The International Telecommunications Satellite Consortium (Intelsat) is a partnership initially established between 14 member nations in 1964 for the purpose of providing global commercial telecommunications via satellite. Since that time, the organization has expanded to include 79 member nations (as of May 1971), and new applications for membership continue to be received.

From the time it was established in 1964 to the present, Intelsat has produced four generations of satellite and ground systems. Development of the initial satellite, nicknamed Early Bird and later designated Intelsat I, was initiated by Comsat in November 1963. Just a year earlier, in August 1962, the U.S. Congress had passed the Communications Satellite Act, which authorized the creation of a private corporation (Comsat) to instigate the development of a global commercial communications satellite system. At the time when Early Bird's development began, the Syncom II satellite had just completed demonstrating that reliable communications could be provided through lightweight synchronous satellites. As a result, the Syncom satellite design formed the basis for the Early Bird spacecraft. Early Bird was launched in early 1965, as indicated in Table 10-1, and by April 22, 1965, had successfully achieved synchronization into the desired geostationary orbit with the satellite located over the Atlantic Ocean. After a period of satellite performance testing, system parameter evaluation using the operating ground stations, terrestrial and satellite circuit lineup, and public demonstrations, commercial operation was initiated on June 28, 1965. The satellite successfully provided commercial communications service between the United States and Europe until it was retired in early 1969. It was reactivated for a brief period later in 1969 when temporary difficulties were encountered with the antenna system of a third generation Intelsat satellite.

Table 10-1. Intelsat I (Early Bird) Spacecraft

Launch Date		April 6, 1965
Manufacturer/Sponsor		Hughes/Intelsat
Launch Vehicle		Thrust Augmented Delta
Synchronous Orbit Parameters*	Apogee (Mi)	22,733
	Perigee (Mi)	21,748
	Period (Min.)	1436.4
	Inclination	0.1°
Status:		June 28, 1965 - Operational Jan. 20, 1969 - Retired Reserve June 29, 1969 - Reactivated Aug. 21, 1969 - Retired (Presently located at 121°W longitude)

*Parameters at initial orbit injection. Attitude control and stationkeeping maneuvers produced changes.

The second generation of Intelsat spacecraft was designated Intelsat II. Even when the Intelsat I system was under development, it was realized that many of the inherent advantages of space communications could not be exploited. Specifically, its antenna characteristics were such as to embrace only the northeastern part of North America and the western part of Europe, and it did not allow for simultaneous intercommunication among numerous earth stations. By late 1965, it was recognized that the constraints imposed by these deficiencies would be incompatible with a NASA requirement for multichannel communications in late 1966 among its tracking stations at Carnarvon, Australia, Ascension Island, Canary Island, tracking ships in the Atlantic, Pacific, and Indian Oceans, and the Manned Space Flight Center in Houston, Texas. In the past, these circuits had been carried by HF radio, but for manned space flights, improved communications were desired. Consequently, in the fall of 1965 the development for Intelsat II had begun with the primary goal of satisfying the NASA requirements; excess capacity was to be used for other commercial traffic. Because of the urgency to satisfy the NASA requirement, the Intelsat II design evolved directly from that of Intelsat I.

Four Intelsat II satellites were produced and launched as indicated in Table 10-2. The first launch occurred in October 1966; but when the satellite's apogee motor malfunctioned, the spacecraft was left in a highly elliptical inclined orbit, making it unusable for full-time commercial operations. Subsequent launches in January and September 1967 successfully placed two satellites into operational service over the Pacific Ocean. A March 1967 launch successfully supplemented the Intelsat II satellite in operation over the Atlantic Ocean. With these three satellites in place, commercial service was available over both the Atlantic and Pacific Oceans. The Intelsat II satellites continued to meet international commercial communications requirements successfully until third generation replacement satellites allowed them to be retired to the active reserve.

The development of Intelsat III was initiated in 1964 with a design study and followed 2 years later with the award of a contract for the design, development, and fabrication of the necessary spacecraft. Eight Intelsat III satellites were launched between September 1968 and July 1970 as indicated in Table 10-3. Launch failures in September 1968, July 1969, and July 1970 made three of these satellites unusable. A successful launch in December 1968 placed a spacecraft in service over the Atlantic. Some difficulties were encountered when this satellite's mechanically despun antenna started sticking in mid-1969. This occurrence made necessary the aforementioned reactivation of Early Bird. The antenna

Table 10-2. Intelsat II Spacecraft

Satellite		F-1	F-2	F-3	F-4
Manufac/Sponsor		← Hughes/Intelsat →			
Launch Date		26 October 1966	11 January 1967	22 March 1967	22 September 1967
Launch Vehicle		← Thrust Improved Delta →			
Orbital Data*	Apogee (Mi)	23,014	22,257	22,254	22,245
	Perigee (Mi)	2,088	22,244	22,246	22,220
	Inclination	17.2°	1.3°	2°	0.9°
	Period (Min)	730.1	1436.1	1436.1	1429.5
Status:		Failed to achieve synchronous orbit due to malfunction of apogee motor. Employed commercially in December 1966 and January 1967.	Placed in service over Pacific at 172° East. Now in reserve at 125° West.	Placed in service over Atlantic at 6° West. Now in reserve at 13° West.	Placed in service over Pacific at 176° East. Now at 171° West.

*Parameters at initial orbit injection. Attitude control and stationkeeping maneuvers produced changes.

Table 10-3. Intelsat III Spacecraft

	Satellite: INTELSAT III Manufacturer/Sponsor Launch Date Launch Vehicle	(F-1) TRW/INTELSAT Sept. 18, 1968 Long-Tank Delta	(F-2) TRW/INTELSAT Dec. 18, 1968 Long-Tank Delta	(F-3) TRW/INTELSAT Feb. 5, 1969 Long-Tank Thrust Augmented Delta	(F-4) TRW/INTELSAT May 21, 1969 Long-Tank Thrust Augmented Delta	(F-5) TRW/INTELSAT July 25, 1969 Long-Tank Thrust Augmented Delta	(F-6) TRW/INTELSAT January 14, 1970 Long-Tank Delta	(F-7) TRW/INTELSAT April 22, 1970 Long-Tank Delta	(F-8) TRW/INTELSAT July 3, 1970 Long-Tank Delta
Orbital Data*	Apogee (mi)	No Orbit Achieved	22,257	22,235	22,166	3355	No Data	No Data	No Data
	Perigee (mi)		22,244	22,215	21,889	167			
	Inclination (deg.)		0.71	1.29	0.50	30.3			
	Period (min.)		1436	1436	1436	146.7			
	Status:	Failed to Orbit; pitch rate system malfunction forced payload destruct	Placed over the Atlantic at 30° W and began service on December 24, 1968. Ceased operation June 29, 1969. Resumed operation Aug. 1, 1969. Now at 48°W. Placed in retired reserve Feb. 1, 1970.	Placed over the Pacific at 174°E and began service on February 16, 1969. Repositioned over Indian Ocean at 62.5° after losing 6 dB of transponder gain due to a malfunction in one stage of the tunnel diode amplifier, and began service there July 1, 1969.	Placed in service over the Pacific at 174°E as a replacement for (F-3) and began service on May 31, 1969.	Unusable because 3rd Stage malfunction placed into incorrect Orbit. Subsequently decayed.	Placed over the Atlantic at 24° W. and began service on Feb. 1, 1970.	Placed over the Atlantic at 19° W. and began service on May 8, 1970.	Failed to achieve synchronous orbit due to a malfunction during apogee motor firing.

*Parameters at initial orbit injection. Attitude Control and stationkeeping maneuvers produced changes.

problem was resolved by August 1, 1969, and commercial operations were resumed until a subsequent January 1970 Intelsat III launch allowed the satellite to be placed in the retired reserve. In April 1970 another successful Intelsat III launch supplemented the operational capability available over the Atlantic.

An Intelsat III satellite was first placed into operation over the Pacific in February 1969. This satellite was supplemented by a second spacecraft in May 1969. When the first Pacific Intelsat III lost 6 dB of transponder gain due to an RF receive amplifier malfunction, it was relocated over the Indian Ocean where the traffic requirements were lighter. As a result, four Intelsat III satellites were, as of May 1971, providing global commercial service over the Atlantic, Pacific, and Indian Oceans.

Development of the fourth generation of Intelsat spacecraft, Intelsat IV, began in the latter portion of the 1960s. These satellites, manufactured by Hughes Aircraft Corporation, have been designed to provide a substantially greater capability to meet the increased global communication needs of the 1970s. The first, in an expected series of eight satellites, was successfully launched by an Atlas Centaur rocket into a geostationary orbit on January 25, 1971. It was positioned over the Atlantic at 24.5°W longitude. Subsequent Intelsat IVs will be launched for service over the Atlantic, Pacific, and Indian Oceans with an additional two satellites as spares in orbit. Each satellite will have a design life expectancy of about 7 years.

Because the Intelsat program has been a commercial venture, the number of major innovations in equipment and techniques employed has been limited. The intent has been to minimize the risk of spacecraft failure and the exceptional reliability record amassed by the system testifies to the success of this policy. Nevertheless, the Intelsat program has made significant contributions to satellite communications.

Numerous subjective tests with Intelsat I demonstrated conclusively that the round trip time delay and echo due to two-wire user terminations were not insurmountable obstacles to the utilization of synchronous satellites for commercial communications. This was in confirmation of preliminary indications obtained on Project SYNCOM.

The Intelsat II spacecraft demonstrated that tunnel diode amplifiers of operational reliability were available for use as RF receive preamplifiers. Utilizing these relatively low-noise, high-gain preamplifiers allowed direct RF to RF conversion in a single stage to be employed. Sufficient spacecraft power and high performance earth terminals allowed these transponders to be designed for linear input/output power transfer characteristics. Additionally, Intelsat II and an expanded ground complex demonstrated the feasibility of extensive multiple accessing of a single satellite transponder by a group of operational ground terminals.

When the wideband Intelsat III satellites were placed into operation, it was necessary to introduce a third generation of earth stations to the system in order to take full advantage of the expanded capabilities of the space subsystem. These terminals employed newly developed 500-MHz bandwidth cooled parametric amplifiers, as well as 500-MHz bandwidth high power traveling-wave tube transmitters, capable of over 6 kW of multicarrier power.

The more recent Intelsat IV spacecraft have contributed to satellite communications technology by demonstrating fixed narrow beamwidth (i. e., 4.5°) antennas mounted on a mechanically despun platform and a highly channelized satellite repeater (i. e., 12 independent transponders). The narrow-beam antennas provide coverage to a fixed, relatively restricted area of the earth but the high antenna gain available significantly increases satellite EIRP. The large number of transponders, each having a 36-MHz bandwidth, allows users with substantially different communication requirements to operate independently of each other in separate satellite channels (e.g., television distribution in one channel, high-capacity telephone trunks in another, and low-duty cycle individual voicelinks in still another). Additionally, a fully variable, demand-access, satellite system will be demonstrated for the first time during the period when the Intelsat IV satellites are being placed into operational service. Comsat has developed a single-carrier-per-voice channel PCM-PSK-FDMA demand-access system nicknamed SPADE that will be employed.

10.2 SYSTEM DESCRIPTION

Transatlantic communications via Early Bird were nominally effected through the Andover, Maine, earth station and one of four European earth stations. A Canadian station at Mill Village, Nova Scotia, also served as the North American terminal about 1 day per week after late 1966. In addition, it carried Early Bird traffic during the Intelsat II launches to release the Andover station for launch support operations. Three of the European stations, located at Goonhilly Downs (England), Pleumeur Bodou (France), and Raisting (Germany), served alternately in the roles of operating station and standby. They were interconnected by microwave links and submarine cables that permitted all European traffic to be carried by any one of the stations. The fourth smaller participating European terminal, located at Fucino (Italy), acted as a terminal for weekend traffic. It was linked to the other three terminals via Frankfurt, Germany. The terminals participating in Early Bird operations are summarized in Table 10-4.

Table 10-4. Intelsat I Participating Earth Terminals

Location	Owner	Ant. Dia. (ft.)	Date of Installation
Andover (Maine)	Comsat	67.7	1965
Mill Village (Nova Scotia)	Canadian Overseas Telecom Corp (COTC)	8.5	1966
Goonhilly Downs (England)	General Post Office	85.0	1965
Pleumeur Bodou (France)	Centre National d'Etudes des Telecommunications (CNET)	67.7	1965
Raisting (Germany)	Deutsche Bundespost	82	1964
Fucino (Italy)	Telespazio	44	1965

The development of Intelsat II with a bandwidth several times that of Early Bird was accompanied by second generation earth station designs such as those for the Brewster Flats, Washington, and Paumalu, Hawaii, installations. A listing of terminals, in addition to those indicated in Table 10-4, participating in operations with Intelsat II satellites, as of April 1968, are listed in Table 10-5. Intelsat II satellites located over both the Atlantic and Pacific Oceans provided multiple-access communications among appropriate groups of these terminals. The wide variety of station antenna sizes stems largely from the fact that many of the smaller ones were required on very short notice to provide communications support for NASA's Apollo program. Many of the smaller aperture stations have now been replaced by ones of higher sensitivity. Their existence did, however, provide experience in working with a variety of stations with a wide range of sensitivities.

Table 10-5. Intelsat II Participating Earth Terminals

LOCATION	ANTENNA DIAMETER (FT.)	DATE INSTALLED
FUCINO (ITALY)	90	1967
BUITRAGO (SPAIN)	85	1968
ORAND CANARY ISLAND (SPAIN)	42	1967
ASCENSION ISLAND	42	1967
BREWSTER FLATS (WASHINGTON)	85	1966
PAUMALU (HAWAII) (NO. 1)	85	1966
PAUMALU (HAWAII) (NO. 2)	42	1968
CARNAROON (AUSTRALIA)	42	1967
TAMAY (PHILIPPINES)	42	1968
SI RACHA (THAILAND)	42	1968
MOREE (AUSTRALIA)	92	1968
IBARAKI (JAPAN)	72	1968
NASA TRACKING SHIPS (3)	30	1967

System planning for the Intelsat III satellite was completed in 1967, and a third generation of earth stations was designed to provide full operating capability with these spacecraft. Of paramount importance to the Intelsat III satellite design was the use of two transponders covering nearly the entire 500-MHz band assigned to communications satellite service. The new earth station designs made this entire band available for use so that carrier frequencies could be assigned without regard for narrow-band equipment. This flexibility guaranteed the success of multi-destination FM-FDM to provide complete satellite multiple access to all earth stations in the network. A complete list of terminals participating in operations with Intelsat III satellites, as of January 1971, is provided in Table 10-6. Multiple access communications nets have been formed among appropriate groups of these terminals to operate with Intelsat satellites located over the Atlantic, Pacific, and Indian Oceans.

Fourth generation earth terminals are presently being constructed to operate with the new Intelsat IV satellites. These terminals provide a large number of carriers to take advantage of the multiplicity of satellite transponders that have become available. As a result, the requirements for linearity in common RF transmitting and receiving elements within these ground terminals have been substantially increased. Additions to the ground complex defined in Table 10-6 that should be operational by the end of 1972 are listed in Table 10-7. Intelsat IV satellites will in the near future assume responsibility for space segment operations over the Atlantic, Pacific, and Indian Oceans. These satellites and new signal processing techniques will allow both fixed assignment and fully variable demand assignment approaches to multiple access to be implemented among appropriate groups of user terminals.

Operating frequencies for the four types of Intelsat spacecraft are defined in Table 10-8. The bands of utilization indicated depict the fact that the Intelsat I, II, and III spacecraft contained two, one and two independent repeaters, respectivel In the case of Intelsat IV, the bandwidth shown spans the total operating frequency

Table 10-6. Intelsat III Participating Earth Terminals

	LOCATION	ANTENNA DIAMETER (FT.)	DATE INSTALLED
1)	Balcarce, Argentina No. 1	No Data	September, 1969
2)	Ascension Island, United Kingdom	42	April, 1967
3)	Moree, Australia	90	May, 1968
4)	Carnarvon, Australia	97	October, 1969
5)	Ceduna, Australia	No Data	December, 1969
6)	Ras Abu–Jarjur, Bahrain	90	July, 1969
7)	Tangua, Brazil	98	February, 1969
8)	Mill Village, Canada No. 1	85	October, 1969 (Last Mod)
9)	Mill Village, Canada No. 2	90	January, 1969
10)	Longovilo, Chile	97	July, 1968
11)	Taipei, Republic of China	100	December, 1969
12)	Choconta, Colombia	97	March, 1970
13)	Pleumeur–Bodou, France No. 1	67.7	June, 1965 (Last Mod)
14)	Pleumeur–Bodou, France No. 2	97	November, 1969
15)	Raisting, Germany No. 1	82	June, 1965
16)	Raisting, Germany No. 2	No Data	October, 1969
17)	Thermopylae, Greece	100	April, 1970
18)	Hong Kong, United Kingdom No. 1	90	September, 1969
19)	Djatiluhur, Indonesia	97	September, 1969
20)	Asadabad, Iran	97	October, 1969
21)	Fucino, Italy No. 1	90	August, 1967 (Last Mod)
22)	Fucino, Italy No. 2	97	July, 1970
23)	Ibaraki, Japan No. 2	90	March, 1968 (Replaced Ibaraki 1)
24)	Yamaguchi, Japan	90	July, 1969 (Last Mod)
25)	Mt. Margaret, Kenya	No Data	August, 1970
26)	Kum San, Republic of Korea	97	April, 1970
27)	Umm Al–Aish, Kuwait No. 1	97	October, 1969
28)	Arbaniyeh, Lebanon	97	September, 1969
29)	Kuantan, Malaysia	No Data	March, 1970
30)	Tulancingo, Mexico	105	January, 1969
31)	Sehouls, Morocco	No Data	December, 1969
32)	Utive, Panama	98	September, 1968
33)	Lurin, Peru	100	July, 1969
34)	Tanay, Philippines No. 1	97	April, 1968
35)	Buitrago, Spain No. 1	85	January, 1968
36)	Buitrago, Spain No. 2	98	April, 1970
37)	Grand Canary Island, Spain	Twin 42 ft.	April, 1967
38)	Sri Racha, Thailand No. 1	97	April, 1968
39)	Sri Racha, Thailand No. 2	97	April, 1970
40)	Goonhilly Downs, United Kingdom No. 1	85	July, 1969 (Last Mod)
41)	Goonhilly Downs, United Kingdom No. 2	No Data	November, 1968
42)	Andover, Maine	67.7	June, 1965
43)	Brewster, Washington	97	December, 1966
44)	Paumalu, Hawaii No. 1	97	December, 1966
45)	Paumalu, Hawaii No. 2	97	December, 1968
46)	Etam, West Virginia	97	October, 1968
47)	Cayey, Puerto Rico	97	January, 1969
48)	Jamesburg, California	97	December, 1968
49)	Pulantant, Guam	98	November, 1969
50)	Bartlett, Alaska	98	July, 1970
51)	Camatagua, Venezuela	98	November, 1970

Table 10-7. Ground Complex Additions by End 1972

Location	Antenna Dia. (ft)	Date Installed
1) Barbados, United Kingdom	No Data	1972
1) Yaounde, Cameroon	No Data	October, 1971
3) Vancouver Island, Lake Cowichan, Canada	No Data	1972
4) Kinshasa, Democratic Republic of Congo	No Data	June, 1971
5) Sululta, Ethiopia	No Data	1972
6) Martinique, France	No Data	1971
7) Libreville, Republic Gabon	No Data	1972
8) Raisting, Germany No. 3	No Data	1972
9) Hong Kong, United Kingdom No. 2	No Data	1971
10) Arvi, India	No Data	1971
11) Emek Haela, Israel	No Data	May, 1972
12) Fucino, Italy No. 3	No Data	1972
13) Abidjan, Ivory Coast	No Data	August, 1971
14) Prospect Pen, Jamaica	No Data	1971
15) Ibaraki, Japan No. 3	No Data	1971
16) Baqa, Jordan	No Data	1971
17) Umm Al-Aish, Kuwait No. 2	No Data	1972
18) Warkworth, New Zealand	97	May, 1971
19) Lanlate, Nigeria No. 1	No Data	1971
20) Lanlate, Nigeria No. 2	No Data	1972
21) Chittagong Hill Tracts, East Pakistan	No Data	1971
22) Karachi, West Pakistan	No Data	1971
23) Tanay, Philippines No. 2	No Data	1971
24) Dahban-Jeddah, Saudi Arabia	No Data	1972
25) Riyadh, Saudi Arabia	No Data	1972
26) Dakar, Senegal	No Data	1971
27) Sentosa, Singapore	No Data	August, 1971
28) Aguimes, Spain	97	April, 1971
29) Tanum, Sweden	No Data	October, 1971
30) Matura Point, Trinidad	No Data	May, 1971
31) Ankara, Turkey	No Data	1972
32) Goonhilly, United Kingdom	No Data	1972
33) Vung Tan, Republic of Viet Nam	No Data	1972
34) Lusaka, Zambia	No Data	1972
35) Tegucigalpa, Honduras	No Data	April, 1971
36) Balcarce, Argentina No. 2	No Data	August, 1971

Table 10-8. Intelsat Frequency Assignments

SPACECRAFT	COMMUNICATIONS	
	Uplink	Downlink
Intelsat I (Early Bird)	6288-6314 MHz	4068-4094 MHz
	6377-6403 MHz	4148-4174 MHz
Intelsat II	6282-6408 MHz	4057-4183 MHz
Intelsat III	5930-6155 MHz	3705-3930 MHz
	6195-6420 MHz	3970-4195 MHz
Intelsat IV	5930-6420 MHz (*)	3705-4195 MHz (*)

(*) Divided into 12 channels each 36 MHz wide.

range of 12 independent repeaters. Downlink center frequencies for each of the 12 repeaters are: 3725, 3765, 3805, 3845, 3885, 3925, 3975, 4015, 4055, 4095, 4135, and 4175 MHz, respectively. Uplink frequencies for each repeater are 2225 MHz above the indicated downlink frequency. The frequencies employed were selected to be compatible with the frequency bands reserved for commercial satellite communications use on a shared basis in 1963. These frequencies were set aside in response to recommendations originated by AT&T during the Telestar program.

With the extensive ground complex and comparatively limited number of spacecraft involved in the Intelsat program, satellite multiple-access techniques and RF modulation employed have been of vital importance to the system. Intelsat I incorporated a multiple-access capability, in a sense, by virtue of its sharing a single TWT between two independent frequency-translating transponders. Since each of these transponders was hardlimiting in nature, the number of carriers accessing each was limited to one. For this reason, the mode of communication was point-to-point, and only one duplex link between the United States and Europe was provided. Conventional voice-channel multiplex equipment similar to that employed in the Bell System and frequency modulation of the radiated carriers were employed. This system configuration, in conjunction with the ground terminals available, provided Intelsat I with a 240-duplex voice-channel capacity.

The Intelsat II system was designed to provide for frequency-division multiple-access (FDMA) of the satellite by a number of earth terminals. Theoretical studies had shown that for multiple large index FM carriers accessing the transponder: (1) the satellite should be designed for a quasi-linear operation, (2) the maximum power input should be limited to 1.5 to 2.0 dB less than the producing transponder saturation, and (3) the level and distribution of the carriers should be such that the intermodulation products are approximately of constant level over the entire transmission band. To ensure compliance with these criteria, carrier control stations were established at Paumalu, Hawaii, and Andover, Maine, whereby the Atlantic and Pacific Intelsat II systems could be monitored, each from a single point. In early operations with Intelsat II satellites, FM carriers centered at specified frequencies were preassigned to individual links between two points, thereby retaining the point-to-point mode of operation employed on Intelsat I. However, multiple point-to-point links were established through the Intelsat II transponders. The system configuration described, together with the second generation ground complex, produced a 240-duplex voice-channel capacity for each Intelsat II satellite.

It was recognized, by the time the Intelsat III satellites started to be put into service, that the satellite capacity could be increased and the system complexity reduced by switching to a point-to-multipoint mode of multiple-access operation. This was implemented by designing each terminal to transmit one preassigned multidestination FM carrier containing channels intended for all users to which it was linked. Baseband channels were preallocated to a particular user as part of a given network plan and were stripped off at each respective receiving site. The Intelsat III satellite transponders were again designed for quasi-linear operation, and the same type of carrier control concept as utilized for the Intelsat II system was employed. The described mode of system operation has allowed the third generation earth terminals to realize a 1200-duplex voice-channel system capacity when operating through an Intelsat III satellite. Alternately, the satellite can provide four television channels.

The Intelsat III approach to modulation, multiple access, and system control will continue to be employed as the new Intelsat IV satellites are introduced to the system. However, it will be supplemented, at an early date, by a fully variable demand-access system called SPADE, which will operate in a separate transponder of the Intelsat IV satellite. The term SPADE is derived from Single-channel-per-carrier, Pulse-code-modulation, multiple-Access Demand-assignment Equipment. The SPADE system will feature PCM encoding of individual voice channels for quadriphase PSK modulation of a carrier. It includes the ability to deactivate carrier transmission to the satellite during periods of talker inactivity and a decentralized control concept allowing self-assignment of available satellite channels. The SPADE system has been assigned to transponder 10 of Intelsat IV satellites. This particular transponder does not have access to the spot beam antennas. SPADE will be compatible with standard manual or automatic international signaling and switching systems. User applications, where the satellite channel requirements vary widely over the period of a day, will find SPADE quite attractive. Each of the Intelsat IV transponders will, in conjunction with the earth coverage satellite antennas and the fourth generation ground complex, provide about 500 full duplex voice channels when FDMA-FM is employed, 800 full duplex voice channels when SPADE is used, or 1 FM color television channel, including the TV audio.

10.3 SPACECRAFT

The Early Bird satellite was very similar to the Syncom III spacecraft. Early Bird's microwave repeater consisted of two independent nonlinear, hard-limiting, frequency translating transponders. Both transponders shared a single TWT output power amplifier. A second TWT was carried on-board the spacecraft for redundancy; however, only one of the tubes was on at a time. A block diagram of the Early Bird repeater is provided in Figure 10-1. The satellite was spin-stabilized for attitude control and the elimination of temperature extremes. The pancake-shaped antenna pattern was squinted to provide high gain coverage of the northern hemisphere alone. Spacecraft design lifetime was only 18 months. However, Early Bird operated successfully for more than 3 years until it was retired from service. Communications characteristics of this satellite are provided in Table 10-9.

The Intelsat II satellite design evolved directly from that of Early Bird. Among the most significant changes were the adoption of a single redundant wideband linear amplifier and an antenna beam that covered both the northern and southern hemispheres. The transponder bandwidth was 125 MHz compared with the two repeaters of 25-MHz bandwidth, each used in Early Bird. A block diagram of the Intelsat II satellite's communications system is shown in Figure 10-2. To maintain the 240-circuit capacity of Early Bird, in spite of the wider antenna beamwidth, Intelsat II employed multiple traveling-wave tubes operating in parallel. Four tubes were included in anticipation that three would be required to meet the EIRP requirements, leaving one tube as a spare. However, the antenna and power efficiencies achieved were such that a 2-tube configuration was adequate. The additional power required by Intelsat II was provided by using a larger solar cell array. In contrast to Early Bird, Intelsat II was designed to support communication through the eclipse periods occasionally experienced in the synchronous orbit. The communication characteristics of Intelsat II are shown in Table 10-10.

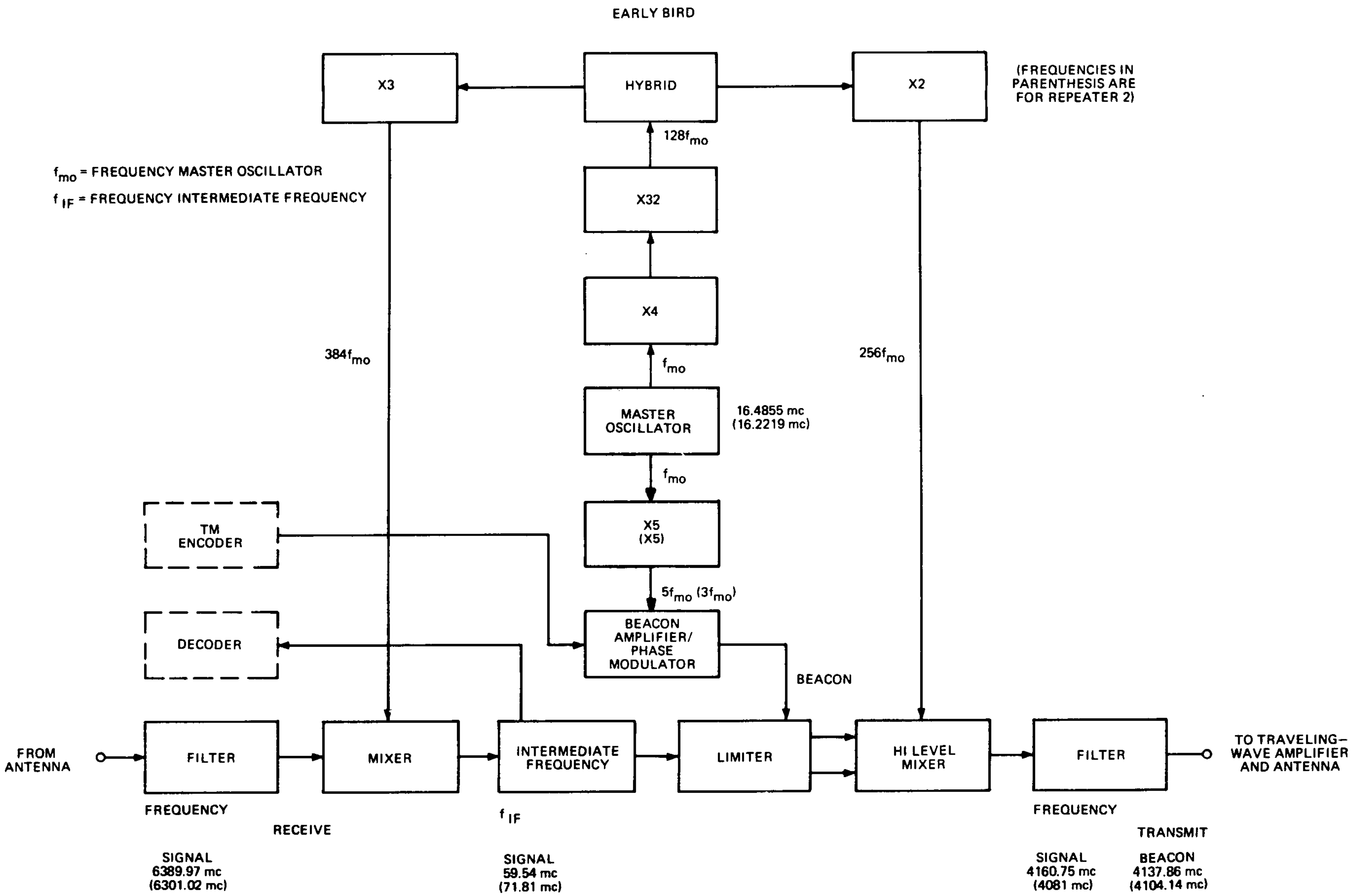

Figure 10-1. Block Diagram of Early Bird Repeater

Table 10-9. Early Bird Communication Characteristics

ANTENNAS		Type	XMTR-Skirted 6-element Collinear Slot Dipoles RCVR - Collinear 3-element Cloverleaf Array
		Number	1 - XMTR 1 - RCVR
		Beamwidth	XMTR - 11° with beam center squinted 7° into northern hemisphere RCVR - 40°
		Gain	XMTR - 9 dB; RCVR - 4 dB
		Polarization	Linear in plane perpendicular to spin axis
REPEATERS		Frequency Band	C-Band
		Type	Hard-limiting, double conversion repeater
		Bandwidth	25 MHz - each repeater @ 0.5-dB points
		Number	Two repeaters sharing a common TWT XMTR
	RCVR	Type Front End	Down Conversion Mixer
		Front End Gain	No Data
		Sys. Noise Figure	Overall - 10 dB
	XMTR	Type	6-watt TWT and identical spare
		Gain	No Data
		Power Out	4.3 watts as operated
		EIRP	10.2 dBW @ beam edge/14 dBW maximum
GENERAL FEATURES	Stabilization	Type	Spin (152 rpm) with H_2O_2 jet attitude & spin rate control
		Capability	No Data
	Power Source	Primary	46.5 watts from 6000 n-on-p solar cells *
		Supplement	1.5 amp-hr. from two 21-cell nickel-cadmium batteries**
		Comm. Power Needs	26.8 watts
		Size	Cylindrical: diameter = 28.4"; height = 23.2"
		Weight	149 lbs at injection, 89-79 lbs after apogee fire

* Capability at launch

** Furnishes power during launch. Eclipse operation not possible.

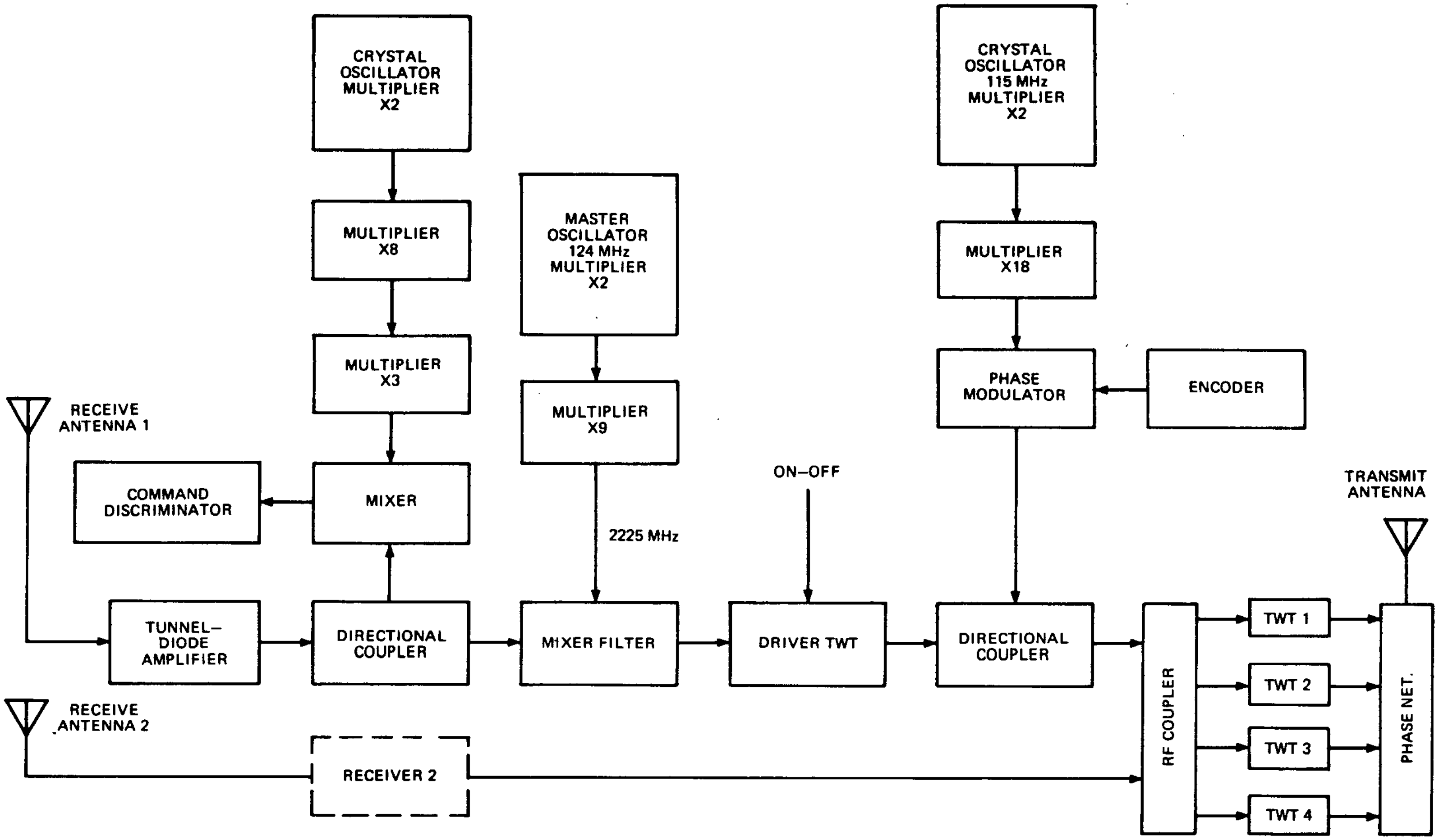

Figure 10-2. Communications System Block Diagram for Intelsat II

Table 10-10. INTELSAT II Characteristics

Antenna		Type	Transmit: Multiple Element Biconical Horn
		Number	One Transmit and 2 Receive
		Beamwidth	Transmit: ±6° (centered at equator) Receive: Essentially omnidirectional
		Gain (4 GHz)	8 dB
Repeater		Frequency Band	C-Band
		Type	Linear Single RF translation
		B.W. (dB)	126 MHz
		Number	2 (1 redundant spare)
	RCVR	Type Front End	Tunnel Diode Amplifier
		Front End Gain	No Data
		Sys. Noise Figure	6 dB
	XMTR	Type	4 TWT's
		Gain	No Data
		Power Out	Nominal 10.8 dBW (7.8 dBW/TWT)
		EIRP (at beam edge)	15 dBW (after back-off for multicarrier operation)
General Features	Stabilization	Type	Spin with H_2O_2 jet attitude control
		Capability	No Data
	Power Source	Primary	85 watts from 12,756 n-on-p solar cells *
		Supplement	9.0 amp/hour from two nickel cadmium batteries **
		Comm. Power Needs	No Data
		Size	Cylindrical: Height = 26.5", Diameter = 56"
		Weight	190 lbs after apogee fire

* Capability at launch

** Initial capability available for eclipse operation

Because the communications subsystem of the Intelsat III satellites provided for two independent transponders, these spacecraft more closely resemble Intelsat I than Intelsat II. The most significant difference between the Intelsat I and Intelsat III transponders is that whereas the former was a hard-limiting, nonlinear, double-conversion repeater, the latter is a linear single-conversion repeater. This is in agreement with the Intelsat II design. Each Intelsat III transponder has a bandwidth of 225 MHz. Together the two transponders cover most of the 500-MHz bandwidth allocated to the communication satellite service in the 4-GHz and 6-GHz bands. The initial satellites in the Intelsat III series employed single tunnel-diode amplifiers in the receiver. However, after satellite F-3 lost 6 dB of transponder gain due to a malfunction in one stage of the tunnel-diode amplifier, all subsequent spacecraft were provided with redundant receive amplifiers to enhance the overall subsystem reliability. A block diagram of the satellite communications subsystem is provided in Figure 10-3. Communications characteristics of the satellite are summarized in Table 10-11.

A further important distinction between Intelsat I and Intelsat III appears in the communication antennas. The antennas of Intelsat I were symmetrical about the spin axis to maintain constant antenna gain. Intelsat III employs a mechanically despun antenna. This mechanically despun antenna is the most important innovation in this series of satellites, and perhaps the most critical. Special lubricants are used for the bearings, which are exposed to the hard vacuum of space and a wide temperature range. Because Intelsat III has no VHF telemetering and telecommand equipment (these functions are handled at C-band), an additional antenna at 6 GHz with substantially omnidirectional properties has been provided to receive telecommand signals for the initial setting up in orbit. The expected lifetime of the satellite is 5 years.

The Intelsat I through III satellite designs produced communications systems that were power limited, even though a high performance ground complex was provided. This situation began to change with the development of the Intelsat IV

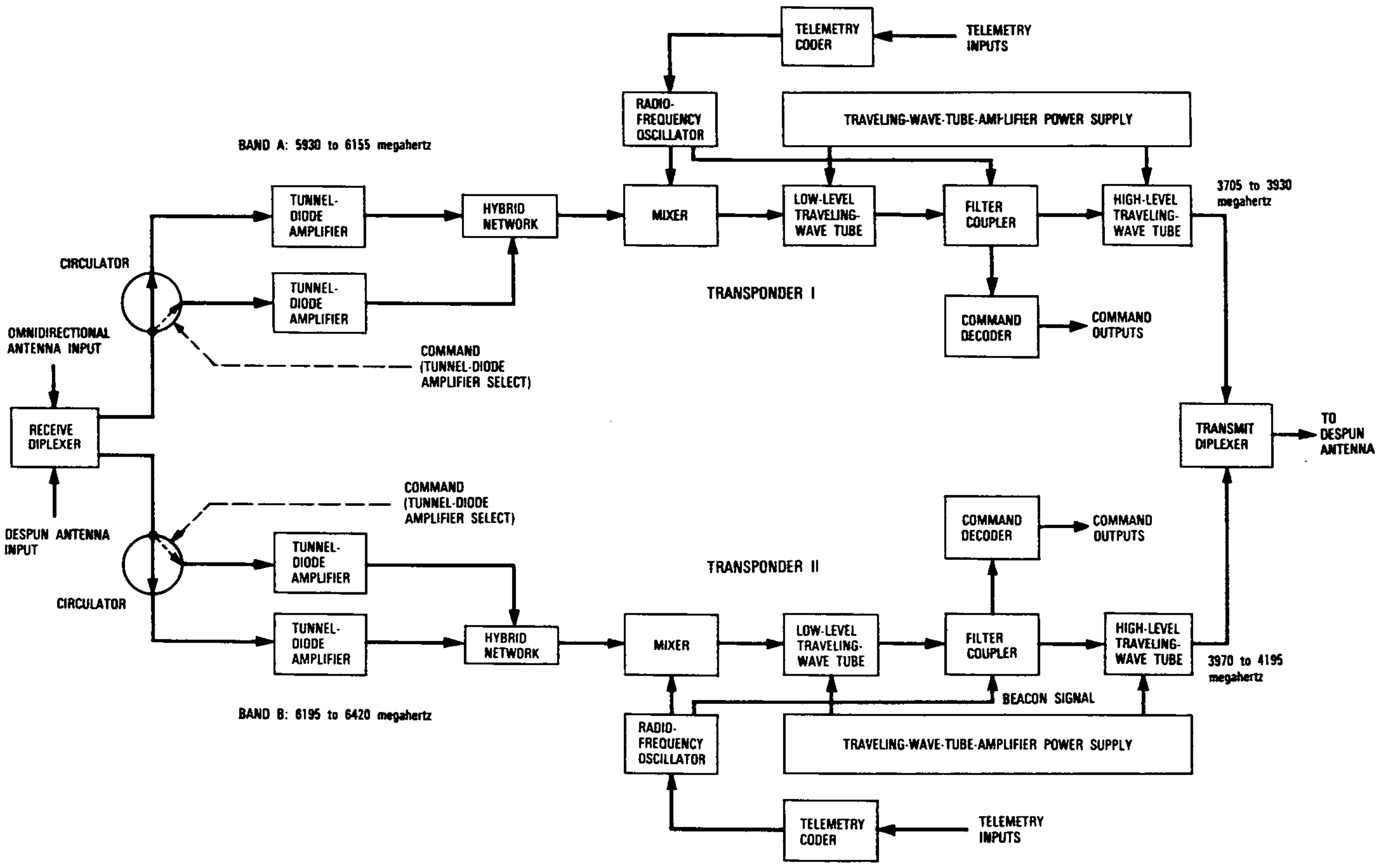

Figure 10-3. Block Diagram of Intelsat III Communications System

Table 10-11. INTELSAT III Characteristics

Antenna		Type	Conical Horn with flat plate reflector, mechanically despun
		Number	1
		Beamwidth (4/6 GHz)	24/14.5°
		Gain (4/6 GHz)	16/21 dB
Repeater		Frequency Band	C-Band
		Type	Two independent linear single conversion repeaters
		B.W. (3 dB)	225 MHz each transponder
		Number	Two
	RCVR	Type Front End	Two stage tunnel diode amplifier
		Front End Gain	31 dB
		Sys. Noise Figure	7 dB
	XMTR	Type	TWT
		Gain	73 dB
		Power Out	12 Watts
		EIRP (beam edge)	22 dBW per transponder
General Features	Stabilization	Type	Spin
		Capability	No Data
	Power Source	Primary	10,720 solar cell array - 161 watts at launch
		Supplement	1 rechargeable 20 cell nickel-cadmium battery
		Comm. Power Needs	99 watts
		Size	Cylindrical 55.4" diameter, 41" height without antenna
		Weight (at liftoff)	632 lbs
		(in orbit)	322 lbs

Polarization: Transmit - RHC
Receive - LHC

spacecraft. When the spot beams of this satellite are employed with high performance ground terminals, a bandwidth limited system results. The Intelsat IV satellites' communications subsystem consists of global receive and both global and spot beam transmit antennas connected to a 12-channel repeater that provides high power amplification for each channel individually. Each of these 12 channels has a bandwidth approaching 40 MHz, thereby providing capacity for about 500 communications circuits. The satellite has the capability, using the EC antenna, for relaying 6000 half duplex telephone calls, or 12 color television programs, or any equivalent combination of such transmissions. The communication system of Intelsat IV is depicted in the block diagram of Figure 10-4. Communications characteristics of the satellite are summarized in Table 10-12.

The spot beam transmit antennas represent the most significant departure from the previous satellite designs of the Intelsat series. Two of these antennas, each a parabolic disc of 50 inch diameter, are mounted on the despun control mast of the satellite. The entire RF portion of the spacecraft is despun. Pointing of the spot beams is prefixed on the ground. These high gain antennas with beamwidths of about 4 degrees, can be used to provide spot coverage in Europe and North and South America, or they can be employed to provide intracontinental coverage within specific countries. The basic physical configuration of the Intelsat IV spacecraft is depicted in Figure 10-5.

10.4 GROUND TERMINALS

The Intelsat ground complex that provided communications through the Early Bird satellite consisted to a large extent of modified versions of terminals initially constructed to participate in Telstar and Relay program experiments (see Sections 6 and 7). The participating terminals were listed in Table 10-4. The Andover earth station, originally built for Telstar, was modified during the period July 1964 through March 1965. The Goonhilly Downs earth station, also an original Telstar terminal, was withdrawn from service in September 1964 for modification to work

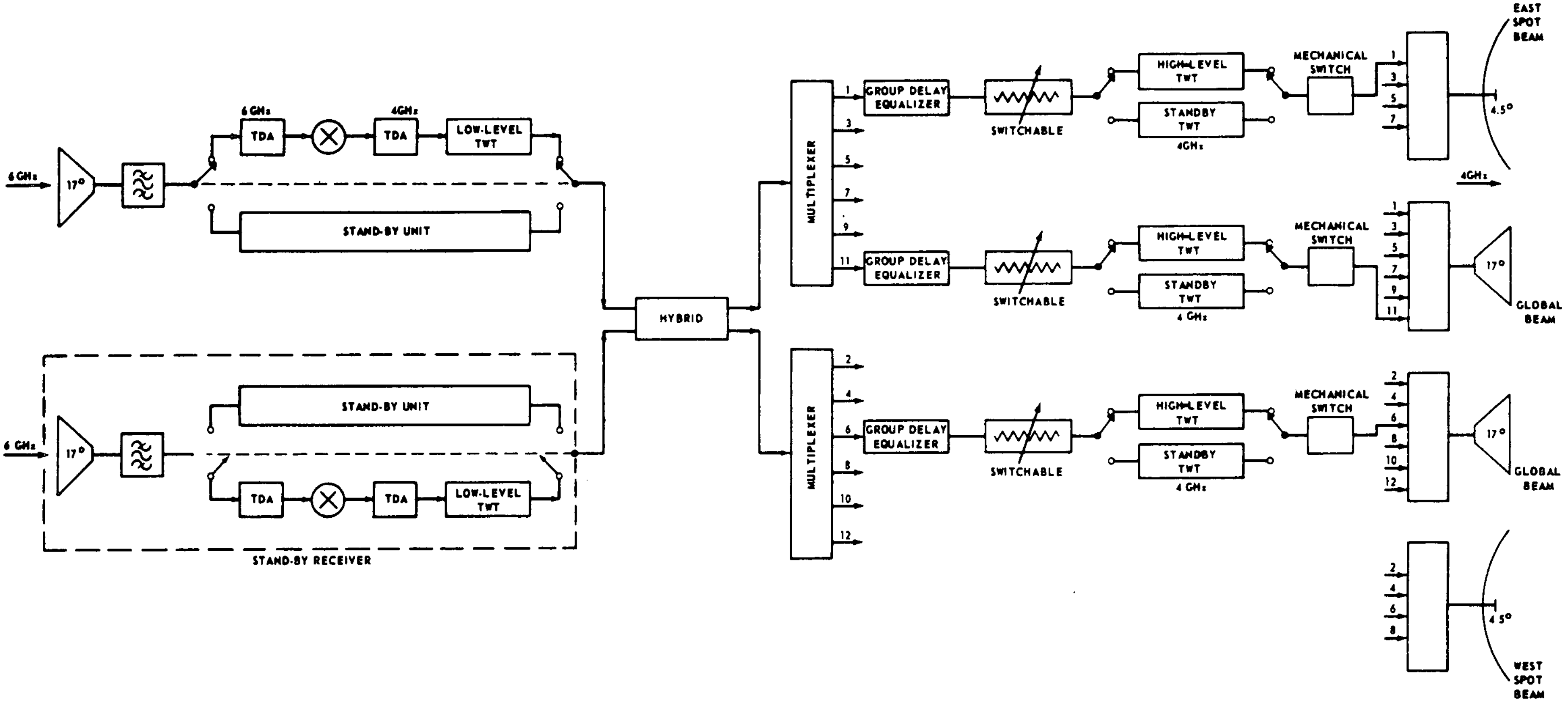

Figure 10-4. Communications Subsystem of Intelsat IV Satellites
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Table 10-12. INTELSAT IV Characteristics

Antenna		Type	Global Receive, Global Transmit: conical horn with flat plate reflection. Spot Beam: 50" parabolic reflector *. Omnidirectional command receive antenna and omnidirectional telemetry transmit.
		Number	2 of each of the above communications antennas
		Xmit. Beamwidth (global/spot beam)	17/4.5°
		Xmit. Gain (global/spot)	20.5/31.7 dB
		Polarization	Circular
Repeater		Frequency Band	C-band
		Type	Linear or limiting** single RF conversion repeater
		B.W. (-1 dB)	36 MHz
		Number	12
	RCVR	Type Front End	Tunnel Diode Amplifier
		Front End Gain	13.8 dB
		Sys. Noise Figure	8.2 dB
	XMTR	Type	TWTA
		Gain	58 dB
		Power Out	8 dBW per transponder
		EIRP***(global/spot beam)	22.5/34.2 dBW per transponder at beam edge
General Features	Stabilization	Type Capability	Spin with hydrazine jet attitude & orbital **** control. Stationkeeping to ±0.25° North-South and ±0.12° East-West. Attitude control to ±0.18°.
	Power Supply	Primary	42,240 solar cells - 750 watts at launch
		Supplement	Nickel-cadmium batteries
		Comm. Power needs	No Data
		Size	Cylindrical: 7'9" diameter, 17'4" height overall, 9'3" solar drum alone
		Weight (at liftoff)	3094 lbs
		(in orbit)	1544 lbs

Notes:
- * Beam pointing adjusted prior to launch. Pointing cannot be changed by ground command.
- ** Selectable by ground command
- *** Measured in anechoic chamber
- **** Both north/south and east/west stationkeeping provided.

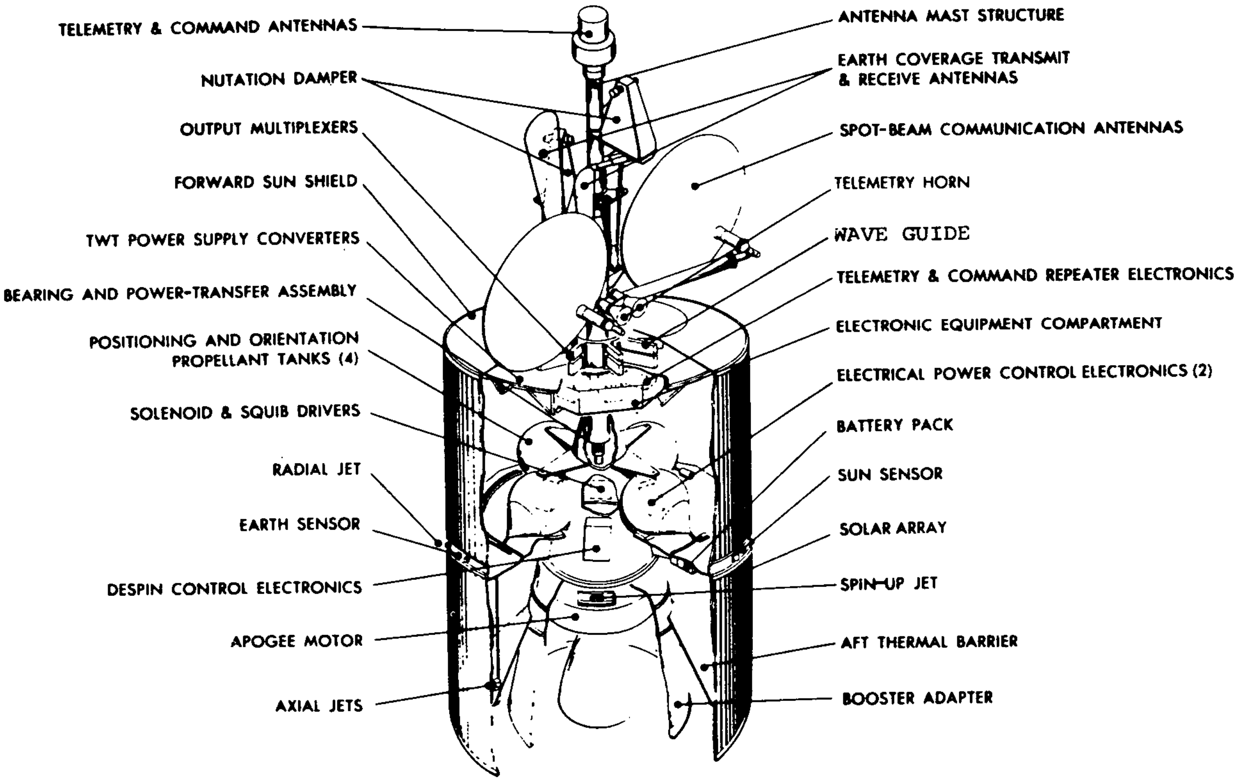


Figure 10-5. Components of the Intelsat IV Satellites

with Early Bird. Prior to modification, the performance of Goonhilly was about 3 dB down as compared to Andover and Pleumeur Bodou. The modification improved the terminal's performance by reducing profile inaccuracies of the reflector, reducing aperture blocking from the feed support structure, and reducing feeder losses. Characteristics of the Andover, Goonhilly, and Raisting earth terminals, as configured for operation with Early Bird, were as indicated in Table 10-13.

Second generation earth terminals were developed to take advantage of the wider bandwidths of the Intelsat II satellites. These earth stations employed more advanced equipment than had previously been available, including solid-state designs, masers of wider bandwidth, Cassegrain feed antenna systems, and dual carrier receiving chains. A technical summary of three typical second generation earth stations that participated in operations with Intelsat II satellites is given in Table 10-14. The original Intelsat I terminals were also used to operate in the Intelsat II system. These terminals were not significantly modified from their Early Bird configurations.

In building the third generation stations for operation with Intelsat III, new 500-MHz bandwidth cooled parametric amplifiers were developed, as well as 500-MHz bandwidth high power traveling-wave tube transmitters capable of over 6 kW of multicarrier power. Antenna sizes become relatively standardized at 97 feet diameter, partly to compensate for the somewhat higher noise temperatures resulting from the wideband feed systems, and partly to obtain a small performance margin for the terrestrial stations. The characteristics for two third generation earth stations, Paumalu (Hawaii) and Fucino (Italy), are presented in Table 10-15.

With both global and spot beam transponders, Intelsat IV will allow earth stations to operate with a large number of carriers. This will result in intermodulation distortion becoming an increasingly important consideration in earth station performance. The higher capacities associated with Intelsat IV require existing earth stations to verify a greater linear deviation capability, evaluate their threshold extension demodulator performance at the larger capacities,

Table 10-13. Characteristics of Typical Early Bird Earth Terminals

Terminal Feature		Terminal		
		Andover *	Goonhilly Downs	Raisting
Antenna	Type	Conical Horn Reflector	Parabolic Reflector	Parabolic Reflector
	Aperture Dia.	67.7 ft	85 ft	82 ft
	Receive Gain	58 dB	58.5 dB	58.4 dB
	Efficiency	70 - 75 %	55 - 60%**	55 - 60%**
	Rec. Beamwidth (3 dB)	0.23^{o}	0.2^{o}	0.2^{o}
Receive System	Type	Traveling Wave	Traveling Wave	
	Preamplifier	Ruby Maser	Ruby Maser	Maser
	Bandwidth	25 MHz @ 3 dB Pts.	25 MHz @ 3 dB Pts.	20 MHZ @ 3 dB Pts.
	Noise Temp.	50^{o}K @ 7.5^{o} Elev.	50^{o}K @ 7.5^{o} Elev.	50^{o}K @ 7.6^{o} Elev.
Transmit System	Type Amplifier	TWT	TWT	TWT
	Bandwidth	30 MHz	30 MHz	30 MHz
	Power Output	3 kW	3 kW	2 kW
Tracking	Type	Monopulse Autotrack	No Data	Programmed Tracking
	Accuracy	$\pm .01^{o}$	No Data	$\pm .01^{o}$
Total Perfor-mance	G/T	41 dB/^{o}K **	41.5 dB/^{o}K **	41.5 dB/^{o}K **
	EIRP	125 dBm **	124 dBm **	123.5 dBm**
Polar-ization	Transmit Feed	No Data	No Data	No Data
	Receive Feed	No Data	No Data	No Data
Installation	Radome	210' Diameter Rubberized Dacron	None	154' Diameter Rubberized Dacron
	Type Facility	Fixed Terminal	Fixed Terminal	Fixed Terminal

Notes: * The terminal at Pleumeur Bodou had essentially the same characteristics

** Derived value based on data available.

Table 10-14. Characteristics of Typical Second Generation Earth Terminals

Terminal Feature		Terminal		
		Buitrago, Spain	Brewster Flats, Washington	NASA Ship ****
Antenna	Type	Cassegrain	Cassegrain	Cassegrain
	Aperture Dia.	85 ft	85 ft	30 ft
	Receive Gain	58.4 dB	58.4 dB	47.8 dB
	Efficiency	60%*	60% *	41%*
	Rec. Beamwidth	0.2°*	0.2° *	0.5° *
Receive System	Type	Cooled Parametric		Cooled Parametric
	Preamplifier	Amplifier	Maser	Amplifier
	Bandwidth	No Data	30 MHz (-1 dB)	110 MHz(-3 dB)
	Noise Temp.	58°K @ 10° Elev.	50°K @ 10° Elev.	135°K @ 7.5° Elev.
Transmit System	Type Amplifier	Klystron	Klystron	Klystron
	Bandwidth	60 MHz (-1 dB)	30 MHz (-1 dB)	70 MHz (-3 dB)
	Power Output	10 kW	10 kW	10 kW
Tracking	Type	Autotrack	Autotrack	Monopulse Autotrack
	Accuracy	No Data	No Data	±0.06°
Total Performance	G/T	40.8 dB/°K *	41.4 dB/°K *	26 dB/°K
	EIRP	130 dBm *	130 dBm *	122 dBm maximum
Polarization	Transmit Feed	No Data	No Data	Linear **
	Receive Feed	No Data	No Data	Linear **
Installation	Radome	None	None	Inflatable 53 ft diameter ***
	Type Facility	Fixed Terminal	Fixed Terminal	Shipboard

Notes:
- * Derived value based on data available.
- ** Modified to circular for Intelsat III operations. Transmit-LHC and Receive-RHC.
- *** Not employed operationally.
- **** Three of these terminals existed on board the Redstone, Vanguard, and Mercury, respectively.

Table 10-15. Characteristics of Typical Third Generation Earth Terminals

Terminal Feature		Terminal	
		Paumalu, Oahu	Fucino, Italy
Antenna	Type	Cassegrain	Cassegrain
	Aperture Diameter	97 ft	90 ft
	Receive Gain	60 dB *	59.9 dB
	Efficiency	60% **	70%*
	Rec. Beamwidth	0.16° *	0.17°*
Receive System	Type Preamplifier	Helium Cooled Paramps.	Helium Cooled Paramps.
	Bandwidth	500 MHz	500 MHz
	Noise Temp.	50°K @ 7.5° Elev.	40°K @ 7.5° Elev.
Transmit System	Type Amplifier	TWT	TWT
	Bandwidth	500 MHz	500 MHz
	Power Output	6 kW	6 kW
Tracking	Type	Autotrack and Manual	Autotrack, Program Track, and Manual
	Accuracy	No Data	Autotrack -0.02°
Total Perfor-mance	G/T	43 dB/°K*	43.5 dB/°K *
	EIRP	129 dBm*	129 dBm *
Polar-ization	Transmit Feed	No Data	Linear or Circular
	Receive Feed	No Data	Linear or Circular
Installation	Radome	None	None
	Type Facility	Fixed Terminal	Fixed Terminal

Notes: * Derived value based on data available.
** Assumed value based on performance typically realized for this type antenna.

augment existing group delay equalization to the larger bandwidths associated with higher capacities, and replace certain traffic bearing and monitoring filters whose bandwidths are related to channel capacity.

Fourth generation earth stations have already been constructed at Talkeetna, Alaska, and Pulantat, Guam. At this writing, the publicly available literature describing the performance of fourth generation Intelsat terminals appears to be quite limited. In general, they are required to provide a receive gain of at least 57 dB and a receive G/T of 40.7 dB/°K. Both the transmit and receive chains will, as a goal, provide a 500-MHz RF bandwidth. Terminal transmitting feeds will be left-hand circularly polarized and receive feeds right-hand circularly polarized. Each terminal will, as a minimum, contain both an autotrack and manual tracking capability.

10.5 EXPERIMENTS

During the course of the operational use of the Intelsat satellites, a number of experimental activities have taken place. Among these were:

a. The effects of transmission delay on subscriber use of the satellite circuits and techniques for echo suppression.

b. Modulation techniques for multiple access of a single satellite transponder.

c. Time division multiple access (TDMA) techniques for a single satellite transponder.

d. Single Channel per carrier, Pulse code modulation, multiple Access, Demand-assignment Equipment (SPADE) techniques.

e. Satellite Switched Multiple Access (SSMA) techniques.

f. Link propagation characteristics at 4 and 6 GHz under various environmental conditions and during the occurrance of various phenomena.

10.6 OPERATIONAL RESULTS

Since the Intelsat program has produced a commercial communications system, the system's operational results obtained during each of the four generations of the space subsystem are of considerable interest. Early Bird was launched on April 6, 1965, and by April 22 it was sufficiently synchronized for the commencement of communications testing. Two groups of tests were conducted concomitantly: the Performance Test Plan to determine how well the spacecraft performance in orbit met contract specifications, and the Experimental Test Plan to determine system parameters when the spacecraft is used with the operating ground stations. The Performance Test Plan was completed in four days and included measurement of the spacecraft's effective radiated power (ERP), receiving sensitivity, transponder gain and frequency response, noise power ratios (NPR), intelligible crosstalk, antenna patterns, polarization, and insensitivity of the command system to interference. The only notable failing of the Performance Test Plan was that the specification for intelligible crosstalk of -45 dB could not be met with TWT No. 1. For this reason, TWT No. 2 was used for all commercial operations.

The Experimental Plan tests were conducted for 18 hours per day for a week. System characteristics with a variety of loading conditions were measured for all stations. It was determined that the 240 circuit capacity could be realized by the four high-capacity stations and that a 6-dB margin existed in fair weather. It was also determined that the antenna gain and receiving sensitivity for the four large stations were similar to within 1 dB.

Tests on system characteristics for monochrome TV were performed until all stations reached agreement on the optimum operating parameters.

Three weeks after launch, the spacecraft and the earth stations were properly tested, and the space segment of the system was ready for use. The terrestrial network operators then began circuit lineup. For the 120-channel multiplex system to be used for the first commercial service, it was necessary to allow 4 weeks for adjustments at a circuit level both in the U.S. and in the four countries in Europe. These tests were completed on schedule, and the system was ready for operation in June.

After a series of successful demonstrations with telephone circuits and television service, commercial operation was initiated on June 28, 1965. Figure 10-6 summarizes commercial usage for telephone and television traffic through November 1967. The satellite contribution to out-of-service time was zero in the Early Bird system. All loss of service was attributable to the seven major earth segment elements--the five earth stations and the U.S. and European interconnects. The reliability history of this service through early 1967 is shown in Figure 10-7 in terms of cumulative percentage outage time. Early Bird was placed in retired reserve on January 20, 1969, after Intelsat III achieved operational status. It was reactivated for a brief period between June 1969 and August 1969 when temporary difficulties were encountered with the despun antenna of an Intelsat III satellite. The Early Bird operational lifetime of 3-1/2 years far exceeded the design lifetime of 1-1/2 years for this exceptionally successful satellite program.

The first Intelsat II satellite (F-1) was launched in October 1966. Although it failed to achieve stationary orbit, the successful functioning of the communications subsystem permitted an 8-hour-per-day voice service to be established between the earth stations in Hawaii and Brewster Flat. Live television between Hawaii and the U.S. mainland was inaugurated via (F-1) on November 18, 1967.

Intelsat II (F-2) and (F-4) were employed for service in the Pacific area. During the time when the (F-4) satellite was undergoing final positioning maneuvers, its longitude was allowed to approach closely that of (F-2) for the purpose of making intersystem interference measurements. At Paumalu, the 85-foot antenna was operating with (F-2) while the 42-foot antenna was available for experimental work with (F-4). Experiments and measurements of interference

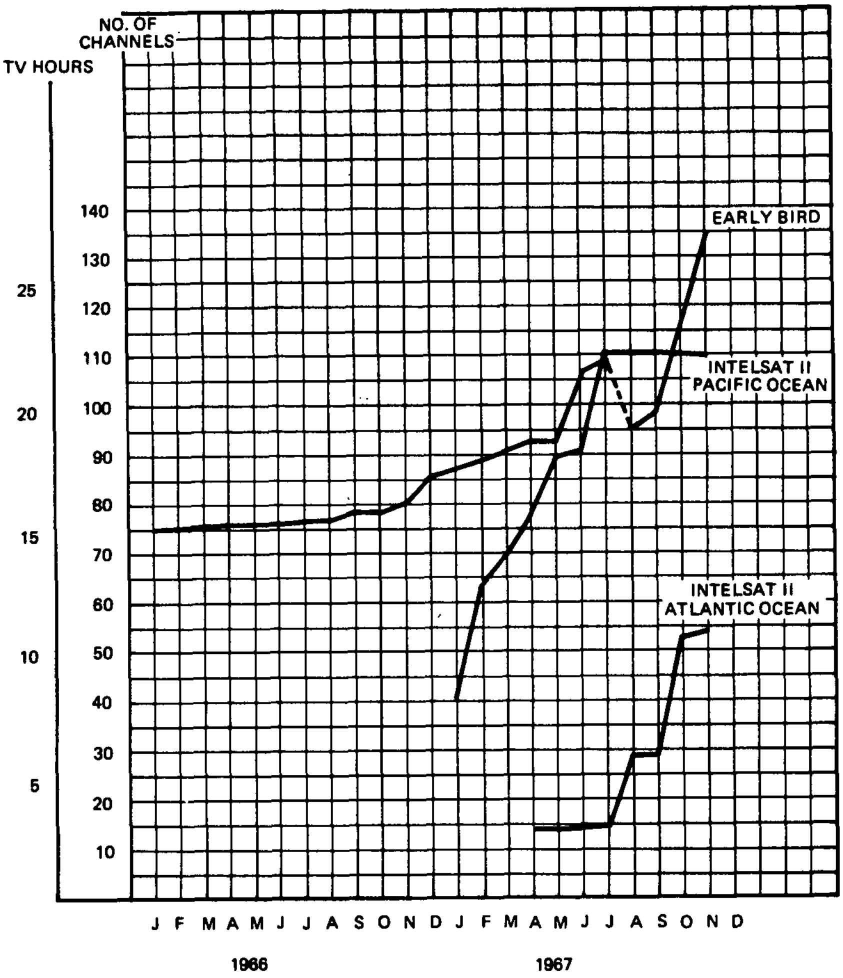


Figure 10-6. Early History of Intelsat System Usage

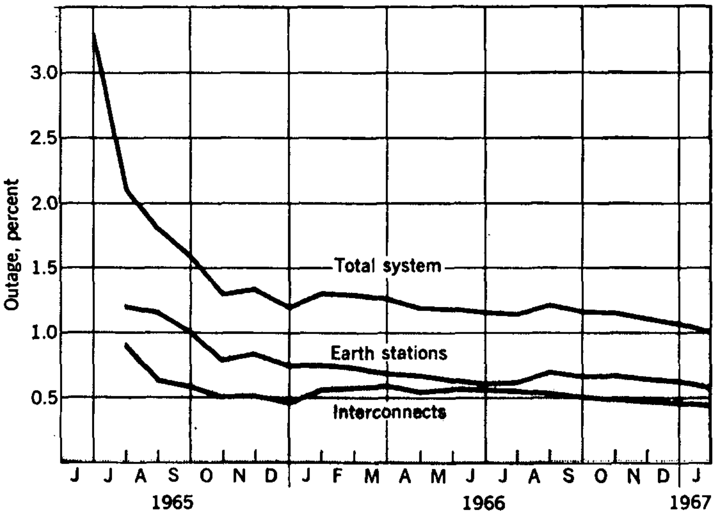


Figure 10-7. Cumulative Outage Performance for Early Bird

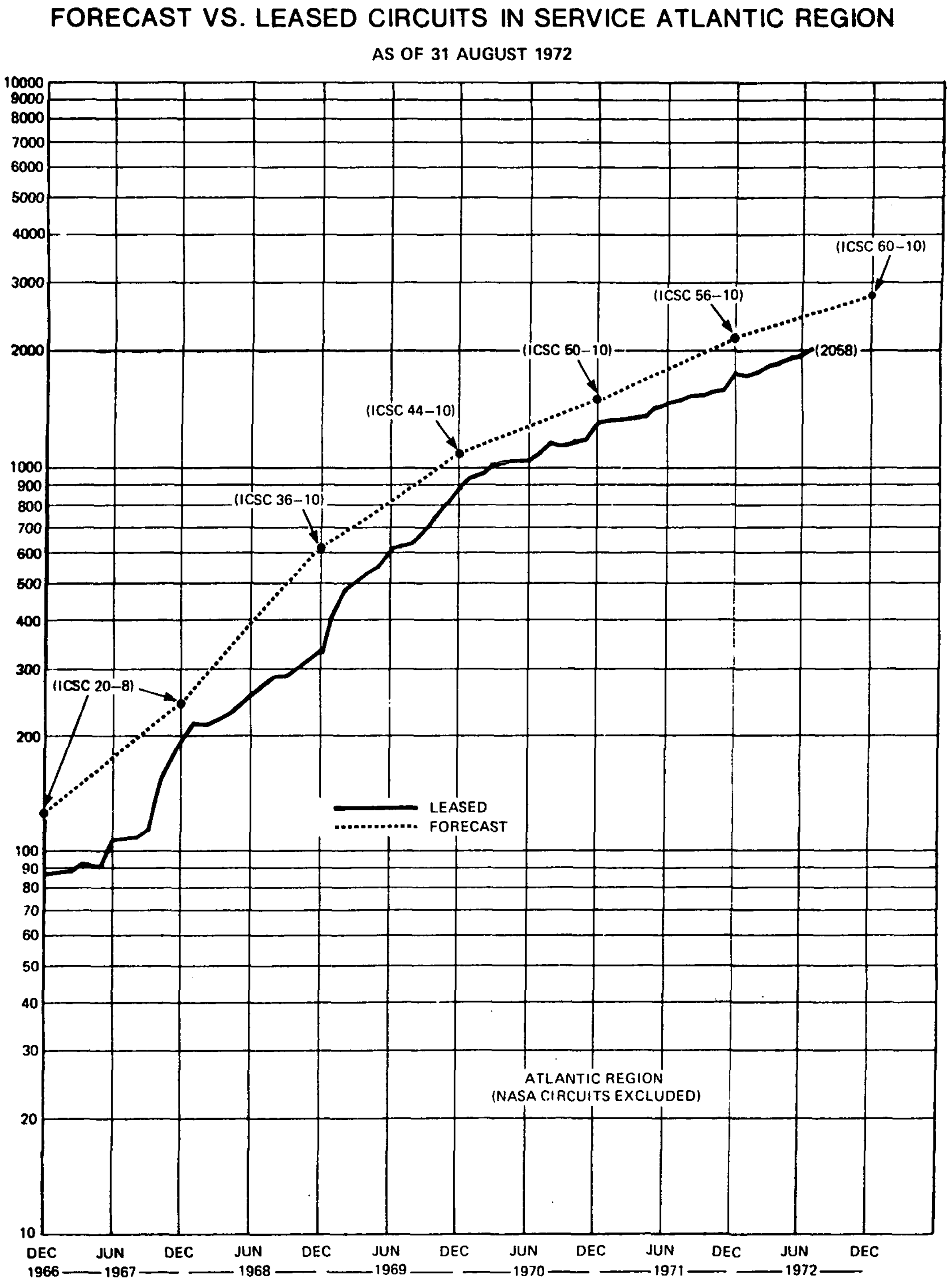
were made as the satellites approached to within 0.5° of each other. It was concluded from these interference measurements that the Intelsat II system can be safely operated with a minimum of 1.6° of longitude separation between satellites. Both of these satellites and (F-3), which supplemented Early Bird in the Atlantic area by providing wide area service, have operated satisfactorily providing commercial communications service. Multiple-access service was successfully initiated with the Intelsat II (F-2) satellite on January 27, 1969.

The first Intelsat III satellite (F-1) was launched in September 1968, but the launch vehicle failed. This was followed by the launch of Intelsat III (F-2) on December 18, 1968. This satellite began operational service over the Atlantic on December 24, 1968. It operated satisfactorily until June of 1969, at which time sticking of the mechanically despin antenna was encountered. This was determined to be due to a thermal gradient problem across the bearings of the despin motor. By August of 1969, the satellite was back in operational service. It continued to be employed until February 1, 1970, when Intelsat III (F-6) assumed the operational load over the Atlantic Ocean and (F-2) was retired from service. Intelsat III (F-3) was launched into orbit over the Pacific on February 5, 1969. It was placed into operational service on February 16, 1969, and continued to be employed in the Pacific location for about 6 months. F-3 was then repositioned over the Indian Ocean after losing about 6 dB of transponder gain due to a malfunction in one stage of the receiver tunnel diode amplifier. The reduced channel loading associated with operations at the Indian Ocean location permitted the satellite to continue in a useful capacity. Intelsat III (F-4) replaced (F-3) in handling the Pacific Ocean operational traffic. Intelsat III (F-7) was successfully placed into service over the Atlantic on May 8, 1970, to supplement (F-6). As of mid-1971 Intelsat III (F-3), (F-4), (F-6), and (F-7) and the associated ground complex continue to perform essentially as expected.

The first Intelsat IV satellite (F-2) was successfully launched into orbit over the Atlantic Ocean on January 25, 1971. Communications tests began on

February 7, and on March 26 earth station antennas in 14 countries, then operating with the Intelsat III (F-6) satellite, began a simultaneous mass pointover to assume operational service through the Intelsat IV (F-2) satellite. Fabrication of follow-on satellites in the IV series continues on schedule. As of mid-1971, future Intelsat IV launches were tentatively planned as follows:

Pacific	Third Quarter 1971
Second Atlantic	Fourth Quarter 1971
Pacific spare	Second Quarter 1972
Atlantic spare	Last Half 1972
Indian Ocean	1973

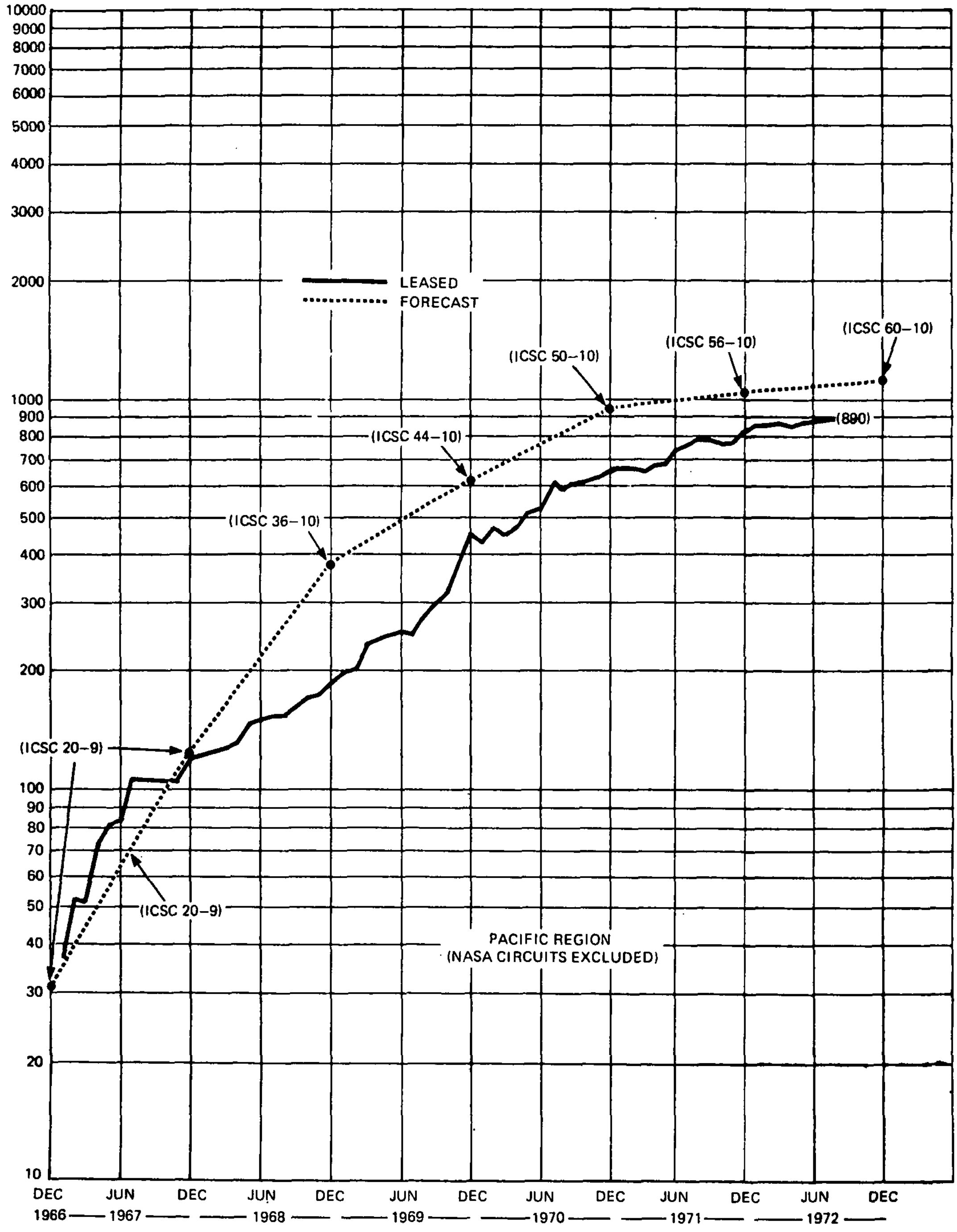


ATEST FORECAST	127	–	242	–	606	–	1045	–	1503	–	2110	–	2784
EASED	86	107	195	254	346	601	893	1051	1302	1452	1749	1917	

Figure 10-8a. Intelsat Traffic Growth Projection

FORECAST VS. LEASED CIRCUITS IN SERVICE PACIFIC OCEAN REGION

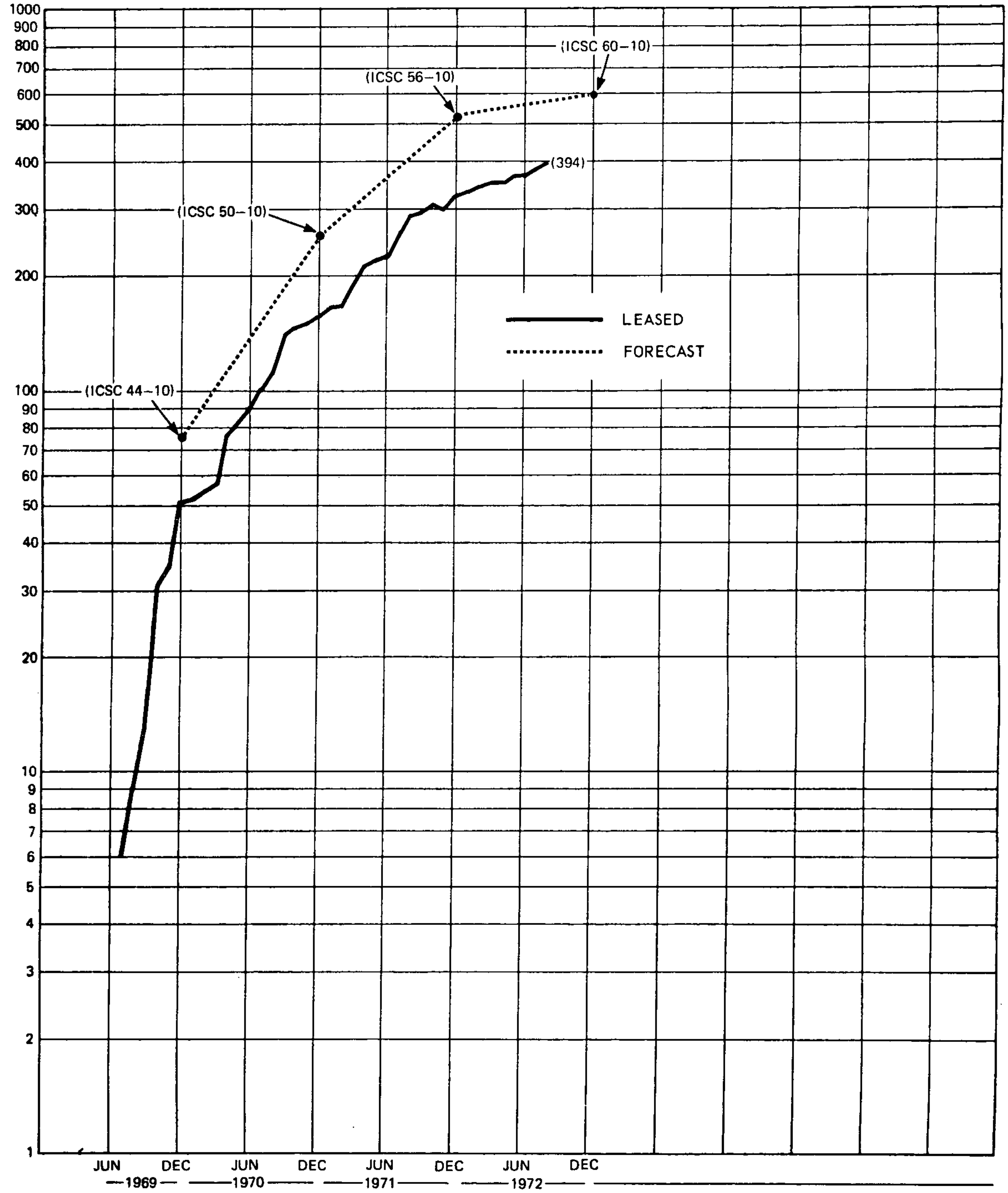
AS OF 31 AUGUST 1972



LATEST FORECAST	31	–	122	–	376	–	607	–	932	–	1075	–	1115
LEASED	–	84	121	150	197	264	445	525	656	740	827	870	

Figure 10-8b. Intelsat Traffic Growth Projection

FORECAST VS. LEASED CIRCUITS IN SERVICE INDIAN OCEAN REGION
AS OF 31 AUGUST 1972



	JUN 1969	DEC 1969	JUN 1970	DEC 1970	JUN 1971	DEC 1971	JUN 1972	DEC 1972
LATEST FORECAST	–	75	–	255	–	508	–	599
LEASED	–	51	89	157	248	327	368	

Figure 10-8c. Intelsat Traffic Growth Projection

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SECTION 11 - MOLNIYA-1

11.1 INTRODUCTION

For the Soviet Union, which occupies about one-sixth of the earth's surface, an efficient system of space communications is a vital necessity. The country covers nearly 6000 miles from east to west and over 2500 miles from north to south, and is crossed by 11 time zones; in addition, there are tremendously varied climatic conditions and vast areas of rugged terrain. For the United States, geostationary orbits over the earth in the equatorial plane have been favored because they permit communications 24 hours per day. For the Soviet Union, whose territory extends up to 80°N latitude, however, such an orbit is not ideal. It does not ensure communications at earth station elevation angles greater than 7.5° for all areas that lie above 70°N latitude. The Soviet Union's communication satellites system, using the Molniya-1 spacecraft, circumvents this difficulty by employing the highly eccentric elliptical orbits described below.

The orbit chosen for Molniya-1 satellites is interesting for two reasons. First, it is highly elliptical, with an apogee of 40,000 km in the northern hemisphere and perigee of 500 km in the southern hemisphere, with a period of revolution of nearly 12 hours. Thus the two daily orbital apogees for any given satellite occur over earth longitudes 180° apart. Second, the angle of inclination of 65° means that the useful period, during one of the two daily orbits of a spacecraft, when the satellite can be employed for radio communication between distant points in the USSR, is between 8 and 10 hours. If three Molniya-1 communication satellites are launched at regular intervals into identical elliptical orbits whose planes are shifted relative to one another by 120°, they will form a system that ensures 24 hours per day communications for the entire USSR. It should be noted that this orbit also affords the possibility of continuous communication between the European USSR and North and Central America, thereby establishing communications between most parts of the northern hemisphere where between 75 and 80 percent of the earth's population resides. The orbital characteristics of the Molniya-1 satellites launched as of mid-1971 are shown in Table 11-1.

It should be further noted that an additional important advantage accrues to the Soviet Union with the selection of an elliptical orbit. For a launch vehicle of given thrust operating from the appropriate Soviet launch site, two or three times the weight can be placed into the selected elliptical orbit as into an equatorial synchronous one. This fact helps explain the uncommonly large weight of about 2000 pounds associated with the Molniya-1 spacecraft when compared to the more modest weights of the United States' geostationary spacecraft.

In addition to its unique orbit, the Molniya program has been responsible for a number of other innovations in satellite communications technology. Major advances provided by the Molniya-1 satellites included a demonstration of an operational system using flywheel stabilization, solar panels that were continually maintained in a 90° aspect relative to the sun line by proper positioning of the body of the spacecraft, and parabolic antennas that tracked the earth independent of the main body of the satellite. This program also produced the first system supplying a regular space television distribution service to a large number of receiving terminals of wide geographic dispersion.

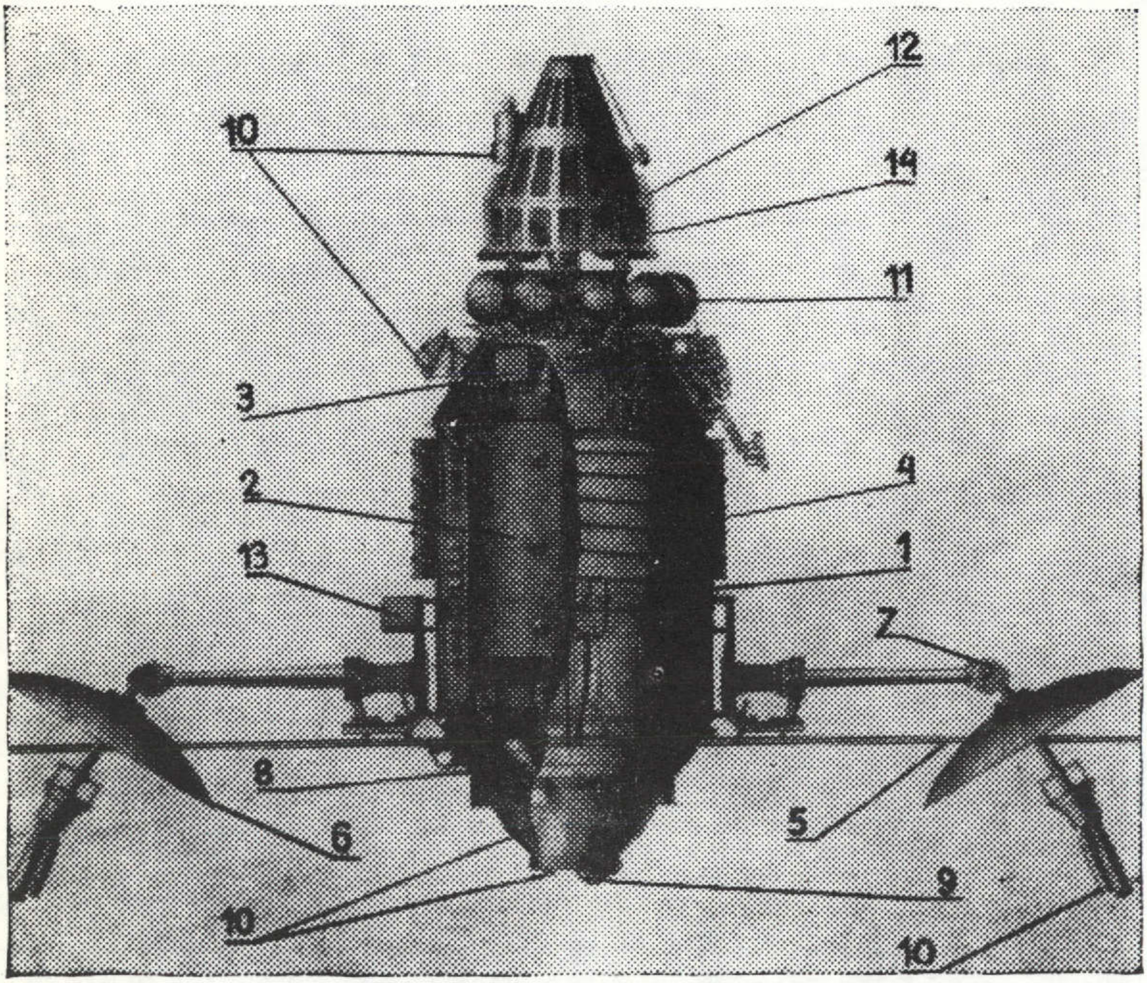
11.2 SPACECRAFT

The Molniya-1 spacecraft is shown in Figure 11-1; its principal communication parameters are summarized in Table 11-2. In form, the spacecraft is cylindrical with conical ends having a diameter and height of about 5 and 10 feet, respectively. Its more apparent features include the six solar cell panels and the two parabolic communication antennas (one in reserve). Within the hermetically sealed body are the primary transponder (along with the complete spares), an electronic computer for equipment control, a gyrostabilizer, chemical batteries, and various electronic equipment. The fact that the spacecraft is gyro, and not spin-stabilized, required the inclusion of equipment for internal temperature regulation; this is

Table 11-1. Molniya-1 Communications Satellites

Satellite	Launch Date	Orbital Parameters				Status
		Apogee (km)	Perigee (km)	Period of Revolution Hr. Min.	Orbital Inclination* (Deg.)	
Molniya-1 A	April 23. 1965	39.381	497	11:48	65	In orbit
Molniya-1 B	Oct. 13, 1965	40.000	501	11:59	65	March 17. 1967**
Molniya-1 C	April 25. 1966	39.500	499	11:50	64.5	In orbit
Molniya-1 D	Oct. 20. 1966	39.700	485	11:53	64.9	Sept. 11. 1968**
Molniya-1 E	May 25. 1967	39.810	460	11:55	64.8	In orbit
Molniya-1 F	Oct. 3. 1967	39,600	465	11:52	65	March 4. 1969**
Molniya-1 G	Oct. 22. 1967	39.740	456	11:54	64.7	Dec. 31. 1969**
Molniya-1 H	April 21. 1968	39.700	460	11:53	65	In orbit
Molniya-1 J	July 5. 1968	39.770	470	11:55	65	May 15. 1971**
Molniya-1 K	Oct. 5. 1968	39.600	490	11:52	65	In orbit
Molniya-1 L	April 11. 1969	39.700	470	11:53	65	In orbit
Molniya-1 M	July 22. 1969	39,500	520	11:51	64.9	In orbit
Molniya-1 N	Feb. 19. 1970	39.175	487	11:43	65.3	In orbit
Molniya-1 P	June 26. 1970	39,527	846	11:58	65.4	In orbit
Molniya-1 R	Sept. 29. 1970	39,300	480	11:46	65.5	In orbit
Molniya-1 S	Nov. 27. 1970	39.729	626	11:58	65.4	In orbit
Molniya-1 T	Dec. 25. 1970	39.600	480	11:52	65	In orbit
Molniya-1 U	July 28. 1971	39.300	470	11:45	65.4	In orbit

*Original parameters supplied by Novosti.
**Date of orbit decay.



1 - body; 2 - equipment rack; 3 - heat regulating system rack; 4 - heat regulating system radiators; 5 - solar cell panels; 6 - communications antenna; 7 - antenna drive; 8 - flywheel gyro; 9 - optical solar orientation sensors; 10 - optical earth orientation sensors; 11 - pressurized air containers; 12 - correcting engine; 13 - radiometer; 14 - vacuum shield insulation.

Figure 11-1. The Molniya-1 Communications Satellite (Cutaway View)

Table 11-2. Molniya-I Spacecraft Description

Antenna		Type	Parabolic Reflector (3' dia.)
		Number	2 (including one reserve)
		Beamwidth (-3dB)	22°
		Gain	16-18 dB
		Polarization	Circular
Repeater		Frequency Band	800-1000 MHz, **
		Type	Nonlinear frequency translating
		Bandwidth	No Data
		Number	1 + 2 reserve
	RCVR	Type Front End	Silicon diode mixer
		Front End Gain	No Data
		Sys. Noise Figure	9-10 dB
	XMTR	Type	2-Stage TWT
		Gain	60 dB
		Power Out	40 W for TV or 14 watts per channel for duplex multichannel telephony
		EIRP	30 dBW*
General Features	Stabili-zation	Type	Gyro
		Capability	No Data
	Power Source	Primary	Silicon Solar Cells, 500-700 watts output
		Supplement	Battery
		Comm. Power Needs	No Data
		Size	Cylindrical: height - 10'; diameter - 5'
		Weight	2200 lbs.

*Derived value based on antenna gain and transmitter output power.

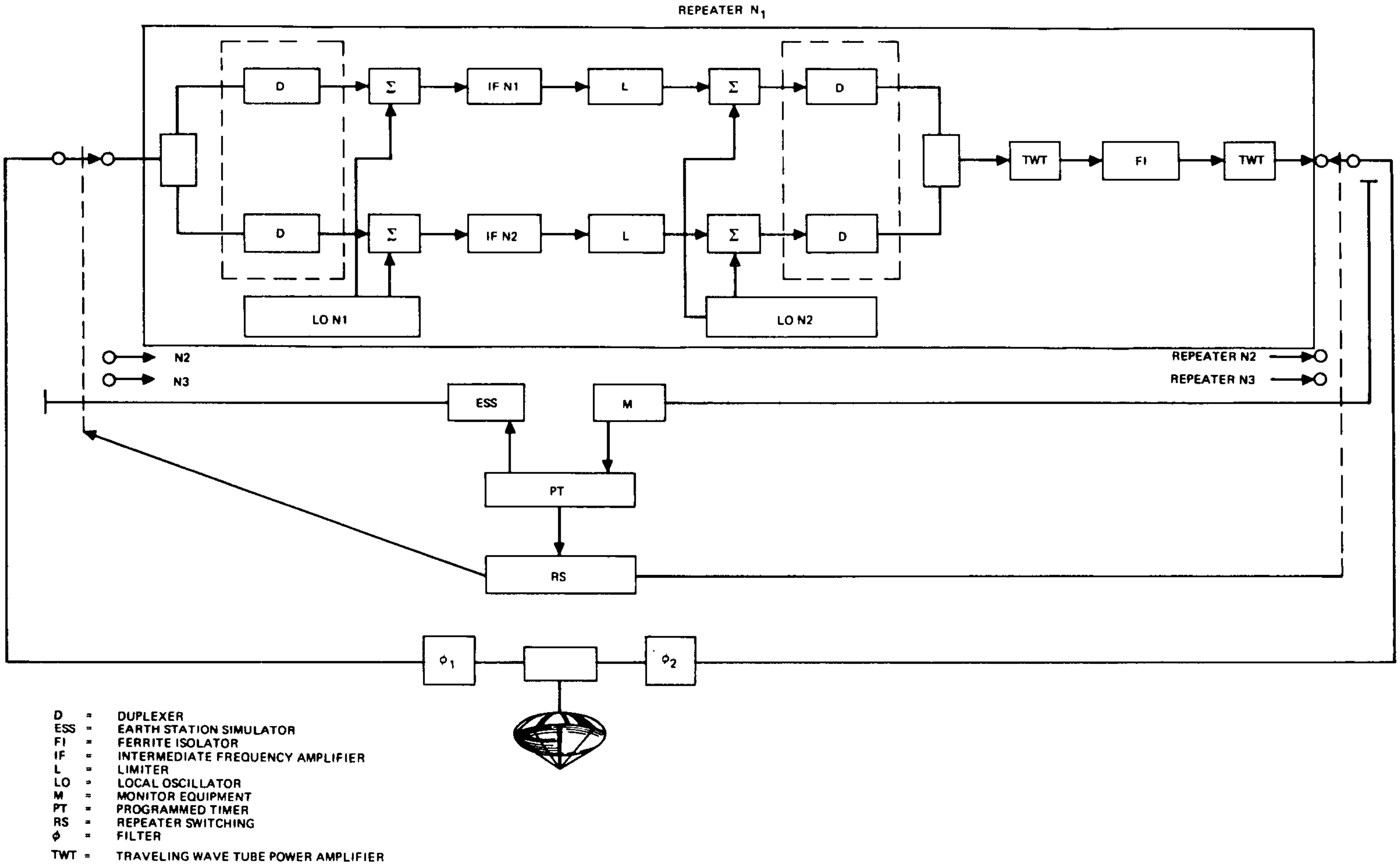
**Some Molniya-1 satellites operated in the 3400- to 4100-MHz band possibly as a checkout for prototype Molniya-II downlink equipment.

accomplished by means of a radiator-condenser (in a cylindrical configuration about the spacecraft body) and a heat panel (in the form of a flat ring).

When the spacecraft attains its final orbit and has separated from the last stage of the launch vehicle, the solar cell panels, originally folded along the body of the satellite, are automatically extended. The orientation system is switched on, the satellite's tumbling motion is arrested by gas-jets, and the body of the satellite, together with the solar cell panels, is oriented toward the sun to maximize the power for the solar cell system. During the entire orbital trajectory, the spacecraft attitude is maintained by a gyro-stabilizer driven by an electric motor so that the solar panels remain directed toward the sun.

After sun acquisition, one of the on-board antennas is directed towards the earth by highly sensitive earth sensors. The earth is acquired, and this antenna continues to track the earth during the entire period of communication. Should it become necessary to switch to the standby antenna, all that is required is to rotate the body of the satellite 180° about its longitudinal axis, using the gas-jet stabilizers.

A block diagram of the transponder "Alpha" used in the Molniya-1 spacecraft[4] is shown in Figure 11-2. The principal communication parameters are summarized in Table 11-2. Both signal reception and transmission are accomplished with the same parabolic spacecraft antenna; isolation filters are used to separate these signals. The signals received from earth stations operating at two different frequencies are further separated by an input duplexer. After intermediate frequency conversion in a silicon diode mixer, the signals are amplified and then amplitude-limited. After passing through a parametric-diode up-converter and output duplexer, the signals are amplified in a two-stage TWT amplifier. The first TWT operates in a linear mode, while the second TWT operates in a saturated mode. A ferrite isolator is employed between TWTs for matching. For duplex telephony, the power output is 14 watts per channel. For television, the output power is the maximum available of 40 watts. Design lifetime of the later Molniya-1 spacecraft was about 2 years as compared to 1 year for initial versions.



D = DUPLEXER
ESS = EARTH STATION SIMULATOR
FI = FERRITE ISOLATOR
IF = INTERMEDIATE FREQUENCY AMPLIFIER
L = LIMITER
LO = LOCAL OSCILLATOR
M = MONITOR EQUIPMENT
PT = PROGRAMMED TIMER
RS = REPEATER SWITCHING
ϕ = FILTER
TWT = TRAVELING WAVE TUBE POWER AMPLIFIER

Figure 11-2. Molniya-1 Communications Repeater

11.3 GROUND TERMINALS

The ground terminal antennas (transmitting and receiving) are 50-foot diameter paraboloids with Cassegrain feeds. They are mounted on rotating units permitting a tracking accuracy of a few angular minutes; tracking is either preprogrammed or self-tracking. To decrease losses in the feeder waveguide equipment, buildings are constructed in direct proximity to the rotating units. The parametric amplifiers of the receiver, along with the receiver duplexer and directional coupler, have been installed in an antenna cabin behind the primary reflector. For the output of the parametric amplifier, the received IF signal is fed to the receiving equipment located in the building. The high frequency power output from the transmitter building is delivered to the antenna feed along a waveguide through the rotating junction.

The transmitting unit consists of an exciter, frequency modulator, power amplifier and supply, monitor, and heat exchanger. The transmitter itself is a 5-kW multicavity klystron. The video bandwidth available for the television mode is 5 MHz. For more efficient transmission of television and telephone signals, there are standard preselection systems. High transmitter carrier frequency stability is achieved by utilizing a quartz master oscillator in the exciter with subsequent multiplication and mixing with the FM modulator signal.

The receiving equipment consists of operating and monitoring receivers. Each consists of a remote parametric amplifier with IF preamplification, IF amplifiers, limiters and demodulators for the television and telephone modes, and supply sources. Moreover, a receiver monitor, video monitor, and received signal level recorder are included as part of the receiving units. The parametric amplifiers of the receivers are two-stage regenerative amplifier-converters. In the Molniya-1 system, the two-stage parametric amplifiers operate at both normal and liquid nitrogen temperatures. The noise temperature of the uncooled paramp is 150° K, and of the cooled is 80° K. The cooled paramp is installed ahead of an isolating filter. The frequency passband is sufficient for quality transmission of black and white or color television. For transmission of group spectra, frequency feedback reduces the passband to 1.5-2.0 MHz. Further details of the ground terminals are provided in Table 11-3.

11.4 EXPERIMENTS

Since the Molniya program has produced an operational satellite communications system, it might be expected that there has been little emphasis on experimentation. Further, what experiments have been conducted are not well documented in the open literature available to the Western World. It might be conjectured that, when the first Molniya-1 spacecraft began to appear in orbit, both the highly elliptical orbit employed and the three-axis stabilized satellite, with its sun-oriented solar panels and tracking antennas, were considered experimental in nature. Obviously, these experiments worked out well, since the operational system continued to incorporate the aforementioned features. Additionally, it is known that the Molniya satellites have been employed to provide measurements of the earth's environment. The orbital paths of these satellites carry them through the earth's radiation belts several times each day, and studies are being made not only of the radiation belts but also of the effects they have on spacecraft equipment, especially solar cells.

11.5 OPERATIONS

The Molniya-1 system was designed for relaying wideband transmission of either duplex multichannel telephone communications (including telegraph and facsimile) or television (black and white or color). Initially, operations were of a point-to-point nature between Moscow and Vladivostok to provide regular telephone and telegraph exchange between the center of the country and the Far East to transmit Central Television programs to viewers in the Maritime territory. The first TV transmission via a Molniya-1 satellite was made on 25 April 1965, just 2 days after the launching of the first vehicle. Under a Franco-Soviet research program, color television broadcasts have been successfully transmitted between Moscow and Paris since December 1967, using Molniya-1 in conjunction with the Secam III system. This research program followed a previously successful Moscow-Paris

Table 11-3. Earth Terminal Characteristics

Terminal Features		Terminal	
		Moscow/Vladivostok	Orbita
Antenna	Type	Parabolic Cassegrain	Parabolic
	Aperture Size	50' diameter	40' diameter
	Receive Gain (3.4 GHz)	52 dB*	50 dB*
	Efficiency	60%**	55%**
	Receive Beamwidth (3.4 GHz)	0.4°*	0.5°*
Receive System	Type Preamplifier	Two-stage regenerative Parametric Amp. (Cooled)	Two-stage paramp. (Cooled to -196°K)
	Bandwidth	No data	No data
	Noise Temp.	230°K	200°K
Transmit System	Type Amplifier	Klystron	None normally
	Bandwidth	5 MHz	Provided
	Power Out	5 kW	Provided
Tracking	Type	Self-tracking or Programmed Tracking	Programmed tracking or self-tracking
	Accuracy	No data	08' of arc
Total Perform.	G/T	28.4 dB/°K*	27 dB/°K*
	EIRP	130 dBM*	None*
Polarization	Transmit Feed	No Data	None
	Receive Feed	No Data	No data
Installation	Radome	No Data	None
	Type Facility	Fixed	Fixed

*Derived value based on data available.

**Assumed value based on common performance for this type antenna.

demonstration. The results of this early demonstration were reported in documents of the 1966 URSI (CCIR) Meeting in Oslo, Norway.

Recently, experimental transmissions of newspaper pages, along with television transmissions, have been carried out via Molniya-1. Newspaper pages from Pravda in Moscow successfully transmitted to Khabarovsk (near Vladivostok) have shown that the imprint of such pages is satisfactory. However, the rapid changes in propagation path length on the ascent and descent of the elliptical orbit does result in some peculiarities, such as an apparent bending in the received newspaper type page. As of mid-1971, equipment was being added to Orbita stations that will further expand their telecommunications capability by permitting the relaying of computer data.

In 1967 the USSR inaugurated a space television distribution system, using Molniya-1 satellites, allowing people in Siberia, the Far East, and the Far North to see broadcasts from Moscow. As of mid-1971, the number of ground stations in this network was about 40. A few of the known receiving site locations are tabulated in Table 11-4. The Orbita stations have achieved an extremely high level of reliability of not less than 99.7 percent. A notable event during 1969 was the building by Soviet engineers of an Orbita receiving station in Ulan-Bator, Mongolia. This terminal began operation on February 2, 1970. A station has also been proposed for Havana, Cuba. Recently, a second generation of ground terminals, Orbita 2, have been described and have begun to be set up.

In addition to the communication functions served by the Molniya-1 satellites, certain spacecraft in the series have been fitted with television cameras and have successfully transmitted detailed photographs of the earth's cloud cover from altitudes ranging between 30,000 and 40,000 km. These pictures are especially important in determining meteorological oonditions in conjunction with "Meteor" class weather satellites that photograph the earth's cloud cover from near circular 625-km orbits.

Molniya-1 satellites have also participated in the Soviet manned space program by relaying communications between surface ships in direct contact with Soyuz -6, -7, and -8 and a central control site within the Soviet Union.

Table 11-4. Orbita Ground Stations

Alma-Ata
Arkhangel'sk
Ashkabad
Bratsk
Chita
Frunze
Irkutsk
Yakutsk
Yuzhno-Sakhalinsk
Dudinka
Salekhard
Zayarsk
Blagoveshchensk
Kemerovo
Khabarovsk
Komsomolsk-on-Amur
Krasnoyarsk
Magadan
Murmansk
Noril'sk
Djezkazgan
Abakan
Dzhezkazgan
Gur'yev
Kyzyl
Zeia
Moscow
Novosibirsk
Petropavlosk (Kamchatka)
Surgut
Syktyvkar
Ulan-Ude
Vladivostok
Gremikha
Anadyr (or Bilibino)
Oka
Ourai
Sovetskaya Gavan
Nebit Dag

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SECTION 12 - INITIAL DEFENSE COMMUNICATIONS SATELLITE PROGRAM

12.1 GENERAL DESCRIPTION

The Initial Defense Communications Satellite Program (IDCSP), as finally implemented, was an outgrowth of Army participation in NASA's Project Syncom and an initial system concept calling for medium altitude polar satellite orbits. By participating in the Syncom Program, the Army gained a nucleus of ground terminals and operating experience applicable in the IDCSP.(1) The satellites resulting from the initial medium altitude system concept were simple state-of-the-art spacecraft. Subsequent to their design, the Titan IIIC became available as a launch vehicle.(2)(3) It became apparent that considerable cost savings could be realized by the employment of separately scheduled and funded Titan IIIC developmental launches to boost a reduced number of previously designed satellites into near-synchronous equatorial orbits. In June 1966 the first seven IDCSP satellites were successfully orbited by a Titan IIIC booster.

The objectives of the IDCSP are listed in Table 12-1.(4)(5) The space subsystem consisting of 26 near-synchronous, random equatorial orbit satellites was placed into orbit in four separate launches (see Table 12-2).(6)(7)(8) The period immediately after the first launch was used for system testing between deployed terminals. In particular, a two-channel duplex link capability between two AN/MSC-46 terminals was demonstrated. In December 1968 emergency operational links were established between Hawaii-Republic of Viet Nam (RVN) and Philippines-RVN. In July 1967 the entire Pacific network was placed in initial operational status and integration of IDCSP into the DCS was begun. Although designed as an R&D system the IDCSP almost immediately became an operational system; however, some R&D was continued in other portions of the system.

Table 12-1. IDCSP

Number	Description
1	Conduct system research, development, testing and evaluation to determine operational compatibility and utility of the Initial Defense Communication Satellite System (IDCSS) to meet user requirements.
2	Establish a research and development communications satellite system in being, designed for the most part to be directly convertible and expandable to an operation system through integration and compatibility with the DCS; thereby capable of providing service to specified users of the National Communications System.
3	Provide an emergency capability for supplementing the Defense Communications System (DCS) and improving its assurance of provision of the minimal essential survival communications for the National Military Command and Control purposes.

Of the 26 satellites launched, 21 were still operational as of 29 June, 1971. The 100-lb satellites are spin-stabilized, solar-powered, and they carry no batteries. They drift randomly (depending upon exact altitude) from West to East at approximately 30° per day so that a single satellite stays within view of a particular ground terminal for about 4-1/2 days. Originally designed for a mean-time-to-failure (MTTF) of 1.5 years (with a goal of 3 years) experience has shown that figure exceeded by a wide margin. As late as the first quarter of 1968 projected MTTF was 4.5 years.(9)

Table 12-2. IDCSP Spacecraft

Satellite	IDCSP				
Manufacturer and Sponsor	Philco-Ford, DOD/DCA/SAMSO				
Launch Vehicle	Titan IIIC				
Launch Date	June 16, 1966	August 26, 1966	January 18, 1967	July 1, 1967	June 13, 1968
Number Launched	7 IDCSP + GGTS 1	8 IDCSP	8 IDCSP	3 IDCSP + DATS 1 DODGE, LES 5	8 IDCSP
Initial Orbit Data					
Period (Min)	1334.2-1344.0	Launch Failed	1330 - 1343	1309.8-1319	1269 - 1350.6
Perigee (St. Mi)	20,913-20,949		20,835-20,935	20,509-20,692	19,121-20,976
Apogee (St. Mi)	21,051-21,350		21,031-21,275	20,846-20,894	21,027-21,401
Incl. (Deg.)	0.0-0.2, Most 0.1		0.0 - 0.1	7.2	0.1
*Status	1 IDCSP Failed May, 1969.			1 IDCSP Failed March 1968, DATS 1 Failed May 1970, and LES 5 Ceased Radiation May 1970.	1 IDCSP Failed June 1971 and several others have a history of intermittent performance.

*Status as of 29 June 1971: 21 IDCSP satellites operational.

NOTE: IDCSP satellite transmitters are scheduled to turn off automatically 6 years from date of launch.

In addition to the IDCSP satellites four experimental satellites have been put into orbit in four successful IDCSP launches. These satellites are also listed in Table 12-2.

The ground subsystem consists of three different terminal types (see Table 12-3). Two large fixed AN/FSC-9 terminals, which were converted from the ADVENT program for use with IDCSP, are located in CONUS at Ft. Dix, New Jersey, and Camp Roberts, California. Twelve large transportable AN/MSC-46 terminals are deployed throughout the world, and two are used for training. This terminal was developed for IDCSP, primarily for entry into the Defense Communications System (DCS). There are 13 highly transportable AN/TSC-54 terminals, some deployed and some on standby for use in case of contingency. All terminals transmit in the 7.9- 8.4-GHz band, and receive in the 7.25- 7.75-GHz band. A fourth terminal, the AN/SSC-3, a small shipboard terminal, was developed but never became operational. It would have served for Navy ship-to-ship and ship-to-shore communications.

Table 12-3. Participating Terminals

Terminal Type	Manufacturer and Sponsor	Antenna Diameter (ft)	Power (kW)
AN/FSC-9	Modified by Radiation, Inc/ Army-SATCOM	60	20
AN/MSC-46	Hughes Aircraft/Army-SATCOM	40	10
AN/TSC-54	Radiation, Inc./Army-SATCOM	Four-dish array, 18 ft. effective	5
AN/SSC-3	Hughes Aircraft/Navy-NAVELEX	6	5

IDCSP has demonstrated the establishment of an operational worldwide military satellite communication network which provides a wide range of services. Included in these services are the transmission of wideband data from RVN to Washington and protected pseudonoise modulation. In establishing the network a number of other technological capabilities have been demonstrated. The Titan IIIC was shown to be capable of transporting and deploying one to eight satellites to near-synchronous altitude. The deployment process itself was a demonstration of the capability to perform a fairly complex operation. It consisted of the deployment of eight separate satellites at timed intervals and with slightly differing initial velocities. Finally, through the DODGE satellite, experience was gained with gravity gradient stabilization. A capability to detumble the satellite was demonstrated, but the gravity gradient stabilization system was unable to achieve or to maintain damping to a degree satisfactory for communication satellites.

12.2 SYSTEM DESCRIPTION

The Defense Satellite Communications System (DSCS) is one part of the total Defense Communications System (DCS), which is a worldwide complex of long haul, point-to-point communications facilities. These facilities include transmission via conventional VLF through HF radio, land and submarine cable, microwave relay, and tropospheric scatter. IDCSP augments and (where required due to physical or technical limitations) replaces these conventional communication methods. The IDCSP provides near-synchronous communication satellites to relay voice and digital communications between fixed and mobile users. It consists of four subsystems: earth station, launch and deployment, space, and control.

A satellite link is formed by an earth station at each end of the link and one satellite. Figure 12-1 shows one-half of a typical user-to-user link. The exact configuration of the earth station/user interface varies depending on the situation. For example, it is possible for the user (especially tactical or contingency users) to be connected directly to the Link Terminal. However, in normal DCS use, the user interfaces with the Technical Control Facility (TCF) as shown in Figure 12-1. The earth station subsystem includes all the elements necessary to establish satellite communication channels which serve DCS stations or directly connected users.

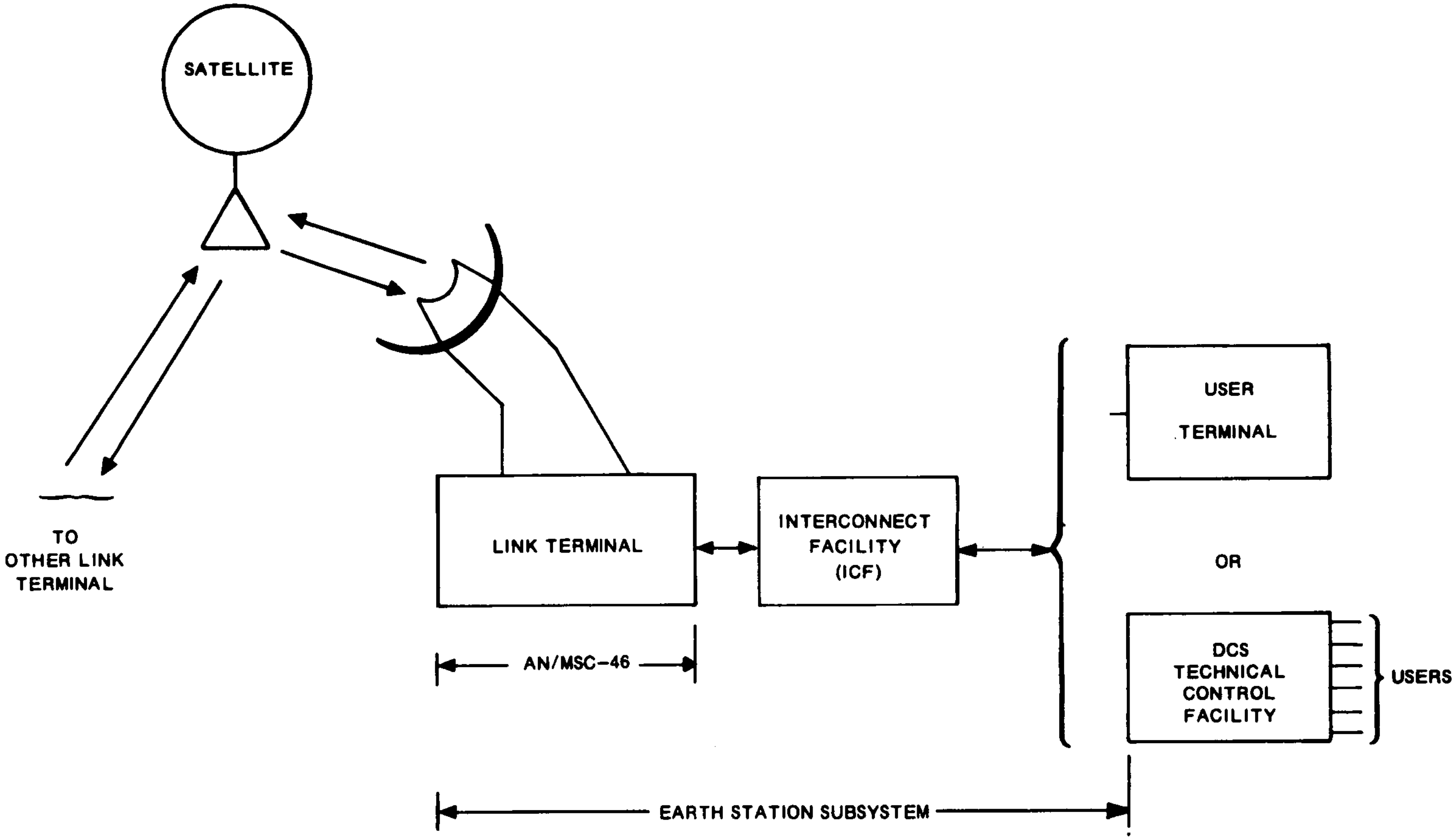

Figure 12-1. Basic Block Diagram of Typical User Link

There are three types of terminals used in the IDCSP. Two AN/FSC-9 terminals are located at Camp Roberts, California, and Fort Dix, New Jersey. They are fixed installations, each equipped with a 60-foot diameter antenna. The AN/MSC-46 link terminals, deployed at high traffic density nodes, are transportable facilities with 40-foot diameter antennas. They are primarily intended for use as DCS trunk terminals. The highly transportable AN/TSC-54 link terminals are used for extension of the DCS into contingency areas for tributary-type links to outlying activities and as Navy shore stations. Local conditions dictate the type of transmission facility used as an interconnect link. Interconnect links in CONUS consist of leased commercial facilities, and those overseas are government-owned and operated radio relay or cable facilities.

The launch and deployment subsystem includes: the Titan IIIC launch vehicles, satellite dispensers and support facilities to implement and support the launch operations, satellite injection into orbit, the ensuing telemetry readout, and tracking and ephemeris determinations. Launch phase technical support was provided by the Air Force Satellite Control Facility (SCF). Since the completion of the launches the SCF has provided orbital tracking data and telemetry monitoring to determine satellite health. This information is forwarded to the Satellite Communication Control Facility (SCCF) to be used in system control.

The space subsystem is composed of 26 satellites launched into random equitorial orbits at a near synchronous altitude of approximately 18,200 nautical miles. At this altitude the satellites, as viewed from the earth, drift from West to East at about 30° of longitude per day. A varying distribution of satellites encircling the earth results, since each satellite is released from the dispenser at a slightly different orbital velocity. The differential velocities are chosen in such a way as to reduce "bunching" of satellites, thus enhancing satellite availability. This type of space subsystem configuration minimizes the effect of any individual satellite's failure. In addition, since no-satellite stationkeeping is necessary, the potential for an enemy gaining control of the satellite and disrupting communications is reduced.

The purpose of the control subsystem is to achieve an orderly allocation of system assets among various users in accordance with validated user requirements. The basic elements of the control subsystem are the Satellite Communications Control Facility (SCCF), the Area Communications Control Function (ACCF), and the Earth Station Control Function (ESCF). The SCCF is the focal point of the control subsystem and is collocated with the DCA Operations Center (DCAOC) in Arlington, Virginia. The primary mission of the SCCF is the preparation and distribution of long term schedules (60 days prepared every 30 days), short term (up to 30-day duration), and emergency satellite/link terminal schedules in accordance with validated user requirements.

To a large extent the circuits provided by the IDCSP appear similar to conventional trunks. Careful engineering of the earth station and DCS station interface make it possible to replace a standard common user trunk with a satellite link (of equal channel capacity) involving a minimum of special consideration and realignment of equipment on the part of the user or operator. However, certain system characteristics of the satellite channel can introduce unfamiliar problems. These are propagation delay, handover, and doppler shift. Propagation delay ranges from about 200 ms to 260 ms. Experience has shown that this amount of delay is not bothersome on typical analog voice circuits and has little effect on the quality of data transmission. The occurrence of outage due to handovers (the transfer from one satellite to another) are normally predictable in advance; with proper scheduling and coordination their effects can be minimized. The handover time design objective is 2 minutes. The maximum doppler shift, 0.21 parts per million, occurs when the satellite is rising or setting with respect to a given link terminal. In general, these shifts are sufficiently small to have no noticeable effects on data transmitted via IDCSP.

To establish communications between two terminals it is necessary that a satellite be mutually visible to the terminals. The SCCF is able to provide satellite scheduling data for all links for a 60-day interval. Satellite availability predictions based on probabilistic analyses for various links are shown in Figure 12-2 as a function of the total number of orbiting satellites. The availability for the Hawaii-Republic of Viet Nam (RVN) link is shown both for at least one satellite and for at least two satellites. Two satellites would be required when the channel requirements exceed the capability of one satellite. Thus, with a system composed of 15 satellites, the availability of at least one satellite for the Hawaii-RVN link is 89 percent and the availability of at least two satellites is 64 percent. Since there is no orbital control to permit repositioning of the satellites, random gaps occasionally occur and are a major cause of satellites being unavailable. In addition, satellites may become temporarily unusable due to conjunctions with other satellites (resulting in multipath) or with the sun or moon (resulting in an increase in system noise temperature). Since the satellites have no batteries they do not operate during eclipse (while in the earth's shadow).

Four forms of modulation are used in IDCSP. They are frequency division multiplex-frequency modulation (FDM-FM), pseudonoise (PN), differential phase shift keying (DPSK), multiple frequency shift keying (MFSK). All link terminals utilize FDM-FM and PN. The AN/TSC-54 link terminals also utilize DPSK and the AN/MSC-46 terminals are capable of operating with MFSK. PN modulation yields a degree of antijam protection to the system.

The FDM baseband consists of nominal 4-kHz channels, or frequency shift keyed (FSK) teletype channels, or combinations of both. The AN/FSC-9 and AN/MSC-46 link terminals were modified to accommodate up to 12 voice channels. The link terminal equipment is also capable of accepting up to five individual TTY channels at direct current and frequency shift keying them into one of the voice channels. It is not anticipated that this latter capability will be used for normal DCS service. It is usually more efficient (a greater number of circuits per VF channel) to multiplex the TTY channels at the DCS facility. This capability could be used, however, for direct access from a user to the satellite link terminal if necessary.

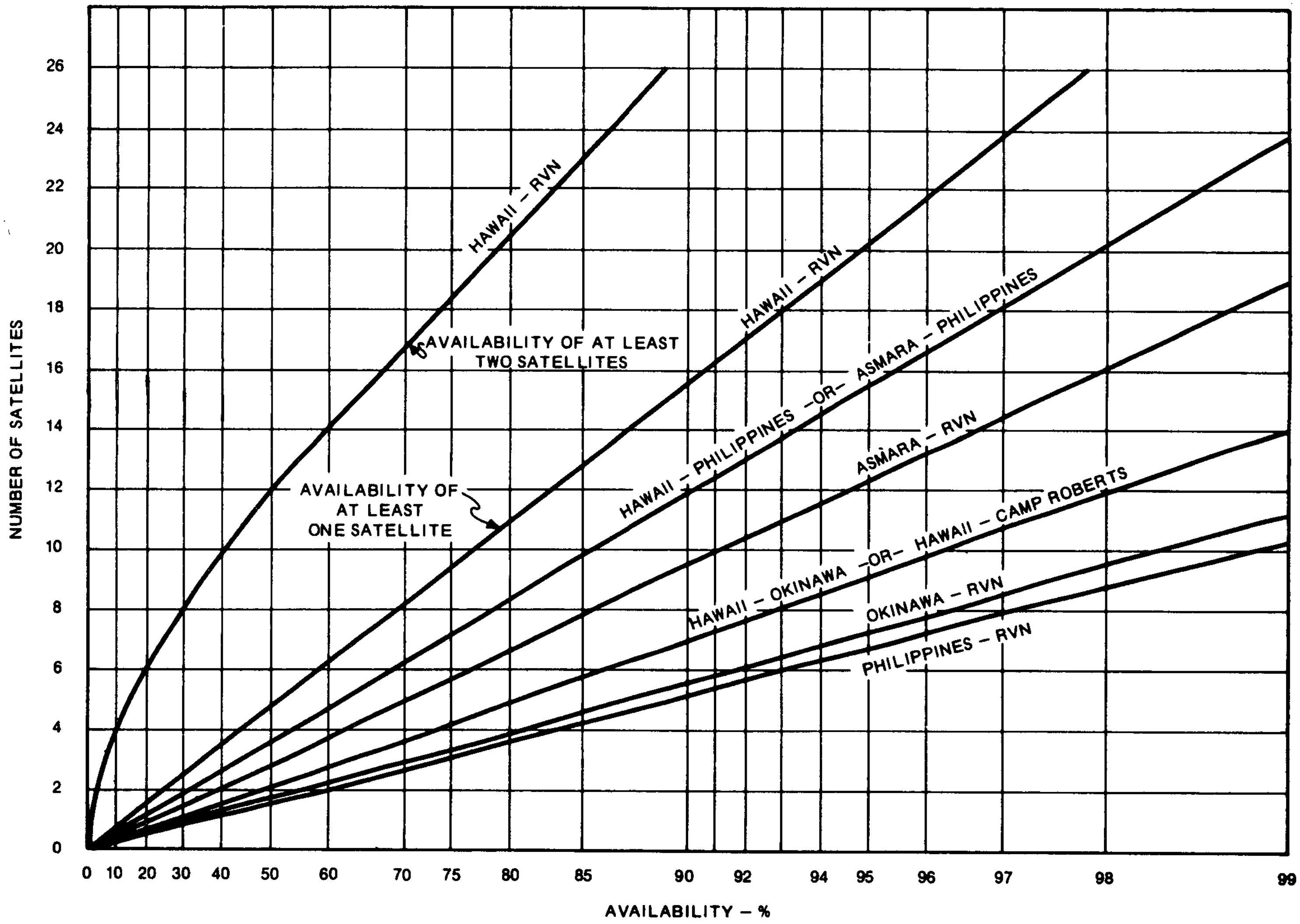

Figure 12-2. Satellite Availability

The baseband configuration of the AN/TSC-54 terminal is compatible with the baseband of the larger terminals; interoperability in the FDM-FM mode is assured. The AN/TSC-54 has no voice frequency multiplex equipment but is equipped with voice frequency telegraph keyers and converters and can provide one voice frequency channel and two out of band TTY.

Certain AN/TSC-54 link terminals are capable of differentially biphase modulating the carrier with serial binary data streams of up to 2400 bps with a design objective of 50 kbps. A teletype time division multiplex (TDM) unit accepts up to 16 75-bps teletype inputs and converts them into a binary stream suitable for DPSK modulation.

Table 12-4 indicates the capacity experienced, in practice, on particular links as a function of terminal type on each end of the link. These figures are for duplex accesses (2-carrier access), the maximum operational satellite loading used in IDCSP. The satellite frequency plan, optimized to yield minimum intermodulation interference, is indicated in Table 12-5.

12.3 SPACECRAFT

The IDCSP satellites are double frequency conversion, hard limiting repeaters that are placed into near-synchronous equatorial orbit at an altitude of approximately 18,200 nautical miles. At this altitude the satellites drift from west to east (relative to the earth) at about 30° per day. The satellites are spin stabilized at approximately 150 rpm (by two nitrogen nozzles) to maintain the spin axis within ±5° of normal to the earth's equatorial plane. These satellites are not equipped with batteries and have a transmitter EIRP of 37 dBm minimum.

The satellites are launched up to eight at a time by a Titan IIIC launch vehicle equipped with a satellite dispenser and using the standard Titan fairing. Each satellite is released from the dispenser with slightly different initial orbit velocity (approximately 35 ft/s differential). This differential initial velocity causes a relatively random orbital distribution of the satellites, which minimizes satellite conjunctions. Signatures are provided by having each satellite in a payload operate at its own unique telemetry frequency in the neighborhood of 400 MHz.

Table 12-4. IDCSP Duplex Channel Capacity and Performance (Dual Two Satellite Access)

Link Terminal Configuration	FDM/FM MODE		DPSK MODE	
	No. of Global Quality Channels	No. of Tactical Quality Channels	Data Rate (bps)	Probability of Error (Pe)
AN/FSC-9 To AN/FSC-9	2	5	-	-
AN/FSC-9 To AN/MSC-46	2	5	-	-
AN/FSC-9 To AN/TSC-54*	0	1	-	-
Improved AN/MSC-46 To Improved AN/MSC-46	5	11	-	-
AN/MSC-46 To AN/MSC-46	2	5	-	-
AN/MSC-46* To AN/TSC-54	0	1	-	-
AN/TSC-54 To AN/TSC-54	0	1	2400	10^{-5}

*Power Control is utilized to equalize received C/kT

Table 12-5. IDCSP Access Frequencies

Satellite RF Access Channel	Frequency (MHz)	
	Downlink (Transmit)	Uplink (Receive)
1	7,267.0250	7,985.7450
2	7,271.7125	7,990.4325
3	7,277.9625	7,966.6825
4	7,285.7550	8.004.4950

The repeater, shown in simplified block diagram form in Figure 12-3, is all solid state except for the TWT transmitter. Amplification and limiting of the signal take place at intermediate frequencies. The mixing frequencies are derived from a basic oscillator and multiplier chains. The output of the IF amplifier/limiter is then summed with the beacon signal, up converted, and fed through the traveling wave tube amplifier and out to the transmitting antenna. A redundant TWT amplifier can be switched on in case the first TWT fails. This switch-over is accomplished automatically and can occur only once. There is also included an automatic power shut-off circuit which activates 6 years after launch.

The transmitting and receiving antennas are separate. They are biconical horns with a toroidal pattern, omnidirectional in azimuth and earth-coverage (28°) in the other plane. Major communications-related characteristics of the satellites are summarized in Table 12-6.

12.4 GROUND TERMINALS

The characteristics of the three terminal types used in the IDCSP are shown in Table 12-7; and block diagrams are shown in Figures 12-4 through 12-6.

12.5 EXPERIMENTS

The primary objective of the Initial Defense Communications Satellite Program (IDCSP) was to support developments in military satellite communications and provide a limited operational capability. The experiments and development testing that have been performed through mid-1971 are summarized in Table 12-8.

12.6 OPERATIONAL RESULTS

The IDCSP has become an operational long-haul satellite communications system. A single satellite is capable of supporting two duplex voice links, each link carrying five voice channels, but operationally, only one duplex link per satellite is allowed to ensure adequate link margins. The system has provided a wideband (450 kbps, 900 kbps under optimum conditions) operational capability for facsimile service

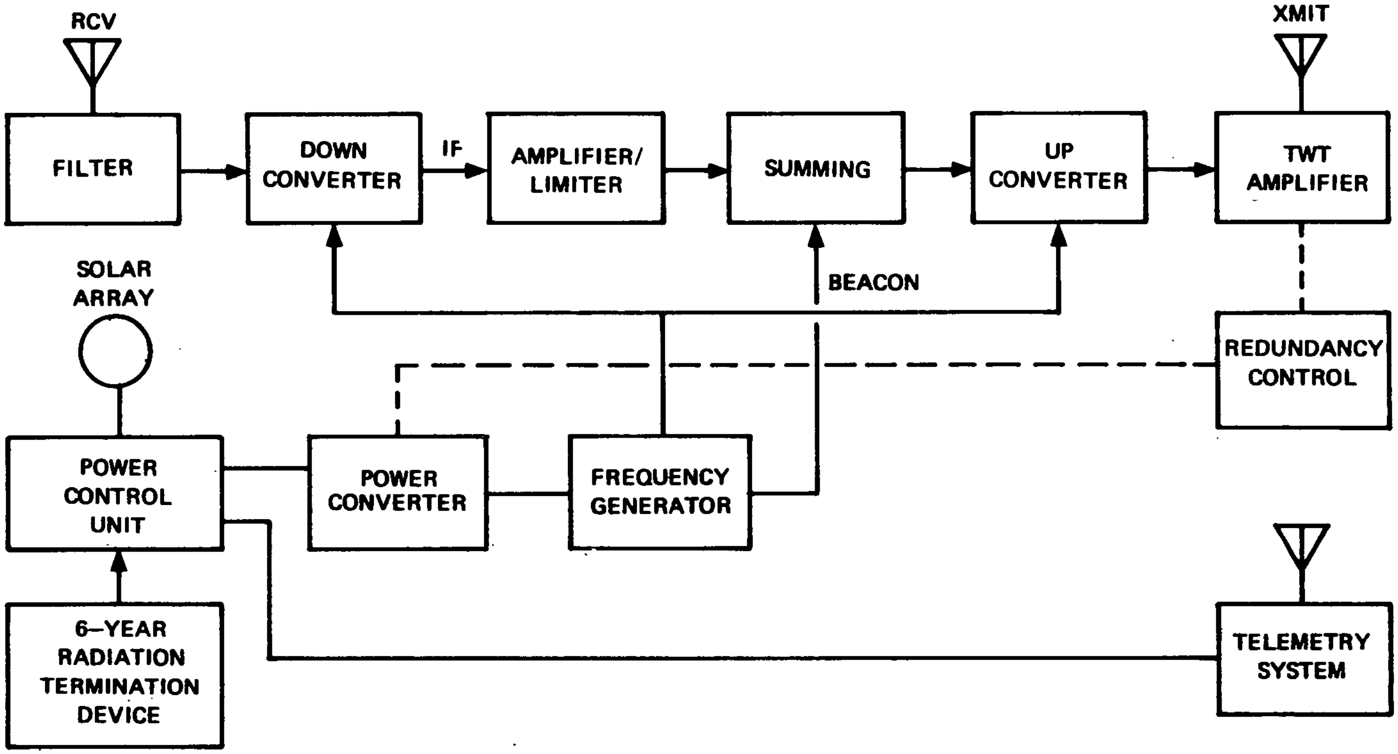

Figure 12-3. IDCSP Satellite Functional Block Diagram

Table 12-6. IDCSP Satellite Characteristics

Antenna		Type	Dual biconical - toroidal pattern
		Number	Two - RHCP receive, LHCP transmit
		Beamwidth	Earth coverage, 360° x 28°
		Gain	5 dB in plane normal to the spin axis, 3 dB minimum in all directions within ±14° of the plane
Repeaters		Frequency Band	SHF - 7.3 GHZ transmit, 8.0 GHz receive
		Type	Hard-limiting, double frequency conversion
		3 dB BW	26 MHz
		Number	One
	Receiver	Type Front End	Down conversion mixer
		Front End Gain	No Data
		System Noise Figure	10 dB
	Transmitter	Type	TWT
		Gain	No Data
		Power Out	3 watt
		EIRP	37 dBm minimum
General Features	Stabilization	Type	Spin at approximately 150 rpm
		Capability	±5° spin axis attitude
	Power Source	Primary	8000 n-on-p solar cells provide 40 watts at launch
		Supplement	None
		Comm. Power Needs	No Data
		Size	36" diameter by 32" high
		Weight	102 lb. or less
	Telemetry	Frequency	≃ 400 MHz
		EIRP	18 dBm minimum in all directions within ± 45° of a plane normal to the spin axis
	Beacon	Frequency	≃ 7.3 GHz
		EIRP	24.5 dBm minimum

Table 12-7. Characteristics of IDCSP Ground Terminals

Terminal Features		Terminals			
		AN/FSC-9	AN/MSC-46	AN/TSC-54	AN/SSC-3
Antenna	Type	Cassegrain	Cassegrain	4 Cassegrain Dish Array	Cassegrain
	Aperture Size	60 ft. Diameter	40 ft. Diameter	18 ft. Diameter Effective	6 ft Diameter
	Receive Gain	58.5 dB*	57.5*	50.5*	41.5*
	Efficiency	30%	55%	55%	60%
	Receive Beamwidth	0.16°	0.24°	0.52°	1.5°
Receive System	Type Preamplifier	Cooled Parametric Amplifier	Cooled Parametric Amplifier	Uncooled Parametric Amplifier	Temperature Stabilized Parametric Amplifier
	Bandwidth	50 MHz (3dB points)	40 MHz (1 dB points)	40 MHz (1 dB points)	40 MHz (3 dB points)
	Noise Temperature	200°K (spec.) @ 7.5° El	204°K @ 7.5° El	283°K @ 7.5° El	250°K @ 7.5° El
Transmit System	Type Amplifier	Klystron	Klystron	Klystron	Klystron
	Bandwidth	50 MHz (3dB points)	40 Hz (1 dB points)	10 MHz (1 dB points)	40 MHz (3 dB points)
	Amp. Power Out	10w to 20 kW	100 w to 10 kW	5 kW max.	5w to 5 kW
Tracking	Type	Autotrack	Autotrack	Autotrack	Autotrack
	Accuracy	No Data	No Data	No Data	No Data

*Derived value based on data available

Table 12-7. Characteristics of IDCSP Ground Terminals (contd)

	Terminal Features	Terminals			
		AN/FSC-9	AN/MSC-46	AN/TSC-54	AN/SSC-3
Total Performance	G/T	34.7 dB/°K	34.0 dB @ 20° El	25.3 dB/°K	16.4 dB/°K
	EIRP	101.2 dBw	98 dBw	87.9dBw	78.7 dBw
Polarization	Transmit Feed	RHCP	RHCP	RHCP	RHCP
	Receive Feed	LHCP	LHCP	LHCP	LHCP
Installation	Radome	None	Yes	None	Yes
	Type Facility	Fixed Terminal	Transportable Terminal	Highly Transportable Terminal	Shipboard Terminal

*Derived value based on data available

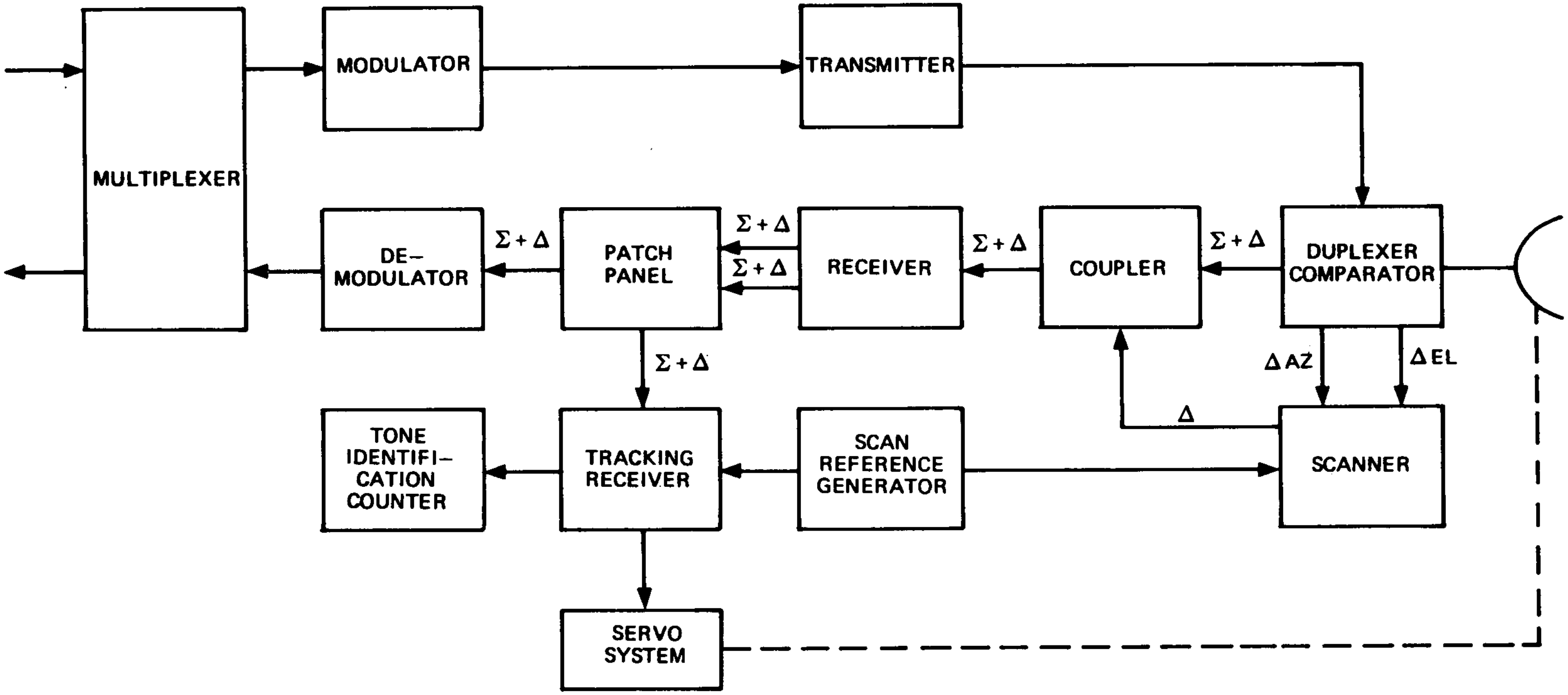

Figure 12-4. AN/FSC—9 Simplified Functional Diagram

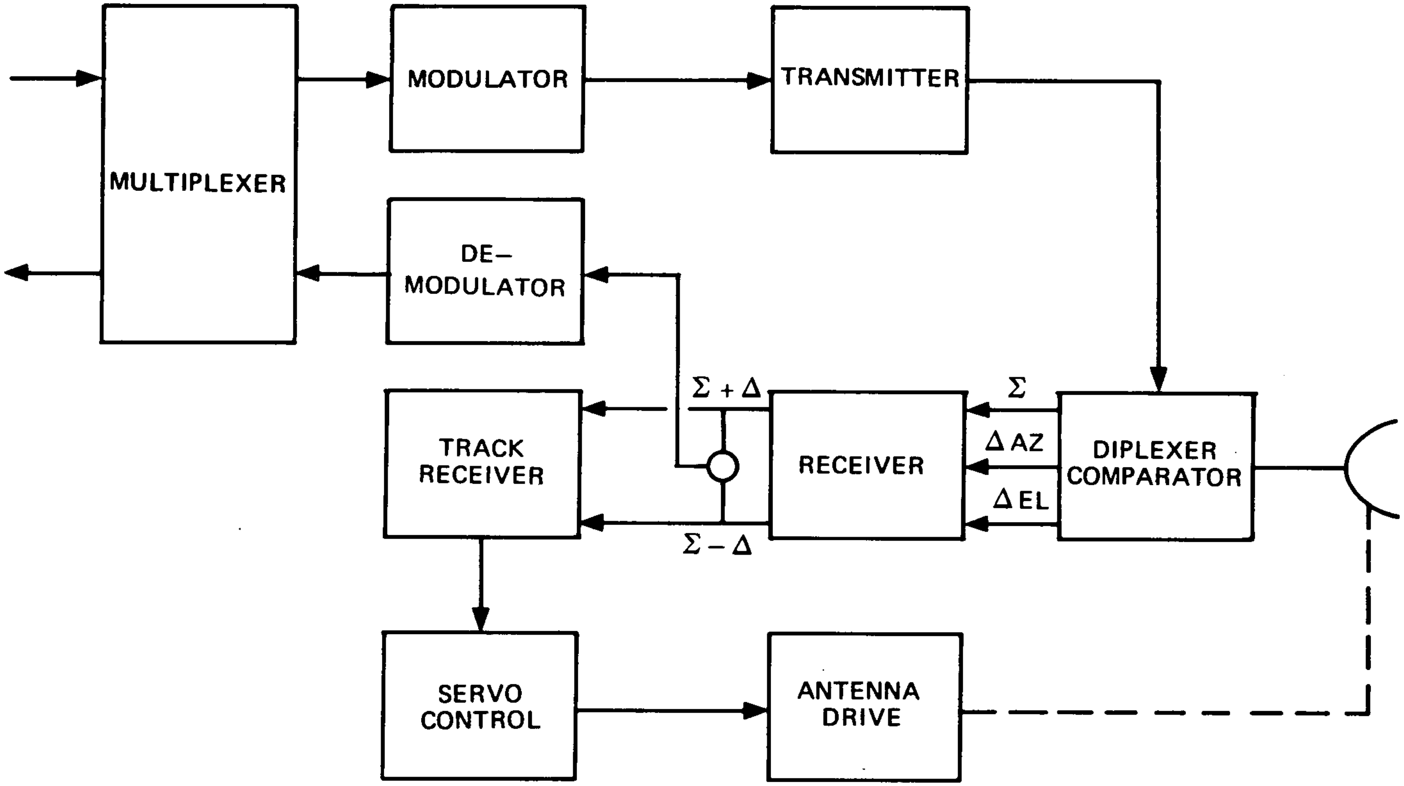

Figure 12-5. AN/MSC-46 Simplified Functional Diagram

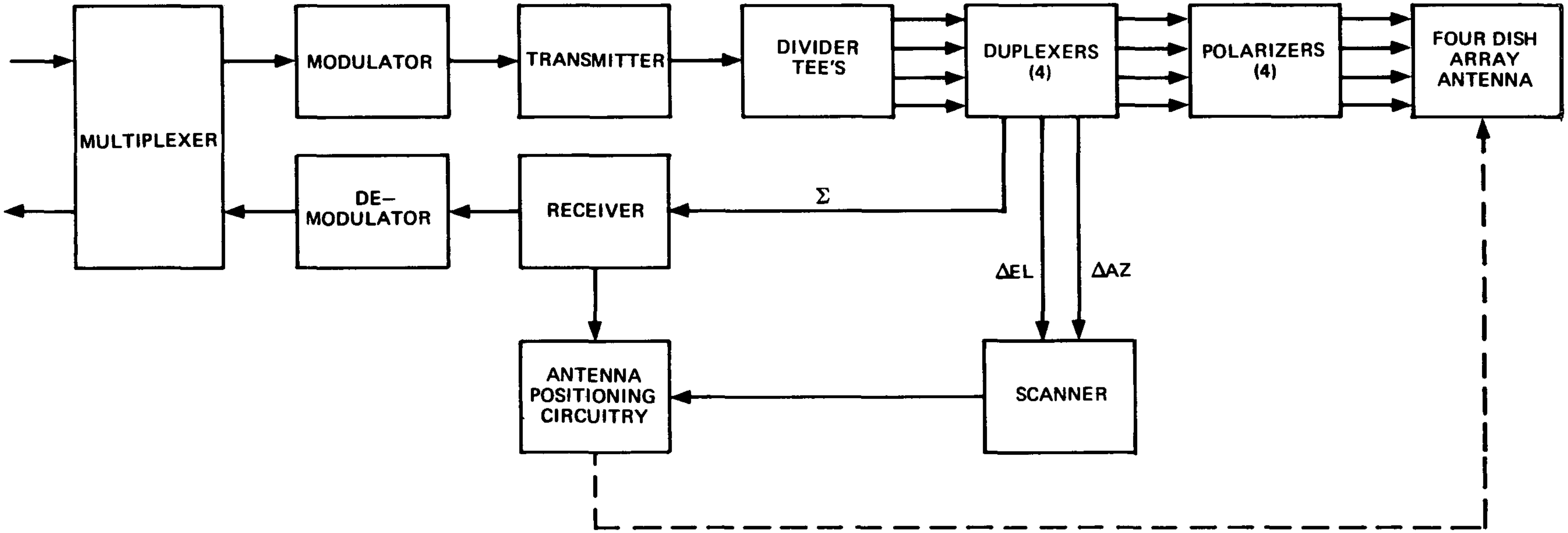

Figure 12-6. AN/TSC-54 Simplified Functional Diagram

Table 12-8. Summary of Program

Type Experiment	Nature of Results Obtained
1. Multiple Launch	Successful launch and injection into near synchronous equatorial orbit of up to 8 satellites from one Titan IIIC launch vehicle.
2. Voice Transmission	Duplex links carrying up to twelve 4 kHz voice channels at Defense Communication System tactical quality.
3. Wideband Data Transmission	Simplex links to 1 Mbps using Multiple Frequency Shift Keying for the transmission of high resolution imagery. Duplex links using Phase Shift Keying for the transmission of high data rate digitized voice traffic, providing secure, high quality voice communications.
4. Communications to Mobile Terminals	Duplex data links to ships (AN/SSC-3) and aircraft, (Wright Patterson Experimental Terminal), 75 bps to 2400 bps, ship to shore and air to ground.
5. Interference and Jamming	With a pseudonoise spread spectrum modulator/demodulator it was demonstrated that duplex communications could be maintained with inband uplink interference/jammer power very much larger than the uplink signal power. Operational tests demonstrated that the Defense Satellite Communication System would be effective under severe uplink jamming conditions.
6. Timing Transfer	Using pseudonoise spread spectrum modulator/demodulators it was demonstrated that timing synchronization could be achieved at satellite earth stations, to better than one microsecond, on a world wide basis.
7. Low Elevation Propagation	Measurements were made of propagation medium effects on wide bandwidths (20 MHz), at 7.3 GHz over satellite to ground paths down to zero degrees elevation. Differential fading results were obtained that could not be explained in terms of any reasonable two component ray propagation model.
8. Electronic Despun Antenna	The Despun Antenna Test Satellite (DATS) demonstrated the practicality of an electronically despun phased array antenna on a spin stabilized satellite to produce a continuously earth-direction beam. Successful tests were completed at low data rates (narrow bandwidth tracking loops), showing the effects of despinning on the communication signals.

Table 12-8. Summary of Program Experiments (Contd)

Type Experiment	Nature of Results Obtained
9. Gravity Gradient Stabilization - DODGE(10) (Department of Defense Gravity Experiment)	Successfully detumbled satellite from an initial 0.6 RPM tumble rate. However, oscillations in pitch, roll, and yawl varied widely and only once in 17 satellite passes during 1967 were the oscillations damped to the level predicted by theory and required for a communication satellite. Also a number of times the satellite has resumed tumbling and has had to be restabilized. Causes have not been determined for all these tumbling occurrences.

over a two-satellite hop link from RVN to Washington, D. C. In addition, the system has provided emergency communications when conventional systems have failed. For example, during the Middle East crisis in May and June 1967, HF radio suffered frequent outages and the West Germany - Ethiopia link provided a primary tracking facility. In September 1967 the Hawaii-RVN link carried five of the highest priority military voice channels for a 10-day period while the commercial Trans Pac submarine cable was broken east of the Philippines. Another submarine cable failure between Thailand and RVN in October 1967 was temporarily covered by the IDCSP.

Since the first satellite launch in June 1966, the satellites have performed better than expected. The major cause of failure has been the failure to turn on again after coming out of eclipse, and in some cases such failed satellites have turned on after subsequent eclipses. The next most frequent problem has been failure of the automatic TWT switching system resulting in switched TWTs before they have actually failed. As of mid-1971 valid TWT switching had been experienced on three satellites as a result of failures. However, switching had also occurred on three other satellites for no known reason.

The major failure experienced with the ground terminals was with the maintenance of the cryogenic cooling system in the AN/MSC-46 terminals. These were to be field-maintainable, but had to be returned to the manufacturer for maintenance. The problem was subsequently fixed by modification. Another problem area was an oversensitive tracking system due to its design to track polar orbiting satellites. A modification narrowing the tracking bandwidth solved this problem. For the AN/MSC-46 terminals the MTTF experienced was about 75 hours. For AN/TSC-54 terminals it was about 300 hours.

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SECTION 13 - APPLICATIONS TECHNOLOGY SATELLITE

13.1 INTRODUCTION

The history of this wide ranging program can be traced back to late 1962 when the National Aeronautics and Space Administration (NASA) initiated design studies for what was then known as the Advanced Syncom.(1) This was a proposed second generation synchronous communications satellite for continuation of the experimentation started in the highly successful Project Syncom. In 1964, the program concept was broadened to include experiments pertinent to meteorology, navigation, and general spacecraft technology. The multidimensioned project thus formed was called the Applications Technology Satellite (ATS) program. By consolidating multiple experiments into a single program, NASA realized significant cost reductions and structured a program that was directly responsive to the responsibilities assigned NASA under the Space Act of 1958 and the Satellite Act of 1962.

The ATS program, as initially conceived and approved by Congress, was a multiyear project involving five unique satellites launched into space to conduct some 20 major experiments and a number of related data-gathering studies. Major objectives of the five flights were to: (1) investigate technology common to a number of space applications; (2) investigate technology for the synchronous orbit; (3) develop spacecraft stabilization techniques; and (4) develop experiments for several satellite applications.

The underlying design philosophy, in developing these satellites, was to provide a large and adaptable volume for mounting the various experiment payloads while employing basic satellite configurations appropriate for either spin or gravity-gradient stabilization. Two satellites were designed in the spin stabilized configuration and three were gravity gradient stabilized. Two subconfigurations existed for the gravity gradient stabilized satellites. The first of the three satellites employing this stabilization technique was designed for a medium altitude circular orbit where no stationkeeping was necessary. The two subsequent spacecraft were configured for operation in synchronous equatorial orbits.

Each of the five satellites contained a separate complement of experiments with a relatively low level of experiment repetition from spacecraft to spacecraft.(2) The exception to the latter was the C-Band communications experiments. All five satellites included identical C-Band repeaters for conducting these experiments.

As development and launching of the initial five satellites proceeded, and NASA began to look towards the future, the main thrust of the ATS program objectives became more exclusively communications oriented. NASA's ATS research effort is now directed towards advanced techniques for bringing satellite communications to an ever-increasing number of small, perhaps mobile, users having multiple access to the satellite system; toward broadcast satellite applications, both radio and television; toward more efficient techniques of frequency utilization through investigation of millimeter wavelengths; and toward satellite aids to lunar, planetary, and interplanetary communications.

NASA has proposed and has received approval to develop two additional ATS satellites. These spacecraft will have a higher in-orbit weight and greater available primary power. They will employ three-axis stabilization to provide greater stabilization accuracy. Additionally, the spacecraft will feature large (i.e., 30-foot diameter) space-erectable antennas producing high antenna directives.

13.2 SPIN STABILIZED SATELLITES

13.2.1 General Description

The experiments carried on the spin stabilized Applications Technology Satellites can be grouped into seven major categories. These categories are listed and defined in Table 13-1.(3)(4) Primary objectives of the SHF (C-Band) communications experiments were to: (1) evaluate a multiple access system having a 1200-channel capacity in voice, teletype, data, and facsimile modes of operation; (2) evaluate wideband transmission techniques;(3) investigate polarization and transmission phenomena; and (4) provide a communications transmission capability in support of other applications technology satellite experiments. Major VHF communications objectives were to demonstrate the feasibility of continuous air-to-ground and ship-to-shore voice communications through a satellite. The satellite VHF transponder also provided the opportunity to: (1) evaluate the feasibility of a meteorological network in which data from small unmanned stations are collected at a central station for dissemination to all interested stations within the satellite coverage area; (2) investigate the feasibility of VHF navigation systems using satellites; and (3) study the practicality of disseminating time via a VHF satellite.

Figure 13-1. Experiment Categories

Number	Description
1	VHF & SHF Radio Communications and Propagation
2	Meteorological Concepts, Applications and Techniques
3	Navigation and Position Location Techniques
4	Despun Antenna Systems
5	Measurements of the Earth Environment
6	Technology Applicable to Spacecraft Stabilization and Stationkeeping
7	Miscellaneous Aspects of Spacecraft Design

Two active repeater satellites employing spin stabilization, ATS-1 and ATS-3, were launched during the ATS program as indicated in Table 13-2.(3)(4) ATS-1 (i. e., ATS-B prior to launch) was successfully launched into a geostationary orbit and positioned over the Pacific Ocean where it has remained. Its initial program of communications related experiments, including radio communications, propagation, and the electronically despun antenna, were all successfully completed and the spacecraft at this writing is being employed for further experimentation. Concurrently, the remaining scientific experiments were also completed and were successful.(5)

ATS-3 (i.e., ATS-C prior to launch) was successfully placed into a geostationary orbit almost a year after the launching of ATS-1; it was initially positioned over the Atlantic Ocean. The location was later shifted westward to a position over the eastern Pacific Ocean at a longitude near the eastern edge of Mexico; it is now located over South America. The satellite's experiments enjoyed results similar to those attained with ATS-1 and it also is presently being employed for additional experimentation.

Table 13-2. Spin Stabilized Spacecraft

Satellite		ATS-1	ATS-3
Manufacturer & Sponsor		**Hughes Aircraft & NASA**	
Launch Date		**12/6/66**	**11/5/67**
Launch Vehicle		**Atlas - Agena D**	
Orbital Data*	**Apogee (mi.)**	**22,920**	**22,254**
	Perigee (mi.)	**22,277**	**22,228**
	Inclination	**Approximately 0°**	
	Period	**Approximately 24 hours**	
Status		**Spacecraft active Limited Stationkeeping capability left. Solar array output degraded. Located at about 149° W. longitude**	**Spacecraft active Solar array output degraded. Located at about 70° W. longitude**

***At initial injection. Attitude control and station keeping maneuvers produced changes.**

The primary earth terminals involved in the SHF communications experiments conducted with the spin stabilized Applications Technology Satellites are listed in Table 13-3.(5) (6) The three NASA terminals indicated also included crossed dipole arrays for VHF experiments and tracking, telemetry and command (TT&C). A myriad of additional terminals participated in portions of the VHF testing. These included fixed and semi-fixed earth terminals, aircraft terminals, shipborne stations, ocean buoy data platforms, and various fixed and mobile land-based data platforms providing information on earth resources. Terminal locations were widely scattered over portions of the world having visibility of ATS-1 and ATS-3. Entities, in addition to NASA, providing VHF terminals included the Environmental Science Services Administration (ESSA) of the U.S. Department of Commerce, the Federal Aviation Administration, Office of Naval Research, Aeronautical Radio Incorporated (ARINC), Hughes Aircraft, various major commercial airlines, and a number of foreign countries. Satellite launchings were provided by NASA.

Table 13-3. Participating Earth Terminals

Location	Sponsor	Antenna Diameter (ft.)	Date Installed
Rosman, North Carolina	NASA	85	1965/66*
Mojave, California	NASA	40	1965/66*
Cooby Creek, Australia	NASA	40	1965*
Kashima, Japan	Radio Research Laboratories Ministry of Posts and Telecommunications, Japan	98.5	1967*

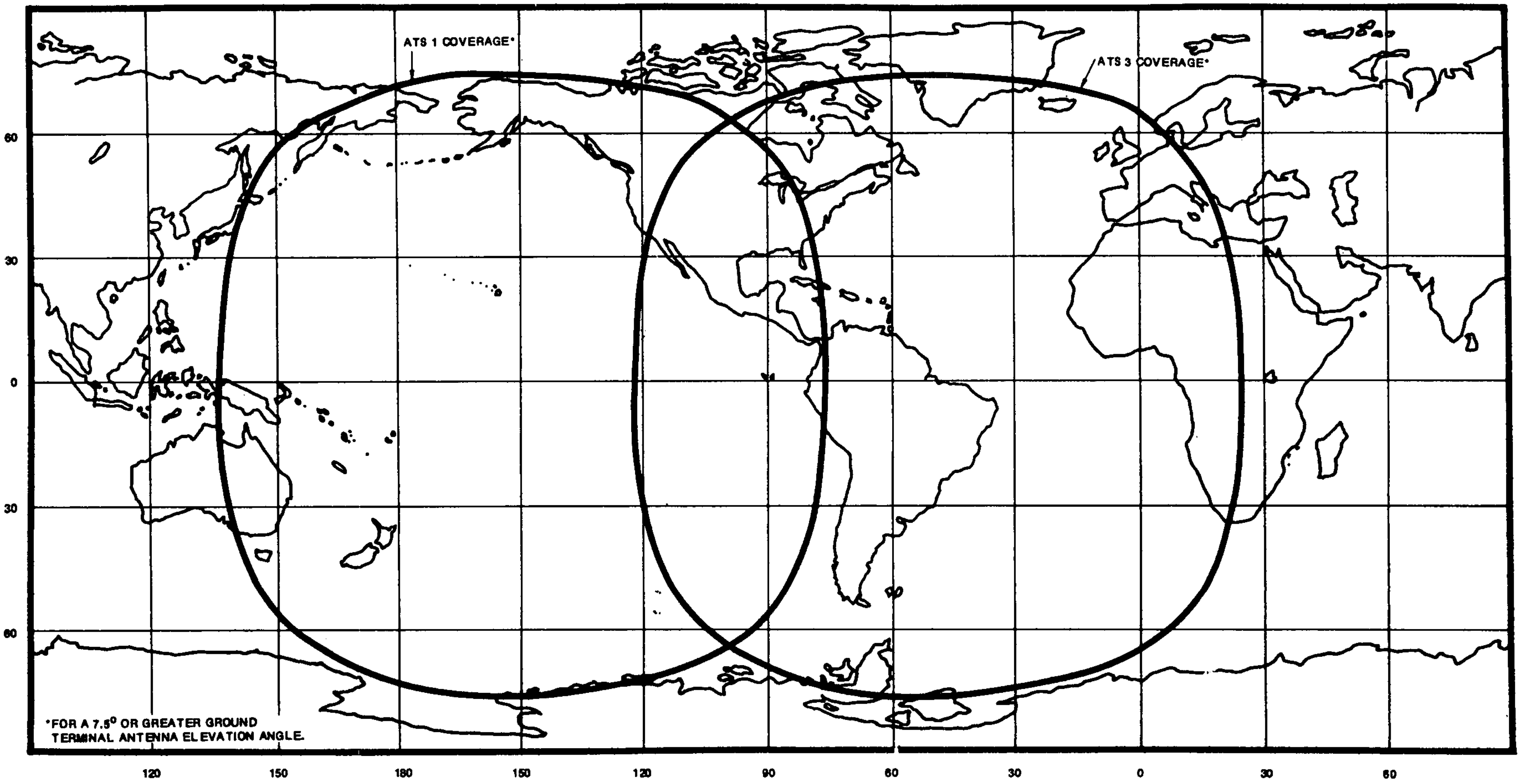
*Date of ATS-related installation alone.

Specific refinements to the state-of-the-art, contributed by the ATS-1 and 3 test programs, were innumerable. There were four contributions of major importance in satellite communication; two of these were in the area of despun antenna technology. ATS-1 demonstrated the feasibility and potential of electronic-despinning using phased arrays while ATS-3 displayed the feasibility and attractiveness of mechanically-despun antennas. The SHF multiple access experiments showed the possibility of the practical implementation of a system employing single-sideband frequency division multiplexing on the uplink and phase modulation by the composite received signal on the downlink. Additionally, the feasibility of VHF communications through a synchronous satellite by small mobile earth terminals was demonstrated.

13.2.2 System Description

The SHF tests with ATS-1 involved all of the terminals listed in Table 13-3. Loop back, half duplex, full duplex, and three terminal multiple access test configurations were all employed. For the ATS-3 tests only Rosman and Mojave terminals had satellite visibility. Tests were therefore performed on a loop back, half duplex, and full duplex basis. VHF tests were conducted in all of these configurations from loop back through full duplex linking. Satellite transponder non-linearity, plus power and bandwidth limitations, tended to limit multiple access capabilities. The NASA-furnished terminals provided two functions in the VHF tests. They conducted baseline evaluations of the satellite VHF transponder and the VHF propagation link to serve as a reference for testing with mobile and remote data terminals. The NASA terminals also participated in the latter tests as central land bases. Typical earth coverages supplied by the geostationary satellites, ATS-1 and ATS-3, are shown in Figure 13-1.

Operating frequencies for the spin stabilized Applications Technology Satellites are shown in Tables 13-4, 5, and 6.(5) The 6- and 4-GHz frequencies were selected to be compatible with the international allocations for commercial satellite communications. The VHF frequencies were selected for a communications experiment because of compatibility with existing frequencies employed for spacecraft TT&C and conventional hardware that could readily be supplied for small mobile terminals (e.g., aircraft terminals).



*FOR A 7.5° OR GREATER GROUND TERMINAL ANTENNA ELEVATION ANGLE.

Figure 13-1. ATS 1 and 3 Earth Coverage

Table 13-4. SHF Communications Frequencies (MHz)

Frequency Translation Mode			Multiple Access Mode*		
Uplink	Downlink	Beacon	Uplink	Downlink	Beacon**
6212.094	4119.599	4135.946	6212.294 to 6217.694	4119.599	4119.599
6301.050	4178.591	4195.172	6301.250 to 6306.650	4178.591	4178.591

* Dual frequencies indicated correspond to two independent repeaters

** Communications carrier which is always present serves as beacon in this mode

Table 13-5. VHF (MHz)

Half Duplex Mode		Full Duplex Mode	
Uplink	Downlink	Uplink	Downlink
149.220	135.600	149.195 149.245	135.575 135.625

Table 13-6. TT&C (MHz)

Command	Telemetry	Beacon
148.260	136.470	137.370 412.050*

*Third harmonic of 137.350 MHz

Basic signal processing techniques employed with the spin stabilized Applications Technology Satellites, when operated in the SHF multiple access mode, were as described in Table 13-7.(7) When in this mode (i.e., SSB-FDMA/PM) the spacecraft is a signal processing repeater. Single side band (SSB) signals from individual terminals are frequency division multiplexed on the uplink. The individual signals are combined in the spacecraft and down-converted to provide a composite baseband that phase modulates the transmitted carrier. The downlink signal is detected by a discriminator in the ground terminal receiver and demultiplexed to derive the desired individual message. In this system, uplink noise becomes a more significant factor in determining total performance but requirements for frequency spectrum and uplink power control are reduced. The use of SSB modulation on the uplink tended to restrict the traffic handled to conventional 4-kHz voice.

Table 13-7. SHF Signal Processing for SHF Multiple Access Mode

Multiple Access/RF Modulation	SSB on uplink and PM on downlink
Ground Demodulator Performance	Threshold estimated at 10-dB C/N based upon employing conventional discriminators
Rosman Receive Carrier-to-Noise	16.7 dB employing 2 TWTs on ATS-1 and a 12-MHz IF bandwidth
Rosman Receive Margin	6.7 dB

A second SHF communications mode, available on ground command, configures the spacecraft repeater as a standard frequency translation transponder. Signal processing employed for operation in this mode is depicted in Table 13-8. Both television and multichannel voice traffic were commonly handled with the spacecraft configured in this manner.

Table 13-8. Signal Processing for SHF Frequency Translation Mode

Multiple Access	Frequency Division* for a limited number of users.
RF Modulation	FM**
Ground Demodulator Performance	Threshold estimated at 10-dB C/N based upon employing conventional discriminators.
Rosman Receive Carrier-to-Noise	14.4 dB employing 2 TWTs on ATS-1 and a 35-MHz IF bandwidth
Rosman Receive Margin	4.4 dB

* Time division and code division (i.e., spread spectrum) multiple access were employed in special tests.

** Binary phase shift keying and quadraphase shift keying were employed in time division and spread spectrum multiple access tests.

For operations involving the VHF satellite repeater, the basic signal processing techniques employed were as indicated in Table 13-9.(8) A single duplex voice channel was typical of the traffic handled by this frequency translation repeater.

Table 13-9. Signal Processing for VHF Repeater

Multiple Access	Frequency division for a limited number of users.
RF Modulation	FM
Ground Demodulator Performance	Threshold estimated at 10-dB C/N based upon employing conventional discriminators
Ground Terminal* Receive Carrier-to-Noise	20.1 dB with ATS-1 and a 100-kHz IF bandwidth
Ground Terminal* Receive Margin	10 dB

*For common type of VHF ATS terminal deployed at the three NASA ATS terminal sites.

13.2.3 Spacecraft

Characteristics of the communications related subsystems of ATS-1 and 3 are described in Tables 13-10 and 13-11,(3)(4)(9)(10) respectively. With the exception of the high power TWTs on one transponder of ATS-3, the SHF transponders aboard the two spacecraft were virtually identical. Functional diagrams depicting each of the three possible modes of the transponder (i.e., frequency translation, multiple access, and onboard camera) are given in Figures 13-2, 13-3, and 13-4. The VHF transponder on each spacecraft is illustrated in Figure 13-5. As indicated by the figure, the VHF transponder on ATS-3 differed from that on ATS-1 in that a capability existed to cross strap the VHF receiver to the transmitter of one of the SHF transponders. In this mode of operation, selectable by ground command, the SHF transponder was operated in the camera mode and the received VHF signal was down-converted to serve as the input to the SHF transponder's voltage controlled oscillator.

13.2.4 Ground Terminals

Two of the three NASA ATS terminals, Rosman and Mojave, are large multifunctional installations supporting numerous other NASA programs. Characteristics of the ATS related facilities at all three locations are summarized in Table 13-12. (See References 5 through 8 and 11.) Major subsystems of the NASA ATS terminals are depicted in the functional block diagram of Figure 13-6.(6)

Equipment and its characteristics are quite similar at all three sites with the major difference being in the size of the SHF antennas. The linear polarized SHF feeds employed at all three sites were compatible with the satellite's transmit and receive polarization. This polarization selection made polarization tracking necessary. For VHF communications, the T&C antenna was normally configured for circular polarization. With the linear polarization employed on the satellite, this resulted in 3-dB uplink and downlink polarization losses.

Table 13-10. ATS-1

Antennas		Type	SHF xmit. -16 element electronically despun phased array. SHF Rec. -collinear array	VHF Comm-8 element electronically despun phased array.	VHF TT&C-8 whip turnstile
		Number	One	One	One
		Beamwidth (3dB)	Pencil beam a maximum of about 21° wide for xmit.	Pencil beam about 60° wide.	Essentially omni-directional
		Gain	Xmit-14 dB Rec-7.8 dB	Xmit-9 dB Rec-8 dB	0 dB
Repeaters		Frequency Band	SHF		VHF
		Type	Triple Mode * supplying: (a) soft limiting IF translation; (b) modulation conversion for multiple access; (c) wideband transmission of onboard data		IF translation hard limiting
		3 dB BW	(a) IF translation-25 MHz; (b) modulation conversion-5.45 MHz uplink & 25 MHz donwlink; (c) Onboard data xmit-25 MHz		100 KHz
		Number	2 independent repeaters		One
	Receiver	Type Front End	Tunnel diode amplifier into down conversion mixer		Down conversion mixer
		Front End Gain	No data		No data
		System Noise Figure	6.2 dB		4.0 dB
	Transmitter	Type	Two TWTs **		8 solid state amplifiers
		Gain	No data		No data
		Power out	4 watt per TWT or 8 watt total		5 watt per amplifier or 40 watt total
		EIRP	22 dBW with 2 TWTs		23 dBW for 1 carrier
General Features	Stabilization	Type	Spin with redundant H_2O_2 reaction control systems and nitrogen jets for spinup.		
		Capability	Spin axis attitude errors of about 0.2° attained		
	Power Source	Primary	N-on-P solar array with 175 watt output at launch		
		Supplement	2 nickel cadmium batteries with 6 amp-hr per battery capacity at launch		
		Comm. Power Needs	Each SHF transponder-35 watts, VHF transponder-90 watts, and electronically despun antenna-8watts		
		Size	Cylindrical-57 inches high and 56 inches in diameter		
		Weight	775 lbs initially in orbit		

* Mode for each SHF transponder independently selectable by ground command.

** Can be operated individually or in parallel.

Table 13-11. ATS-3

Antennas		Type	SHF-mechanically despun cylindrical parabolic collimator illuminated by col linear xmit and recv. line feeds. *	VHF Comm.-8 element electronically despun phased array	VHF TT&C-8 whip turnstile
		Number	One	One	One
		Beamwidth (3 dB)	Pencil beam about 20° wide	Pencil beam about 60° wide	Essentially omnidirectional
		Gain	Xmit-16 dB Recv-17.5 dB	Xmit-10 dB Recv-8 dB	0 dB
Repeaters		Frequency Band	SHF		VHF
		Type	Triple mode ** supplying: (a) soft limiting IF translation; (b) modulation conversion for multiple access; (c) wideband transmission of onboard data		IF translation soft limiting
		3 dB-dW	(a) IF translation-25 MHz; (b) modulation conversion-5.45 MHz uplink and 25 MHz downlink; (c) Onboard data xmit-25 MHz		100 KHz
		Number	2 independent repeaters		one
	Receiver	Type Front End	Tunnel diode amplifier into down conversion conversion mixer		Down conversion mixer
		Front End Gain	No data		No data
		System Noise Figure	6.2 dB		3.5 dB
	Transmitter	Type	Two TWTs ***		8 solid state amplifiers
		Gain	No data		No data
		Power Out	Xponder 1-4 watt/TWT or 8 watt total Xponder 2-12 watt/TWT or 24 watt total		6.3 watt per amplifier or 50 watt total
		EIRP	Xponder 1-24.5 dBW with 2 TWTs Xponder 2-29.3 dBW with 2 TWTs ****		25.8 dBW for 1 carrier
General Features	Stabilization	Type	Spin with H_20_2 or hyrazine reaction control systems and nitrogen jets for spinup.		
		Capability	Spin axis attitude errors of about 0.2° attained		
	Power Source	Primary	N-on-P solar array with 175 watt output at launch		
		Supplement	2 nickel cadmium batteries with 6 amp/hr per battery capacity at launch		
		Comm. Power Needs	SHF Xponder 1-35 watts, SHF Xponder 2-90 watt, VHF Xponder-100 watts, and mechanically despun antenna-15 watt		
		Size	Cylindrical - 71 inches high and 58 inches in diameter		
		Weight	805 lbs initially in orbit.		

* Fail safe mode can be initiated by blowing parabolic reflector off antenna to get pancake pattern and about 7 dB gain.

** Mode for each SHF transponder independently selectable by ground command.

*** Can be operated individually or in parallel.

**** One 12 watt TWT failed to function making 26.5 dBW maximum EIRP available.

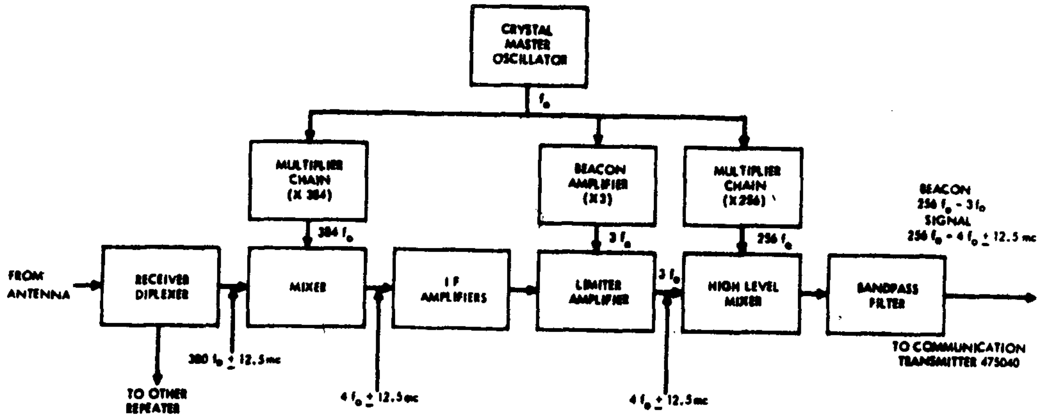


Figure 13-2. Frequency Translation Functional Block Diagram

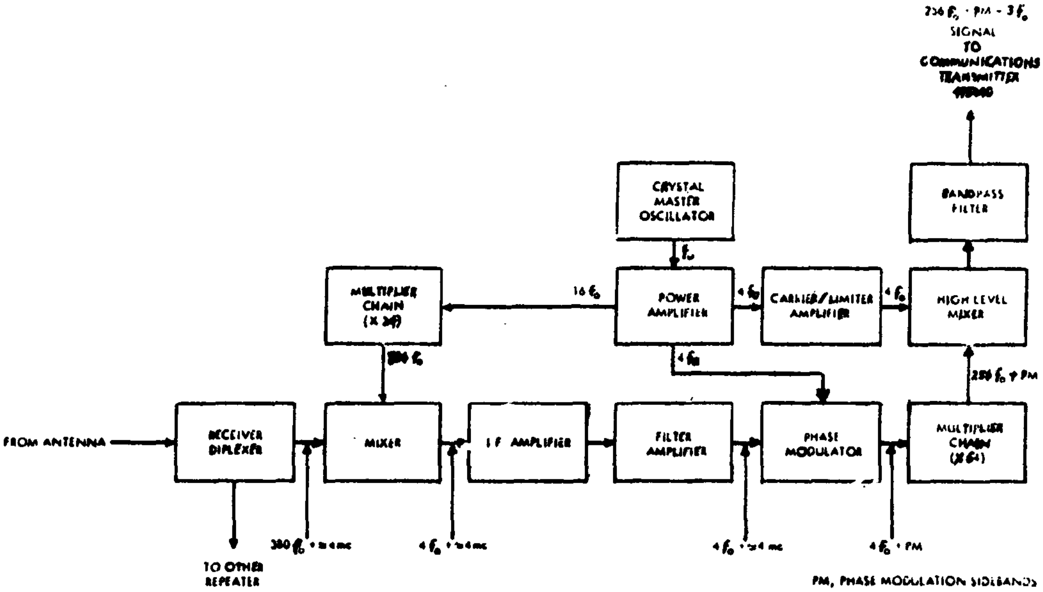


Figure 13-3. Multiple Access Functional Block Diagram

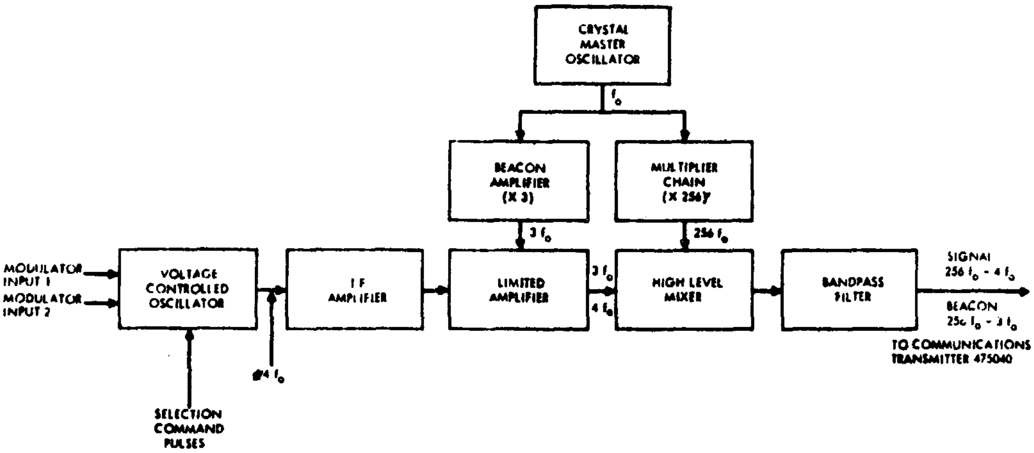


Figure 13-4. Camera Mode Functional Block Diagram.

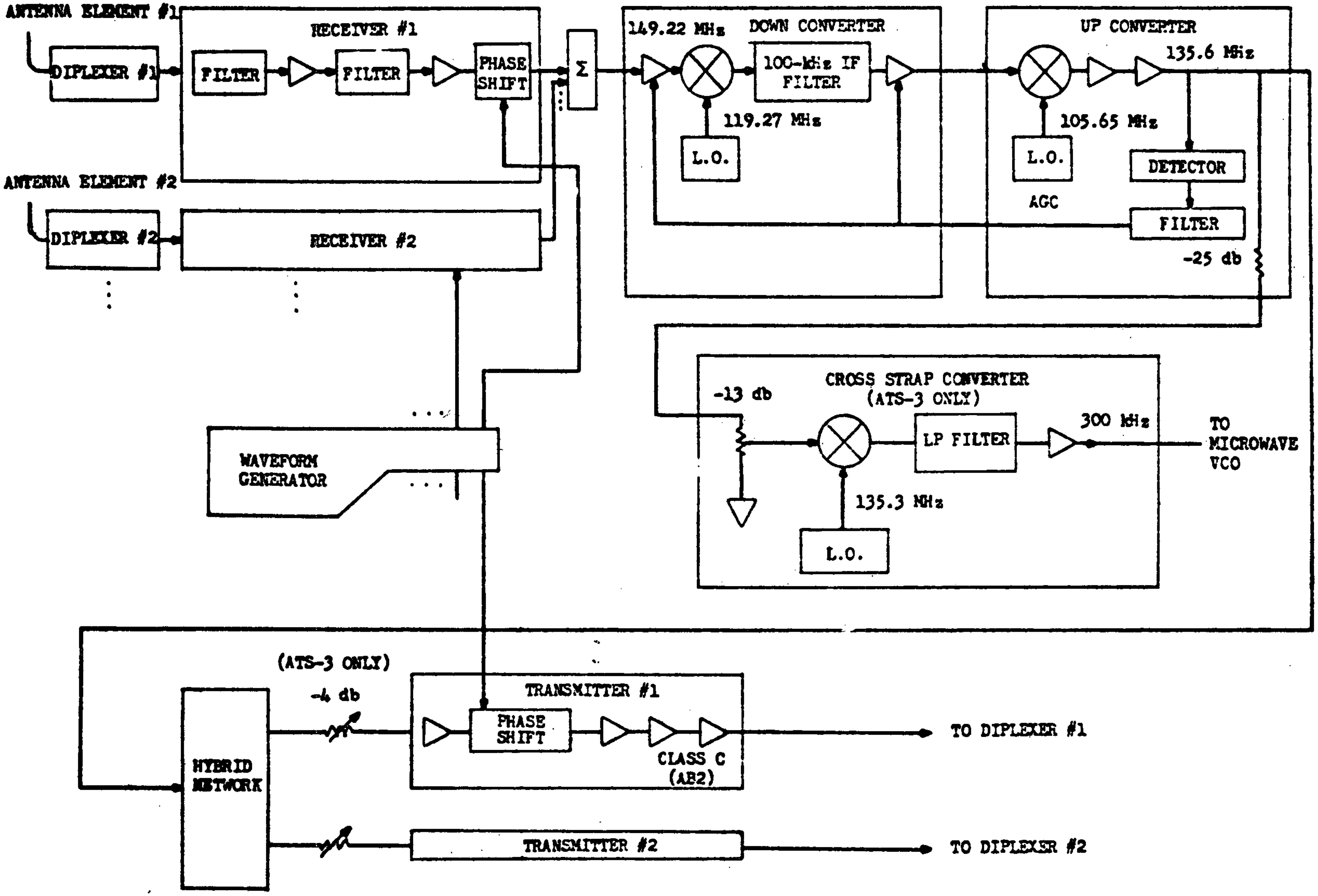


Figure 13-5 VHF Transponder Block Diagram.

Table 13-12. NASA ATS

	Terminal Feature	Terminal			
		Rosman (SHF)	Mojave (SHF)	Cooby Creek (SHF)	All 3 Terminals (VHF)
Antenna	Type	Cassegrain	Cassegrain	Cassegrain	Cross Dipole Array(4)
	Aperture Size	85 ft. Diameter	40 ft. Diameter	40 ft. Diameter	About 15 ft x 15 ft
	Receive Gain	58.4 dB	51 dB	51.5 dB	22 dB
	Efficiency	50%	48%	54% *	65% *
	Receive Beamwidth	.2° * @ 3 dB Pts.	.4°(1) @ 3 dB Pts	.4° * @ 3 dB Pts.	13°
Receive System	Type Preamplifier	Cooled Parametric Amplifier	Cooled Parametric Amplifier	Cooled Parametric Amplifier	No data
	Bandwidth	30 MHz	30 MHz	30 MHz	11 MHz *
	Noise Temperature	75°k @ 7.5°El.	75°k @ 7.5° El.	75°k @ 7.5° El.	1230°k
Transmit System	Type Amplifier	Klystron	Klystron	Klystron	No data
	Bandwidth	25 MHz	25 MHz	25 MHz	No data
	Amp. Power Out	1 KW in SSB modes & 2 KW in FT mode ***	1 KW in SSB mode & 2 KW in FT mode **	1 KW in SSB mode & 2 KW in FT mode **	2.5 KW
Tracking	Type	Monopulse auto-track on X-Y mount	Monopulse auto-track on X-Y mount	Monopulse auto-track on Az-El mount	Monopulse auto-track * on X-Y mount
	Accuracy	±0.03° in winds up to 20 mph	±0.04° in winds up to 20 mph	±0.04° in winds up to 20 mph	±0.5°
Total Performance	G/T	39.6 dB	32.2 dB	32.7 dB	-8.9 dB *
	EIRP	122.1 dBM *	115.5 dBM *	116 dBM *	76 dBM *
Polarization	Transmit Feed	Linear	Linear	Linear	Circular or linear ****
	Receive Feed	Linear	Linear	Linear	Circular or linear ***
Installation	Radome	None	None	None	None
	Type Facility	Fixed Terminal	Fixed Terminal	Transportable ***	Fixed except at Cooby Creek **

* Derived value based on data available.

** SSB and FM power amplifiers use same model klystron which is capable of up to 10-KW average output.

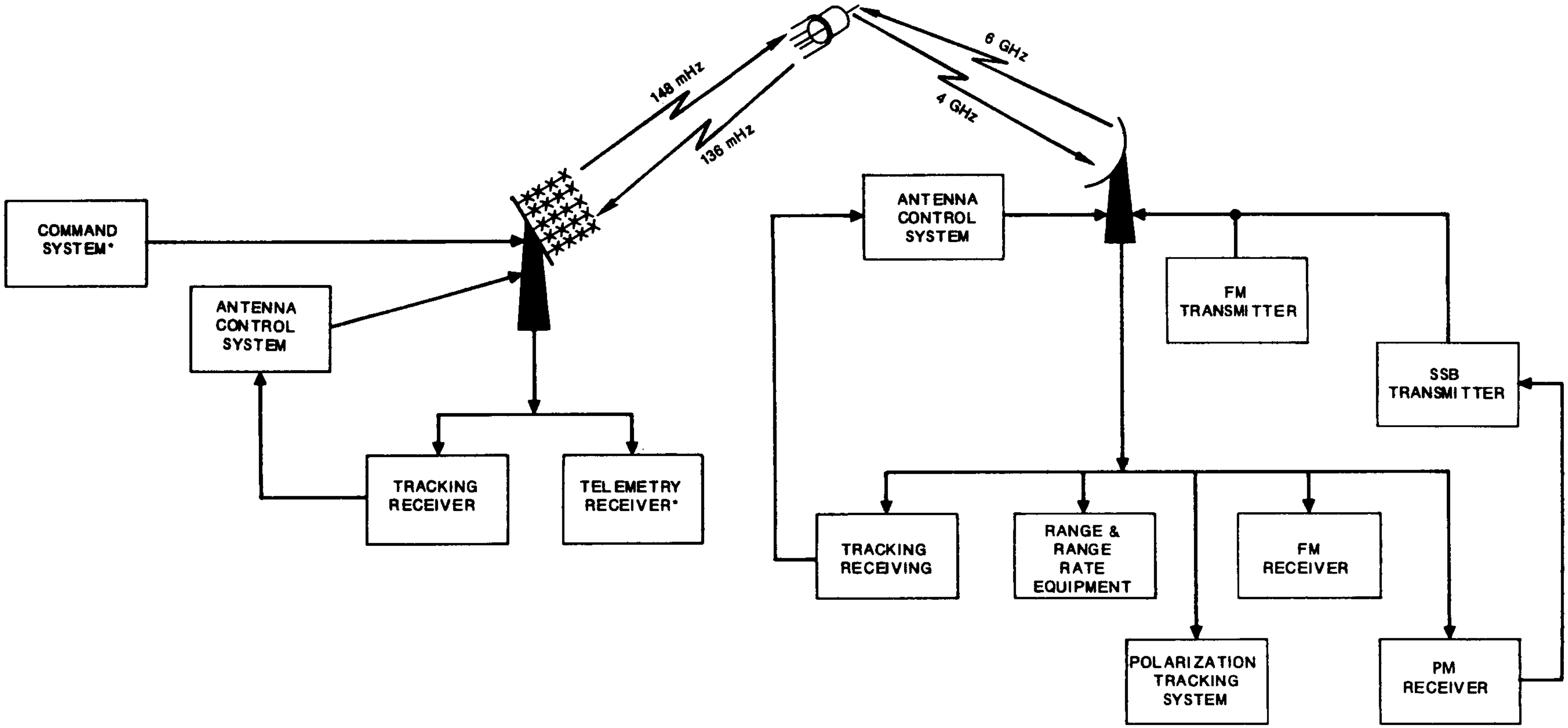
*** 13 air-transportable vans in addition to SHF and T&C antenna existed at Cooby Creek.

**** Separate Yagi transmit and receive antennas of same type integrally mounted on same base.

***** Selectable bandwidths of 10 KHz, 30 KHz, 100 KHz, 300 KHz, 1 MHz, and 3 MHz are available.

** Manual positioning used at Cooby Creek.

**** Non-rotatable in the linear configuration.



*EQUIPMENT IS RECONFIGURED FOR VHF COMMUNICATIONS TRANSMISSION & RECEPTION

Figure 13-6. Major Subsystems of a NASA ATS Terminal.

13.2.5 Experiments

Experiments conducted as part of the spin stabilized ATS program are listed in Table 13-13.(3)(4)(5) The table shows the seven major experiment categories, listed in Table 13-1, into which the individual experiments can be grouped. In the case of the satellite VHF transponder experiments, some overlap between categories existed. These transponders supported selected meteorology and navigation experiments in addition to the communications and propagation experiments.

Specifically, in the WEFAX experiment, the satellite VHF transponder relayed Environmental Science Services Administration (ESSA) weather data (including ATS SSCC photographs) in facsimile format from Suitland, Maryland to Automatic Picture Transmission (APT) stations in the U.S., Japan, and Australia.(12) As part of OPLE, the spacecraft VHF repeater relayed interrogations and responses between the OPLE Control Center (OCC) and small remote platforms which were sometimes in motion. Responses included data from local sensors and OMEGA navigation system VLF tones received at the remote platforms and up converted to VHF.(13) Various other navigation and postion location experiments employed the spacecraft VHF transponder for ranging measurements.

The meteorological experiments, defined in Table 13-13, produced a vast number of high quality pictures from the spacecraft camera systems and demonstrated the feasibility of weather facsimile through the satellite's VHF repeater. The spacecraft stabilization experiments have displayed that nutation sensing and damping, for nutation angles between 0.001° and 5.0°, can be satisfactorily accomplished and that hydrazine thrusters are feasible; the resistojet stabilization experiment was not as successful. The entire ammonia fuel load was depleted on ATS-1 (probably by a leak at a pressure transducer port) and particle contamination resulted in abnormal valve operation and thrusting performance on ATS-3.(5) Considerable data was obtained on the navigation and satellite technology experiments with the result that all major objectives have for the most part been met. Additionally,

Table 13-13. Summary of ATS 1 and 3 Experiments

Experiment	Spacecraft	Category of Activity
1. Microwave Communications	1 & 3	Communications and propagation evaluation
2. VHF Communications	1 & 3	Communications and propagation evaluation
3. Phased Array Antenna	1	Comparison despun antenna technology
4. Mechanically Despun Antenna	3	Comparison despun antenna technology
5. Spin Scan Cloud Cover (SSCC) Camera	1 & 3	Meteorology concept consideration
6. WEFAX	1 & 3	Meteorology concept consideration
7. Image Dissector Camera System	3	Meteorology concept consideration
8. Nutation Sensor	1 & 3	Spacecraft stabilization investigation
9. Resisto-jet	1 & 3	Spacecraft stabilization investigation
10. Hydrazine Rocket System	3	Spacecraft stabilization investigation
11. Omega Position Location Experiment (OPLE)	3	Navigation techniques study
12. Self-Contained Navigation System	3	Navigation techniques study
13. Reflectometer	3	Satellite technology evaluation
14. Apogee Motor Plume	3	Satellite technology evaluation
15. Supra thermal Ion Detector	1	Earth environment measurements
16. Magnetometer	1	Earth environment measurements
17. Omnidirectional Electron-Proton Detector	1	Earth environment measurements
18. Multielement Particle Telescope	1	Earth environment measurements
19. Solar Cell Radiation Damage	1	Earth environment measurements
20. Thermal Coatings	1	Earth environment measurements
21. Electron Magnetic Deflection Spectrometer	1	Earth environment measurements

the environmental measurements experiments have been providing valuable information that is adding to the pool of knowledge on the space environment in the vicinity of the earth.

The phased array antenna, employed on ATS-1, consisted of 16 antennas arranged around a circle of one wavelength radius with each antenna composed of four collinear dipoles. Phasing of the radiated output was accomplished using eight ferrite phase shifters. Each phase shifter provided two equal amplitude outputs whose phase was varied in an opposite sense by inputs from the Phased Antenna Control Electronics, PACE. The two phase shifter outputs were connected to two diametrically opposite antennas. The PACE derived phase shifter control signals from satellite spin rate inputs and orbital position. This antenna system realized a measured in-orbit gain of about 12. 5 dB with a beamwidth of approximately 22° due to the array. Beamwidth due to the stack of dipoles was determined, prior to launch, to be about 17°. The PACE system demonstrated reliable performance and accurate pointing of the radiated beam. The total drive power requirement of the phase shifters was about 2 watts.

The mechanically despun antenna, employed on ATS-3, consisted of a rotating cylindrical parabolic collimator illuminated by a two element collinear array feed. Each array element was a full wave dipole. The parabolic collimator was rotated in opposition to the direction of spacecraft spin by a 128-step synchronous stepping motor and encoder controlled by the Mechanical Antenna Control Electronics, MACE. The MACE system was essentially identical to the PACE system employed on ATS-1. The measured in-orbit gain of this antenna was about 17 dB with a beamwidth of approximately 20°. The PACE system displayed a capability of pointing the antenna beam towards the earth within about ±0. 7 degrees. Antenna system reliability was, in general, quite good. During the satellite's first year in orbit, several malfunctions of the despinning mechanism were observed due to stalling of the stepping motor. No thermal effects could be related to this anomaly. It was hypothesized that a failure of the electric damper circuit associated with the stepping motor Regulator

No. 2 was responsible for the abnormal behavior. A switchover to backup electronics eliminated these malfunctions.

Prime objectives of the microwave communications experiments were defined in Paragraph 13.2.1. The final objective, providing support to other onboard experiments, was readily accomplished through numerous transmissions of wideband data from other satellite experiments. The spacecraft television cameras were the chief beneficiaries of this mode of operation.

Multiple access experiments of primary interest and their basic results are described in Table 13-14.(7)(14) Additionally, measurements of system noise power ratio and multiplex channel linearity, envelope delay, harmonic distortion, and frequency response were carried out with satisfactory results. The experiments indicated that CCIR and CCITT standards on communications transmission can be met with this type of system. Frequency control and a high level of inherent frequency stability are necessary to eliminate mutual interference on the uplink and to allow accurate demodulation to baseband of the SSB signal containing no reference carrier. Automatic level control is necessary to assure a proper balance of modulation indexes for all signals accessing the satellite's PM transmitter. Adequate short term frequency stability was found to be the most difficult requirement to meet but numerous special tests at NASA ground terminals indicated that much can be done to reduce instabilities. As expected, the higher receive antenna gain and EIRP of the ATS-3 satellite afforded greater performance capabilities than experienced with ATS-1.

Experiments employing the spacecrafts' wideband frequency translation repeater measured frequency division multiplex and television system performance. The frequency division multiplex tests were conducted employing a simulated loading of up to 1200 one-way voice channels at Rosman and up to 240 one-way channels at Mojave and Cooby Creek. Measurements of RF signal power and propagation losses; baseband frequency response and envelope delay; system noise power ratio; and multiplex channel frequency stability, level stability, S/N ratio, data error

Table 13-14. SSB-FDMA/PM

Type Experiment	Nature of Results Obtained
1. RF Power Level and Propagation Losses	Good correlation with predicted uplink and downlink values
2. Baseband Frequency Response	S/C degrades performance little if any. Flat from 300 Hz to 6 MHz.
3. Frequency Stability	Long term stability no problem when closed loop * AFC from pilot tone relayed thru satellites is employed. Short term stability found to be a problem. ** Contributers to problem in order of significance were: incidental modulation at power line frequencies, oscillator 1/f phase noise, 1.6 Hz phase modulation due to S/C spin *** and oscillator thermal noise. The latter two were of little consequence.
4. Level Stability	Employing an Automatic Level Control system ****, with a 0.1 dB/S response time, long term level variations were no problem. Short term fluctuations at 1.6 Hz due to S/C spin were not corrected by level control loop but 0.5 dB peak-to-peak variations were no problem.
5. Voice Channel S/N	Rosman tests using 1200-channel spectrum with 600 channel noise loading demonstrated a 40 dB capability with ATS-1 at maximum power. With companders giving a 15 dB improvement,a 55 dB S/N would be obtained
6. Data Error Rate	At 1.2 Kbps using non-coherent FSK an error rate of 6.3×10^{-7} bit/bit was obtained for channel S/N ratio between 30 and 40 dB. At low data rates (i.e., 50, 100, and 300 bps) it was shown that excessive frequency jitter can effect error rates. †

* Open loop correction could not be employed since S/C oscillator frequency offsets were sufficient to cause pilot frequencies to fall in multiplex signal spectrum.

** AFC loop cannot correct these errors due to the 0.27 second lag caused by the propagation delay of the synchronous satellite

*** Caused by antenna phase center being off S/C spin axis

**** Same pilot tone as employed for AFC loop is used.

† Caused by the narrow bandwidths employed at low data rates

rate, linearity, envelope delay, harmonic distortion and frequency response were taken.(7)(14) Performance was compared with standards given by the CCIR and EIA recommendation TR-141 and found to be, in general, compatible with the high quality expected for long haul telephony. With 1200-channel loading, compandors would be required to meet S/N ratio requirements. Frequency instabilities were, in this case, almost entirely due to differential doppler but were not significant. An AFC loop was not required.

For the television tests, major system design characteristics were as indicated in Table 13-15.(7)(14) Monochrome TV test terminals were installed at all three ATS earth stations and color test facilities were available at Rosman. Experiments conducted and their basic results are described in Table 13-16. In addition to these tests, numerous demonstrations have been conducted and events of interest televised. Included were the "Our World" demonstration in June 1967, the address by Japanese Prime Minister Sato during his Australian visit in October 1967, and coverage of the Olympics in Mexico City in 1968.

Investigations of transmission phenomena included measurements of spacecraft spin modulation, transmit and receive antenna patterns, and repeater saturation characteristics plus ground terminal G/T, antenna pointing accuracy, and transmit and receive antenna patterns. Results were in general agreement with previous independent measurements and theoretical expectations. Investigations of polarization phenomena included evaluations of SHF Faraday rotation as projected from VHF measurements and the effect of satellite antenna beam position on observed polarization at the ground. The latter determined that the ATS-1 polarization angles (polang) changes about 0.11° per degree change in satellite beam position while the ATS-3 polang is constant to approximately ±4° from peak of beam.

Additionally, numerous special tests were performed by NASA ground terminal engineers and the Japanese and Australian governments. The Japanese tests employed the Kashima ground terminal and repeated many of the SSB-FDMA/PM

Table 13-15. TV System Design Characteristics

Parameter	Value
1. RF Carrier Deviations	
a. By video signal	± 10 MHz peak
b. By audio subcarrier	± 1 MHz peak for 6 MHz subcarrier, ± 0.715 MHz peak for 4.5 MHz subcarrier, or ± 1.3 MHz peak for 7.5 MHz subcarrier.
2. Audio Subcarrier Frequencies	6.0 MHz (4.5 or 7.5 MHz optional)
3. Subcarrier Deviation by Audio	± 200 KHz peak
4. Video Section Bandwidth	30 Hz to 4.5 MHz (3.5 MHz optional)
5. Audio Section Bandwidth	30 Hz to 13 KHz

Table 13-16. Frequency Translation TV System Experiments

Type Experiment	Nature of Results Obtained
1. Continuous Random Noise	51 dB peak-to-peak signal to weighted rms noise measured at Rosman with peak power on ATS-3. CCIR standards require 56 dB for 99% of time.
2. Periodic Noise (Power supply hum)	S/N of 43 dB with all significant components below 1 KHz obtained to exceed CCIR recommendations by 8 dB.
3. Crosstalk	An initial audio-to-video problem caused by coupling in a common baseband equipment power supply was eliminated to reduce crosstalk level to 75 dB down or more.
4. Linear Waveform Distortion	Frequency response, short time wave form distortion line-time and field-time waveform distortion, and envelope delay evaluated. CCIR recommendations for international TV circuit met and those for system M (Canada and USA) partially met.
5. Non-Linear Waveform Distortion	Differential gain and color vector error (equivalent of differential phase) evaluated. CCIR recommendations for international TV circuit met but those for system M were not met.
6. Insertion Gain Variations	Found to be negligible.

and frequency translation mode tests performed by the NASA ATS terminals. Major differences were a greater emphasis on digital traffic handling capabilities and an investigation of the feasibility of time division multiple access employing frequency translation repeaters. The latter culminated in the demonstration of practical 4-phase and 2-phase systems operating at 13 Mbps and 27 Mbps, respectively.(15) Australian experiments employing the NASA Cooby Creek ground terminal, evaluated digital transmission over satellite voice circuits,(16) telephone signaling systems compatible with satellites,(17) and computer-to-computer communications at bit rates up to 2.4 kbps.(18) The feasibility of operational systems was demonstrated in all cases.

Major objectives of experiments performed using the VHF repeaters of the two satellites were defined in Paragraph 13.2.1. However, prior to conducting the indicated investigations, a series of ground-to-satellite-to-ground tests were conducted employing the VHF facilities of the NASA ATS earth terminals to provide baseline data. These tests and their primary results are described in Table 13-17.(19)

Aircraft to ground communications through the satellite has been successfully demonstrated on a number of occasions by commercial air flights over both the Atlantic and Pacific.(5)(20) A number of airlines in the United States plus such foreign carriers as Qantas, Japan Airlines, and BOAC have participated in these tests. Briefly, the aircraft terminals have consisted of a frequency modulation transceiver capable of radiating up to 500 W, data acquisition equipment, and specially designed circularly polarized antenna installations.

Ground-satellite-aircraft tests have demonstrated the feasibility of realizing a high operational reliability in such links. Multipath fading, scintillation, and aircraft antenna anomalies (i.e., variations in gain as function of aspect angle to satellite and polarization ellipticity) have been primary causes of signal fading. High solar and magnetic field activity affected propagation but did not present unmanageable problems. Precipitation static discharges raised normal 1100°K antenna temperatures to 70,000°K. To achieve acceptable communications during these

Table 13-17. NASA Baseline VHF Tests

Type Test	Nature of Results Obtained
1. Receive Signal Level	Good correlation with theory. Diurnal trend indicated showing peak signal level reached in evening hours following sunset. Daily variation is as much as 6 dB.
2. Carrier to Noise Versus Uplink EIRP	Downlink limited region or maximum C/N reached at a ground transmitted EIRP of about 40 dBW. Maximum measured C/N on ATS-1 was 17 dB and on ATS-3 was 20 dB.
3. Signal to Noise, Carrier to Noise & Data Error Rate	Predicted and measured S/N and C/N displayed good agreement. Data error rate at 1.2 Kbps showed that local RFI was a predominant factor.
4. Satellite Transponder Passband Frequency Response	On ATS-1, 2 equal accessing carriers could differ in transmitted power by as much as 9 dB due to gain variations across passband plus compression. On ATS-3, maximum difference was 4 dB.[*]
5. Satellite Transponder Compression[**]	On ATS-1, 6 dB of small carrier compression displayed for 10 dB small carrier to large carrier input ratio. No significant compression measured on ATS-3.
6. Carrier Intermodulation[**]	ATS-1 closely followed theoretical hard limiter performance. Sum of 3rd and 5th harmonics on ATS-1 was 8 dB down. On ATS-3 the sum was 17 dB down.
7. Interference Effects	Various levels and frequency separations for AM and FM interference evaluated as a function of measured voice channel articulation index (AI) of desired signal.[***] Results inconclusive due to difficulties in interpreting mechanized measurements of AI.

[*] Improvement over ATS-1 primarily due to lack of compression in near linear transponder.

[**] Two input carriers employed.

[***] FM employed on desired signal.

disturbances, antenna noise temperatures must be limited to a maximum value of 7000°K. Aircraft receiving from the satellite experienced interference when operating within line-of-sight of aircraft or ground stations transmitting co-channel in the conventional environment.

Aircraft-satellite-ground links have, generally, displayed a lower reliability than the links in the opposite direction. A major cause has been insufficient radiated power from the aircraft and uplink interference caused by conventional VHF communications systems within the satellite's area of earth coverage. The factors producing variations in link performance are, in general, the same as for the ground-satellite-aircraft link. It has been recommended that an operational system employ circularly polarized satellite antennas and linearly polarized aircraft antennas to minimize antenna caused performance variations.

Maritime radio communications via geostationary satellite has been demonstrated to be feasible in a number of ship-to-shore and ship-to-ship communications tests.(5) Participating ships have included the Coast Guard cutters Glacier and Klamath, the S. S. Santa Lucia,(21) and the German ships Gauss and Meteor. Successful experiments have been conducted with ships operating in the Pacific, the Arctic, the Antarctic and the Atlantic Oceans. Indications were that S/N ratios of about 40 dB could conveniently be attained on a voice channel and data error rates on the order of 10^{-3} and 10^{-4} bits/bit realized at 600 bps transmission rates. Short term fade depths in the order of 12 dB were observed in some tests.

Data dissemination in a meteorological network was displayed in the WEFAX experiment. Data collection from small unmanned stations was demonstrated as part of OPLE. Additionally, special hydrological(22) and ocean buoy experiments(23) have shown successfully that satellites can be employed for remote station interrogation and data transfer. Signal fading was observed to be a significant factor to be considered in designing operational systems.

VHF ranging experiments have displayed the feasibility of employing satellites operating at these frequencies for navigational purposes. Tests indicated that position fixing accuracies within ±1 n. mi. were attainable.(24) The satellite's VHF transponder has also been used in time dissemination experiments conducted by ESSA and the National Bureau of Standards. Accuracies of better than 10 microseconds have been demonstrated.(25)

The VHF transponders on ATS-1 and 3 have, additionally, been employed in various special tests and demonstrations. These include communications support for selected Apollo landings and tests of: aircraft to aircraft communications when the two aircraft are operating near opposite poles of the earth,(26) chirp modulation as a means of overcoming multipath effects and doppler shifts,(27) educational and public radio transmissions in Alaska, and VHF propagation phenomena. The latter include measurements of multipath, scintillation, and Faraday rotation effects. Each satellite's telemetry beacon and the Third Harmonic Generator (i.e., third harmonic of telemetry beacon) on ATS-3 have also been employed for such measurements. These measurements, in addition to supplying direct propagation information, have been useful in studies to determine the temporal makeup of the earth's ionosphere.

13.2.6 Operational Results

Since ATS-1 and 3 were experimental satellites, no operational traffic was carried. The operational performance of the NASA ATS ground terminals was good. In general, it was also shown that operational mobile VHF terminals were feasible. However, in specific cases of hastily assembled experimental VHF facilities, operational difficulties including insufficient transmitter power, antenna anomalies, and poor equipment reliability were encountered.

The operational performance of the two spin stabilized satellites was basically quite good. Specific minor difficulties encountered on ATS-1 included a gradual decay of radiated power when both SHF transponders and all four TWTs were energized and occasional SSCC picture streaking. The former was determined to be a temperature problem and operation with three TWTs was found to be sustainable. The latter occurred during periods when the spacecraft load exceeded solar array output to the extent that the batteries were depleted resulting in an abnormally low battery voltage.

Operational difficulties on ATS-3 included the failure of one 12-watt TWT to operate, a spurious SHF emission at 4201 MHz when operating in the FT mode, spacecraft response to commands intended for ATS-1, and a malfunction of the mechanically despun antenna (MDA). The spurious SHF emission was conjectured to be due to thermal effects, occuring during eclipse, creating an electrical or mechanical/electrical path to allow sustained passage of sufficient electrical energy to activate the VCO employed in the SSB-FDMA/PM mode. Responses to ATS-1 commands were determined to be due to the address assignments made and not due to equipment abnormalities. As a result, the address assignments for ATS-4 and 5 were changed. The despun antenna malfunction was verified to be produced by stalling of the MDA motor as discussed in Paragraph 13.2.5.

13.3 GRAVITY GRADIENT STABILIZED SATELLITES

13.3.1 General Description

The experiments carried on the Application Technology Satellites that featured evaluations of gravity gradient stabilization can be grouped into six major categories. These categories are listed and defined in Table 13-18.(28), (29), (30) The objectives of the SHF C-Band experiments were the same as indicated in the "General Description" of the spin stabilized ATS (see Section 13.2.1). The objectives of the L-Band experiments were to demonstrate the feasibility of air-to-ground communications at these frequencies and to investigate propagation effects. The objective of the millimeter wave experiment was to investigate propagation at 15 and 32 GHz.

Three active repeater satellites (i.e., ATS-2, ATS-4, and ATS-5) were launched during the ATS program for the express major purpose of evaluating gravity gradient stabilization. The status of these spacecraft is reviewed in Table 13-19.

Table 13-18. Experiment Categories

Number	Description
1	Gravity Gradient Stabilization at Medium and Synchronous Altitude
2	C-Band, L-Band, and Millimeter Wave Radio Communications and Propagation
3	Meteorological Experiments
4	Measurements of the Earth Environment
5	Technology Applicable to Spacecraft Stabilization and Stationkeeping
6	Miscellaneous Spacecraft Technology

ATS-2 (i.e., ATS-A prior to launch) failed to reach its intended 6000 nautical mile circular orbit when the second stage of the launch vehicle failed to restart leaving the spacecraft in a highly elliptical orbit having a relatively low perigee. This precluded proper testing of the gravity gradient control system although the stabilization booms were successfully deployed. Limited data was obtained on most of the remaining spacecraft experiments including data on the C-Band communications, meteorological, and environment measurements experiment.

Table 13-19. Gravity Gradient Spacecraft

Satellite		ATS-2	ATS-4	ATS-5
Manufacturer & Sponsor		Hughes Aircraft & NASA		
Launch Date		4/5/67	8/10/68	8/12/69
Launch Vehicle		Atlas-Agena D	Atlas-Centaur	
Orbital Data*	Apogee (mi.)	6947	480	22,277
	Perigee (mi.)	115	135	22,196
	Inclination	28.4°	29°	2.6°
	Period (min.)	218.9	94.5	1436
STATUS		Satellite was shut down 10/23/67. Orbit decayed 9/2/69 resulting in spacecraft destruction	Orbit decayed 10/17/68 resulting in satellite destruction	Satellite spinning around longitudinal axis but in synchronous orbit located at about 105°W. longitude.

*At initial injection. Altitude control and station-keeping maneuvers produced changes.

ATS-4 (i.e., ATS-D prior to launch) fell short of its intended synchronous orbit when the Centaur failed to re-ignite for a second burn leaving the spacecraft in a low altitude parking orbit with the Centaur still attached. Shortly after second burn failure, the ATS-4-Centaur conglomerate went into a tumble about a traverse axis. Subsequent maneuvers by the spacecraft attitude control systems were unable to completely correct this condition. As a result the gravity gradient system could not be tested and little information was obtained on the other satellite experiments although all subsystems appeared to be operating properly. Among the operations accomplished was a partial deployment of the stabilizing booms, boom scissoring and successful firing of the ion engines.

Table 13-20. Millimeter Wave and L-Band Terminals

Location		Sponsor	Antenna Diameter (FT)	Frequency Band
Bedford, Massachusetts*		Air Force Cambridge Research Labs	28	Millimeter Wave
Cambridge, Massachusetts*		Department of Transportation	10 (2 Dishes)	Millimeter Wave
Ottawa, Canada	Prime Site*	Canadian Communications Research Center	30	Millimeter Wave
	Secondary Site*		8	
Rome, New York*		Rome Air Development Center	15	Millimeter Wave
Holmdel, New Jersey*		Bell Telephone Laboratories	20	Millimeter Wave
Lakehurst, New Jersey*		U.S. Army Satellite Communications Agency	30	Millimeter Wave
Greenbelt, Maryland	Receive Site	NASA, Goddard Space Flight Center	15	Millimeter Wave
	Transmit Site		10	
Waldorf, Maryland*		Naval Research Labs	60	Millimeter Wave
Columbus, Ohio***	Fixed Site*	Ohio State University	30	Millimeter Wave
	Mobile Site*		15	
Rosman, North Carolina** ***		NASA, Goddard	15	Millimeter Wave
Boulder, Colorado*		ESSA Wave Propagation Lab	10	Millimeter Wave
Boulder, Colorado*		Westinghouse Georesearch	12	Millimeter Wave
Orlando, Florida*		Martin Marietta Corp.	12	Millimeter Wave
San Diego, California* ***		Naval Electronics Laboratory Center	60	Millimeter Wave
Austin, Texas* ***		University of Texas	10 2 Dishes)	Millimeter Wave
Rosman, North Carolina**		NASA, Goddard	15	L Band
Mojave, California**		NASA, Goddard	15	L Band
S.S. Manhattan** ****		NASA, Goddard	3	L Band

*Receiver only

**Transmit/Receive installation

***Active participants in NASA/GSFC Millimeter Wave Experiment. Remaining Millimeter Wave stations are independent experimenters

****Experimental icebreaking oil tanker

ATS-5 (i.e., ATS-E prior to launch) was successfully placed into the planned synchronous orbit but was left spinning about the spacecraft's longitudinal axis. Spin stabilization about this axis was the planned method of satellite control during the transfer orbit, apogee motor firing, and maneuvers to position the spacecraft on station. However, greater than expected nutation during this phase produced loss of spacecraft control and ultimately resulted in the present spin about the proper axis but in a direction opposite (i.e., counterclockwise) to that needed for the planned operation of the two-stage yo-yo despin mechanism. Consequently, a scheduled investigation of gravity gradient stabilization was again left unaccomplished. Modifications to earth terminal equipment, however, have allowed many of the remaining experiments aboard this satellite to be partially successful. In particular, objectives have been partially attained with regard to the millimeter wave, L-Band, and environmental measurements experiments.

The primary earth terminals involved in the few C-Band communications operations conducted included the terminals employed for the testing on ATS-1 and ATS-3 (see Table 13-3) with the addition of the terminal at Ahmedabad, India. The latter became operational in 1967 and conducted tests and demonstrations with ATS-2. The major terminals participating in the L-Band and millimeter wave tests on ATS-5 are defined in Table 3-20.(31, 32, 33) All of these terminals became operational in 1969 and 1970. Tracking, telemetry, and command (TT&C) was provided by separate installations included in the NASA ATS facilities located respectively at Rosman, North Carolina; Cooby Creek, Australia; and Mojave, California. In addition, some telemetry and tracking was provided by terminals at Johannesburg, South Africa; Tananarive, Madagascar; and Kauai, Hawaii. Satellite launchings were provided by NASA.

The launch difficulties on ATS-2 and 4 precluded any significant contributions to satellite communications by the experiments on board these spacecraft. However, ATS-5 did make several contributions, first, its millimeter wave experiment has provided valuable data that will contribute towards opening this band for satellite communications; secondly, its L-Band experiment has given a preliminary indication of the potential that these frequencies hold for aircraft and maritime control, communications, and navigation; and third, this satellite displayed the potential difficulties involved in injecting a gravity gradient stabilized satellite into a synchronous orbit and deploying it to a desired station.

13.3.2 System Description

The SHF (i.e. C-Band) tests conducted were done primarily on a loop back or half duplex basis. The system configuration for the millimeter wave tests was as shown in Figure 13-7. The figure indicates, uplink propagation measurements were performed in the satellite and telemetered to the ground. Downlink measurements are performed on the ground. A system block diagram of the initially planned L-Band communications test configuration is shown in Figure 13-8. Signals are sent from the ground stations to the satellite at C-Band. These signals are combined in the satellite and retransmitted to the aircraft at L-Band. The ground stations monitor the L-Band transmissions from the satellite for frequency control and ground-to-satellite range measurements. Aircraft transmissions arrive at the satellite at L-Band where they are combined and transferred to C-Band for transmission to the ground stations. An L-Band ground station transmit capability is also provided to allow full testing of the satellite from the ground. The earth coverage supplied by ATS-5 for the millimeter wave and L-band tests is shown in Figure 13-9.

SHF, C-Band, operating frequencies on the gravity gradient stabilized spacecraft were the same as on ATS 1 & 3 (see Table 13-4).

The same is true of the TT&C frequencies (see Table 13-6). The millimeter wave and L-Band operating frequencies are shown in Table 13-21.(31, 32) The indicated millimeter wave frequencies are of interest in that they are located at the first two windows in the frequency spectrum above 10 GHz where water vapor and oxygen absorption are low. Millimeter wave propagation, in general, is of interest in that it offers a possible means of reducing overcrowding in the lower bands. Additionally, it offers extremely wideband capabilities, high gain-small aperture antenna

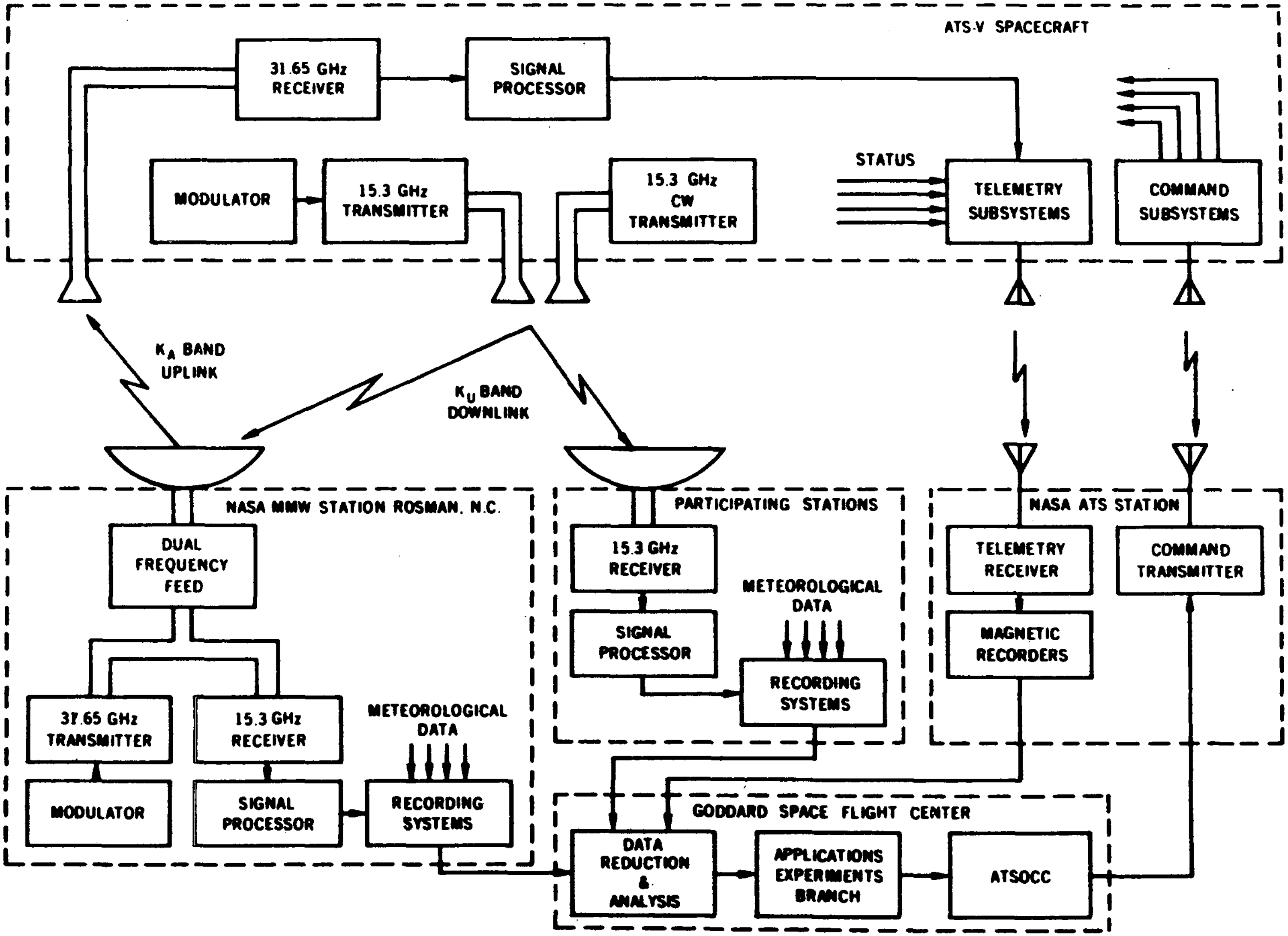


Figure 13-7. System Configuration for Millimeter Wave Tests

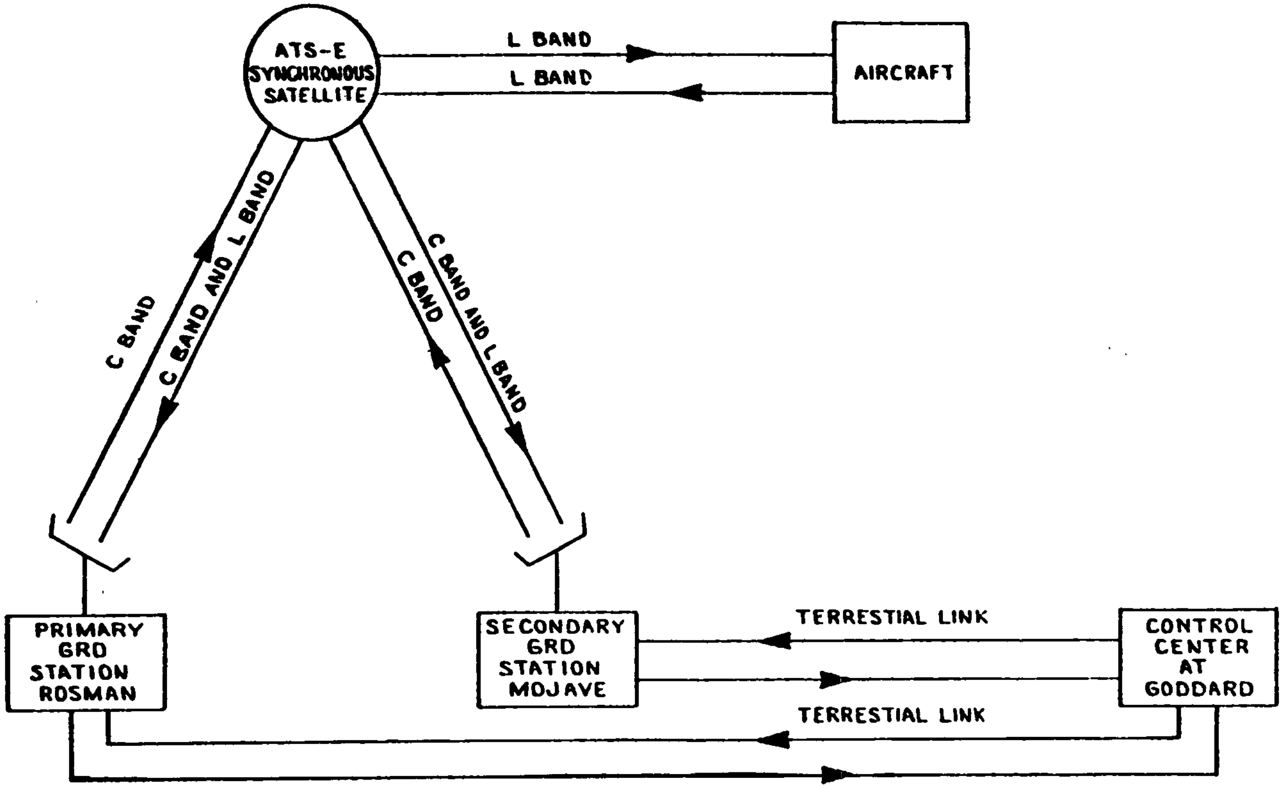


Figure 13-8. System Block Diagram for L-Band Tests

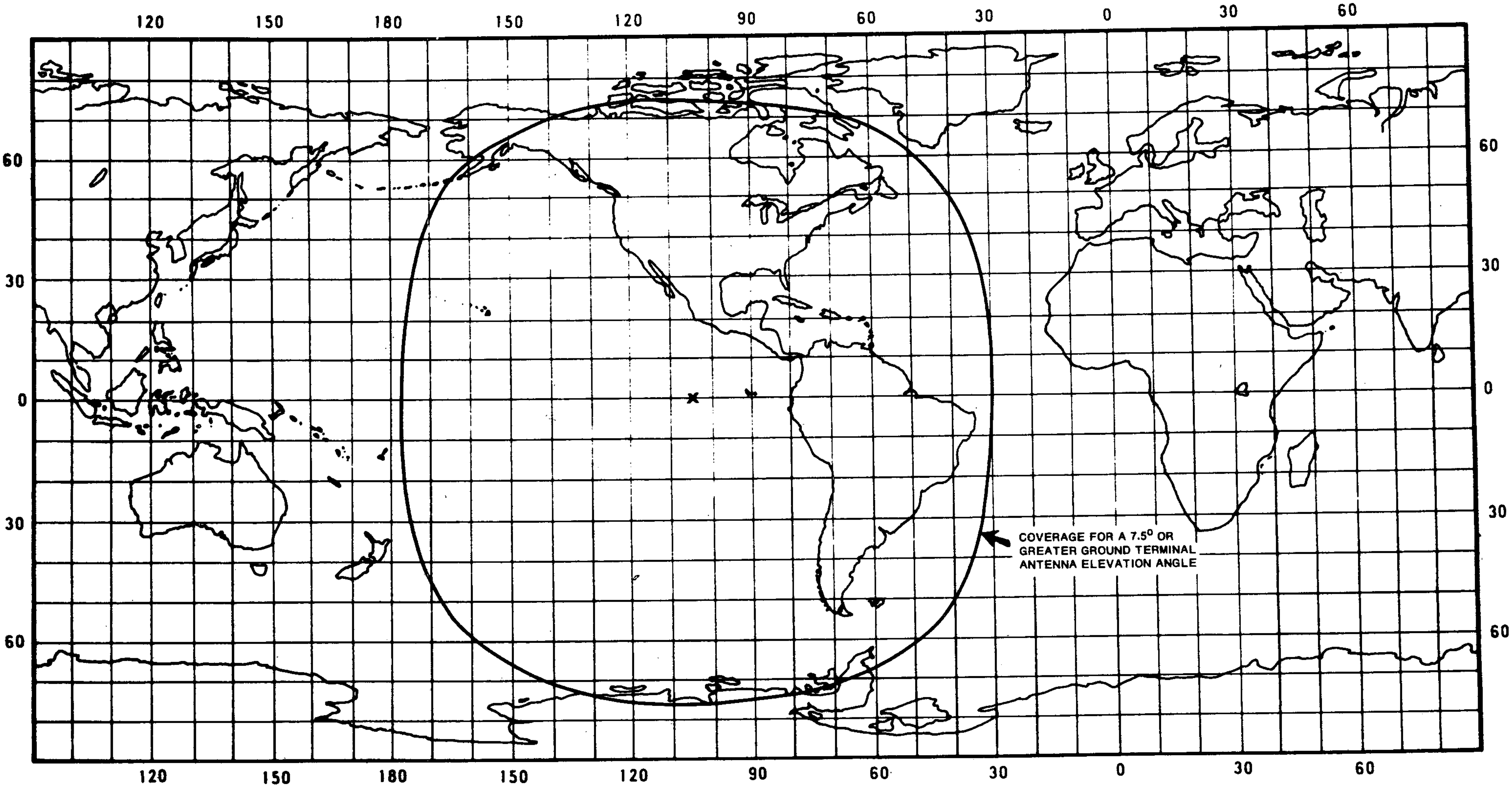


Figure 13-9. ATS-5 Earth Coverage

characteristics, and reduced size and weight of components. The L-Band frequencies are of interest for aircraft control, navigation, and communications. The VHF frequencies are also commonly considered for this purpose since they are compatible with existing equipment. L-Band offers the potential of more accurate satellite ranging and wider bandwidths for multiple access communications and control.

Table 13-21. Millimeter Wave and L-Band Frequencies (GHz)

Millimeter Wave		L-Band	
Uplink	Downlink	Uplink	Downlink
31.65	15.3	1.65	1.55

The basic signal processing techniques employed for C-Band tests were the same as used in ATS-1 and ATS-3 tests (see Tables 13-7 and 13-8). The millimeter wave experiment provided two complete and independent propagation measurement links. Similar signal processing techniques were employed on each link. It basically consisted of modulating a carrier with a single tone such that a carrier and first order upper and lower sidebands all of equal level are produced. This was accomplished by a varactor phase modulator in the satellite and a varactor frequency upconverter, which was capable of AM, FM, or PM modulation, in the ground transmitter. For the uplink, sidebands could be set at ± 1.0, ± 10, or ± 50 MHz from the 31.65 GHz carrier. For the downlink, settings of ± 0.1, ± 1.0, ± 10 or ± 50 MHz from the 15.3 GHz carrier were possible (34) Receivers employed down conversion mixing, filtering, envelope detectors, and phase detectors to derive measurements of carrier, upper sideband, and lower sideband amplitude plus relative sideband phase.

The L-Band signal processing employed was dependent upon the modes selected for satellite operation. Four modes were commonly employed as follows:

1. Narrowband L-L (FM/FM)

   Spacecraft receives at L-Band and retransmits at L-Band (frequency translation).

2. Cross Strap L-C & C-L

   a. L-C Cross-strap (SSB/FM)

      Spacecraft receives at L-Band (SSB), translates to video (500 to 600 kHz) and uses the video signal to modulate (FM) the spacecraft C-Band VCO; the output of which is then translated to C-Band and retransmitted.

   b. C-L Cross-strap (FM/FM)

      Spacecraft receives at C-Band, frequency translates to L-Band, and retransmits (Frequency translation).

3. L-L (SSB/FM)

   Spacecraft receives at L-Band (SSB) translates to video (500 to 600 kHz) and uses the video signal to modulate (FM) the Spacecraft L-Band VCO; the output of which is then translated to L-Band for transmission to the earth station.

4. Wideband Data Mode (FM downlink only)

   Video signals from onboard-spacecraft equipment modulates (FM) the satellite L-Band VCO the output of which is upconverted to L-Band for transmission to earth. A fifth possible mode was identical to narrowband L-L (FM/FM) except a wide bandwidth was supplied.

Link performance for modes involving the C-Band downlink and a high uplink S/N was essentially as defined in Tables 13-7 and 13-8. Typical link performance for modes involving the L-Band downlink and a high uplink S/N was as described in Table 13-22 for a narrowband L-L FM/FM link. The frequency translation modes were not designed primarily for multiple access. The planned multiple access modes of operation employed the L-L SSB/FM and the L-C SSB/FM satellite transponder configurations.

Table 13-22. Signal Processing for L-L Satellite Channel

Multiple Access	FDMA for limited number of accesses
RF Modulation	FM
Ground Demodulator Performance	Threshold estimated at 6 dB C/N based upon employing FMFB receivers
Rosman Receive Carrier-to-Noise	9 dB employing 2 TWTs, 2.2 MHz IF bandwidth, and 1 satellite access
Rosman Receive Margin	3 dB

13.3.3 Spacecraft

Characteristics of the communications-related subsystems of ATS-2 and ATS-4 are described in Table 13-23.(10, 28, 29) Block diagrams of the three possible modes of the SHF transponders were shown in Figures 13-2, 3 and 4. The Table displays some of the major system design differences in synchronous-altitude and medium-altitude gravity gradient stabilized communications satellites. These include, for the latter, low antenna gains for earth coverage beams; no need for an onboard apogee motor and spin stabilization prior to positioning "on station;" and no need for stationkeeping during gravity gradient stabilization "on station."

Characteristics of most of the communications-related subsystems on ATS-5 are shown in Table 13-24.(10, 30, 32, 34) A functional diagram depicting the L-Band transponder, and its various selectable modes, is given in Figure 13-10.(32) With the exception of the antenna system, the characteristics of the onboard millimeter wave equipment are not described in the Table since this equipment does not include a millimeter wave communications transponder. Its primary purpose was simply to make propagation measurements.

Table 13-23. ATS-2 and 4 Characteristics

		Satellite	ATS-2		ATS-4	
Antennas		Type	SHF-Horns used for both xmit and receive	TT&C-8 whip turnstile	SHF-Planar array used for both xmit and receive	TT&C-Essentially the same as for ATS-2
		Number	One	One	One	
		Beamwidth (3 dB)	45° pencil beam xmit and receive	Essentially omnidirectional	23° pencil beam xmit and receive	
		Gain	10.5 dB xmit and receive	0 dB	16.5 dB xmit and receive	
Repeaters		Frequency Band	SHF (C-Band)		SHF (C-Band)	
		Type	Essentially the same as for the repeaters on ATS-1 (See Table 13-10)		Essentially the same as for the repeaters on ATS-1 (See Table 13-10)	
		3 dB BW				
		Number				
	Receiver	Type Front End				
		Front End Gain				
		System Noise Figure				
	Transmitter	Type				
		Gain				
		Power Out				
		EIRP	18 dBW with 2 TWT's		24 dBW with 2 TWT's	
General Features	Stabilization	Type	Gravity gradient with no stationkeeping capability		(2) Spin initially* with nitrogen Jets for spin-up and hydrasine gas jet reaction control. Gravity gradient "on station" with micro-thruster station-keeping**	
		Capability	No data due to launch failure		No data due to launch failure	
	Power Source	Primary	N-on-P solar array with 140 watts at launch		Essentially the same as for ATS-2	
		Supplement	Two nickel cadmium batteries with 6 amp-hr./battery capacity at launch			
		Comm. Power Needs	Each SHF transponder - 35 watts and gravity gradient - 35 watts			
		Size	Cylindrical - 72 inches high and 56 inches in diameter			
		Weight	815 lb initially in orbit		864 lb initially in orbit	

*During the transfer orbit and until the spacecraft is positioned on station

**Subliming solid jets also available for satellite inversion if stabilization occurs at 180° from desired attitude

Table 13-24. ATS-5 Characteristics

Antennas		Type	L Band - 12 Helix planar array used for both xmit and receive	Millimeter Wave - Conical horns used for both xmit and receive	SHF (C Band) - Essentially the same as for ATS-4 (See Table 13-23)	TT&C - Essentially the same as for ATS-2 (See Table 13-23)
		Number	One	One		
		Beamwidth (3 dB)	24° pencil beam for xmit	20° pencil beam xmit and receive		
		Gain	Xmit. - 14 dB Rec. - 15 dB	Xmit. - 19 dB Rec. - 19 dB		
Repeaters		Frequency Band	L-Band*			SHF (C Band)
		Type	Multiple mode** supplying: (a) narrowband IF translation*** (b) wideband IF translation*** (c) modulation conversion for multiple access (d) wideband transmission of onboard data (e) C-L band**** and L-C† band cross-strap			Essentially the same as for one of the repeaters on ATS-1 (See Table 13-2)
		3 dB BW	(a) narrowband translation-2.5 MHz (b) wideband translation-25 MHz (c) modulation conversion-100 KHz uplink and 25 MHz downlink (d) onboard data xmit-25 MHz (e) cross strap-25 MHz for C-L and 100 KHz uplink into 25 MHz downlink for L-C			
		Number	One			
	Receiver	Type Front End	Tunnel diode amplifier into down conversion mixer			
		Front End Gain	No data			
		System Noise Figure	8.5 dB			
	Transmitter	Type	Two TWT's††			
		Gain	No data			
		Power Out	12 watt per TWT or 24 watt total			
		EIRP	25.4 dBW with 2 TWT's			24 dBW with 2 TWT's
General Features	Stabilization	Type	Spin initially††† with nitrogen jets for spinup and hydrazine gas jet reaction control. Gravity gradient "on station" with microthruster stationkeeping.			
		Capability	Excessive nutation with apogee motor attached during spin stabilized phase. No gravity gradient data obtained.			
	Power Source	Primary	N-on-P solar array with 175 watts at launch.			
		Supplement	2 nickel cadmium batteries with 6 amp. hr/battery capacity at launch.			
		Comm. Power Needs	C band xponder-35 watt, L band xponder-90 watt, gravity gradient-35 watt, and millimeter wave experiment - 30 watt			
		Size	Cylindrical - 72 inches high and 60 inches in diameter			
		Weight	954 lbs. initially in orbit			

Notes:
* Transponder is an adaption of one of C band transponders appearing on previous Applications Technology Satellites
** Modes are independently selectable by ground command
*** Soft limiter
**** Wideband IF translation
† Modulation conversion for multiple access (i.e., SSB-FDMA/FM)
†† Can be operated inividually or in parallel
††† During the transfer orbit and until the spacecraft is positioned on station Subliming solid jets also available for satellite inversion if stabilization occurs at 180° from desired attitude

A separate unrelated millimeter wave receiver and transmitting system were provided to aid in evaluating propagation at two different frequencies. The transmitting system included a primary and secondary transmitter operating at the same frequency. Additionally, a capability existed to receive and detect a TV signal to be used to modulate the L-Band satellite transmitter.(35) However, the spinning condition of ATS-5 precluded transmissions of TV signals.

The spacecraft millimeter wave receiver utilized a balanced mixer front end with a 17 dB maximum noise figure working into a 1.05 GHz solid state IF amplifier having a 47.5 dB gain.(34) Maximum received signal level was -85 dBm and minimum sensitivity was -120 dBm. The receiver phase locked on the carrier with the aid of a track-and-search circuit providing a ± 5 kHz minimum pull in range over a ±320 kHz band. The solid state primary millimeter wave transmitter supplied 250 mW (unmodulated) and 70 mW per line (modulated) of downlink power. The secondary transmitter was identical but could not be modulated by a tone.

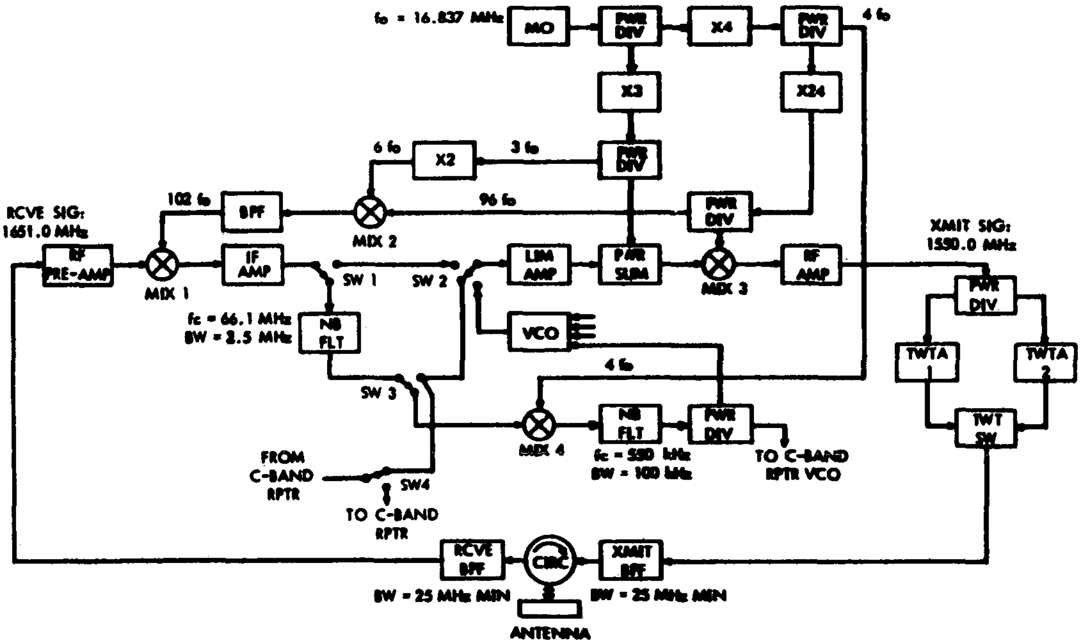


Figure 13-10. ATS-5 L-Band Repeater Block Diagram

In addition to the communications related subsystems, ATS-2 provided (28): a) two 1-inch 800-line advanced vidicon cameras, one narrow-angle and one wide-angle, and a tape recorder as a meteorological experiment; b) two 525-line TV cameras measuring boom thermal-bending characteristics plus a power control unit, solar aspect sensor, and two IR earth sensors to support the gravity gradient experiment; c) an environmental measurements package including omnidirectional proton-electron counters, electron magnetic deflection spectrometer, multi-element particle telescope, VLF whistler mode detector, cosmic radio noise receiver, solar cell radiation damage array, thermal coating samples, and electric field experiment; and d) a DOD albedo experiment.

In addition to the communications-related subsystems, ATS-4 provided (29): a) hydrazine gas jets plus passive and active nutation control systems for spacecraft stabilization and stationkeeping during the period of spin stabilization; b) a two-stage yo-yo despin mechanism; c) resisto jet and cesium ion microthrusters for stationkeeping during gravity gradient stabilization; d) a TV camera monitoring booms plus solar aspect and IR earth sensors to support the gravity gradient experiment; e) an image orthicon day-night camera as a meteorological experiment; and f) a magnetometer sensor measuring spacecraft charge as an environmental measurements experiment.

In addition to the communications-related subsystems, ATS-5 provided (30): a) essentially the same equipment as listed in items a) through d) for ATS-4; b) an environmental measurements package including a tridirectional particle detector measuring protons with energies between 30 and 250 keV and electrons between 30 and 300 keV, a unidirectional particle experiment to study auroral particle fluxes, a bidirectional particle experiment to map electrons and protons on constant lines of force and determine properties of acceleration within the magnetosphere, an omnidirectional particle experiment measuring electrons in 12 discrete energy ranges and the flux of solar cosmic rays, a radiometer measuring solar radio bursts between 50 kHz and 4 MHz, and an electric field measurements experiment; and c) other experiments in spacecraft technology including a magnetic damper, a solar cell voltage monitor, heat pipes for solar panel thermal equalization, a third harmonic generator similar to that on ATS-3, a solar cell damage experiment and a magnetometer experiment.

13.3.4 Ground Terminals

Major NASA terminals supporting SHF, C-Band, operations were the same as employed on ATS-1 and 3. These terminals were described in Table 13-2. Terminals participating in millimeter wave and L-Band experiments were defined in Table 13-20. The millimeter wave installation at NASA's Rosman, North Carolina facility and the L-band installation at Mojave, California are typical of the earth terminals employed for these two respective groups of experiments. Major characteristics of typical millimeter wave and L-Band terminals are described in Table 13-25. (32), (34) Terminal block diagrams are provided in Figures 13-12(31) and 13-13. (32)

The millimeter wave terminal block diagram displays the interest that existed in finding meteorological measurement techniques which could be useful in predicting propagation losses at these frequencies. The L-Band terminal was configured such as to allow operation in the satellite L- to C-Band cross strapping mode. The linear polarization employed at the millimeter wave terminal and the circularly-polarized feeds of the L-Band terminal were compatible with the spacecraft polarizations making link losses due to this source small.

13.3.5 Experiments

Experiments that were planned for ATS-2, 4, and 5 are summarized in Table 13-26. (28), (29), (30) The Table also indicates the six major experiment categories, listed in Table 13-18, into which the individual experiments can be grouped.

Some data was obtained on most of the experiments onboard ATS-2. The data, generally, was of limited value, however, since a launch vehicle failure left

Table 13-25. Characteristics of Millimeter Wave and L-Band Ground Terminals

Table 13-25. Characteristics of Millimeter Wave and L-Band Ground Terminals

	Terminal Feature	Terminal Rosman (Millimeter Wave)	 Mojave (L Band)
Antenna	Type	Cassegrain	Cassegrain
	Aperture Size	15 ft. Diameter	15 ft. Diameter
	Receive Gain	54dB	35.5 dB
	Efficiency	45%*	65%*
	Receive Beamwidth	.3°(1) @ 3 dB Pts.	3°(1) @ 3 dB Pts.
Receive System	Type Preamplifier	Tunnel Diode	Uncooled Parametric Amplifier
	Bandwidth	600 MHz** @ 3 dB Pts.	No Data***
	Noise Temperature	1000°K	340°K
Transmit System	Type Amplifier	TWT	Klystrom
	Bandwidth	450 MHz** 3 dB Pts.	7 MHz @ 3 dB Pts.
	Amp. Power Out	1KW****	1KW
Tracking	Type	Conical Scan Autotrack & Program-Autotrack	Slaved to 40ft. C Band Antenna Autotrack
	Accuracy	No Data	No Data
Total Performance	G/T	22 dB/°K	9.2 dB/°K
	EIRP	116 dBM	93.6 dBM
Polarization	Transmit Feed	Linear	Circular
	Receive Feed	Linear	Circular
	Terminal Feature	Rosman (Millimeter Wave)	Mojave (L Band)
Installation	Radome	None	None
	Type Facility	Transportable	Transportable

NOTE:
- * Derived Value Based on Data Available
- ** RF Bandwidth
- *** 25 MHz Required to Receive Wideband Data from Satellite
- **** Normally Operated at 10 to 100 Watts

Transmitter is Linear to About 200 Watts for Use in Multiple Access Mode

Conical Scan Could Not be Used Due to the Spin Condition of ATS-5

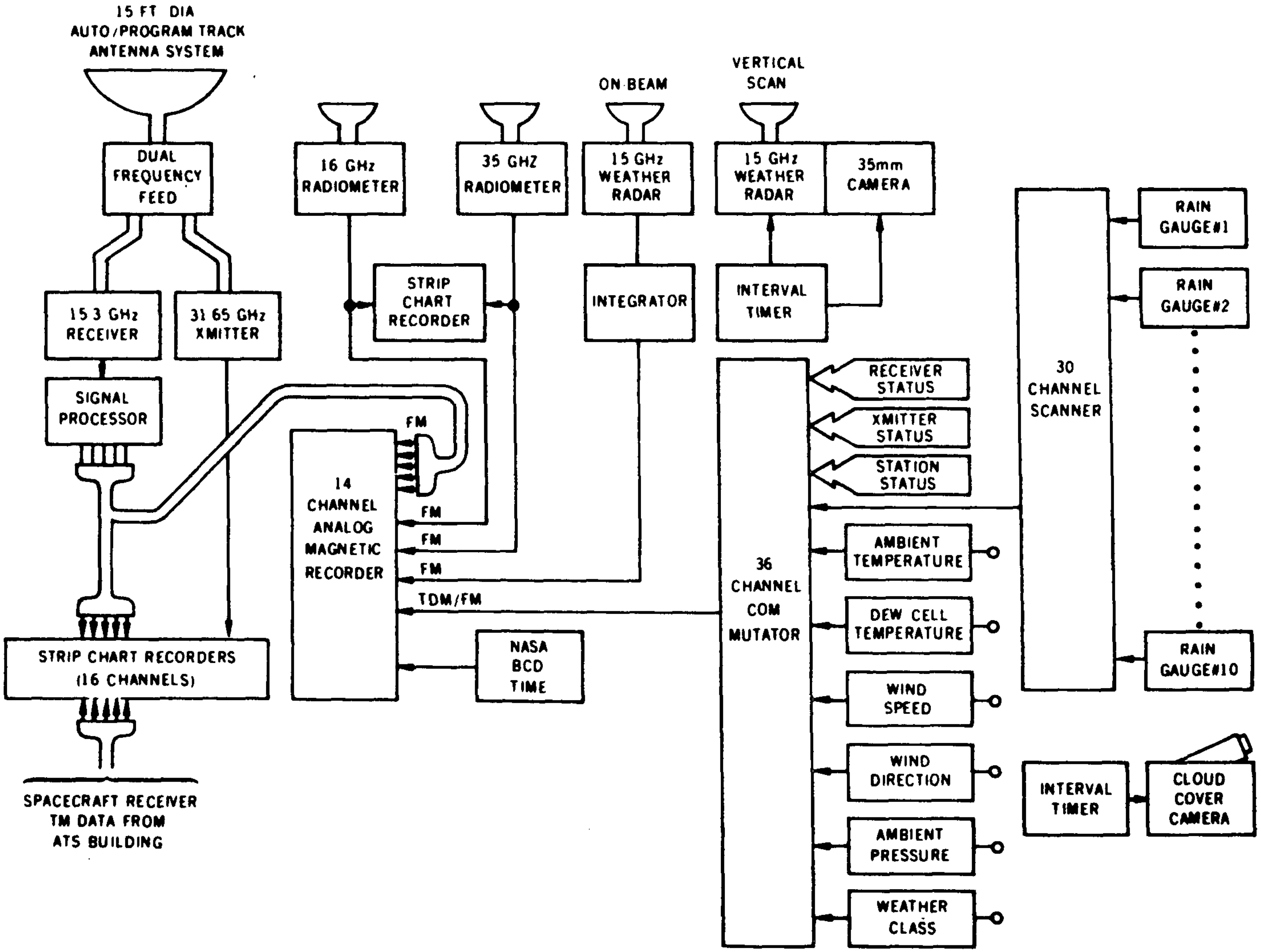


Figure 13-11. The NASA Rosman, North Carolina Millimeter Wave Station

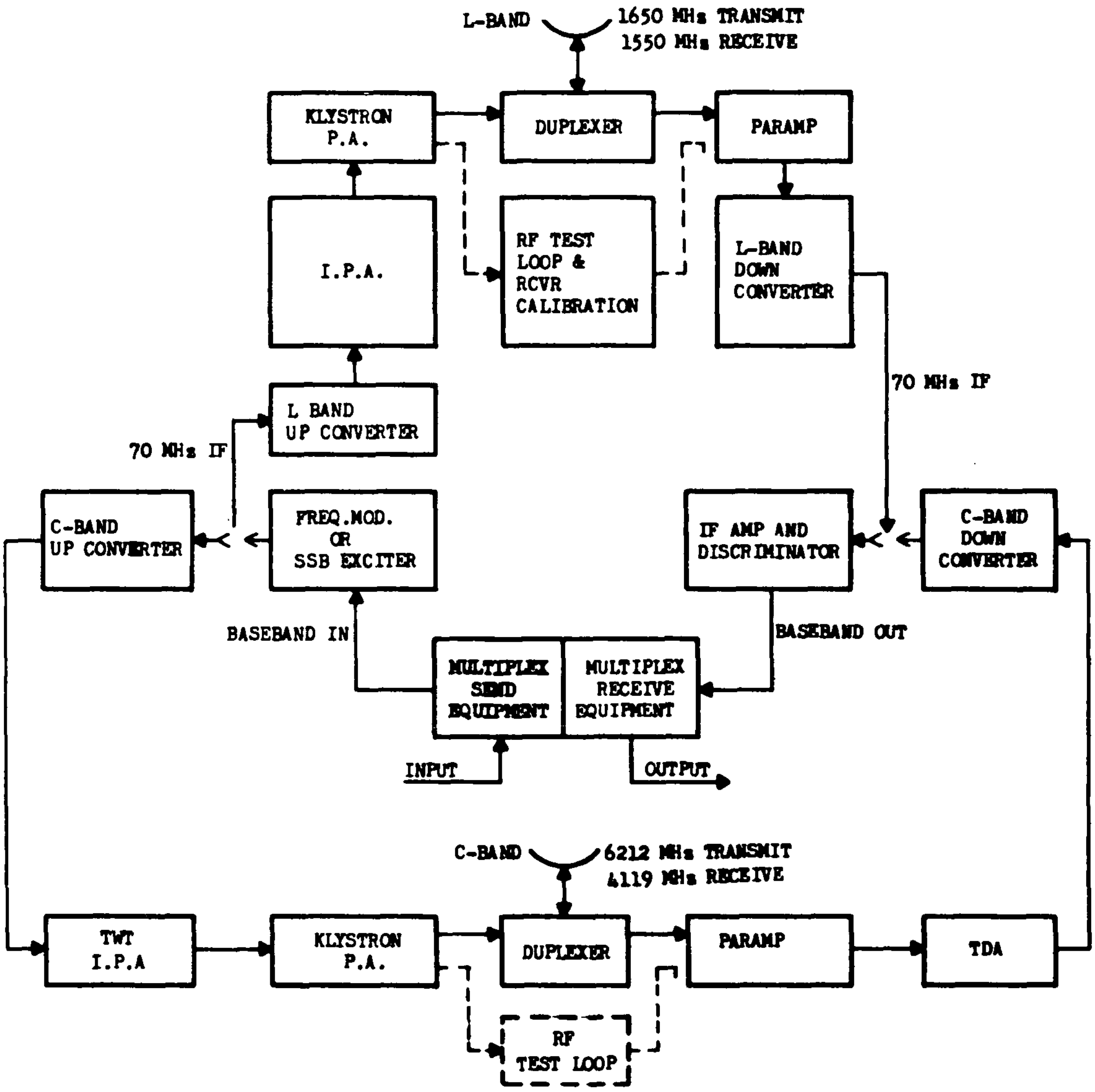


Figure 13-12. L-Band System Earth Station Block Diagram

Table 13-26. Summary of ATS-2, 4 and 5 Experiments

Experiment	Spacecraft	Category of Activity
1. Microwave (C-band) Communications	2, 4 & 5	Communications and propagation evaluation
2. Millimeter Wave Propagation	5	" " " "
3. L Band Communications	5	" " " "
4. Gravity Gradient Stabilization	2, 4 & 5	Gravity gradient stabilization investigation
5. Advanced Vidicon Camera	2	Meteorology concept consideration
6. Image Orthicon Camera System	4	" " "
7. Subliming Solid Engine	2, 4 & 5	Study stabilization & stationkeeping technology
8. Resistojet	4 & 5	" " " " "
9. Ion Engine	4 & 5	" " " " "
10. Albedo	2	Miscellaneous spacecraft technology consideration
11. Magnetic Damper	5	" " " "
12. Voltage Monitor	5	" " " "
13. Heat Pipe	5	" " " "
14. Solar Cell Damage	5	" " " "
15. Third Harmonic Generator	5	" " " "
16. Magnetometer	4 & 5	" " " "
17. Omidirectional High-Energy Particle Detector	2 & 5	Earth environment measurements
18. Cosmic Radio Noise Receiver	2 & 5	" " "
19. Electric Field Measurements	2 & 5	" " "
20. Electron Magnetic Deflection Spectrometer	2	" " "
21. Multi-element Particle Telescope	2	" " "
22. VLF Whistler Mode Detector	2	" " "
23. Solar Cell Radiation Damage Array	2	" " "
24. Thermal Coating Samples	2	" " "
25. Tridirectional Medium Energy Particle Detector	5	" " "
26. Bidirectional Low Energy Particle Detector	5	" " "
27. Unidirectional Low Energy Particle Detector	5	" " "

the spacecraft tumbling in a highly elliptical orbit. The stabilization booms were successfully deployed but the tumbling nature of the satellite resulted in the loss of one boom and in another being broken. Operation of the C-Band transponders was demonstrated including transmissions by the earth terminal at Ahmedabad, India. ATS-4 produced even less in the way of successful results than ATS-2. Among the accomplishments were partial deployment and scissoring of the stabilization booms plus successful firing of the ion engines.

Some of the experiments on board ATS-5 were also lost when the spacecraft was left spinning rather than gravity gradient stabilized. In particular, it was not possible to obtain data from the gravity gradient, resistojet, ion engine, solar cell voltage monitor, heat pipe solar panel temperature equalization, cosmic radio noise, or from the electric field measurements experiments. If the booms could be deployed the latter two could be successfully completed. Noteworthy successes have been obtained from the earth environment measurements, L-Band and millimeter wave experiments. The latter two were obtained through ground terminal modifications to accommodate the periodic nature of the received signal, caused by the spacecraft spin.

For the millimeter wave experiment, the spacecraft spin rate (i.e., 76 rpm) resulted in a received signal pulse having a 26 ms time duration between 1 dB down points, that occurred every 789 ms.(36) Ground complex modifications to accommodate this type of received signal included exclusive employment of program tracking rather than autotracking, installing a manual override to prevent the receiver phase lock loop from going into a search mode during deep fades of the peak signal, tripling the data sampling rate to 108 samples-per-second (i.e., one every 9.2 ms) and selecting the maximum valued sample as the only valid data point during any given second. Detrimental effects of the spacecraft spin have included loss of the millimeter wave to L-band TV transmission capability, a loss of fade measurement range which in itself was not of major significance, a serious degradation of the differential sideband phase measurement capability due to spin-induced doppler effect and settling time of the quadrature phase detectors, and loss of the ability to detect short term signal fades occuring at rates greater than about 0. 5 Hz. The detrimental effects of spacecraft spin plus a 9 dB drop in primary transmitter outputs, occurring about 3 months after satellite launch, also made it impossible to obtain coherence bandwidth measurements at 15. 3 GHz.

Data was obtained on the statistics of long term fades, correlation between various attenuation prediction techniques and actual measured attenuation, effects of site diversity at 15. 3 GHz, and coherent bandwidth at 31. 65 GHz. Preliminary results are tabulated in Table 13-27.(31), (34), (36)

Table 13-27. Preliminary Results Millimeter Wave Experiment

Type Experiment	Nature of Results Obtained
1) Attenuation at 15. 3 GHz	1 to 3 dB in light rains or dense fog, 3 to 7 dB in continuous rains (5 to 50 mm/hr) and number of fades exceeding 12 dB in heavy thunderstorms.
2) Evaluation attenuation prediction techniques	Excellent results using radiometer measurements* of sky temperature. Fair results employing radar backscatter readings at millimeter wave frequency. Better results at lower frequencies. Poor results using rain gage measurements of rainfall rate. Results improved with more gages over greater area.
3) Effects site diversity at 15. 3 GHz	Durations of 6 to 10 dB fades reduced by approximately two orders of magnitude using simple diversity system with 4 km ground separation between terminals.
4) Coherent bandwidth at 31. 65 GHz	Measured relative amplitude variations of sidebands have been within ±2 dB of carrier for sidebands at ±1. ±10, and ±50 MHz.

*Operating at same frequency as propagation link.

For the L-Band experiment, the spacecraft spin produced about a 22 ms sample time during which the received signal was within 1 dB of peak. The impact of the spinning spacecraft upon the original experiment objectives was that: a) all satellite loop tests had to be performed using a sampling technique that was synchronized to the spacecraft spin rate; b) the earth station AGC time constant had to be small compared to variations in the received signal to allow maximization of the sample time; c) fading at rates greater than about one half the sampling rate, but not as great as those that could be observed in one sampling interval, were impossible to record; and d) FDM two-way voice or multiple access voice demonstrations could not be completed. The tests were completed and their results are summarized in Table 13-28.(32) The results indicated that accurate navigation and high quality communications are feasible at L-Band. However, more data may be required to allow refined system designs.

13.3.6 Operational Results

ATS-2, 4, and 5 were experimental satellites, therefore, no operational traffic was carried. Operation of C-Band, L-Band and millimeter wave terminals was quite satisfactory. Spacecraft operation, in the case of ATS-4, was very limited and all equipment appeared to be performing well. On ATS-2 and 5, however, operations were more extensive and some anomalies were encountered.

The anomalies on ATS-2 included a missing and a broken stabilization boom, unplanned environmental measurements package turnoffs, inadvertent gravity gradient regulator turnoffs, and an inability to retract gravity gradient booms. The missing and broken booms were the result of the whipping action produced by spacecraft tumbling. The equipment turnoffs were determined to be due to low battery voltage caused by poor spacecraft aspect angle relative to the sun. No significant problems resulted from the turnoffs. The inability to retract booms was theorized to be due to boom motion preventing a smooth entrance into the rollers of the retraction mechanism.

Table 13-28. L-Band Experiments

Type Experiment	Nature of Results Obtained
1) Spacecraft Antenna Patterns	Half-power beamwidth 24° for transmit and 28° for receive
2) L Band Propagation	Diurnal variations due to ionosphere were less than ±0.3 dB based on four 24 hour test sequences. Observed short term fading and scintillation effects were less than ±0.3 dB on both uplink and downlink
3) Spacecraft Oscillator Frequency Offset	Spacecraft VCO offset from nominal decreased from about -245 KHz at turn on to about -180 KHz 200 minutes later. Spacecraft master oscillator caused offset in earth station baseband signal of about 4 KHz at turn on and stabilized to about 500 Hz 15 hours later
4) Spacecraft Intermodulation Distortion (SSB/FM)	At normal power output levels intermodulation products are approximately 26 dB below either of two test tones
5) Spacecraft Transponder Compression (FM/FM)	The initial point where a 2 dB increase in input power causes only a 1 dB increase in satellite output occurs at an earth station transmit power of 39.6 dBm
6) Spacecraft SSB/FM Modulator Linearity	Response of the SSB/FM L-band modulator to a tone received at several RF levels was linear up to a modulation index of 12 radians rms
7) Spacecraft Frequency Response	In narrow band FM/FM, a 2 MHz 3 dB BW measured. In SSB/FM mode, half power BW was 115 KHz
8) Doppler Due to Spacecraft Spin	At 20 dB down points on spacecraft antenna pattern, varies from +12 Hz at a maximum to -46 Hz minimum
9) Multiplex Channel S/N (SSB/FM)	Signal to thermal noise ratio was measured to be 36 dB* at earth station transmitter power output of 50 dBm. S/N decreased linearly with decrease in SSB transmitter power
10) Spin Modulation Compensation Test	By modulating uplink power in synchronism with spacecraft spin and such as to compensate for variations in satellite receive antenna pattern, usable uplink window was increased from 52 ms to 100 ms

* At Mojave terminal.

The only significant operational difficulties encountered on ATS-5 have involved the primary and backup millimeter wave transmitters.(35), (36) The main transmitter functioned perfectly during the first 3 months in orbit. On November 22, 1969, however, the output power was down 6 dB at turn-on. This condition continued until December 17 when a further 3 dB loss was recorded. Transmitter power has remained stable at this level to the present writing. The dc input power has shown no change from pre-launch level during this entire time. Further the 30.6 GHz local oscillator power has shown no significant change. This indicates that the loss is occurring in the solid state multiplier chain above the L-Band portion where the receiver local oscillator power is coupled out. The exact location and cause of the failure has not been determined.

The backup millimeter wave transmitter showed normal power characteristics from launch until October 22, 1969. The transmitter output power was then observed to decrease over time periods as short as 2-1/2 hours and as long as 9 hours to a level between 3 and 4 dB below normal output at which time the output abruptly dropped to zero. A period of nonoperation has always restored the transmitter to normal output. A loss in dc input power that correlates with the loss of RF output power has been recorded. It has been evident that the thermal sensitivity of the transmitter is responsible for the power loss.

13.4 LARGE APERTURE ANTENNA SPACECRAFT (ATS-F and G)

13.4.1 General Description

NASA's Applications Technology Satellites (ATS) F and G are for demonstrating the use of a synchronous orbit spacecraft as a relay station for several communications experiments. They will provide accurate three-axis attitude control using inertia wheels and/or gas jets as control actuators. The communications subsystems of these spacecraft include a parabolic reflector antenna of 30-foot diameter, a composite multifrequency antenna feed assembly, a multiple frequency transponder, and two separate major propagation experiments. A primary objective of these spacecraft is the demonstration of the 30-foot space deployable antenna. This antenna, in conjunction with the remainder of the communication system, provides a highly effective radiated power making possible the utilization of small inexpensive receiving terminals for such uses as relay links with spacecraft, ships, aircraft, and low-cost ground stations. Experiments employing terminals of this type have been designed for use with the ATS-F spacecraft and are described in a later section. Because no experiments have been approved for ATS-G as of mid-1971, the following discussion considers only the ATS-F program.

13.4.2 The ATS-F Spacecraft

The composite feed assembly shown in Figure 13-13 is used in conjunction with the reflector to provide efficient antenna performance over a broad range of frequencies and a wide variety of beam shapes, sizes, and functions. Although individual feed elements are used for each frequency band to permit optimum performance, a great deal of commonality exists among the radiating elements. To satisfy polarization, weight, and size requirements, cavity-backed cross-dipole elements are used for S, L, and UHF feeds. These elements offer simple and reliable radiators capable of operating at the frequencies, bandwidths, and polarizations defined by the experiments. With the exception of VHF radiators, the feed layout enables placement of all radiating elements in the parabola's focal plane, and minimizes interaction between neighboring feeds.

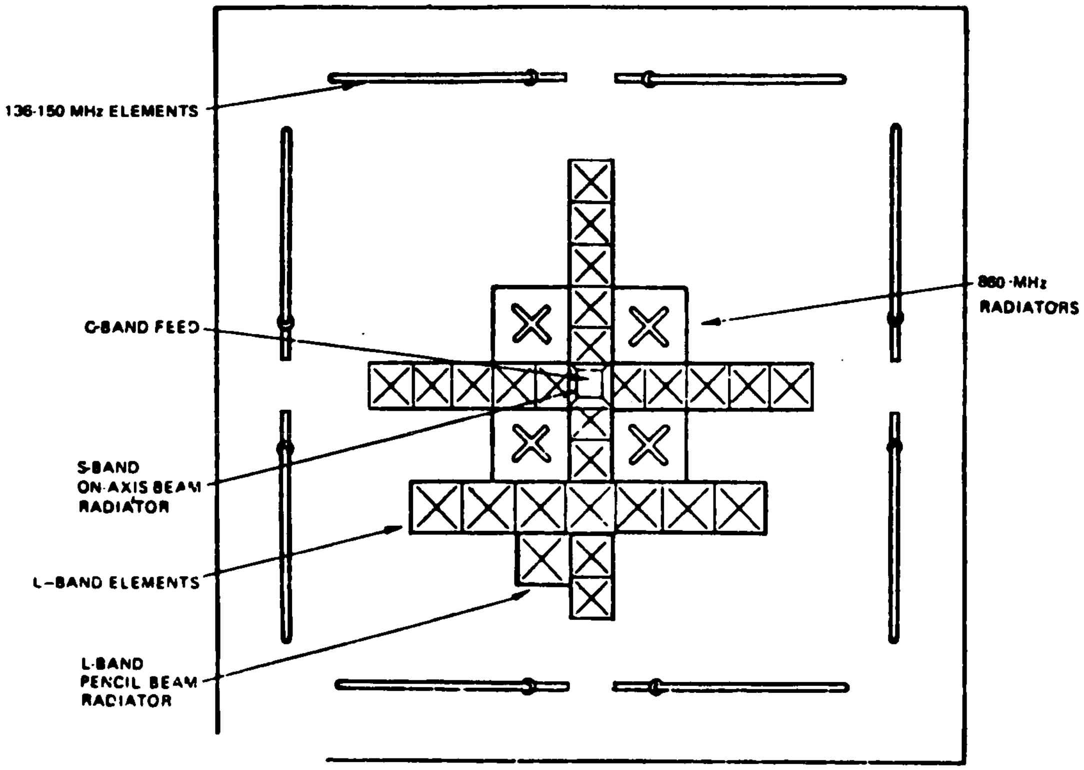


Figure 13-13. Composite Feed Assembly (Plan View)

Signal interfaces for the multiple frequency transponder are illustrated in Figure 13-14.(37) Its configuration is shown in the communication subsystem block diagram of Figure 13-15.(37) The transponder consists of the receiver assembly, IF amplifier assembly, synthesizors, and transmitters. Its characteristics are summarized in Tables 13-29, 30, 31, 32, and 33.(37) The receiver assembly design follows proven technology with appropriate redundancies to increase reliability. More interesting is the IF amplifier assembly, consisting of an IF input switch matrix, three identical 150-MHz IF amplifiers, and an IF output switch matrix. To achieve high reliability with maximum flexibility, IF switching is provided to interconnect the various circuits. The input switch matrix allows any down-converter to be connected to any IF amplifier. As many as three IF channels can be accommodated simultaneously. The output switch matrix allows any IF amplifier to be connected to any up-converter. Further, the wideband data unit can be connected to any up-converter.

The IF amplifier is a cascade type with high gain wide-bandwidth stages so that the frequency response is determined by the bandpass filter. The nominal bandwidth of the filter is 40 MHz and this fixes the maximum bandwidth of the amplifier. The signal can be further filtered, on command, to a 12-MHz bandwidth.

Within the output processor, the signal can be amplitude limited before reaching the output, or the signal can be detected in a single sideband detector. The baseband output from the detector is used to phase-modulate an internally generated carrier. This converts the multiple-carrier frequency division multiplex (FDM) information at the input to phase-modulated information at the output.

The AGC loop has three basic modes of operation that optimize performance for the particular experiments. For the wideband experiment, a predetection AGC loop is used that detects the total received signal (signal plus noise) and varies the gain to keep the output power constant. For the PLACE experiment post detection, AGC is used with a 1-MHz bandwidth. The output signal from the IF amplifier is fed to the frequency synthesizer.

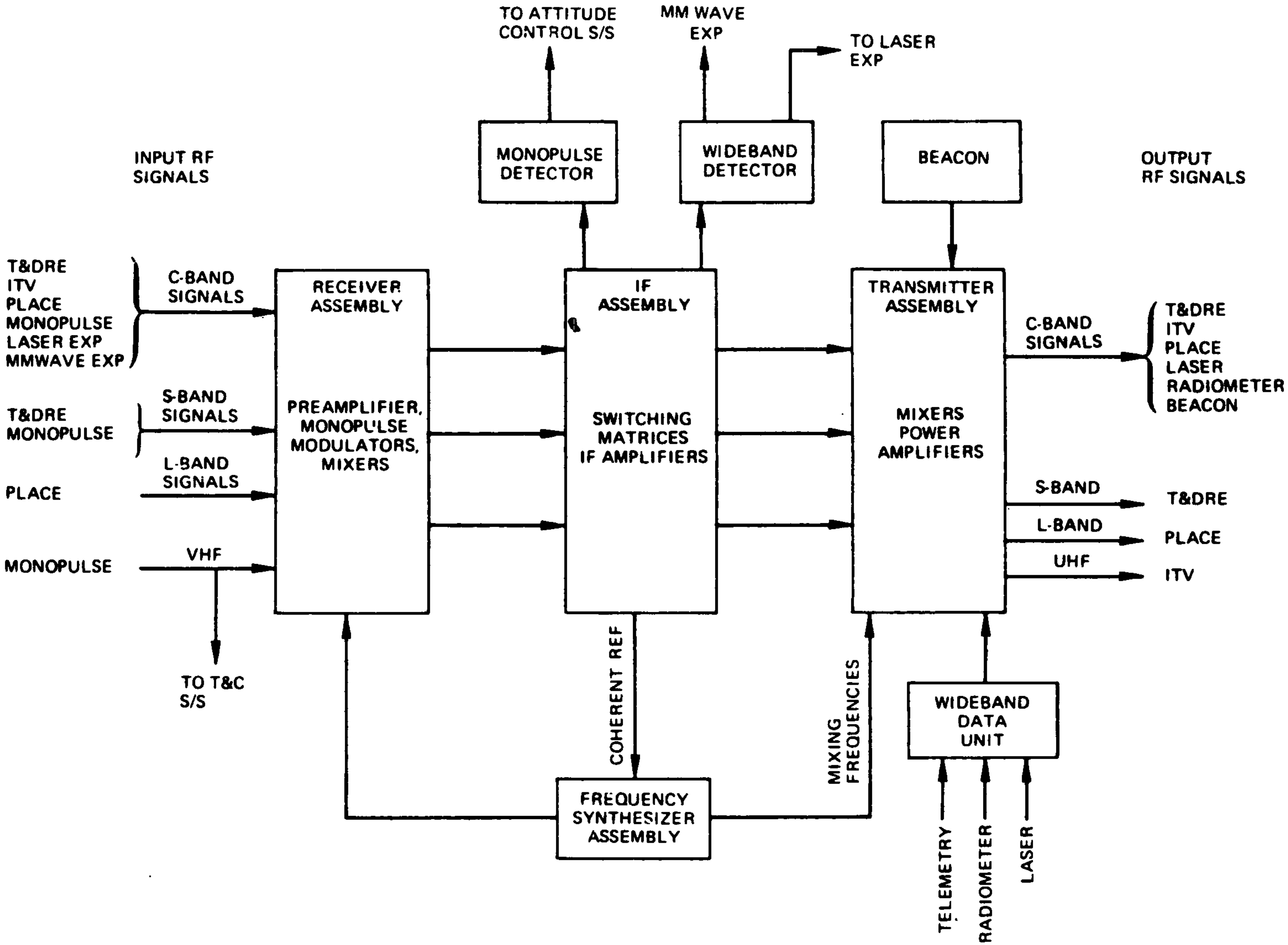


Figure 13-14. Transponder Signal Interfaces

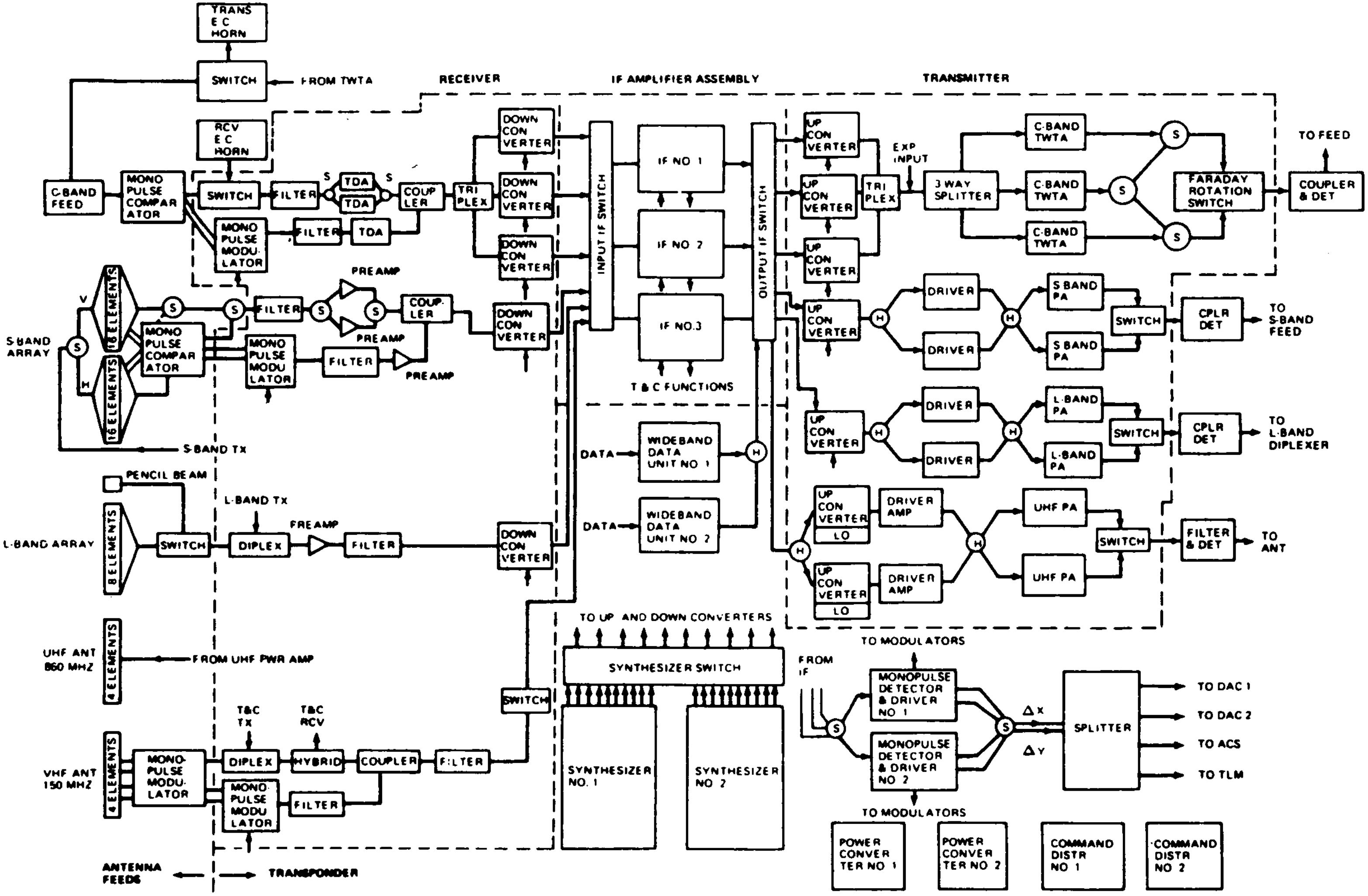


Figure 13-15. Communications Subsystem Block Diagram

Table 13-29. Communications Subsystem Characteristics

							RECEIVER		TRANSMITTER		
MODE	USER	NOMINAL FREQUENCY (MHz)	BANDWIDTH (MHz)	POLARIZATION	ANTENNA FIELD OF VIEW (DEGREES)	PEAK ANTENNA GAIN (dB)	MIN G T OVER FOV (dB°K)	G/T (PEAK) (dB°K)	TRANSMITTER OUTPUT POWER (WATTS)	MIN. ERP OVER FOV (dBW)	ERP (PEAK) (dBW)
30-FOOT C-BAND RECEIVE	LASER MMW MONOPULSE	6350 6150 5950	40 12	LINEAR	0.4	49.0	10.5	13.5	--		
30-FOOT C-BAND TRANSMIT	LASER MMW ANTENNA TEST	3750 3950 4150	40	LINEAR	0.6	46.0	-	-	21.0	51.5 (1) 47.2 (2)	54.5 (1) 50.2 (2)
HORN C-BAND RECEIVE	T&DRE ITV PLACE MMW LASER ATS-R	6350 6150 5950	40 12	LINEAR	20	16.5	-20	-17	-	--	-
HORN C-BAND TRANSMIT	T&DRE BEACON PLACE MMW LASER RADIOMETER RFI	3950 3750 4150 3950	40 500	LINEAR LINEAR	>20 >20	16.6 16.7	--	--	21.0 20.0	25.0 (1) 20.7 (2)	28.0 (1) 23.7 (2)
30-FOOT C-BAND RECEIVE	RFI	6150	500	HORIZONTAL VERTICAL RCP	0.4	48.5	NA	NA	NA	NA	NA
30-FOOT S-BAND RECEIVE SCAN	T&DRE	2250	40	RCP	13.2 (3)	40.5	-	-	-	-	--
30-FOOT S-BAND TRANSMIT ON AXIS	T&DRE	1800	12	RCP	--	39.5	-	-	20.0	--	50.5
30-FOOT S-BAND TRANSMIT SCAN	T&DRE	1800	12	RCP	13.2 (3)	39.0	-	-	20.0	48	--
30-FOOT S-BAND RECEIVE ON AXIS	T&DRE	2250	12 40	RCP	-	40.5	--	9.5	--	--	-
30-FOOT L-BAND PENCIL BEAM RECEIVE	PLACE	1650	12	RCP	1.5	38.5	2.5	5.5	-	-	-
30-FOOT L-BAND PENCIL BEAM TRANSMIT	PLACE	1550	12	RCP	1.5	38.5	--	-	40.0	49.0	51
30-FOOT L-BAND FAN BEAM RECEIVE	PLACE	1650	12	RCP	1 x 7.5	31.5	-5.0	-2	-	--	-
30-FOOT L-BAND FAN BEAM TRANSMIT	PLACE	1550	12	RCP	1 x 7.5	31.5	-	-	40.0	42.0	45
30-FOOT UHF TRANSMIT	ITV	850	40	RCP	3.0	33.0	--	-	80.0	48.0	51
30-FOOT VHF RECEIVE	MONOPULSE	150	6	LINEAR	>15	17	-20	-18	--	-	-
30-FOOT VHF RECEIVE	COMMAND	148.26 154.2	.03	LINEAR	>15	17	-20	-18	--	-	-
30-FOOT VHF TRANSMIT	TELEMETRY EME	136.23 137.11	2	LINEAR	>15	17	--	--	2.0	17	20

(1) SINGLE CARRIER OPERATION (2) DUAL CARRIER OPERATION (3) THIS IS A 13.2 DEGREE PLANE INCLUDING THE Z AXIS

Table 13-30. C-Band Performance

RECEIVE	
Transponder Input to Preamp Losses	
Sum Channel	
Diplexer	0.3 dB
TDA Switch	0.2 dB
Error Channel	
Modulator	1.0 dB
Filter	0.3 dB
Preamplifiers	
Noise Figure	5.5 dB
Gain	15.0 dB
Preamp to IF Losses	
Coupler	
Sum Channel	1.2 dB
Error Channel	7.0 dB
Triplexer	1.0 dB
Downconverter	8.0 dB
IF Switch	0.5 dB
IF Noise Figure	5.0 dB
Overall Receiver Noise Figure *	
Sum Channel and Horn	7.13 dB
Error Channel	9.5 dB
TRANSMIT	
TWTA Output Power (20 W)	+43 dBm
Switch Loss	0.25 dB
Coupler & Waveguide Loss	0.1 dB
Diplexer Loss	0.2 dB
Transponder Output Power	+42.45 dBm

*Includes input to preamp losses.

Table 13-31. S-Band Performance

RECEIVE	
Transponder Input to Preamp Losses	
Sum Channel	
Filter	0.15 dB
Preamp Switch	0.2 dB
Error Channel	
Modulator	1.0 dB
Filter	0.15 dB
Preamplifiers	
Noise Figure	3.7 dB
Gain	34.0 dB
Preamp to IF Losses	
Coupler	
Sum Channel	1.2 dB
Error Channel	7.0 dB
Downconverter	7.0 dB
IF Switch	0.5 dB
IF Noise Figure	5.0 dB
Overall Receiver Noise Figure *	
Sum Channel & Cross Array	4.10 dB
Error Channel	4.93 dB
TRANSMIT	
Power Amplifier Output Power (21 W)	+43.2 dB
Switch Loss	0.2 dB
Cable Losses	0.2 dB
Transponder Output Power	+42.8 dBm

*Includes input to preamp losses.

Table 13-32. L-Band Performance

RECEIVE	
<u>Transponder Input to Preamp Losses</u>	
Diplexer	1.1 dB
<u>Preamplifier</u>	
Noise	4.4 dB
Gain	25.0 dB
<u>Preamp to IF Losses</u>	
Filter	0.1 dB
Downconverter	7.0 dB
IF Switch	0.5 dB
<u>IF Noise Figure</u>	5.0 dB
<u>Overall Receiver Noise Figure*</u>	5.57 dB
TRANSMIT	
Power Amplifier Output Power (40 W)	+46 dBm
L-Band TX/RCV Diplexer Loss	0.2 dB
Cable Losses	0.2 dB
Transponder Output Power	+45.6 dBm

*Includes input to preamp losses.

Table 13-33. VHF and UHF Performance

VHF RECEIVE (150 MHz)	
<u>Transponder Input Losses</u>	
Sum Channel	
T&C diplexer	1.0 dB
T&C hybrid	3.0 dB
Coupler	1.0 dB
Error Channel	
Modulator	1.0 dB
Filter	0.2 dB
Coupler	7.0 dB
Both channels filter	1.0 dB
Line Switch	0.5 dB
IF Switch	0.5 dB
<u>IF Noise Figure</u>	5.0 dB
<u>Overall Receiver Noise Figure*</u>	
Sum Channel	12.0 dB
Error Channel	15.2 dB
UHF TRANSMIT (860 MHz)	
Power Amplifier Output Power (80 W)	+49 dBm
Filter Loss	0.2 dB
Cable Loss	0.2 dB
Transponder Output Power	+48.6 dBm

*Includes input to preamp losses.

The synthesizer uses direct synthesis from a single frequency standard. A simplified block diagram of the synthesizer is shown in Figure 13-16. The figure shows the signal flow for the coherent repeater operation mode at L-Band. When it is desired to have the synthesizer operate independently of the received frequency, a highly accurate reference oscillator is substituted in place of the IF signal in the phase detector and the synthesizer locks to the reference oscillator. Redundancy is achieved by using two synthesizers.

Solid state power amplifiers are used for all but the C-Band transmitter. The C-Band transmitter consists of three traveling-wave tube amplifiers. Command logic circuitry is used to initiate switching and TWTA selection to effect either a single power output (10 W) from any one of the three TWTAs, or a combined power output of 20 W from any two of them. The third TWTA performs as a redundant unit capable of being employed in either of the 10- or 20-W power output modes. The UHF, L-Band, and S-Band power amplifier are all transistorized. There is no downlink communications capability available at VHF.

Separate equipment, consisting of an RF Oscillator-Multiplier unit and a 20/30 GHz Modulator-Amplifier unit is also provided onboard the spacecraft for the Millimeter Wave Experiment (MWE) described in Section 13.4.4. This equipment can be used either to generate two CW signals at 20 and 30 GHz, or to synthesize two coherent multitone spectra each consisting of a carrier and four tones on each side spaced at 180-MHz intervals and centered at 20 or 30 GHz. In addition, the 6 GHz uplink signals received by the basic ATS-F multifrequency transponder can be cross-strapped at IF to the MWE equipment to provide modulated downlink signals at 20 and 30 GHz. A block diagram of the MWE equipment package is shown in Figure 13-17. In the CW or cross-strapped modes the output signal powers at 20 and 30 GHz are limited to 2 watts each; for the coherent multi-tone spectrum the output power is 17.8 dBm per tone. The MWE will employ both horn antennas and the main parabolic reflector antenna. The beam peak gains for the 20 and 30 GHz horns will be 27.6 dB and the parabolic antenna gains will be 37.0 and 39.0 dB, respectively, for the 20 and 30 GHz signals.

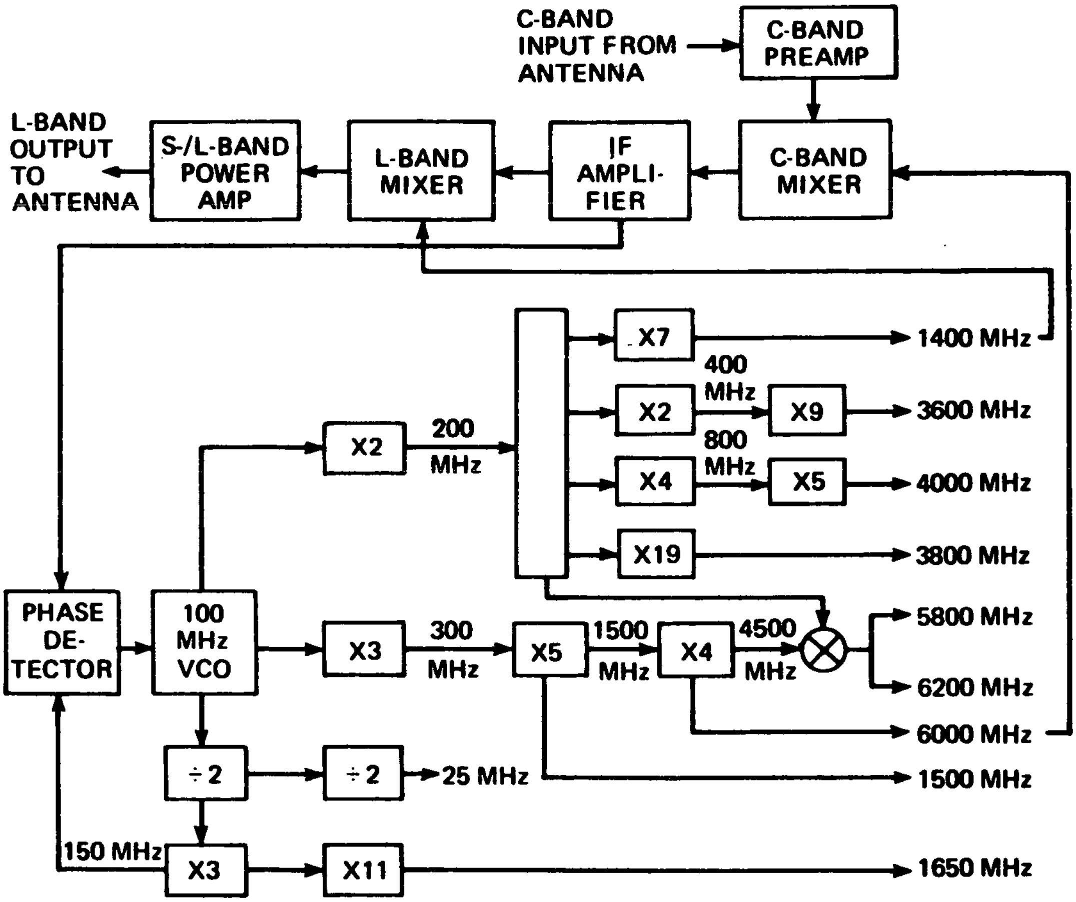


Figure 13-16. Frequency Synthesizer Block Diagram

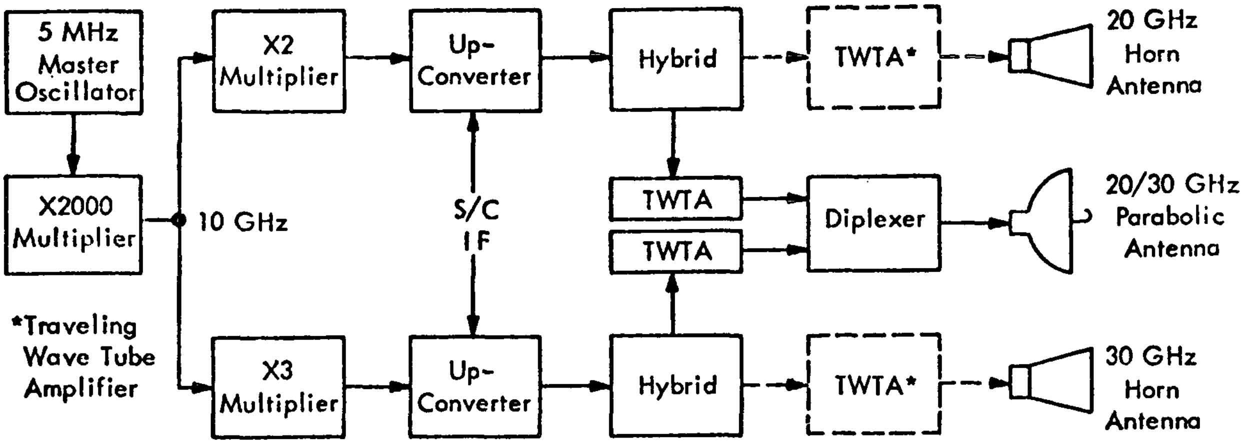


Figure 13-17. Millimeter Wave Equipment Package

A separate and independent single frequency conversion transponder is also being included on-board the ATS-F spacecraft for the COMSAT Propagation Experiment (CPE). Separate channels are provided at 13.19 - 13.20 GHz and 17.79 - 17.80 GHz with full redundancy in each channel. A signal received in either of these bands will be translated to 4.15 GHz and amplified in a three-stage tunnel diode amplifier. The outputs from the two channels will then be filtered, combined in a hybrid network, and the combined signal delivered to two independent power amplifiers, each consisting of a three-stage tunnel diode amplifier in cascade with a traveling wave tube amplifier. A block diagram of the CPE transponder, which uses less than 14 watts of spacecraft power, is shown in Figure 13-18.

The per carrier output of the transponder at 4 GHz will be -36 dBw for the 18 GHz diversity experiment carriers, and -29 dBw for the 18 GHz and -37 dBw for the 13 GHz dual frequency terminal carriers. The on-axis gain of the receiving antenna will be 28.6 dB and 25.8 dB above isotropic at 18 and 13 GHz, respectively. At 18 GHz the antenna beamwidth will be 4° by 8.5°. The on-axis gain of the transmitting horn antenna will be 17 dB above isotropic at 4 GHz; the corresponding high-power beamwidth will be 20°.

13.4.3 Ground Terminals

Four NASA ATS ground terminals will provide the main support for operations conducted on the ATS-F and ATS-G spacecraft. All four stations will provide C, S, and L-Band frequency modulated (FM) transmitters and C, S, and L-Band FM receivers. Operations for which they will be responsible include spacecraft command and control, collection of range and range-rate data for orbit determination, recording polarization data for spacecraft attitude determination, and performance of technological and scientific experiments. One station will be located at Rosman, North Carolina, and two will be located at Mojave, California. One of the latter is a Transportable Ground Station (TGS). After the launch of ATS-F, the TGS will be moved overseas. The C-Band portions of each of these terminals, and the L-Band installation at Mojave,

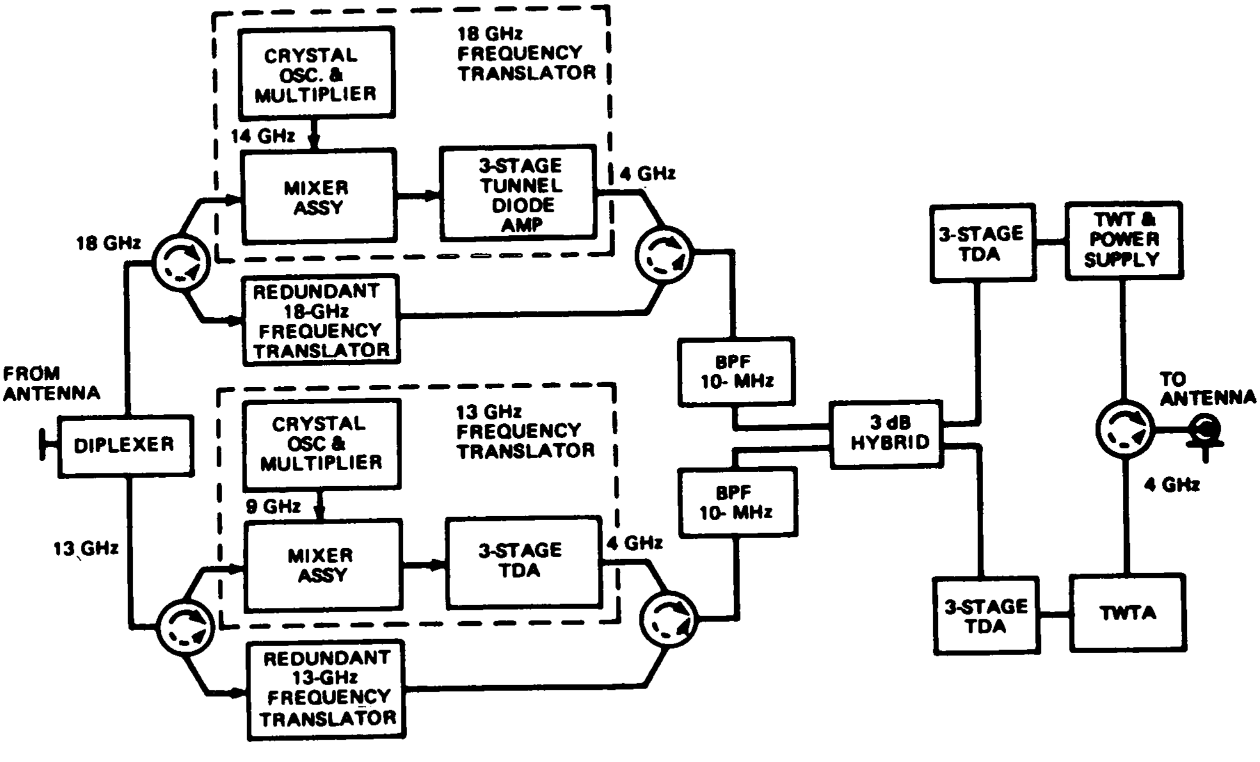


Figure 13-18. Transponder Block Diagram

will be modified versions of the facilities employed in previous ATS experiments. The fourth terminal is a mobile station that will allow the experimenters' equipment to be remotely located. In addition, it will serve as a backup to the TGS and will contain UHF equipment to support the 860 MHz downlink for the ITV experiment. The three stations, Rosman, Mojave, and the TGS will have nearly identical communications and telemetry and command equipment. The major difference is in the antenna systems. A separate transportable millimeter wave terminal for the Millimeter Wave Experiment will be located adjacent to the ATS facilities at Rosman. Major characteristics of these terminals are summarized in Table 13-34.(37) A block diagram of the communications facilities at Rosman and in the mobile terminal are shown in Figures 13-19 and 13-20,(37) respectively.

The instructional television experiment will be conducted by the Indian Government in cooperation with NASA. Three Indian stations, located at Ahmedabad, Bombay, and Delhi will originate TV programs for relay through ATS-F. These signals will be received by small inexpensive terminals scattered throughout India.

All spacecraft maneuvers and experiments will be controlled by direction from the ATS Operations Control Center (ATSOCC) at Goddard Space Flight Center (GSFC) at Greenbelt, Maryland. All test data obtained will be forwarded from the ground stations to GSFC for processing, evaluation, and distribution to experimenters. Ground complex circuits for effecting this control and distribution of data are illustrated in Figure 13-21.(37)

13.4.4 Experiment

The primary objective of ATS-F and G is to demonstrate the feasibility of a 30-foot diameter deployable spacecraft antenna with good RF performance up to 6 GHz.(38) In addition, the spacecraft is to provide an earth synchronous oriented platform stabilized along three axes for advanced technology and scientific experiments. In the field of communications, six very important technological experiments will be performed. These are:

Table 13-34. Characteristics - Millimeter Wave Experiment Terminals

ITEM	DESCRIPTION	STATION			
		ROSMAN	MOJAVE	TRANSPORTABLE	MOBILE TERMINAL
ANTENNA SYSTEMS	C BAND				
	Type	Parabolic Reflector with STADAN Prime Focus Feed and ATS Cassegrain C Band Feed	Parabolic Reflector with Cassegrain Feed		Parabolic Reflector with Prime Focus Feed
	Diameter	85 ft	40 ft		21 ft
	Polarization	Linear			
	Mount	X Y		AZ EL	Polar
	Receive Freq.	3.7 to 4.2 GHz			
	Transmit Freq.		5.925 to 6.425 GHz		
	*G/T (3.7 GHz) (Zenith)	38.4 dB	31.5 dB	32.0 dB	24.8 dB (Cooled)
	Gain Receive (3.7 GHz)	56.0 dB	49.5 dB	50.0 dB	44.8 dB
	Gain Transmit (5.9 GHz)	61.0 dB	53.0 dB	53.5 dB	48.9 dB
	Receive System Noise Temp. (Zenith)	58°K	63°K		100°K Cooled 625°K Uncooled
	S AND L BAND				
	Type	Parabolic Reflector with Prime Focus Feed			
	Diameter	**15 ft			
	Polarization	Circular			
	Mount	AZ EL			Polar
	Receive Freq.	S Band: 2.05 to 2.1 GHz L Band: 1.5 to 1.58 GHz			
	Transmit Freq.	S Band: 2.2 to 2.3 GHz L Band: 1.62 to 1.7 GHz			
	G/T: L Band (Zenith)	10.6 dB			
	G/T: S Band (Zenith)	12.1 dB			
	Gain				
	S Band RCV	35.7 dB			
	L Band RCV	33.6 dB			
	S Band XMT	36.9 dB			
	L Band XMT	34.3 dB			
	Receive System Noise Temperature (Zenith)				
	L Band	200°K			
	S Band	230°K			
	UHF				
	Type				Parabolic Reflector with Prime Focus Feed
	Diameter				21 ft
	Polarization				Circular
	Mount				Polar
	Receive Freq.				835 -885 MHz
	G/T (Zenith)				5.2 dB
	Gain Receive				31.7 dB
	Receive System Noise Temp. (Zenith)				450°K
	MMW EXPRMNT				
	Type	Parabolic			
	Diameter	15 ft			
	Feeds	Dual Frequency Linear			
	Mount	AZ EL			
	Receive Only Frequency	20 and 30 GHz			
	*G/T: 20 GHz 30 GHz	28.0 dB 29.5 dB			
	Gain: 20 GHz 30 GHz	56 dB 58 dB			
	Receive System Noise Temperature (Zenith)	20 GHz 630°K 30 GHz 710°K			
RECEIVERS	C BAND				
	Noise Temp	18°K			
	RF Bandwidth	500 MHz			
	IF Bandwidth	Up to 50 MHz			
	S AND L-BAND				
	Noise Temp	100°K			
	RF Bandwidth	Up to 50 MHz			
	IF Bandwidth	Up to 50 MHz			
TRANSMITTERS	C BAND				
	Max. Power Output	8 kW			2 kW
	RF Bandwidth	50 MHz			
	S AND L-BAND				
	Max. Power Output	S Band. 100 W (CW) L Band: 1 kW (CW)			
	RF Bandwidth	S-Band: 50 MHz L Band: 10 MHz			

*Minimum at peak unless otherwise noted.

**The existing 15 ft L Band antenna at Mojave is being modified to include S Band capability.

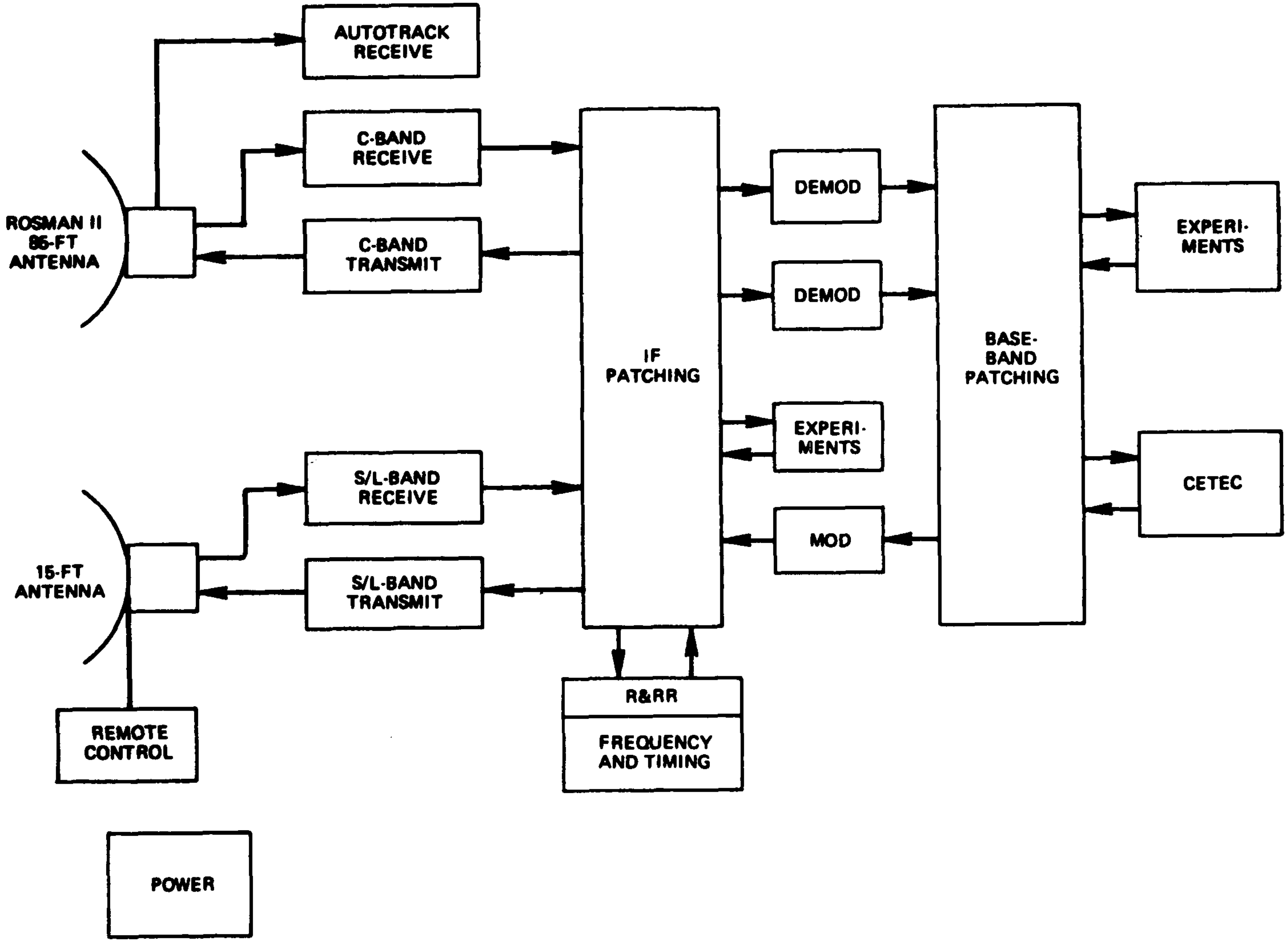


Figure 13-19. Rosman Ground Station Block Diagram

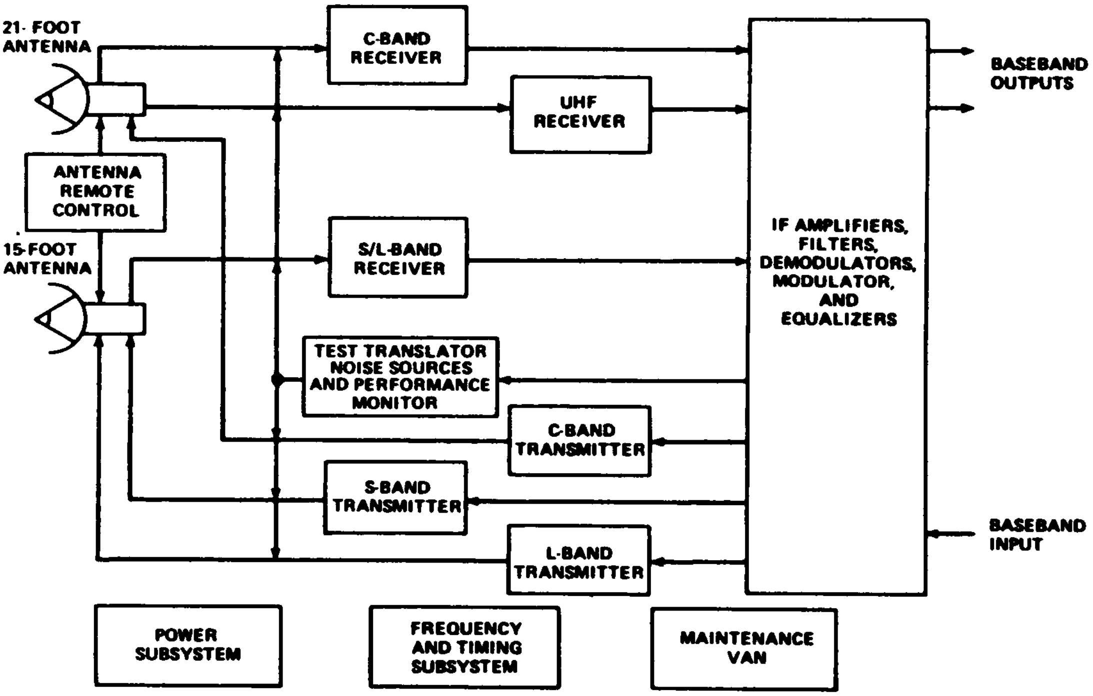


Figure 13-20. ATS-F and G Mobile Terminal System Block Diagram

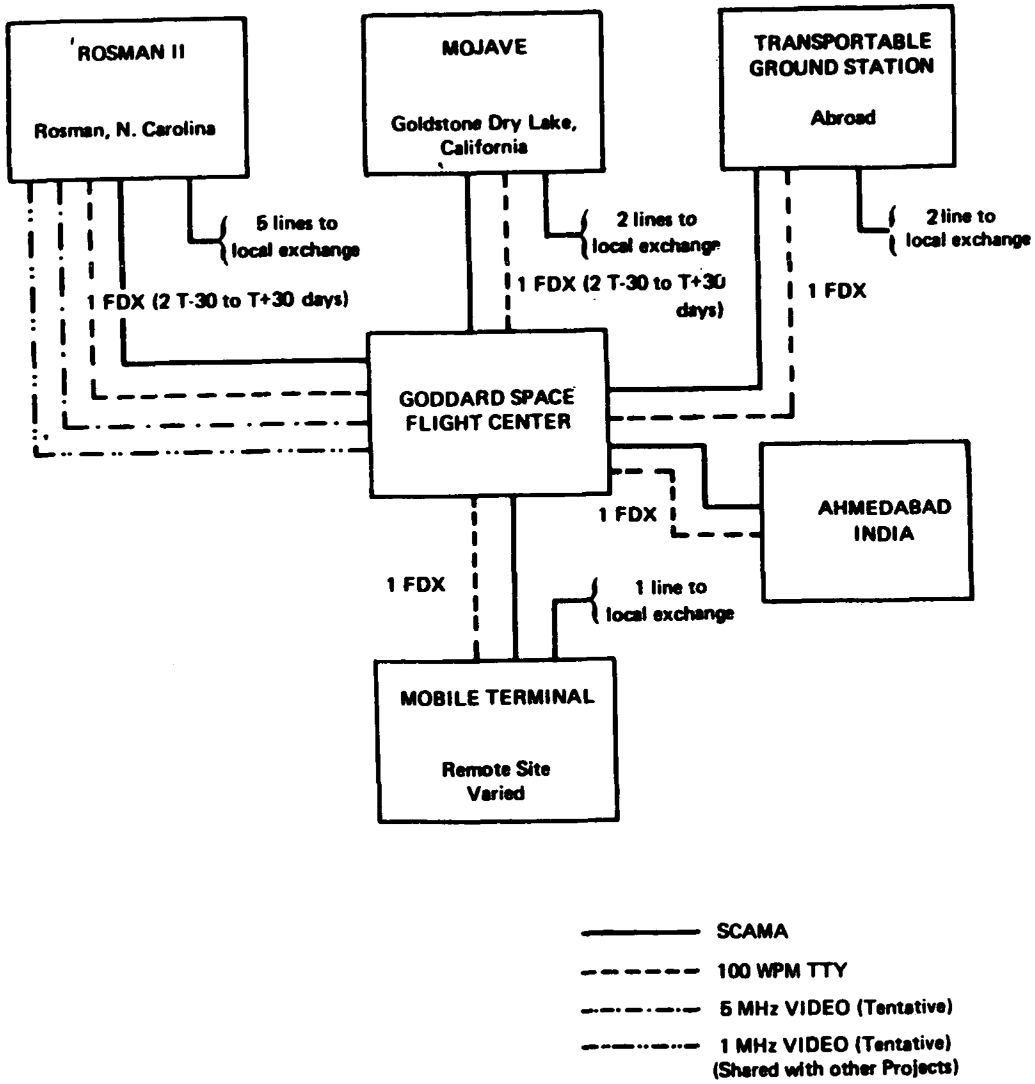


Figure 13-21. ATS Communications Landlines

- Tracking and Data Relay Experiment (T&DRE)
- Position Location and Aircraft Communications Experiment (PLACE)
- Instructional Television (ITV) Experiment
- Millimeter Wave Communications and Propagation Experiment (MWE)
- 13 and 18 GHz Propagation Experiment
- Radio Frequency Interference (RFI) Experiment

Other related experiments include Television Relay Using Small Terminals (TRUST), Very High Resolution Radiometer, Spacecraft Attitude Precision Pointing and Slewing Adaptive Control Experiment, Cesium Bombardment Ion Enginer, Laser Retroreflector, Educational Television, Radio Beacon, and Environmental Measurements.

13.4.4.1 Tracking and Data Relay Experiment(39)

The tracking and data relay experiment (T&DRE) will employ the ATS spacecraft to relay command, tracking, and telemetry data between ground stations and the low orbiting satellite NIMBUS-E. The systems concept associated with this experiment makes it possible to view the low orbiting spacecraft from an earth-synchronous satellite for durations nearly six times greater than are presently possible from a single ground station. Two such synchronous satellites could provide almost continuous coverage and would eliminate the need for tape recorders to store data on the low-orbiting spacecraft. The objectives of the experiment are, (1) to determine the extent to which the orbit of an earth-orbiting satellite can be established from another orbiting spacecraft, and (2) to develop the technology and demonstrate the feasibility of a data relay system.

To accomplish the first objective, four-way range and range-rate (R&RR) data will be obtained on the NIMBUS and relayed to the control ground station. The R&RR system uses a series of tones to modulate an RF carrier, the modulated carrier is transmitted from the ground station to ATS-F, then down to NIMBUS, up to ATS-F, and then back down to the ground station. The phase delay and doppler shift of the returning signal yields the total four-way range and cumulative range rate over the signal path from which the orbit of NIMBUS can be determined. The transmission link between the ATS spacecraft and the ground is at C-Band; between the ATS and NIMBUS spacecraft S-Band signals are employed.

T&DRE design objectives for uncertainties in raw tracking data are 4.0 meters in range and 0.6 centimeters/s in range rate. Based on the availability of long-arc tracking data, studies have shown that it should be possible to determine the NIMBUS orbit to within 50 meters in a total elapsed time of several hours. This constitutes a substantial improvement over ground-based tracking systems which typically require days and weeks of data processing to determine orbits which at best are known only to within hundreds of meters. Verification of these theoretical studies is considered the major scientific and application goal of the T&DRE.

To accomplish the second objective, that of developing the technology and demonstrating the feasibility of a data relay system, data from NIMBUS will be relayed via ATS-F. The data transmission capacity of the NIMBUS to ATS-F link is determined by the power of the transmitter and antenna gain available on the NIMBUS spacecraft; this capacity is more than sufficient to provide highly reliable transmissions of normal 4 kbps data from NIMBUS to the ground via ATS-F. To perform a more meaningful evaluation of T&DRE return link performance, test data will be transmitted at rates of 50, 100, 200 and 400 kbps. Signal detection at the ATS ground station will be done using a high-performance carrier tracking phase demodulator which will track the residual carrier component of the transmitted signal under all system doppler conditions.

13.4.4.2 Position Location & Aircraft Communications Equipment(39)

The Position Location & Aircraft Communications Experiment (PLACE) will obtain engineering data and provide practical experience to apply in developing an improved air traffic control system using a satellite operating in the aeronautical

L-Band. PLACE is designed to promote both improved methods for aircraft position location and two-way communications between the ground and many aircraft. There are two primary objectives:

- To prove the feasibility of synchronous satellite relay of multichannel two-way voice and digital data communications between participating aircraft and their ground control centers
- To investigate the feasibility and to evaluate the absolute and relative accuracy of position location techniques using a single satellite.

To accomplish the first objective the ground control facilities transmit, to the satellite, voice and data signals at C-Band. The ATS-F satellite receiver phase locks to these incoming signals which are then coherently converted to L-Band at 1500 MHz. These signals are transmitted to the aircraft transponder which phase locks to the L-Band signal. All stations are thus coherent with each other. Communication with a specific aircraft is accomplished by modulating that baseband channel assigned to that aircraft, the aircraft transceiver receives the composite signal but only demodulates its assigned channel within the baseband. Information from the aircraft is transmitted in the band from 1650 MHz to 1652 MHz. ATS-F receives this spectrum and, after preamplification, down-converts it to baseband in the IF amplifier. This baseband signal is used to phase-modulate a carrier which is transmitted back to the ground control facilities at C-Band. The ground station receives the carrier and recovers the aircraft's subcarrier signal.

To accomplish the second objective, unique surveillance and ranging tones will be used to modulate the carrier from the master control simultaneously with the voice and data signals. In ATS-F this signal is processed the same as the voice and data signals. All aircraft will transpond these tones, on a time-shared basis, back to ATS-F where they are relayed to the ground station for processing in real time to determine the location of each aircraft.

The inflight performance experiments will be conducted as a combined effort of Goddard Space Flight Center and the Federal Aviation Administration, and possibly other experimenters. The experiments will include actual aircraft flights to determine the effects of multipath, the ionosphere, noise environment, and geographic location on both the L-Band communication and position location links.

13.4.4.3 Instructional Television Experiment(39)

In the Instructional Television (ITV) Experiment, a television signal is relayed from the ground through the ATS-F spacecraft to small inexpensive earth terminals. Its purpose is to advance the state-of-the-art in space communications by combining the proven technology of satellite relay of wideband FM signals with the new technology of the ATS-F spacecraft's large aperture parabolic reflector in the geostationary orbit. The experiment will be conducted by the Government of India in cooperation with NASA. The Indian government will develop, provide, and maintain the ground receiver segment of the ITV experiment; and develop and use program materials that will carry out the instructional objectives of the experiment. Three different uplink stations at Ahmedabad, Bombay, and Delhi will be used during the experimental period. In isolated villages, standard TV receivers will be augmented with 10-foot diameter antennas for direct reception of the 860-MHz satellite radiated signal. In urban areas, the signal will be received with 15-foot diameter antennas and then rebroadcast from standard television transmitting stations.

The primary objective of the ITV experiment is to demonstrate the transmission of CCIR quality television signals to small inexpensive ground UHF receiving terminals. A secondary objective is to observe the effects of ionospheric dispersion on system performance as a function of electron density distribution, ground station location, and other system variables and to compare the observations with theoretical predictions.

13.4.4.4 Radio Frequency Interference Experiment(40)

The Radio Frequency Interference Experiment is designed to measure and evaluate the amount of mutual interference between communication satellite and terrestrial microwave relay systems at the shared common carrier frequency bands of 4 and 6 GHz. Although mutual interference can occur in two distinct modes, satellite-to-terrestrial or down-link mode and terrestrial-to-satellite or uplink mode, only the up-link interference mode at 6 GHz is presently being considered for the ATS-F experiment plan. The technical objectives of the up-link interference tests and measurements are:

- To determine the integrated interference power from all 6 GHz terrestrial sources sharing the common carrier band within the r-f field of view of the ATS-F satellite
- To establish practical G/T limits for satellites sharing the 6 GHz common carrier band
- To determine the geographical and frequency distribution of 6 GHz terrestrial sources sharing the common carrier band
- To establish the protection ratio of wanted-to-unwanted carrier power (C/X) required at the satellite receiver.

The RFI measurements will be performed using standard noise-power-ratio (NPR) tests with the earth terminal configured in a back-to-back loop through the satellite. The reference NPR measurements will be made using the earth coverage (low gain) antenna of the satellite with the main beam of the high gain (30-foot) antenna pointed to a quiet spot on the earth. In order to relate the interference levels to the wanted-to-unwanted signal ratios (C/X), the system carrier-to-noise and base-band signal-to-noise ratios will also be measured. The main beam of the high gain antenna will then be pointed toward a high density population area such as the north-eastern coastal region of the United States and the measurement technique repeated. This set of measurements now contains both the simulated desired signals (and basic noise) plus the real (unwanted) noise signals from all earth sources within the field of view of both satellite antennas. These unwanted noise signals, sharing the same common carrier frequency as the simulated system, can now be determined by remeasuring the system NPR, carrier-to-noise, and baseband signal-to-noise ratios. The measurements will be repeated to determine the interference noise levels as a function of source latitude, frequency, and time.

13.4.4.5 Millimeter Wave Communications and Propagation Experiment

The purpose of the Millimeter Wave Communications and Propagation Experiment (MWE) is to provide additional information about the millimeter wave propagation characteristics of the earth's atmosphere so that this portion of the electromagnetic spectrum can be utilized effectively for communications and scientific purposes. The propagation effects of interest in Space-Earth Millimeter Wave links include atmospheric attenuation (absorption and scattering), refraction, dispersion, and noise considerations. Associated with these effects is the propagation medium bandwidth limitation, as related to very wideband communications and data transmission systems.

The objectives of the MWE are to:

- Provide propagation characteristics of Space-Earth Links at 20 and 30 GHz under defined meteorological conditions
- Provide engineering data on Space-Earth Communications Links operating at 20 and 30 GHz under various meteorological conditions and modulation techniques
- Establish a model for the prediction of millimeter wave propagation effects.

To achieve these objectives the data obtained from the experiment will be analyzed using three general areas of investigation identified as Propagation Data Analysis, Communications Link Analysis, and Channel Correlation Analysis. The Propagation Data Analysis includes accumulation and cumulative comparison of the received signal effects versus such meteorological data as rainfall rate, weather radar return, radiometer temperature, and speed and direction, temperature, barometric pressure and refractive index. The Communications Link Analysis will permit a direct comparison to be made between such measures of link performance as carrier-to-noise ratio and bit error rate and the link parameters of modulation index, transmission rate, and carrier frequency. The Channel Correlation Analysis will study the channel characterization by two-dimensional correlation measurements to provide a measure of such important channel parameters as coherence bandwidth, delay spread, fading bandwidth, and coherence time.

To accomplish the objectives of the MWE, probing signals will be transmitted from the ATS-F satellite at 20 and 30 GHz to a number of earth terminals in three modes of operation: a multi-tone mode consisting of a coherently-related carrier and four tones on each side, all spaced at 180-MHz intervals; a carrier wave (CW) only mode at the frequencies of 20 and 30 GHz; and a communications mode designed to repeat the ATS-F 6 GHz uplink modulation by means of an IF cross-strap to the basic ATS-F communications transponder. As presently planned, the prime communication and propagation experiment station will be at Rosman, North Carolina, and will employ a 15-foot diameter parabolic antenna. Other sites located in the Washington, D.C., area including COMSAT, the Naval Research Laboratory (NRL), and one fixed and one transportable site being established for the NASA Radio Interference Propagation Program (RIPP) will participate and perform diversity testing. It is further expected that the Ohio State University's (OSU) multi-site capability developed under the ATS-F program will be utilized by RIPP for acquisition of additional diversity data. Experimental data will be recorded over a period of 6 months to provide information on seasonal and diurnal variations in propagation conditions at these frequencies.

13.4.4.6 The 13 and 18 GHz Propagation Experiment

The 13 and 18 GHz Propagation Experiment is designed to gather data on satellite signal attenuation at these frequencies caused by atmospheric hydrometeors at ground stations located in representative climatological areas. The data from this experiment will permit determination of minimum power margins needed in spacecraft communications systems operating at frequencies above 10 GHz. The technical objectives of the experiment are:

- To obtain the statistical distribution of signal attenuation at 13 and 18 GHz for widely varying climatic and geographical earth station locations
- To obtain, at 18 GHz, joint distributions of attenuation magnitude and duration as a function of earth station separation, climatology, and season
- To determine the feasibility of employing spot beam techniques at frequencies of 13 GHz or lower to overcome localized fading.

To accomplish these objectives 15 participating earth stations will be established throughout the eastern half of the U.S. and separated from each other by at least 160 km. Each of these stations will be capable of transmitting, to the ATS-F, two frequencies near 13.2 and 17.8 GHz. In addition, diversity operations will be established at three of these dual frequency terminals by locating in the vicinity of each three single frequency terminals transmitting near 17.8 GHz. The separation between the diversity terminals will be less than 40 km. The specific site locations for the transmitting earth terminals have not been selected as of mid 1971. The ATS-F transponder will receive these signals from the earth terminals, translate them to the 4 GHz band, and retransmit them to a single receiving terminal. The receiving terminal will receive the signals at 4 GHz, separate out the individual carriers, envelope detect them, and record the power of each carrier on magnetic tape. The duration of the experiment will be sufficiently long to permit a statistical comparison between the measured attenuations and the general meteorological parameters that are routinely collected by the weather bureau, such as rainfall rate, number of thunderstorm days, and total precipitation.

13.4.5 Operational Results

Since these are experimental satellites no operational traffic will be carried. Further, since the ATS-F launch (as of mid-1971) is not anticipated until about 1973 no operational experience has been accumulated on the satellites or on the planned ground complex.

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SECTION 14 - TACSAT

14.1 PROGRAM DESCRIPTION

The Air Force has the long-range objective to provide combat forces with satellite communications between mobile tactical terminals.(1) A series of prior successful satellite developments and experiments in the Lincoln Experimental Satellite Program (see Section 9) led to a contract in January 1967 for the development of a prototype version of an operational satellite, the Tactical Communications Satellite (TACSAT).

Specific objectives of the Tactical Satellite Communications (TACSATCOM) program are listed in Table 14-1.(2)(3)(4)

Table 14-1. TACSATCOM Objectives

Number	Description
1	Develop, test, and experiment with space and surface hardware in UHF and SHF bands.
2	Develop, demonstrate, and evaluate operational concepts for use with many mobile tactical terminals. These include problems of multiple access and power control.
3	Provide UHF voice link between the Apollo spacecraft and recovery aircraft, ships, and ground stations.

The active repeater satellite was launched into a geostationary orbit (see Table 14-2) and positioned over the United States where it has undergone a successful testing program that is continuing. TACSAT also performed very well in support of Apollo recovery operations. The experiment involved a number of mobile terminals, specifically developed for this program, that can be divided into UHF and SHF types and subdivided by platform type. These are listed in Table 14-3.(5)(6) In addition, various other existing terminals were used for the TACSATCOM experiments.

Table 14-2. Participating Spacecraft

Satellite		TACSAT
Manufacturer and Sponsor		Hughes Aircraft and AF Space and Missile Systems Organization
Launch Date		9 February 1969
Launch Vehicle		Titan IIIC
Orbital Data(*)	Apogee (mi)	22,397
	Perigee (mi)	22,331
	Inclination	0.6°
	Period	Approx. 24 hrs.
Status		Spacecraft Active

*At initial injection. Attitude control and stationkeeping produce changes.

The design of TACSAT represented some major advances in spacecraft technology. It is a prototype for new high power communication satellites as well as a test vehicle for tactical communications. Features include use of the gyrostat stabilization principle to allow more flexibility in spacecraft design, complexity of repeater design, development of a new 20-watt SHF TWT, and development of load-bearing solar panels. The design of families of UHF and SHF earth terminals based on extensive commonality of equipment represented another advancement. The feasibility of UHF and SHF communications through a synchronous satellite by small mobile earth terminals was demonstrated. Use of the tactical transmission system (TATS) frequency-hopping modem for multiple access and overcoming multipath interference was also demonstrated and the attendant problem areas investigated.

14.2 SYSTEM DESCRIPTION

The UHF and SHF tests were conducted on a half and full duplex basis. The TACSAT spacecraft is designed to operate in a variety of modes to accommodate the planned tests with terminals of different capabilities. Functionally, the communications subsystem consists of a UHF frequency translating repeater and a SHF

Table 14-3. Participating Terminals

Type	Sponsor	Frequency Band	Antenna
AN/TSC-80 Shelter Terminal	US Army Satellity Comm. Agency (USASCA)	SHF	4-ft diameter parabola
AN/MSC-54 Vehicular Terminal	USASCA	SHF	3-ft diameter parabola
AN/TSC-79 Teampack	USASCA	SHF	3-ft diameter parabola
AN/TRR-30 Alert Receiver	USASCA	SHF	1-ft diameter parabola
AN/ASC-14 Airborne Terminal	USASCA	SHF	2.75-ft diameter Cassegrain
AN/ARC-146 Airborne Terminal	AF Electronics Systems Div. (AFESD)	UHF	Blade; crossed dipole
AN/WSC-1 (V) Shipboard Terminal	AFESD	UHF	Large ship - 4-element array crossed dipole Small ship - single element crossed dipole Submarine - dipole; Helix
AN/TRC-157 Shelter Terminal	AFESD	UHF	Short backfire
AN/MSC-58 Vehicular Terminal	AFESD	UHF	Short backfire
AN/TRC-156 Teampack	AFESD	UHF	Short backfire
AN/TRR-32 Alert Receiver	AFESD	UHF	Monopole

frequency translating repeater, each capable of operating with selectable bandwidths from 50 kHz to 10 MHz. In addition, there are two crossover modes of operation, from UHF to SHF and from SHF to UHF.

The modes are under control of commands transmitted by the satellite control ground station. In keeping with the concept of mobile terminal simplicity, the satellite performs system frequency control by transmitting UHF and SHF beacon signals that are used as references for all transmit and receive function frequencies generated at the terminals, and for antenna pointing.

Table 14-4 shows the operating frequency bands at UHF and SHF for communication and T and C purposes.

Table 14-4. TACSAT Frequencies (MHz)

Purpose	Uplink	Downlink
SHF Communications	7977.5 to 7987.5	7252.5 to 7262.5
SHF Beacon	--	7298.5
UHF Communications	302.5 to 312.5	249.3875 to 249.8125
UHF Beacon	--	254.1
T&C	No data	No data

The UHF frequency band has three modes of operation, although all terminals do not use all modes. The modes are narrow-band FM voice, TATS, and broadcast alert. Table 14-5 presents the signal-processing techniques utilized in each mode.

The SHF communication band has a frequency plan that permits great versatility in modes of operation. The frequency plan is shown in Figures 14-1 and 14-2.(5) In Figure 14-1, the composite plan for utilizing the 10-MHz satellite bandwidth is shown. Figure 14-2 shows the specific carrier frequencies for Bands A and B, which are the 50-kHz and 1-MHz satellite operating bandwidths, respectively. The center of these bands is coincident with channel 3 shown in Figure 14-1.

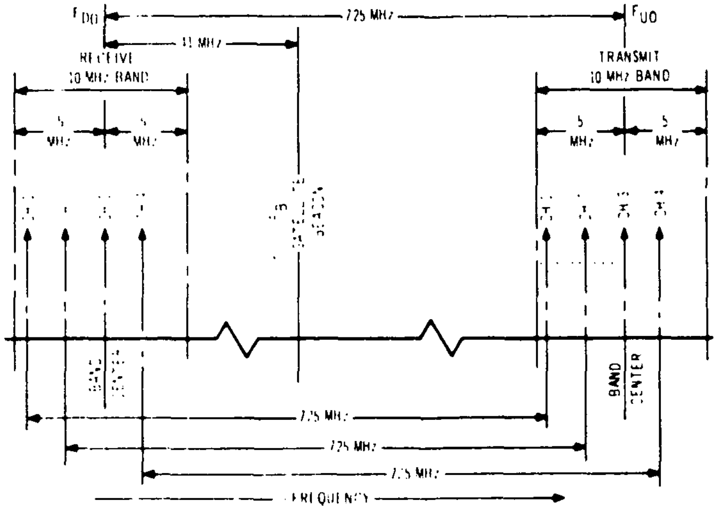

Figure 14-1. Ground Terminal RF Channel Frequency Plan

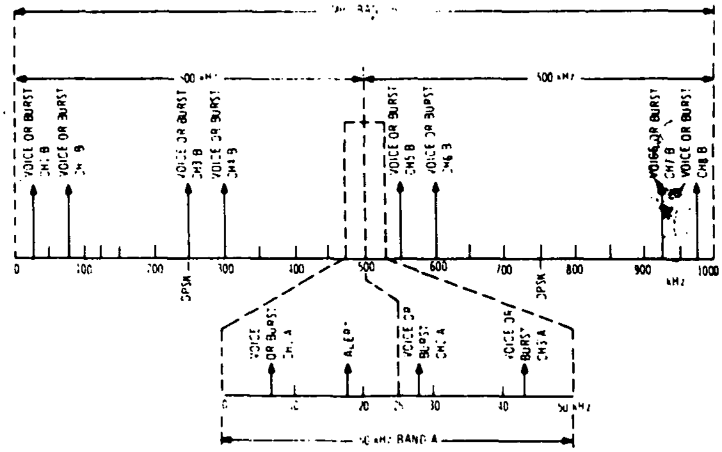

Figure 14-2. Typical Frequency Allocation Chart

Table 14-5. Signal Processing for UHF Modes

Mode	Narrow-band FM Voice	TATS	Broadcast Alert
Multiple Access	FDMA - 11 channels available	See Section 9.3	Only one warning transmission at any one time.
RF Modulation	FM	MFSK and frequency hopping	FSK
Ground Demodulator Performance	Threshold estimated at 10-dB C/N based upon employing conventional discriminators	Threshold is 8 dB for $P_E = 1x10^{-3}$	Threshold estimated at 10-dB C/N based upon employing conventional disc.
Ground Terminal* Receive Carrier-to-Noise	29.3 dB** 16.7 dB	24.1 dB*** 11.5 dB	21.7 dB**
Ground Receive Margin*	19.3 dB 6.7 dB	16.1 dB 3.5 dB	11.7 dB

*Higher value is for strongest UHF terminal pair and lower value is for weakest UHF terminal pair. All results for single access.

**Based on 15-kHz IF bandwidth.

***Based on 50-kHz detection bandwidth for high data rate TATS mode.

The SHF frequency band has four modes of operation, although all terminals do not use all modes. The modes are frequency modulation for voice or data, TATS, DPSK, and broadcast alert. Table 14-6 presents the signal-processing techniques utilized in each mode.

14.3 SPACECRAFT

Characteristics of the communications-related subsystem of TACSAT are described in Table 14-7. A block diagram of the communications repeater is shown in Figure 14-3. There are eight ground commandable modes corresponding to the

Table 14-6. Signal Processing for SHF Modes

Mode	FM	TATS	DPSK (288 kbps)	Broadcast Alert Warning
Multiple Access	FDMA	See Section 9.3	FDMA	Only one warning transmission at any one time
RF Modulation	FM	MFSK plus frequency hopping	DPSK	FSK
Ground Demodulator Performance	Threshold estimated at 6-dB C/N based upon employing phase-lock demodulator	Threshold is 8 dB for $P_E = 1 \times 10^{-3}$	Threshold is estimated at 6-dB C/N based upon employing phase-lock demodulator	No Data
Ground Terminal* Receive Carrier-to-Noise	26.7 dB** 11.4 dB	21.5 dB*** 6.2 dB	12.1 dB†	No Data
Ground Receive Margin*	20.7 dB 5.4 dB	13.5 dB -1.8 dB****	6.1 dB	No Data

NOTES: *Higher value is for strongest SHF terminal pair and lower value is for weakest SHF terminal pair. All results for single access.

**Based on 15-kHz IF bandwidth.

***Based on 50-kHz detection bandwidth for higher data rate TATS mode.

****TATS modem is not used by teampack (weakest link) at present.

†Based on 432-kHz IF bandwidth. Shelter terminal is only station equipped with DPSK modem.

Table 14-7. TACSAT Characteristics

Antennas		Type	UHF- Five element helical array for transmit and receive	SHF- Separate fin loaded horns for transmit and receive	T & C- Biconical Horn
		Number	One	One	One
		Beamwidth	Earth coverage (19°). Receive and transmit patterns not identical and not symmetrical.	Earth coverage (19°). Receive and transmit patterns not identical and not symmetrical.	Approximately 30°
		Gain	Receive peak -17.58dB minimum over coverage area -12.79dB Transmit peak -17.12dB minimum over coverage area -14.67dB	Receive peak -19.3dB minimum over coverage area -15.2dB Transmit peak -18.4dB minimum over coverage area -15.2dB	No data
Repeaters		Frequency Band	UHF	SHF (X-BAND)	
		Type	Hard limiting IF translation. Adjustable bandwidth and crossover to SHF repeater by command.	Hard limiting IF translation. Adjustable bandwidth and crossover to UHF repeater by command.	
		3dB BW	Straight through modes-50kHz, 100kHz and 425kHz;crossover modes 425kHz and 10MHz	Straight through modes- 50kHz, 1MHz and 10MHz;crossover mode 425kHz	
		Number	One with some redundancy	One with some redundancy	
	Receiver	Type Front End	Transistor preamplifier into down conversion mixer	Tunnel diode amplifier into down conversion mixer	
		Front End Gain	No data	No data	
		System Noise Figure	3.7dB	6.9dB	
	Transmitter	Type	16 parallel transistor amplifiers with summing of any number possible	3 TWTs - Any 2 summed in an output TWT switch.	
		Gain	No data	No data	
		Power Out	Carrier power (16 power amplifiers) -23.6dBW Beacon power (16 power amplifiers) -8.0dBW	Carrier power (2 TWTs) -14.6dBW Beacon power (2 TWTs) -0.2dBW	
		EIRP	Carrier -40.7dBW Beacon -25.1dBW	Carrier -33.0dBW Beacon -18.6dBW	
General Features	Stabilization	Type	Gyrostat - consists of spinning cylinder containing solar cells and a despun platform containing communications equipment. Bearings and slip rings used between the 2 sections. Nitrogen spinup system, hydrogen peroxide reaction jets and nutation damper are used.		
		Capability	Overall pointing capability is approximately 0.1 degree rms. However, intermittent nutation of about 1 degree occurs. Has been investigated and confirmed theoretically and can be corrected on future spacecraft.		
	Power Source	Primary	Solar array with 980 watts output		
		Supplement	Battery capacity-over 20 ampere-hours		
		Comm. Power Needs	No data		
		Size	Cylinder 25 feet long and 9 feet in diameter		
		Weight	About 1600 lbs. in orbit		

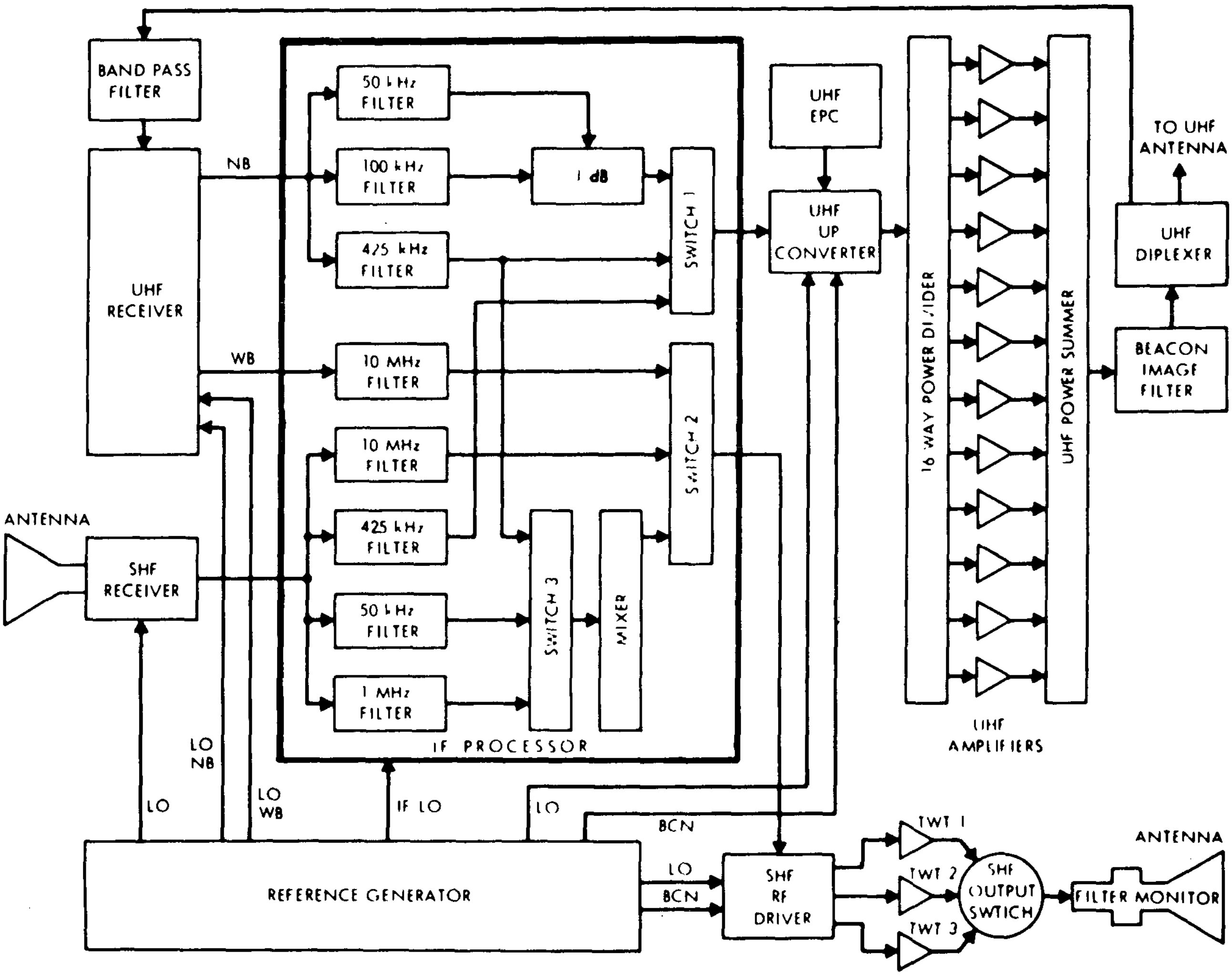

Figure 14-3. Communications Repeater Block Diagram

four filter bandwidths at each frequency band. Two of the modes represent cross-coupled operation between the UHF and SHF repeaters.

TACSAT is the first U.S. spacecraft stabilized with gyrostat technology.(4) This means that the satellite does not have to be spun about its maximum moment of inertia and thus frees the designer of onboard equipment from the moment of inertia design constraints.

The spacecraft consists of a large spinning cylinder within which is mounted a cone-shaped structure. A bearing assembly attached to the cone structure supports, on its housing, a despun platform containing antennas and communications and telemetry equipment. The spinning section contains solar cells, batteries, auxiliary telemetry, tracking, and command equipment, despin control electronics, the hydrogen peroxide propulsion system, and the nitrogen spinup system. A pendulum liquid damper is used for nutation damping.

The intent of the program was to provide experimental hardware for testing tactical satellite communications and, therefore, to be conservative in the spacecraft development approach. Space-proven technology was used wherever possible. However, the satellite requirements could not be met without some major advances in spacecraft technology. These included: use of the gyrostat stabilizing concept; intricacy of the repeater design; use of beryllium within the structure; development of a new 20-watt TWT; and development of load-bearing solar panels.

Biphase digital modulation beacon signals are associated with each of the repeaters. The modulating signal is a pseudorandom binary bit stream that may be used at the ground stations for synchronization or timing functions. In addition, the beacon frequency is used as a reference frequency for all tactical ground terminals.

The satellite UHF receiver processes the received RF signal, which varies in level from -150 to -105 dBW. The signal is split into two channels, one for narrowband and the other for wideband operation.

The wideband channel is downconverted to a band around 92.5 MHz, hard-limited and cross-coupled to the SHF transmitter. The narrow-band channel is downconverted to a band around 16.6 MHz, hard-limited and then coupled to the various filters. A ground commandable mode selection switch routes the desired channel output to the UHF transmitter.

The SHF received signal level varies from -150 to -85 dBW. The signal is downconverted to a band around 92.5 MHz. This signal is split into two paths, one of which is amplified in the 10-MHz channel and limited. The signal in the other path is downconverted to a band around 16.6 MHz for the SHF narrow-band channel modes. A ground commandable mode selection switch routes the desired channel output to the SHF transmitter.

14.4 EARTH TERMINALS

Two families of tactical terminals were developed for use in the two TACSAT frequency bands as listed in Table 14-3. Each family employed considerable commonality of equipment with terminal-specific equipment mainly in the categories of antenna, preamplifier, transmitter, and number and types of modems. Figures 14-4 and 14-5 show block diagrams of the UHF and SHF terminals, with all the possible modes of operation in each frequency band included.

As discussed previously, the satellite beacons at UHF and SHF were used as frequency references for all ground terminals. In the UHF receivers, the ground terminal reference oscillator was compared to the beacon and adjusted manually once a week. In the SHF receivers, a phase-lock loop was used to keep the ground terminal frequency standard locked to the beacon frequency. Major characteristics of the terminals are shown in Tables 14-8 and 14-9.

14.5 EXPERIMENTS

The experiments performed can be grouped under two general types: technical and operational. The technical experiments investigated satellite and ground terminal

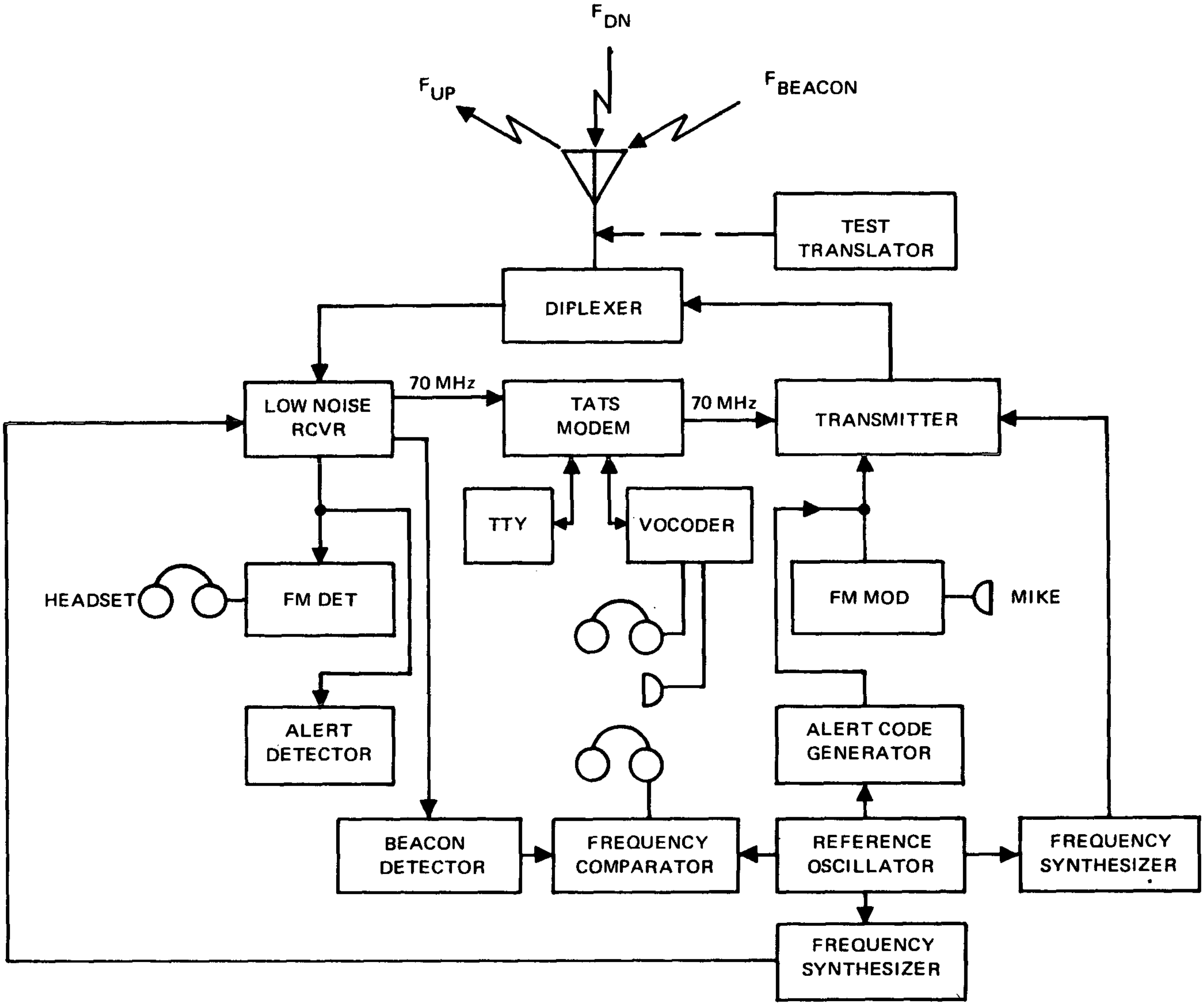

Figure 14-4. Block Diagram of TACSAT UHF Ground Terminal

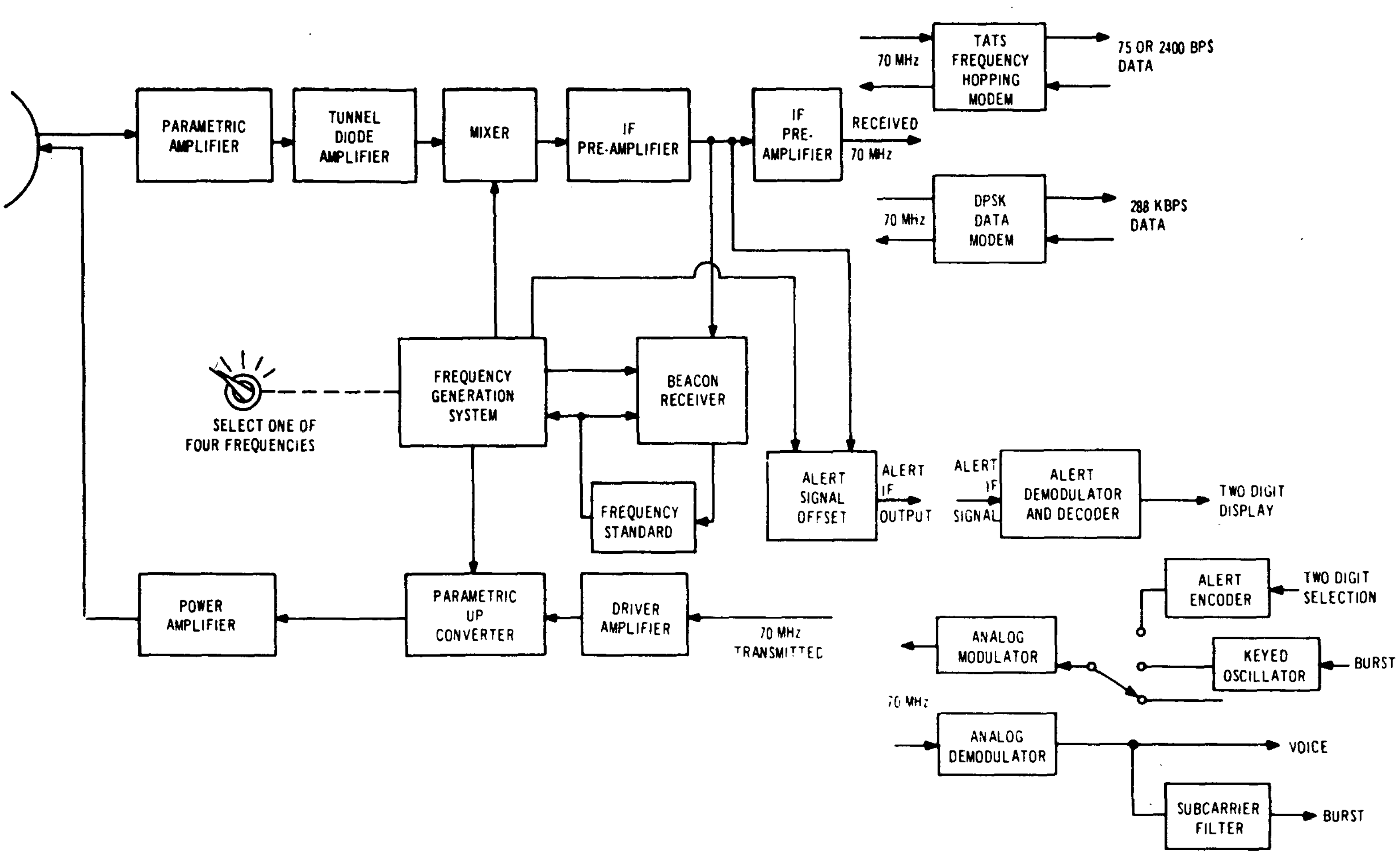

Figure 14-5. Block Diagram of TACSAT SHF Ground Terminal

Table 14-8. Characteristics of UHF Earth Terminals

	Terminal Feature	Terminal					
		AN/ARC-146	AN/WSC-1(V)	AN/TRC-157	AN/MSC-48	AN/TRC-156	AN/TRR-32
Antenna	Type	Blade for low elevation angles up to 30°; crossed-dipole for higher elevation angles	Large ship antenna-four element crossed dipole array over a ground plane. small ship antenna-single element crossed dipole over a ground plane	Short backfire; balun-fed crossed sleeve dipoles with front reflector and rear ground-plane reflector	Short backfire; balun-fed crossed sleeve dipoles with front reflector and rear ground-plane reflector	Short backfire; balun-fed crossed sleeve dipoles with front reflector and rear ground-plane reflector	Monopole
	Aperture Size	Blade-contained in structural members 5-1/6 in. by 13/16 in. by 8-5/8 in.; crossed dipole-contained in structural member 12-15/16 in. by 15-31/32 in. by 8-5/16 in.	Large ship-ground plane square 55-1/4 in. on a side; small ship-ground plane circular 38 in. diameter	Ground plane- 84 in. by 84 in.	Ground plane similar to AN/TRC-157	Ground plane similar to AN/TRC-157	11 in. long (1)
	Receive Gain	Blade-nominal 0dB Crossed-dipole-6dB at zenith	Large ship-12dB Small ship-7dB	13.5dB	13.5dB	8.5dB minimum	2 dB
	Efficiency	No data	No data	No data	No data	No data	No data
	Receive Beamwidth	No data	No data	40° minimum	40° minimum	Similar to AN/MSC-157, and -58	No data
Receive System	Type Preamplifier	Transistor (1)	Transistor (1)	Transistor (1)	Transistor (1)	Transistor (1)	Transistor (1)
	Bandwidth	RF-240 to 260MHz IF- 250kHz either side of RF channel center frequency (±0.5dB pts.)	RF-240 to 260MHz IF- 250kHz either side of RF channel center frequency (±0.5dB pts.)	RF-240 to 260MHz IF- 250kHz either side of RF channel center frequency (±0.5dB pts.)	RF-240 to 260MHz IF- 250kHz either side of RF channel center frequency (±0.5dB pts.)	RF-240 to 260 MHz IF- 250kHz either side of RF channel center frequency (±0.5dB pts.)	4kHz
	Noise Temperature	630°K	900°K (2)	530°K	530°K	600°K	Less than 440°K
Transmit System	Type Amplifier	No data	No data	No data	No data	No data	
	Bandwidth	RF-300 to 315MHz IF- amplitude response within ±5MHz of band center frequency: 1 to 10 watts - ±2.0dB, 10 to 100 watts - ±0.5dB, 100 to 1000 watts - ±0.8dB	RF-300 to 315MHz IF- amplitude response within ±5MHz of band center frequency: 1 to 10 watts - ±2.0dB, 10 to 100 watts - ±0.5dB, 100 to 1000 watts - ±0.8dB	RF-300 to 315MHz IF- amplitude response within ±5MHz of band center frequency: 1 to 10 watts - ±2.0dB, 10 to 100 watts - ±0.5dB, 100 to 1000 watts - ±0.9dB	RF-300 to 315MHz IF- amplitude response within ±5MHz of band center frequency: 1 to 10 watts - ±2dB, 10 to 100 watts - ±0.5dB	RF-300 to 315MHz IF- amplitude response within ±5MHz of band center frequency is ±1.0dB	No transmit capability
	Amp. Power Out	Continuously adjustable 1 watt to 1000 watts	Continuously adjustable from 1 watt to 1000 watts	Continuously adjustable from 1 watt to 1000 watts	Continuously adjustable from 1 watt to 100 watts	Two output levels selectable -2 watts and 20 watts	
Tracking	Type	None (3)	None-manual positioning aided by signal strength meter (4)(5)(6)	None-manual positioning aided by signal strength meter	None-manual positioning aided by signal strength meter	None-manual positioning aided by signal strength meter	None-manual positioning
	Accuracy	Not Applicable	No data on positioning accuracy	No data on positioning accuracy	No data on positioning accuracy	No data on positioning accuracy	No data on positioning accuracy
Total Performance	G/T (7)	Blade: - 28dB/°K Crossed dipole: -22dB/°K	Large ship: -17.5dB/°K Small ship: -22.5dB/°K	-13.8dB/°K	-13.8dB/°K	-15.8dB/°K	No data
	EIRP	Blade: 30 to 60 dBm Crossed dipole: 36 to 66dBm	Large ship: 42 to 72dBm Small ship: 37 to 67dBm	43.5 to 73.5dBm	43.5 to 63.5dBm	15dBm and 25dBm	No transmit capability
Polarization	Transmit Feed and Receive Feed	Blade - linear Crossed dipole-circular	Circular	Circular	Circular	Circular	Linear
Installation	Radome	Yes	None	None	None	None	None
	Type Facility	Airplane mounted	Shipborne	Transportable by truck or aircraft	Mobile-jeep mounted	Transportable-two or three men	Transportable-one man

Notes:
(1) Estimated from data available.
(2) Nominal value. Ranged up to 2000°K on some ships.
(3) Antennas switched depending on elevation angle.
(4) After positioning, antenna is slaved to ship's gyro-system to follow movement in azimuth plane
(5) On some large ships a dual antenna system, one forward and one aft of the ship's superstructure is used. The antennas are automatically switched to provide an unobscured satellite view.
(6) Submarine used UHF SATCOM antenna system employing a helix antenna (4 to 5dB gain) for high elevation angles and a dipole antenna (2dB gain) for low elevation angles.
(7) Derived value based on data available.

Table 14-9. Characteristics of SHF Earth Terminals

Terminal Feature		Terminal				
		AN/ASC-14	AN/TSC-80	AN/MSC-57	AN/TSC-79	AN/TRR-30
Antenna	Type	Cassegrain	Parabolic	Parabolic	Parabolic	Parabolic
	Aperture Size	33 inch diameter	48 inch diameter	36 inch diameter	36 inch diameter	12 inch diameter
	Receive Gain	33.1dB	36.5dB	33.5dB	33.5dB	23.8dB
	Efficiency	52% (1)	54% (1)	54% (1)	48% (1)	46% (1)
	Receive Beamwidth	3.5° @ 3dB pts.	2.4° @ 3dB pts.	3.4° @ 3dB pts.	3.4° @ 3dB pts.	10.3° @ 3dB pts.
Receive System	Type Preamplifier	Uncooled parametric amplifier followed by tunnel diode amplifier	Uncooled parametric amplifier followed by tunnel diode amplifier	Uncooled parametric amplifier followed by tunnel diode amplifier	Tunnel diode amplifier	Tunnel diode amplifier
	Bandwidth	10MHz	10MHz	10MHz	10MHz	10MHz
	Noise Temperature	(2) -325°K	230 - 315°K	(2) -325°K	(2) -920°K	896 - 915°K
Transmit System	Type Amplifier	No data	Klystron	Travelling wave tube	Travelling wave tube	
	Bandwidth	10MHz	10MHz	10MHz	10MHz	No transmit capability
	Amp. Power Out	1400 watts maximum (3)	Adjustable from 1.5 watts to 450 or 500 watts	80 to 100 watts maximum	Selectable 3 watts or 10 watts	
Tracking	Type	Modified conical scan plus gyros to remove attitude changes	None-manual positioning aided by signal strength meter	None-manual positioning aided by signal strength meter	None-manual positioning aided by signal strength meter	No data
	Accuracy	No data	Setting accuracy of better than ±0.5°	Setting accuracy of better than ±0.5°	Setting accuracy of better than ±0.5°	
Total Performance	G/T	(2) to 8dB/°K (1)	12.9 to 11.5dB/°K (1)	(2) to 8.4dB/°K (1)	(2) to 3.9dB/°K (1)	-5.7 to -5.8dB/°K (1)
	EIRP	95.6dBm (1) maximum	Adjustable from 69.3dBm to 94.0 or 94.5dBm (1)	83.5 to 84.5dBm (1) maximum	Selectable 69.3dBm or 74.5dBm (1)	No transmit capability
Polarization	Transmit Feed	Circular	Circular	Circular	Circular	Circular
	Receive Feed	Circular	Circular	Circular	Circular	Circular
Installation	Radome	Yes	None	None	None	None
	Type Facility	Airborne	Transportable by truck or aircraft	Transportable by small vehicle and accessory trailer for prime power supply	Transportable by two or three men	Transportable by one man

Notes: (1) Derived value based on data available.
(2) No data on lower limit.
(3) At power amplifier flange.

performance characteristics and system performance characteristics with the various modems employed singly and under multiple-access conditions. The operational experiments evaluated TACSATCOM performance during armed force operational exercises. In addition, there were various special tests employing TACSAT.

It was originally intended that technical experiments be performed before operational experiments but late equipment delivery necessitated that the two types be performed concurrently in some cases. Table 14-10 presents the major technical experiments together with the salient results obtained.

The operational experiments, conducted by the Navy, are termed a Fleet Operational Investigation (FOI) and are intended to investigate tactical concepts, operating procedures, and techniques. These overlapped, to some degree, technical experiments but were intended to determine effects of operationally imposed factors. The following categories of operational experiments were established:

1. Multiple-access capability
2. Operational techniques and procedures
3. Environmental influences on operational characteristics
4. Special purpose operational applications.

   The specific experiments were of three types: teletype, voice, and simultaneous voice and teletype.

Successful communications were maintained during typical maneuvers such as helicopter operations from a ship, destroyer maneuvers, aircraft launch and recovery operations aboard a carrier, and orbit of a C-130 aircraft. The FM voice mode was of high quality and very reliable. Secure digitized voice was more cumbersome and less reliable and intelligible than FM voice. However, it provides a high level of security. Secure teletype communication was excellent, provided synchronization was achieved. The probability of achieving synchronization was not as high as

Table 14-10. Technical Experiment Results

Experiment Type	Experiment Configuration	Nature Of Results Obtained
1. Limits Of Satellite Coverage Area	UHF and SHF shelter terminals in Maryland. UHF and SHF teampack terminals in various Pacific Island locations. Used FM voice channel employing special data modem	At UHF no degredation above 10 degree elevation angle. At lower angles signal deteriorated but data was obtained to at least 4 degrees. At SHF no representative data is available.
2. Parameters of TACSAT Operating Modes	Using CW transmission to measure parameters.	All test results agreed closely with theoretically predicted values or equipment specifications.
3. Terminal Antennas	Ground, ship, submarine and aircraft mounted antennas were tested.	Ground, ship and submarine antennas performed well. Data was obtained on performance of various antenna designs for fixed wing aircraft and helicopters.
4. Terminal Characteristics	Standard tests were used to determine the characteristics	Basically the terminals performed within nominal limits and met most of the electrical and mechanical requirements. Shipboard UHF terminals had considerably higher noise temperatures (up to 2000°K) than other UHF terminals (below 1000°K).
5. FM Voice Modem	Single satellite access voice link at UHF and at SHF	Both the UHF and SHF FM voice links performed satisfactorily and had sufficient system margin.
6. Single TATs Modem With Ground Terminals	Single transmitting modem configuration using every UHF, SHF and cross-strap mode capable of supporting TATs modem.	Under stable conditions modem performance via satellite is within 1dB (as determined by E_b/N_o vs. error rate) of back-to-back performance. Interference appears to be unavoidable in 10MHz bandwidth UHF uplink and is present in 500 kHz UHF band at times. Variations along the radio-wave propagation path also contribute to variations of several dB.
7. Single TATs Modem With Aircraft Terminal	Single transmitting modem configuration using UHF from ground transmitter to aircraft terminal. A ground receive terminal used to provide a reference data base.	In general, the tests demonstrated the capability of the TATs modem to operate satisfactorily with a aircraft communication system including its multipath environment. About 3dB maximum fade, with a period of about 3.5 seconds, observed at elevation angle to the satellite less than five degrees. When using blade antenna modem lost lock during 360-degree turns and with aircraft heading directly away from sub-satellite point. Using reference data base antenna system gain vs. elevation angle was calculated for the two onboard antennas.
8. Multiple TATs Modem	Up to five transmitting modems are combined, and transmitted. The test was performed using the satellite and in a back-to-back setup.	Unexpectedly poor performance was noted during several of the runs using the satellite relay. No results are reported for tests using the satellite. Back-to-back tests which eliminate on-orbit signal fluctuation, intermodulation, and possibly interference were performed. They gave information on limitations in use of address codes to prevent false acquisition and maintain adequate link margin.
9. DPSK Modem (288kbps)	6-channel PCM communications using TD-660 and the 288-kbps modem. SHF shelter terminal-to-SHF shelter terminal full duplex.	The 1-MHz satellite bandwidth was used with carriers spaced 500kHz apart. This resulted in spectrum overlap and test results showed that the present system will not support 6-channel PCM.

desired, due to a slight incompatibility between the TATS modem and the cryptographic equipment. The teletype mode was considered the most useful because of the large number of simultaneous accesses and security.

Complete random access to the satellite repeater is complicated by the necessity to control the uplink power of the users. Joint Service Monitor/Control experiments were performed to determine tradeoffs involved between a system that is too costly or unreliable (no control) and a system that operationally is too restrictive in use (complete control). The experiments were conducted using the TACSAT UHF mode. The primary control concept allowed complete random access for all 75-bps TTY, TATS users and for all alert message users subject only to EIRP restrictions. All other communications modes had to obtain prior approval from the real-time monitor/control agency before accessing the satellite. A schedule of priority in user communication modes was set up, and each service was allocated a portion of the satellite EIRP for nonrandom access communication modes. For power control, all UHF terminals were allowed one of two radiated power magnitudes, depending on the receiving and transmitting antenna gains. Experimental results were obtained that will be useful in the design of an operational system.

The development of different modulation and multiple-access techniques led to an investigation of the capability and compatibility of simultaneous use of different techniques. One experiment involved simultaneous use of TATS and FM/FDM with the TACSAT 500-kHz bandwidth UHF mode. Only certain TATS codes were used such that the TATS signal energy did not fall in a selected portion (81.6 kHz wide) of the repeater bandwidth. This allowed use of FM channels one through seven. Twelve low data rate TATS at 18 dBW per access, two high data rate TATS at 29 dBW per access, and three FM accesses at 31 dBW per access were used. Results showed a C/kT of 59 dB for the FM accesses and a test tone plus noise-to-noise ratio of 26 dB.

Members of the Avionics Laboratory of the ECOM conducted digital data transmission tests with TACSAT, using the TATS modem and the UHF-equipped helicopter.

The purpose was to determine the effects of the helicopter environment on the capability of the TACSAT system to relay digital data that could be extrapolated to simulate air traffic control data.

The power level was varied in steps and the digital error rates recorded. Aircraft engines and rotor and aircraft heading all affected the error rate vs. power level. However, the results showed that with sufficiently high transmitted power levels no errors occurred.

A series of tests using the USS Independence and NELC successfully demonstrated the feasibility of establishing automatic digital data links between remotely located participants.

The technical feasibility of transferring real-time ASW operational display data to and from a computer-equipped P-3 aircraft and a ground-based computer terminal was demonstrated. The experiment was performed at UHF, and the modulation was 2400-bps FSK because the TATS modems were unavailable.

A 2-way UHF-TDM communication mode used for air traffic control and carrier landing operated successfully through the TACSAT repeater.

Vocoder voice word intelligibility experiments using the TATS modem were conducted using TACSAT. The word intelligibility vs. $\frac{c}{N_o}$ values reached a maximum of 80 percent in some tests and 90 percent using other terminals.

Experiments were performed to determine degree of improved traffic flow in a star net using automatic control. Functions, such as addressing of members and assignment of channels, were performed by a computer installed at the net control station in Bedford, Massachusetts. Automatic Net Control units were installed at ground-based terminals and Eastern Test Range C-135 aircraft.

Although the experiments were considered preliminary and additional work remains, the results showed that automatic polling significantly improved traffic flow in star nets.

Experiments with terminals located in Panama were performed to determine the effect of tropical environment, particularly attentuation due to foliage, on UHF and SHF communications. The average attenuation at UHF in foliage was about 8 dB. At SHF no signal acquisition was obtained in the foliage. There were equipment problems directly related to temperature and humidity.

14.6 OPERATIONAL RESULTS

One of the objectives of the TACSATCOM program was the support of Apollo missions. TACSAT was used to support Apollo missions 10 through 13 in the following capacities.

1. Command and control of the Apollo Range Instrumentation Aircraft while enroute and at their staging bases.
2. Astronaut voice relay from the spacecraft to Mission Control Center in Houston during orbit, translunar injection burn, and recovery operations.
3. Following the aircraft transporting the lunar samples to Houston.
4. Recovery ship-to-shore communications(7).

High-power UHF ground-based transceivers were used and the aircraft and ships were equipped with TACSAT terminals. Communications during all operational phases were outstanding.

In addition, the TACSAT SHF communication band was used to provide satellite relay of live television coverage of the moon landing from the continental United States to Alaska. A modified army SHF terminal in Anchorage, Alaska, was used for this purpose.

From launch to June 1970 (latest date data is available), all major satellite subsystems performed well with two exceptions; a nutation anomaly and a drop in UHF ERP. It was found that the nutation angle, instead of decaying after separation, maintained a fairly steady level of about 1 degree. The nutation disappeared eventually but has since reappeared at intervals. A study indicated that certain rotor destabilizing forces are much larger than anticipated. These can be decreased by minor changes in the design of future spacecraft. The nutation angle is not large enough to affect communication system performance.

The UHF ERP dropped after several months from 38.4 dBW to 35.4 dBW ±2 dB with erratic variation about the mean. In addition, the transmitting antenna pattern changed significantly. Laboratory tests have demonstrated that all the phenomena observed could be caused by a short circuit to the ground plane or an open circuit on the first turn of any of the four outer helix antennas.

In addition, there have been three component failures, none of which has affected system operation; one of the four earth sensors is behaving erratically, one of the redundant decoders of the TT and C subsystem has produced extraneous outputs at times, and one SHF TWT has suffered a reduced power level, probably due to helix current changes caused by temperature sensitivity.

The UHF terminals developed for the TACSATCOM program were considered as advanced development models, while the SHF terminals were considered as feasibility models. Basically, the terminals met most of the electrical and mechanical requirements. The UHF equipment was fairly reliable, but the reliability of the SHF terminals and the TATS modem designed for TACSATCOM use were not as high as desired.

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SECTION 15 - SKYNET

15.1 PROGRAM DESCRIPTION(1)

In 1962, the first tentative studies were started to determine the feasibility of a satellite system to meet the United Kingdom's military needs. During 1963 and 1964 subsequent studies proceeded toward a goal of choosing an optimum system. Meanwhile, the U.S. was planning the deployment of its Interim Defense Satellite Communication System (IDSCS). The U.S. intended to devote the first year of IDSCS to testing, and the U.K. was invited to participate in the test phase.

The U.K. program to participate in the IDSCS testing consisted of building five earth stations and work began on these stations in 1965. Three, with 40-foot dishes, were designed by Marconi to have an operational capability within the SKYNET program. The fourth was designed and developed by the Admiralty Surface Weapons Establishment. This terminal was entirely experimental to test and confirm the basic design requirements for shipborne terminals. The fifth station - a mobile land terminal - was built by the Signals Research and Development Establishment. This terminal was also an experimental tool.

The first Marconi station was completed in the middle of 1966, and the other four stations were all working and participating in testing before the end of that year. During the testing a large number of R&D tests - typically, measurements of propagation conditions, path loss, earth station performance, and experiments on advanced modulation techniques - were accomplished to aid in the design of the SKYNET System.

In 1966 a Memorandum of Understanding was signed between the U.K. and the U.S. whereby the U.S. would build and launch two satellites required by the SKYNET Program. Philco-Ford was to build the satellites and the USAF Space and Missile System Organization (SAMSO), with technical support from the Aerospace Corporation, was to act as the procurement agent for the U.K.

Two satellites were to be launched in 1969-70, with one satellite acting as a backup for the other to provide a 5-year system capability. SKYNET I "A" was successfully launched into synchronous orbit in November 1969. SKYNET I "B" was launched in August 1970 and was a total loss when it failed to reach synchronous orbit. It was generally believed that the apogee kick motor used to circularize the orbit exploded. Table 15-1(1)(2)(3) summarizes launch and status information on the SKYNET satellites.

The U.K. has initiated procurement of additional higher power satellites from Marconi, U.K., which is working under license to Philco-Ford, U.S. The U.K. anticipates launching the first of the SKYNET II series in the summer or fall of 1972. SKYNET II will be similar in design to SKYNET I but will have considerably higher EIRP (20-watt TWT vs 3.0-watt TWT).

The operational requirements dictated the use of nine earth stations, five of which were to be stationary and four mobile. The stationary stations are in the U.K., Cyprus, Bahrain, Gan and Singapore. Although the stations are considered stationary, all stations with the exception of the U.K. station have been designed so that they can be moved if necessary. Two of the mobile stations are fitted in ships - the assault headquarters ships HMS Fearless and HMS Intrepid. The last two stations are mobile stations ashore. These two terminals are to be held in strategic reserve and deployed for contingency operations. Table 15-2(2)(4 through 9) is a summary of the terminals participating in the SKYNET Program.

The operational aims are to provide long distance strategic point-to-point digital communications and to meet selected tactical communication needs with the mobile terminals.

The central requirement of the system is for multiple access. It was deemed essential that any stationary terminal be able to communicate with any other, subject to the limitation of satellite effective radiated power and the amount of terminal equipment available for the link in question. In a real sense the central requirement goes beyond multiple access and includes an element of random access.

Table 15-1. Participating Spacecraft

Satellite		Skynet IA	Skynet IB	Skynet II
Manufacturer		Philco-Ford (U. S.)		Marconi (UK) under license to Philco Ford (U. S.)
Sponsors		United Kingdom Ministry of Technology, United Kingdom Ministry of Defense		
Launch Date		November 21, 1969	August 19, 1970	Estimated Summer/Fall 1972
Launch Vehicle		Augmented Thrust-Thor-Delta		
Orbital Data	Apogee (mi)	21,559.5*	No orbit Achieved	In procurement
	Perigee (mi)	22,791.7*		
	Inclination	less than 3°		
	Period (hrs)	approximately 24		
	Position (°E)	39 ± 3		
Status		Satellite is operating normally, one TWT has failed	Spacecraft lost due to Apogee kick motor failure	In procurement

*Value at initial injection. Subsequent stationkeeping maneuvers have produced changes.

Table 15-2. Participating Earth Terminals

Location	Ant. Diam. (ft.)	Utilization	Type	Date Installed	Manufacturer	Comment
UK (Oakhanger)	40	Static-operational traffic	I	1969	Marconi Ltd	Main station
Cyprus	40	"	II	1966	Marconi Ltd	
Singapore	40	"	II	1966	Marconi Ltd	
Bahrain	21	"	III	1969	GEC-AEI Electronics Ltd	Air Transportable
Gan	21	"	III	1969		"
Contingency	21	Contingency	IV	1969		Helicopter Transportable
Contingency	21	"	IV	1969		
HMS Fearless	6	Shipborne	V	1970	Plessey Radar Ltd	
HMS Intrepid	6	"	V	1970		
Christchurch	40	Testing	--	1966	Marconi Ltd	
Oakhanger	60	Telemetry, Command and Control	--	1969	Radiation Inc.	Same design as USAF satellite tracking station

Since this has been an operational system, its contributions to satellite communications technology have, by intent, been constrained. Nevertheless, it has been the first satellite communications system to provide an all-digital mode of operation. This was accomplished by employing spread spectrum multiple access for users of the 20-MHz channel of SKYNET. In implementing the system, operational spread spectrum modems and time-division multiplex equipment were developed and tested to meet specific SKYNET requirements.

15.2 SYSTEM DESCRIPTION

Based on the two sets of requirements for communications within the SKYNET System: (1) long distance strategic point-to-point digital communications, and (2) selected tactical communications with mobiles, it was decided that two independent satellite bands would be required (20 MHz and 2 MHz). Table 15-3(2)(3) gives the frequencies of the two bands.

Table 15-3. Skynet Frequencies

	2-MHz Channel (MHz)	20-MHz Channel (MHz)	Beacon (MHz)
Uplink	7976.02 to 7978.02	7985.12 to 8005.12	------
Downlink	7257.3 to 7259.3	7266.4 to 7286.4	7299.5

The satellite, with two independent bands, allowed tailoring of the modulation and multiple access to satisfy all system requirements. Other specified features of the system include providing reliability of communications under various conditions of weather, loading and interference, and providing flexibility in terms of interconnections and traffic carried.

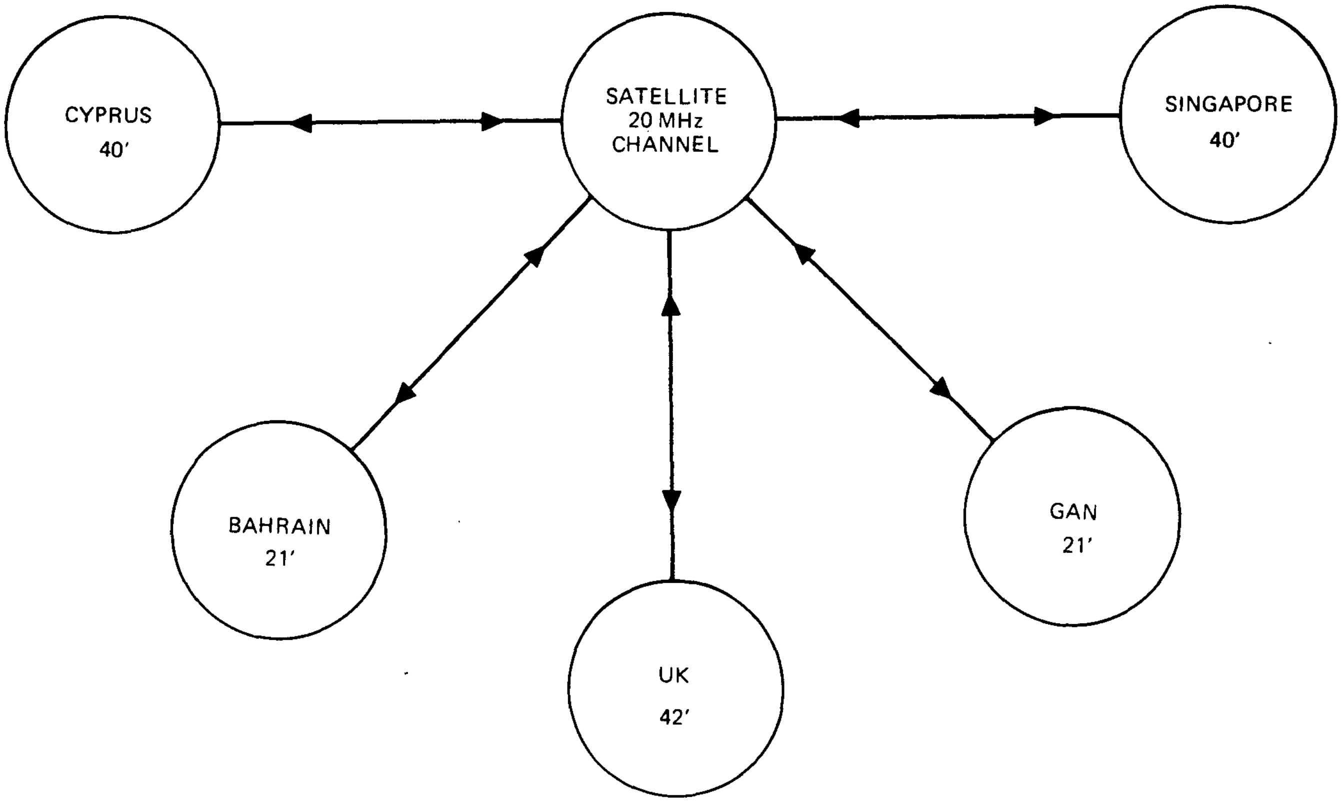
The various requirements of SKYNET communications led to a choice of terminals of varying capacities. In addition, the satellite antenna pattern was designed broadly enough for coverage from the United Kingdom in the West to Singapore in the Far East. The U.K.'s other areas of interest fall between these two extremes.

Traffic requirements were in the form of telegraphy, speech, and medium speed data circuits. It was decided that the strategic system would be designed specifically for digital signals at medium speed rates meeting the form of 75×2^n bits/second and would use the 20-MHz channel. Once the digital philosophy was adopted, a telegraph time division multiplex capable of assembling an assortment of synchronous and nonsynchronous telegraph signals of differing data rates into a single synchronous data stream was developed.

For the 20-MHz channel, SSMA was chosen over FDMA. This choice allowed frequency planning to be eliminated since SSMA transmissions could be superimposed to any desired degree, subject only to the normal capacity limit of the system. Additional advantages of this choice were (1) SSMA signals are virtually immune to intermodulation effects except for the small loss of useful power (approximately, 1 dB) due to the radiation of intermodulation, and (2) inherent jamming protection is provided. Figure 15-1(2)(10) indicates the SSMA links established among the fixed terminals operated in the 20-MHz channel. Table 15-4(2) summarizes the typical link performance in the 20-MHz band.

In the more difficult mobile terminal case, it was decided to use FDMA with FM as the basic modulation in the 2-MHz satellite band. In addition, the 2-MHz channel is used to provide engineering teletype orderwire facilities between fixed stations. Figure 15-2(2) indicates the FM links to be established in the 2-MHz band. Link-power limitations dictate that the mobile and shipborne terminals communicate only with a 40-foot station. Table 15-5(5)(6)(9) gives the FM performance characteristics of the demodulators used by the mobile and shipborne terminals.

Since reliability of communications is of paramount importance, adequate link margins were allowed in all cases for unpredictable losses due to weather, misalignments and equipment degradation. Estimates of 2 dB for excess path



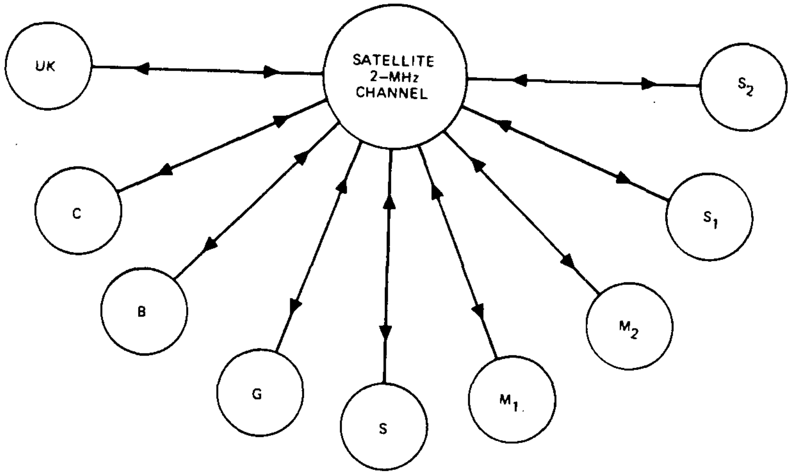
NOTE: ALL STATIONS CAPABLE OF COMMUNICATION WITH ONE ANOTHER

Figure 15-1. SKYNET SSMA Links

Table 15-4. Power Budget for Typical SSMA Links

Uplink	(1)	Received power at satellite (dBm)	-72.8
	(2)	Receiver noise level for a 2750 noise temperature (dBm/Hz)	-165.2
	(3)	Signal/noise ratio at receiver (dB) in 20-MHz bandwidth	19.4
Downlink	(1)	Received power (dBm)	-99.2
	(2)	SSMA noise density (dBm/Hz)	-169.2
	(3)	Thermal noise density (250°K) (dBm/Hz)	-174.6
	(4)	Total noise density (dBm/Hz)	-168.1
	(5)	Signal/noise power density (dB/Hz)	68.9
	(6)	Required signal/noise power density (dBm/Hz) using DPSK modulation with 2400-bps channel for error rate of 1 in 1000	42.0
	(7)	Intermodulation loss (dB)	1.0
	(8)	Margin (dB)	8.0
	(9)	Residue (dB) 5 - (6 + 7 + 8)	17.9
		This indicates that 62 digital streams of 2400 bps can be accommodated.	

UK, C, B, G, S USE NARROWBAND FOR FM/FDMA TELETYPE ORDER-WIRE OR TO COMMUNICATE WITH S_1, S_2, M_1, M_2



S_1, S_2, M_1, M_2 ONLY COMMUNICATE TO A 40 FOOT TERMINAL

UK = 40' TERMINAL AT OAKHANGER
C = 40' TERMINAL AT CYPRUS
B = 21' TERMINAL AT BAHARAIN
G = 21' TERMINAL AT GAN
S = 40' TERMINAL AT SINGAPORE

M_1 & M_2 = 21' CONTINGENCY TERMINALS
S_1 = 6' SHIPBORNE TERMINAL
S_2 = 6' SHIPBORNE TERMINAL

Figure 15-2. FM/FDMA Links (2-MHz Channel)

Table 15-5. FM Demodulator Performance

FM	Maximum Baseband Frequency (kHz)	Peak Frequency Deviation (kHz)	Equivalent Carrier BW (kHz)	Carrier BW (dB/Hz)	Threshold of Conventional Discriminator C/N_o (dB/Hz)	Threshold of Phase-Lock Loop Used in SKYNET System (dB/Hz)
	4	4	16	42	52	50.7
		7.5	23	43.6	53.6	52.1
		13	34	45.3	55.3	53.3

attenuation and $110^{o}K$ for excess noise are used for earth stations in the U.K. and Singapore that are served by a suitably disposed geostationary satellite. (11) Losses are likely to be somewhat greater in the case of an earth station with a radome because of the attenuation of a water film on the surface. Reductions in signal/noise ratio of up to 6 dB have been observed with a radome under conditions of very heavy rain. Margins must be allowed for both "up" and "down" links if a local rain squall is not to upset the power balance of the entire system. Total margin required was 7 to 8 dB.

Control, as exercised in the SKYNET System, is of three different types: control of the spacecraft, the earth station complex, and the traffic. Accurate control of the spacecraft is essential to successful operation of the communication system. It is necessary to maintain spacecraft position and attitude by on-board control systems and to switch spare repeater subsystems if malfunctions occur. The control is exercised at Oakhanger by the Telemetry and Command Station on the basis of computations performed at Royal Aircraft Establishment Farnborough.

Engineering control of the communication system is exercised from the Master Engineering Control Centre (MECC) collocated with the Type I earth station at Oakhanger. The status of each earth station in the system is displayed and instructions on power levels, frequencies, and operating modes to be used as well as positional information relating to the spacecraft, are broadcast over engineering orderwire circuits from this station.

Traffic control takes place at speech and telegraph facility control centers which are remote from the earth stations and connected to them by telephone lines.

15.3 SKYNET SPACECRAFT

Spacecraft characteristics for the SKYNET satellites are displayed in Table 15-6.(2)(3) A simplified block diagram depicting the communications configuration of the satellite is shown in Figure 15-3. (3)

Table 15-6. SKYNET I Satellite Characteristics

ANTENNAS	Type	X-Band mechanically despun	UHF array for TT&C with redundant UHF transponders and command/telemetry processing equipment
	Number	One	Two
	Beamwidth	19"	Essentially omni-directional
	Gain (dB)	18.5	0.7
REPEATERS	Frequency Band	X-Band	
	Type	Hard-limiting dual channel	
	1 dB Bandwidth	20-MHz and 2-MHz channels	
	Receiver		
	Type Front End	Down-conversion mixer into linear amplifier*	
	Front End Gain	No Data	
	Noise Figure	2750°K (10.2 dB)	
	Transmitter		
	Type	Redundant TWT	
	Gain	No Data	
	Power Output (dBm)	31.0	
	EIRP (dBm) peak of beam	49.5 (in each channel)	
GENERAL FEATURES	Stabilization		
	Type	Spin 90 rpm 5 years	
	Capability (stationkeeping)	+ 3" for 5 years	
	Power Source		
	Primary	Cylindrical array of silicon solar cells, capable of providing 97 watts of prime power throughout 5 years of orbit life	
	Supplement	Two redundant 16-cell nickel cadmium batteries for operation during eclipse (6 AH per cell)	
	Communication Power Needs (watts)	64	
	Size (inches)	54 diameter 60 high	
	Weight (lbs.)	Launch 535, on orbit 280	

*Dynamic range (a) 20-MHz channel 90 to -45 dBm
(b) 2-MHz channel 100 to 45 dBm

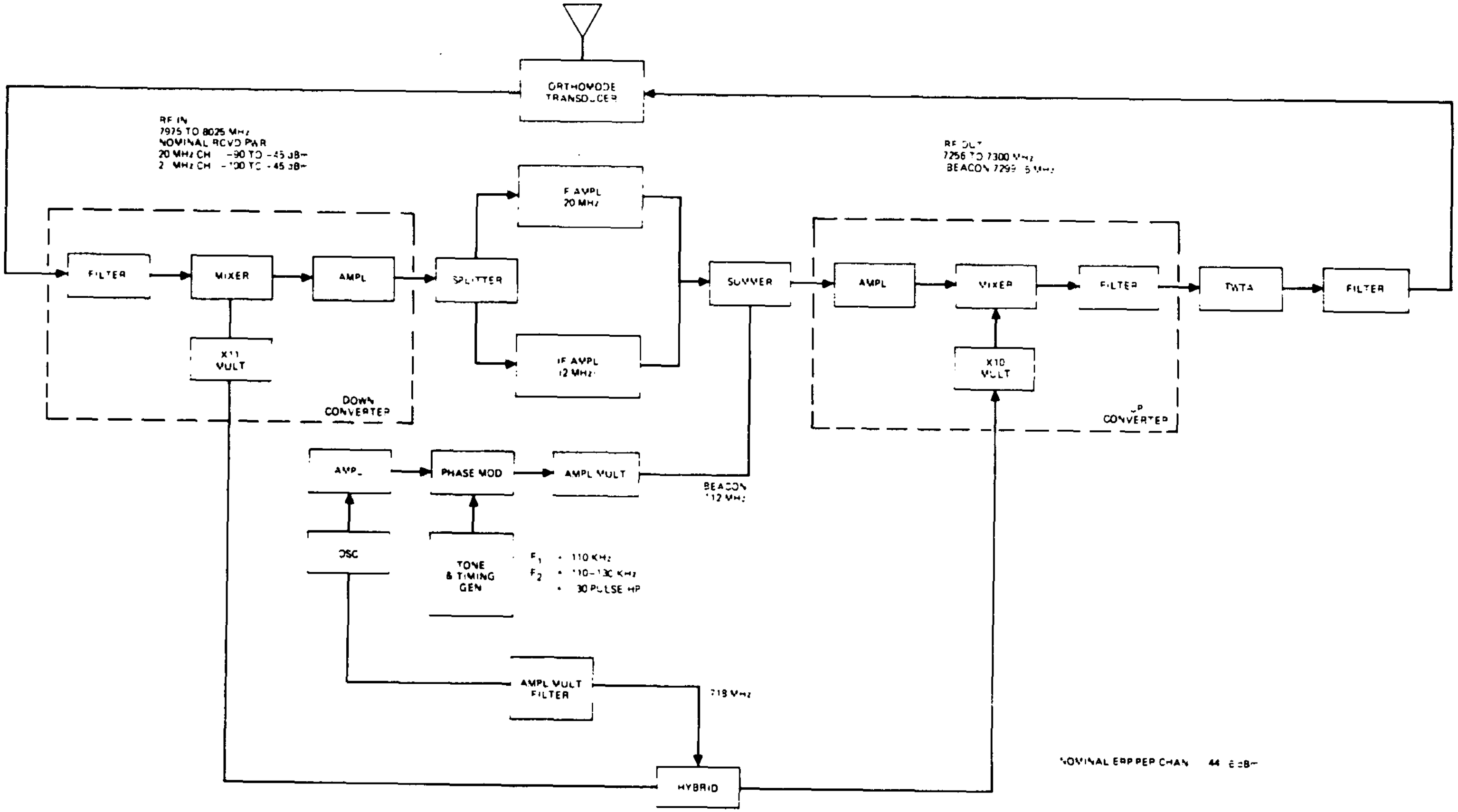


Figure 15-3. Communications Transponder

The Communications Subsystem (shown in Figure 15-3) receives, translates in frequency, amplifies, and retransmits X-band signals. Two channels, 20- and 2-MHz bandwidth (1 dB), are provided. The total output power is divided equally between the two channels. Figure 15-3 indicates the single thread path. The complete equipment redundancy and cross-strapping which is employed to achieve reliability is not shown. Selection of either set of communications equipment, operating with either traveling wave tube amplifier, is accomplished by ground command.

The received signal is: (1) isolated by polarization diversity in the orthomode transducer, (2) downconverted to IF, (3) split into separate channels for amplification and hard-limiting, (4) recombined and up-converted to output frequency, (5) amplified to output power in the TWT, and (6) introduced into the communications antenna through the orthomode transducer. A signature tone timing signal is frequency modulated on the beacon carrier and introduced into the communication band in the channel summer.

The communications antenna consists of the RF assembly and the motor drive assembly (MDA). RF energy is circularly polarized, collimated into a plane wavefront and focused upon the flat plate reflector. The beam axis, reflected through 90° angle, is continuously directed toward the subsatellite point by the despun motion of the radiating aperture. A rotary choke joint at the lower end of the MDA housing permits efficient transfer of energy between the spacecraft fixed and despun waveguide sections. A hydrazine reaction control subsystem provides for attitude control and stationkeeping and, in addition, would allow the relocation of the SKYNET satellite to a more optimum location if system requirements change.

Three redundant antenna pointing control systems, earth horizon sensors, sun angle sensors, and a backup earth to satellite command link, are provided. A UHF subsystem, also redundant, is provided for telemetry tracking and command services (TT&C).

Electrical power is supplied to the satellite from solar arrays. Batteries are also provided for eclipse operation. Redundant power control units are used to provide regulation, battery charging and load control.

15.4 GROUND TERMINALS

The major characteristics of the ground terminals employed in the SKYNET system are shown in Table 15-7. (4)(5)(6)(9)

15.4.1 Type I & II Earth Terminals

The Type I station at Oakhanger is the master station of the SKYNET system. Most electrical design features, apart from redundancy, are commonly used with the Type II stations to simplify training and maintenance support.

The Type I antenna is a 42-foot diameter parabolic reflector with a Cassegrain feed system mounted on a fully steerable azimuth elevation mount installed on a three-legged gantry.

Azimuth rotation is accomplished by two dc motors driving in a counter-torque configuation to minimize backlash. The elevation drive consists of two mechanically coupled recirculating ball screws.

The Type II antenna mount is fundamentally different. To meet the original air transportability specification, a double walled inflatable radome was used with a non-orthogonal mount. This mount allowed the antenna to be more readily demountable into pieces of a size suitable for the aircraft and also produced a smaller swept volume than a standard azimuth-elevation mount, thus requiring a smaller radome.

The profile of the Type I main and subreflectors has been shaped from the paraboloid to ensure a nearly uniform illumination of the main reflector. By this technique, overall antenna efficiency and gain were increased. The composite four-horn feed consists of four horns, four circular polarizers and diplexers, transmit power dividers and static split combination networks.

Table 15-7. Characteristics of Skynet Earth Terminals

	TERMINAL TYPE	I	II	III	IV	V
ANTENNA	Type	Cassegrain (paraboloid reflector)	Cassegrain (paraboloid reflector)	Cassegrain (shaped surface)	Cassegrain (shaped surface)	Cassegrain (paraboloid reflector)
	Mount	Az. Elev.	non orthogonal	Az. Elev.	Az. Elev.	three axis
	Aperture Size (ft)	42	40	21	21	6
	Receive gain (dB)	56**	56	52	52	40.5
	Efficiency (%)	54*	50*	73	73	63*
	Receive Beamwidth (°)	0.23*	0.24*	0.4	0.4	1.6*
RECEIVE SYSTEM	Type Preamplifier	Two stage uncooled parametric	Two stage uncooled parametric	Two stage liquid nitrogen cooled parametric	Two stage liquid nitrogen cooled parametric	Ambient temperature parametric
	Gain (dB)	30	30	30	30	20
	1 dB Bandwidth (MHz)	50	50	50	50	50
	Tuning Capability (MHz)	500	500	500	500	500
	Noise Temperature (°K)	120	120	50	50	220
TRANSMIT SYSTEM	Type Amplifier	Klystron	Klystron	Klystron	Klystron	Klystron
	Bandwidth (MHz)	50	50	50	No Data	No Data
	Amp Power Output (kW)	20	20	5	5	5
TRACK-ING	Type (monopulse)	Automatic	Automatic	Automatic	Automatic	Automatic
	Accuracy (3σ)	0.05	0.05	0.09	0.09	0.15
FREQ. CONTROL	Long Term (1 yr)	1n10^7	1n10^4	1n10^7	1n10^7	No Data
	Short Term (1 s)	1n10^9	1n10^9	1n10^9	1n10^9	
TOTAL PERF.	Sys. Noise Temp. °K	250	230	120	120	300
	G/T	32.0*	32.4*	31.2***	31.2***	15.7*
	EIRP (dBW)	100*	100*	90*	90*	78*
POLARI-ZATION	Transmit Feed	Right Hand Circular	Right Hand Circular	Right Hand Circular	Right Hand Circular	Right Hand Circular
	Receive Feed	Left Hand Circular	Left Hand Circular	Left Hand Circular	Left Hand Circular	Left Hand Circular
INSTAL-LATION	Radome	Yes	Yes	No	No	No
	Type Facility	Fixed	Fixed but movable	Fixed but air transportable	Mobile Helicopter transportable	Shipborne

Calculated from other measured parameters

** Actual gain is 57 dB. 1 dB is lost in cable runs that allow maintenance and repair on paramps while station is still operating. This was done to accomplish high reliability.

*** G/T of 28.8 dB when parametric amplifier is run at ambient temperature.

The Type I and II station receiving systems are similar except that in the Type I station it is duplicated, with a remotely controlled waveguide changeover switch in the signal path. A simplified diagram of the essentials of the communications chain is shown in Figure 15-4.(4)

The low noise receiver is preceded by a "waffle-iron" type low pass filter giving 93 dB of protection against the transmitter signal spaced only 500 MHz away.

The duplicated transmitter subsystem is designed to provide accurate control of power output from 100 W to 20 kW, with control of power sharing between the fm and SS paths. Channel combining is performed at shf to avoid the risk of fm and spread spectrum intermodulation that could arise with a common upconverter stage.

The operational requirements of frequency flexibility and high stability are met by deriving the local oscillator signals from frequency synthesizers in the 100- to 150-MHz band locked to a high stability (1 part in 10^{10}) Master Oscillator at 1 MHz.

The Type I and Type II stations have a duplicated Master Oscillator and one spare synthesizer (as a compromise between full redundancy and economy) for the three operational LO sources (receive, SS, and fm transmit).

15.4.2 Type III and IV Earth Terminals

The SKYNET Type III and IV earth terminals have 21-foot diameter antennas. Both types of stations are identical, but the Type IV is helicopter transportable, where the Type III is only air transportable by standard aircraft. The simplified block diagram of the signal paths in the Type III and IV earth terminals are shown in Figure 15-5.(5)(6) A five-horn static split system is used for tracking and all the microwave equipment is mounted on the back of the antenna disk. The antenna mount is a simple two-axis elevation/azimuth system.

The received signals pass through a diplexer and a band-stop filter to reject transmitted frequencies, and then into a two-stage liquid nitrogen-cooled parametric

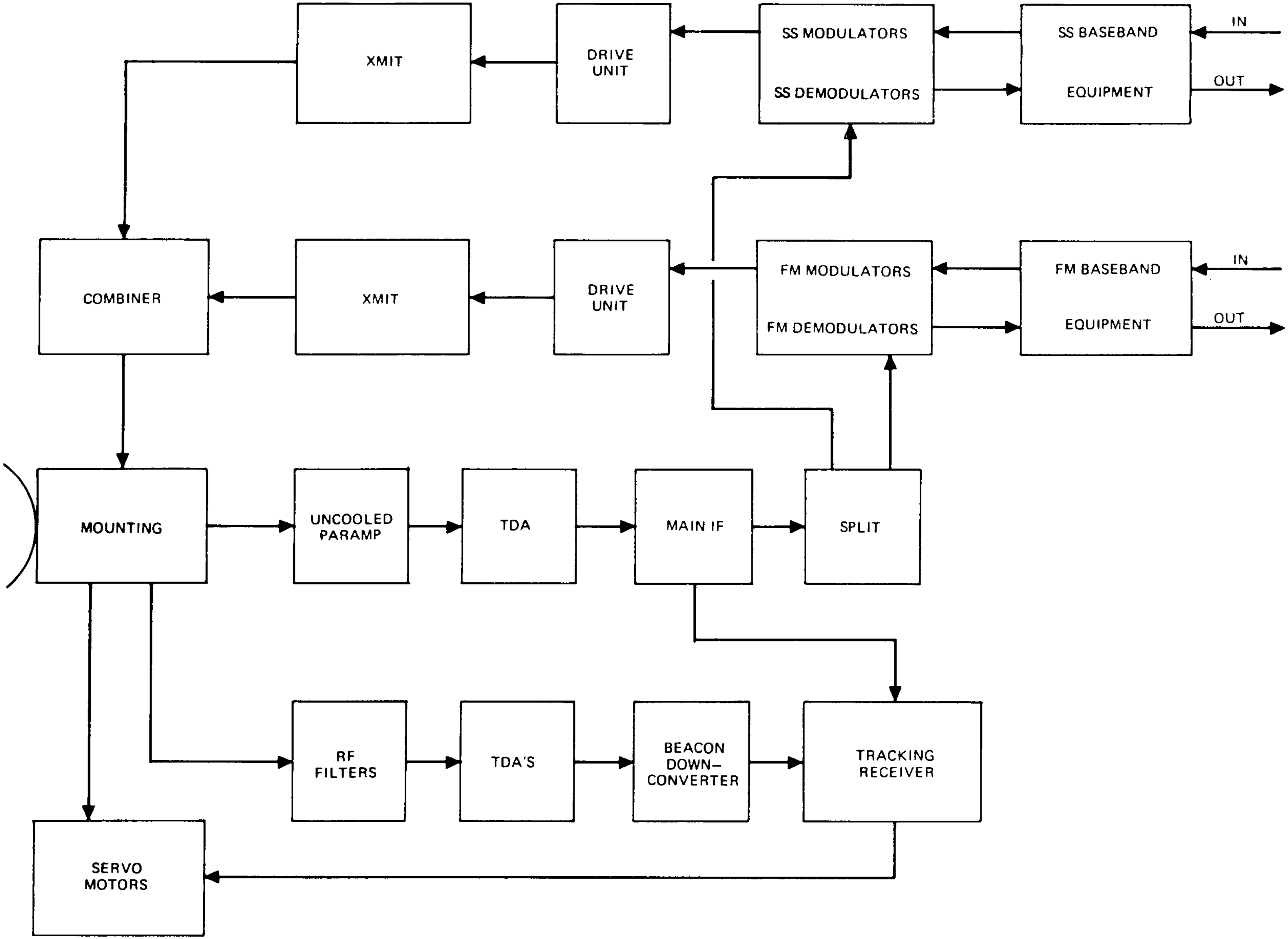


Figure 15-4. Type I and Type II Simplified Block Diagram

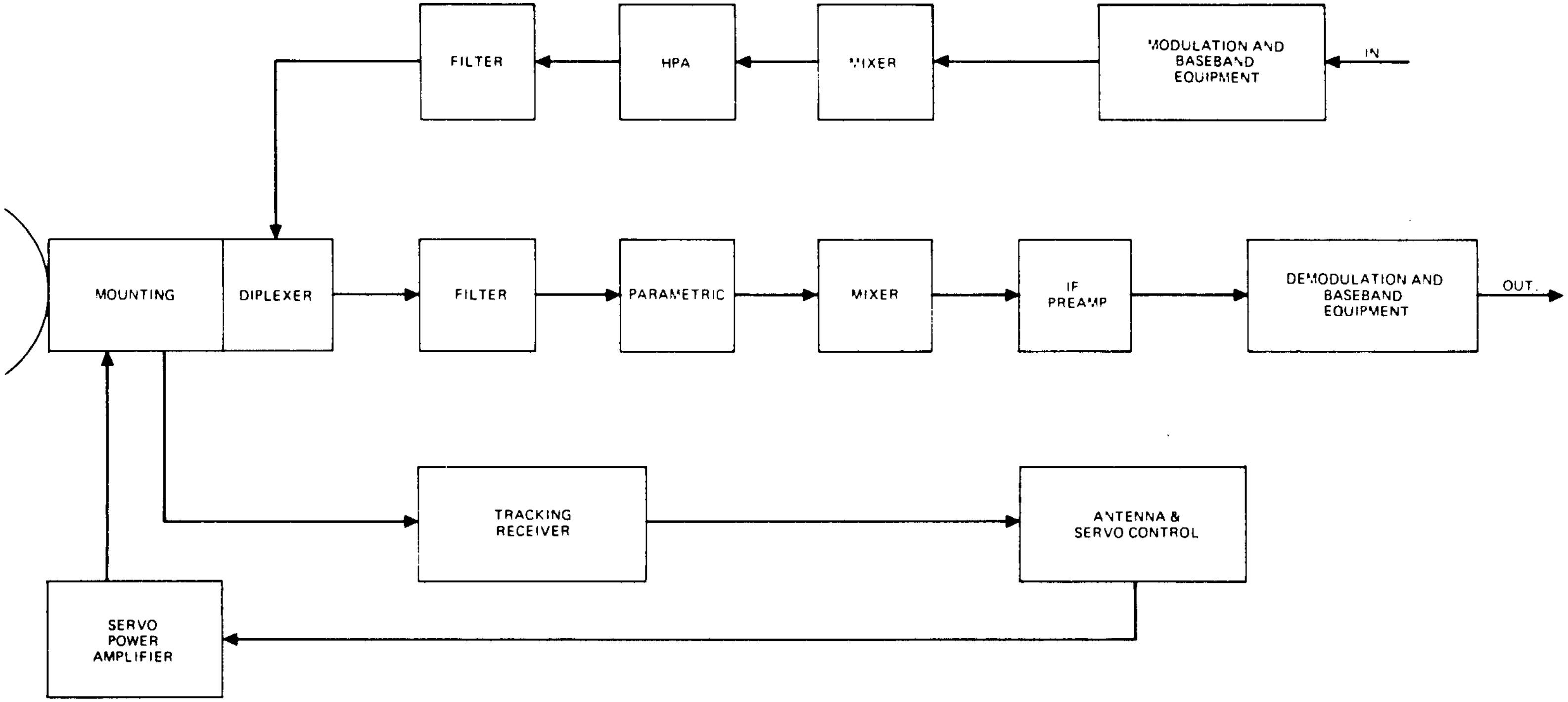


Figure 15-5. Type III and Type IV Simplified Block Diagram

amplifier. Subsequently, they pass to a mixer/IF preamp combination and then to an IF amplifier where the FDM and spread spectrum signals are separated.

The combined uplink IF signal is fed into the transmitter unit. There it is converted to the final frequency, amplified in an intermediate power amplifier, followed by a higher power, liquid-cooled, five-cavity klystron (VA925E).

Frequency control is the same as in the Type I and II terminals.

15.4.3 Type V Shipborne Terminal

Figure 15-6(9) illustrates the essentials for the Type V terminal.

Information signals to be transmitted by the terminal are passed through the baseband equipment to the exciter, which produces a low-power microwave carrier modulated by the baseband signal. The microwave signal is amplified to a level of a few kilowatts and fed to the waveguide system and the antenna.

The waveguide system contains the necessary filter and diplexers for separating received from transmitted signals. It also contains a monopulse comparator for deriving angular misalignment signals which are fed to the tracking receiver. Received communications signals are first amplified in a low-noise preamplifier. After down-conversion to a suitable intermediate frequency and filtering to select the wanted carriers, they are then demodulated in the receivers. The latter feed the baseband equipment with outputs to the user equipment (telephone, telegraph, etc.).

Stabilization of the antenna beam is by reference to the gyro assembly, which provides an inertial reference pointing angle. Any misalignment of the beam with respect to this reference is sensed by the gyro pickoffs, and corrections are applied by power servo and drive motors. The inertial reference point angle is updated by signals derived from the tracking receiver so that the beam always points at the satellite. Manual pointing data for initially acquiring the satellite may also be fed to the gyro assembly.

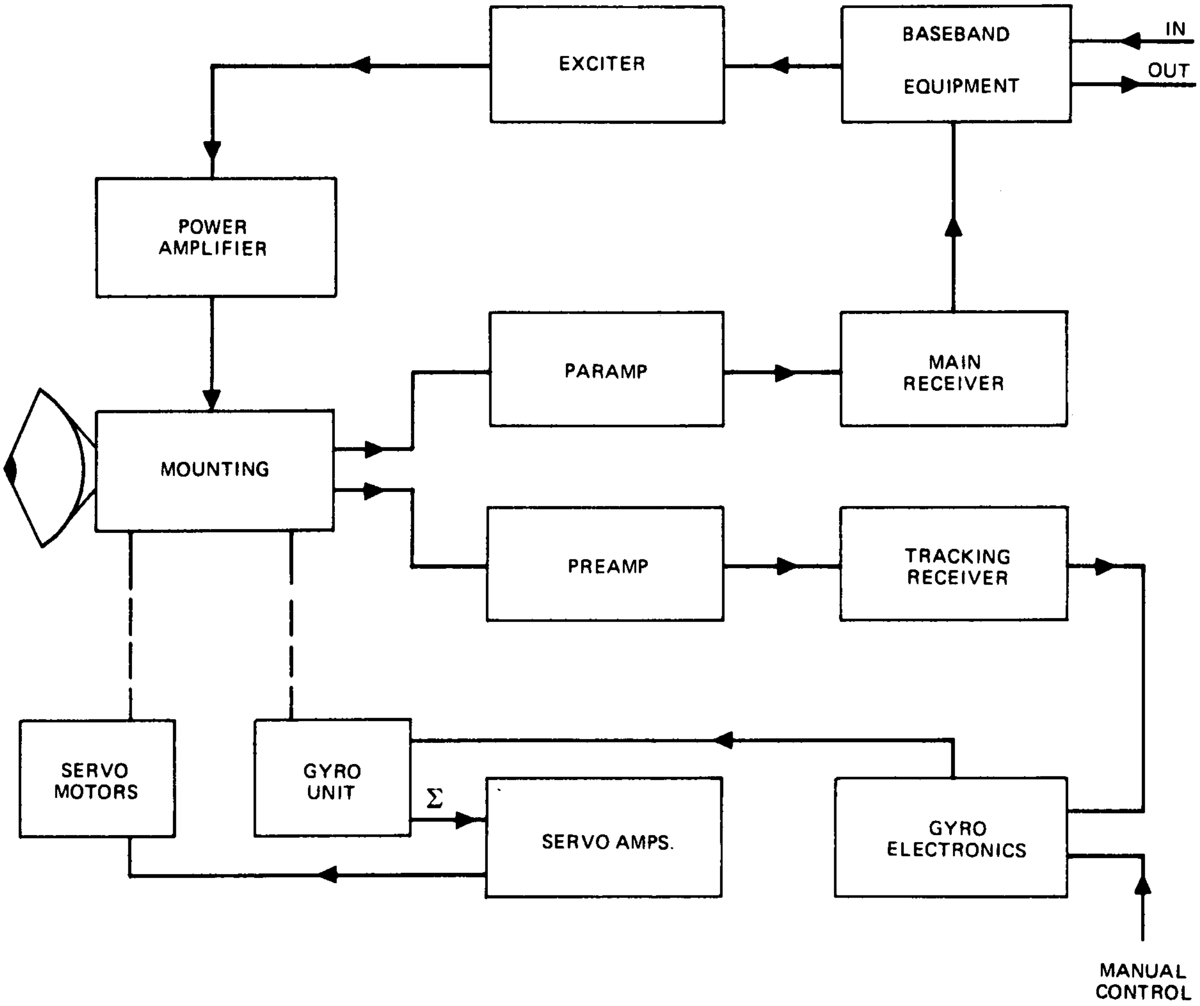


Figure 15-6. Shipborne Terminal

For a terminal located on a ship, due to pitching and rolling motions, a two-axis mount is inadequate for tracking the satellite through regions requiring high mount velocities and accelerations. Therefore, a three-axis mount was employed.

15.5 EXPERIMENTS DESCRIPTION

Since this is an operational system, few experiments have been conducted. The repeater performance, which is crucial to the performance of the entire system, has been measured in orbit by means of the special earth station test facility at SRDE (Christchurch, U.K.). To date no significant change from the performance measured by Philco-Ford in the laboratory before launch has been observed.

15.6 OPERATIONAL RESULTS

The SKYNET system was designed in a conservative manner and the satellite and ground terminals developed met their specifications. As a result, the operational performance has been within the limits that were anticipated. The only spacecraft malfunction of significance was the failure of 1 TWT after a year of in-orbit operation.

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SECTION 16 - NATO SATELLITE SYSTEM

16.1 PROGRAM DESCRIPTION

In 1963/65 the first tentative studies were started to determine the feasibility of a satellite system to satisfy NATO communication needs. After the signing of the Memorandum of Understanding between the U.K. and the United States in 1966 for the SKYNET satellites, the United States proposed that NATO utilize the satellite technology developed for SKYNET in order to have a viable synchronous satellite communication system built and deployed by 1971. In 1967, a Memorandum of Understanding was signed between the United States and NATO, whereby the U.S. would build and launch two SKYNET-type satellites. Philco Ford was to build the satellites. The USAF Space and Missile System Organization (SAMSO), with technical support from the Aerospace Corporation, was to act as the procurement agent for NATO.

Further system engineering studies indicated that two rather minor changes in the SKYNET-type satellite would provide a more optimum system for NATO. The first modification was to change the equal power division between the 20-MHz and 2-MHz channels to a 6-to-1 ratio, respectively. The second change was to shift the antenna aiming point from the subsatellite point on the earth to between 40° and 45° N latitude, since all NATO earth terminals were to be located north of the Equator. This yielded a more optimum power spread for NATO coverage over the Northern Hemisphere.

In addition, NATO decided to participate in the IDCSP test program. This early part of the project was called NATO SATCOM Phase I. NATO initially leased and finally purchased two 15-foot diameter "MASCOT" satellite ground terminals built by Philco Ford. These terminals were used in test operations with IDCSP satellites to train personnel for the coming of the advanced system (NATO SATCOM Phase II).

The second Phase of the program included launching the two modified SKYNET-type satellites and building a satellite ground system. Phase III of the NATO program is post-1975 and is presently in the early planning stages.

For NATO SATCOM Phase II, the two satellites were to be launched in 1969/1970, with one satellite acting as a backup to provide a 5-year system capability. NATO I was successfully launched into synchronous orbit in March 1970. The launch of NATO II was delayed until 1971 due to the apogee motor failure that occurred during the launch of SKYNET I "B." NATO II was successfully launched into synchronous orbit in February 1971. Table 16-1(1) (2) summarizes launch and status information on the NATO satellites.

The operational requirements dictated the utilization of 12 stationary earth terminals. The 12 stations are located near the capital cities of the 12 following countries: Belgium (L1), Germany (L2), United States (L3), UK (L4), Norway (L5), Turkey (L6), Italy (L7), Canada (M2), Netherlands (M3), Denmark (M4), Greece (M5), and Portugal (M6). Although the stations are stationary, they can be disassembled and relocated to a prepared site. Table 16-2(1) is a summary of the participating earth terminals of the NATO SATCOM Phase II systems.

Originally, two types of ground stations were planned, one employing an antenna 42 feet in diameter, which was designated a large (L#) capacity terminal and one with a 21-foot antenna designated a Medium (M#) capacity terminal. However, system engineering studies indicated that if the satellite power was divided in a more optimum way (6-to-1 power split versus equal power split), it would be more realistic to use only one type of ground terminal. The change to all identical ground terminals (42 feet in diameter) provided much more flexibility and reduced the total logistic problem. The definitions of large and medium capacity terminals remained.

The operational objective of the NATO SATCOM Phase II has been to provide highly available voice and telegraph communication circuits between the NATO countries and the military and political headquarters. The central requirement of the system is for multiple access. It was deemed essential that the number of circuits should be fixed and the quality of the circuits should be constantly monitored and controlled.

Table 16-1. Participating Spacecraft

Satellite		NATO I	NATO II
Manufacturer		Philco Ford (USA)	
Sponsors		North Atlantic Treaty Organization (NATO), Brussels, Belgium Supreme Headquarters, Allied Powers Europe (SHAPE), Casteau, Belgium	
Launch Date		3/20/70	2/3/71
Launch Vehicle		Augmented-Thrust-Thrust Delta	
Orbital Data	Apogee (mi)	22,619	23,024
	Perigee (mi)	21,420	21,432
	Inclination	Less than 3°	Less than 3°
	Period (hrs)	Approximately 24	Approximately 24
	Position (°W)	18 ± 3 **	26 ± 3 **
Status		Satellite is operating normally, one TWT, has	Satellite is operating normally.

* At initial orbital injection. Attitude control and station-keeping maneuvers change orbital parameters.

** Positions were chosen so that at the extremities (i.e., 15°W and 29°W) the minimum elevation angle from any NATO ground terminal would be greater than 10°

Table 16-2. Participating Earth Terminals

Location	Description	Ant. Dia.	Utilization	Date Installed	Manufacturer
Belgium**	L1	42'	Operational and primary system control	1970/ 1971	Standard Electric Lorenz*(Germany) Prime contractor: led a consortium of companies from the NATO Countries to build ground terminals, modulation, multiplex, control, and interconnect facilities.
Germany**	L2		Operational traffic and backup system control		
United States	L3		Operational traffic		
U.K.	L4				
Norway	L5				
Turkey	L6				
Italy	L7				
Canada	M2				
Netherlands	M3				
Denmark	M4				
Greece	M5				
Portugal	M6				
Hague, Netherlands	--	30'	Testing	1968/ 1969	SHAPE Technical Center

*SEL is a subsidiary of International Telephone and Telegraph Corp.

**Main station interconnect by LOS microwave.

The NATO SATCOM Phase II was built entirely from existing technology in order to minimize system risk. This approach to design has produced a successful operational system. Its consequence is that no major contributions toward advancing the state-of-the-art in satellite communications have been made.

16.2 SYSTEM DESCRIPTION

System studies based on the requirements for communications within the NATO System indicated that the optimum choice for multiple access would be FDMA, since no random access was required. It was further determined that the seven large capacity terminals would operate in the 20-MHz band, each transmitting a single multidestination 24-voice channel FM access, and that the five medium capacity terminals would operate in the narrow-band (2-MHz) channel, each transmitting a single multidestination, 3-channel FM access. All stations, both large and medium capacity, receive and demodulate a number of carriers dependent on the individual station connectivity requirement. Table 16-3 gives the frequencies of the two satellite channels. Figure 16-1(1) indicates the connectivity of the NATO SATCOM Phase II system.

Since the satellite transponder is hard-limiting, frequency planning to control intermodulation and accurate power control are required. The frequency planning was accomplished via computer analysis and verified by measurements on a simulator.

The three most important overall criteria that were used in designing the system were:

1. Performance
2. Availability
3. Proven techniques

The single most dominant requirement was to provide a system that would minimize the probability that a given communication circuit might become unavailable. This was achieved by a combination of realistic performance estimates for equipment,

Table 16-3. NATO SATCOM Phase II Frequencies

	2-MHz Channel (MHz)	20-MHz Channel (MHz)	Beacon (MHz)
Uplink	7976.02 to 7978.02	7985.12 to 8005.12	--
Downlink	7257.3 to 7259.3	7266.4 to 7286.4	7299.5

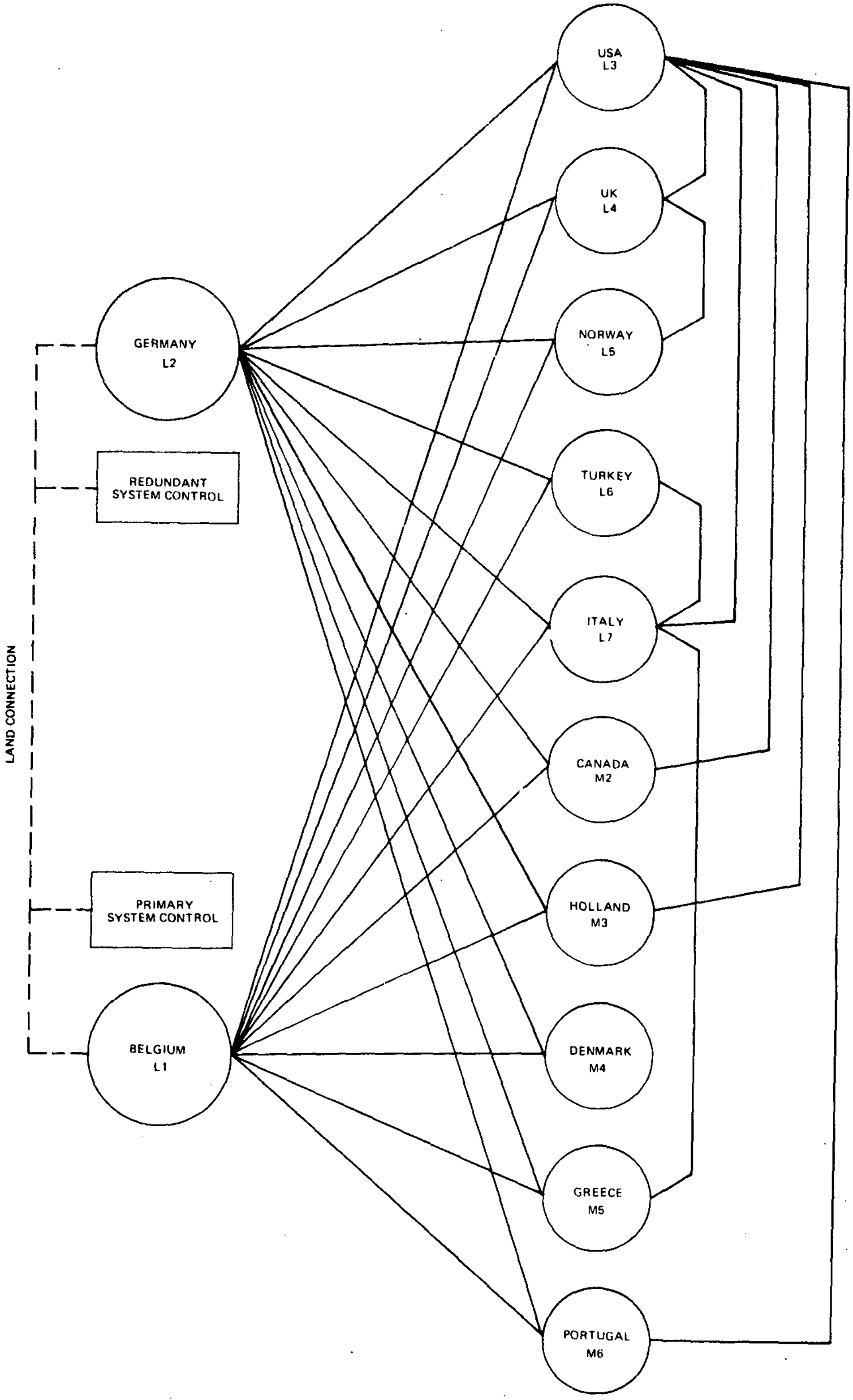

Figure 16-1. NATO SATCOM Phase Interconnectivity

inherently reliable units, redundancy, and rapid fault diagnosis and repair. In addition, performance margin was provided to protect the system against environmental extremes.

In view of the need to achieve a highly reliable system, great emphasis was placed on the importance of using techniques and equipment that had already been proven. Traffic requirements are in the form of telegraphy, speech, and low-speed digital circuits that can be carried on a voice channel.

A second stage of the NATO SATCOM program is being considered. In Stage 2, a limited number of stations may be equipped with spread spectrum equipment. Provision for the introduction of spread spectrum modulation equipment in the satellite ground terminals was incorporated in the original design of the stations.

Table 16-4(1) gives the FM performance characteristics of the demodulators used in the system. The number of modes that are provided allow the system to change capacity and configuration as long-term requirements vary.

Table 16-5(1) gives a typical downlink power budget for the NATO System for conditions that should exist 99 percent of the time at the worst geographic station. Margins at all other stations are 0.1 to 2.7 dB higher than those shown in the table. Since reliability of communications is of paramount importance, margins were allowed for unpredictable losses due to weather, power control, misalignments and equipment degradation.

As for the SKYNET system, control of the NATO SATCOM Phase II system is provided in a number of different forms, viz, of the spacecraft, the earth terminal complex, and the traffic. Spacecraft control is exercised by the USAF Satellite Control Facility, Sunnyvale, Calfiornia, through its worldwide network of satellite monitoring facilities.

Control of the distribution of satellite output power is exercised from the Primary Control Center (PCC) collocated with the Belgium earth station or from the Secondary Control Center (SCC) collocated with the German earth station. The method

Table 16-4. FM Demodulator Performance

Mode	Number of Voice Channels Transmitted	Carrier-to-Noise Density Ratio at Threshold (dBHz)	Carrier-to-Noise Density Ratio for -30 dBmOp Weighted Noise in Worst Channel (dBHz)	Nominal IF Bandwidth (kHz)
1	24	64.3	68	575
2	18	63.2	67	475
3	12	60.8	65	325
4	6	58.3	62	150
5	3	56.1	60	100
6	2	54.6	59	50
7	1	49.7	55	15

Table 16-5. Power Budgets for Typical NATO FM Performance at the Worst Geographic Position

	Parameter	20-MHz Band*	2-MHz Band*
Uplink	(1) Received power at satellite (dBm)	$-71.4^{+0.5}_{-1.3}$	$-71.4^{+0.5}_{-1.3}$
	(2) Satellite receive noise (dBm)/Hz power density (2750°K)	-165.2	-165.2
	(3) Carrier/noise ratio (dB)	$+19.5^{+0.5}_{-1.3}$	$+28.9^{+0.5}_{-1.3}$
Downlink	(1) Satellite ERP (minimum) (dBm)	+50.3	+42.8
	(2) Intermodulation loss (dB)	-1.2	-1.3
	(3) Power sharing (dB)	-8.5 ±1.0	-7.0 ±1.0
	(4) Carrier uplink uncertainty (dB)	$0^{+0.5}_{-1.3}$	$0^{+0.5}_{-1.3}$
	(5) Power control (dB)	0 ±1.0	0 ±1.0
	(6) Net ERP/carrier (dBm)	$+40.6^{+1.5}_{-1.9}$	$33.3^{+1.5}_{-1.9}$
	(7) Downlink losses (dB)	$-203.0^{+0}_{-1.3}$	$-203.0^{+0}_{-1.3}$
	(8) Receive antenna gain (dB)	$+58.0^{+0.3}_{-0.1}$	$58.0^{+0.3}_{-0.1}$
	(9) Receive input carrier power (dBm)	$-104.4^{+1.5}_{-2.3}$	$111.7^{+1.5}_{-2.3}$
	(10) Receive thermal noise power density (220°K) (dBm/Hz)	-175.2	-175.2
	(11) Intermodulation Noise Density (dBm/Hz)	-178.2	-174.6
	(12) Total Noise Density (dBm/Hz)	-173.4	-171.9
	(13) Receive carrier to noise (dBm/Hz)	$69.0^{+1.5}_{-2.3}$	$60.2^{+1.5}_{-2.3}$
	(14) Minimum margin to threshold (dB)	2.4**	1.8**

*99 percent of the time values will be within these limits.

**All other stations should have margins that are from 0.1 to 2.7 dB better.

of power control utilized is manual. Manual control is dependent upon the judgment of the controller to react properly to a given set of circumstances within a highly ordered set of procedures. The controller provides the intangible asset of making critical decisions under highly unexpected circumstances. Methods were chosen and equipment provided to allow the controller a wide latitude of choice.

Equipment has been provided for the continuous monitoring and measuring of system performance. The information from each system terminal is forwarded continuously to the system controller by means of an automatic data reporting network. Both system control stations, at Belgium and Germany, receive and process the same information independently. The two control stations are interconnected via a land data link so that the system can be controlled from either, using the equipment provided at the other station. In effect, there is a total redundancy in the control system. Each control center is provided with computation and display equipment for the analysis and display of the incoming data. A TTY orderwire network via the satellite has been provided to allow the controller to forward specific control instructions to any station.

Traffic control takes place at speech and telegraph facility control centers that are remote from the earth stations.

16.3 NATO SPACECRAFT

Spacecraft characteristics for the NATO satellites are displayed in Table 16-6(1). The simplified block diagram depicting the communications configuration of the satellite is the same as shown in Figure 15-3 for the SKYNET satellite. The spacecraft functioning and subsystems are identical to those described in Paragraph 15.3 for SKYNET.

16.4 NATO SATELLITE GROUND TERMINALS

The NATO SATCOM Phase II System utilizes 12 identical ground terminals. The ground terminals at Belgium (L1) and Germany (L2) are the master stations of the

Table 16-6. NATO Satellite Characteristics

ANTENNAS	Type	X-Band mechanically despun with lens to aim center of beam at 42° –45° N.	UHF array for TT&C with redundant UHF transponders and command/telemetry processing equipment
	Number	One	Two
	Beamwidth	No Data Available	Essentially omnidirectional
	Gain (dB)	17.5	-0.7
REPEATERS	Frequency Band	X-Band	
	Type	Hard-Limiting dual channel	
	1 dB Bandwidth	20 MHz and 2 MHz channels	
	Receiver		
	Type Front End	Down conversion mixer into linear amplifier*	
	Front End Gain	No Data	
	Noise Figure	2750°K (10.2 dB)	
	Transmitter		
	Type	Redundant TWT	
	Gain	No Data	
	Power Output (dBm)	33.0 (20 MHz) 24.5 (2 MHz channel)	
	EIRP (dBm) peak of beam	50.5 (20 MHz channel) 42.0 (2 MHz channel)	
GENERAL FEATURES	Stabilization		
	Type	spin 90 rpm – 5 years	
	Capability (stationkeeping)	±3° for 5 years	
	Power Source		
	Primary	Cylindrical array of silicon solar cells, capable of providing 97 watts of prime power, throughout 5 years of orbit life	
	Supplement	Two redundant 16 cell nickel cadmium batteries for operation during eclipse (6 AH per cell)	
	Communication power needs (watts)	64	
	Size (inches)	54 diameter 60 high	
	Weight (lbs.)	Launch 535. In orbit 280	

*Dynamic range (a) 20 MHz channel – 90 to –45 dBm
(b) 2 MHz channel – 100 to –45 dBm

network. Table 16-7(1) summarizes the performance of the NATO ground terminals. The antenna is a 42-foot diameter Cassegrain with a reflector shaped to provide high efficiency. It is mounted on a fully steerable azimuth/elevation mount.

The basic IF interface is 70 MHz (both transmit and receive). A simplified diagram of the essentials of the communications chain is shown in Figure 16-2(1). The entire transmit and receive chain components are redundant.

The parametric amplifier, which is designed to have a low noise figure, uses a varactor diode that is operated at its parallel resonance frequency. The output signal from the parametric amplifier is then fed to the microwave receiver. Down-conversion to 70 MHz is accomplished by standard heterodyning techniques.

The transmitter subsystem is designed to provide accurate power control (±0.5 dB) from 100 W to 5 kW. In addition, a summing amplifier is provided (390 MHz) to potentially combine up to eight separate uplink signals. Signal power is first increased by the use of an intermediate power amplifier, which is a TWT. The TWT output directly feeds the high power kylstron, which is a Varian Type VA-925F cooled by distilled water. The most important features of the transmit chain are frequency stability and setability. Stringent frequency and power control are required to maintain satellite output power balance.

The operational requirements of frequency flexibility and high stability are met by a derived local oscillator supplied from frequency synthesizers locked to a high stability (1 part in 10^{11}) master oscillator.

16.5 EXPERIMENTS DESCRIPTION

The repeater performance, which is crucial to the performance of the system, has been measured in orbit by means of the special earth station test facilities at SRDE (Christchurch U.K.) and the SHAPE Technical Center (STC), the Hague. To date no significant change from the performance measured by Philco Ford in the laboratory prior to launch has been observed.

Table 16-7. Characteristics of NATO Earth Terminals

ANTENNA	Type	Cassegrain Shaped Surface
	Mount	AZ ELEV
	Aperture Size (ft)	42
	Receive gain (dB)	58
	Efficiency (%)	75
	Receive Beamwidth (^{o})	0.23*
RECEIVE SYSTEM	Type Preamplifier	Varactor diode
	Gain (dB)	No Data
	1 dB Bandwidth (MHz)	50
	Tuning Capability (MHz)	500
	Noise Temperature (^{o}K)	90 100
TRANSMIT SYSTEM	Type Amplifier	KLYSTRON
	Bandwidth (MHz)	50
	Amp Power Output (kW)	5 6
TRACKING	Type (monopulse)	Automatic
	Accuracy (3σ)	0.025**
FREQ. CONTROL	long term (1 yr)	1 in 10^9
	short term (1 sec.)	1 in 10^{11}
TOTAL PERF.	Sys. Noise Temp. ^{o}K	210
	G/T	34.8*
	EIRP (dBW)	94*
POLARIZATION	Transmit Feed	right hand circular
	Receive Feed	left hand circular
INSTALLATION	Radome	Yes***
	Type Facility	Fixed****

*Calculated from other measured parameters

**This can degrade to 0.05 per channel if manual track is required

***All except L2 Germany

****Can be relocated to prepared site

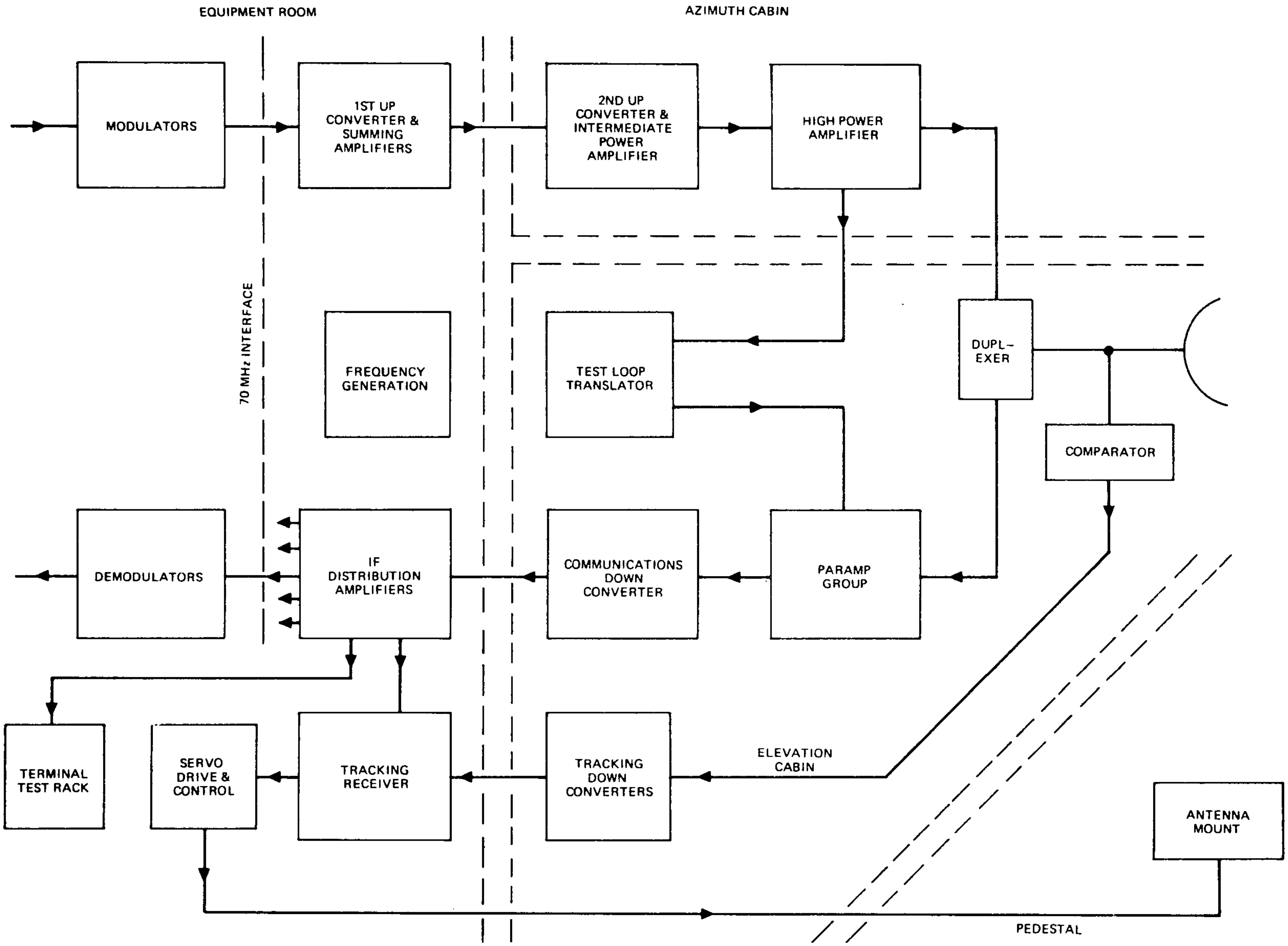

Figure 16-2. NATO Ground Terminal Simplified Block Diagram

16.6 OPERATIONAL RESULTS

As of May 1971, measurement of the operational performance of the NATO Phase II system has not been accomplished. The only spacecraft malfunction of significance has been the failure of one TWT after 6 to 8 months of orbit operation.

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SECTION 17 - PHASE II DEFENSE SATELLITE COMMUNICATIONS SYSTEM

17.1 PROGRAM DESCRIPTION

In June 1968 the Department of Defense announced its decision to acquire six satellites and additional earth terminals as the second phase of the Defense Satellite Communications System (DSCS). The first phase (the IDCSP) had successfully completed its research and development objectives and since late 1967 had been providing a restricted operational capability.

The objective of the second phase, or Phase II, of the DSCS is to establish an operational military satellite communications system which will provide substantial increases in performance together with a wider variety of services for users. When completely operational the Phase II DSCS will be a part of the Defense Communications System (DCS) and will function as both a long haul strategic trunking system and a system capable of supporting military contingency operations. In addition, the system will be capable of supporting service to small tactical users, if needed.

Two of the six satellites procured under this program are, as of mid-1971, scheduled to be launched aboard a Titan IIIC booster into synchronous orbit in late 1971, and should become operational in early 1972. Definite dates for the follow-on launches have not been scheduled, but will be made on an as-required basis for replenishment and to establish additional in-orbit operational satellites. Table 17-1 summarizes launch and status information on the Phase II DSCS satellites.

The earth terminals presently being used with the IDCSP (see Section 12.1) will be modified and upgraded for operational use with the Phase II DSCS. In addition, a limited quantity of new terminals will be procured and deployed to fulfill the operational requirements. A summary of the present IDCSP terminals is presented in Table 12-3. Table 17-2 presents a summary of the new terminals which will participate in the Phase II DSCS.

Table 17-1. Phase II DSCS

Satellite	Phase II DSCS
Manufacturer & Sponsor	TRW/U.S. Air Force
Launch Date	- Dual satellite launch - Dec. '71 - No decision on additional launch dates
Launch Vehicle	Titan IIIC
Orbital Data Apogee (Mi.) Perigee (Mi.) Inclination Period (Min.)	In procurement (planned for synchronous orbit) as of mid-1971
Status	In procurement as of mid-1971

Table 17-2. New Phase II DSCS

Type	Antenna Diameter	Utilization	Sponsor	Date Available
HT	60 ft	High density traffic	USASCA*	Mid-'73
MT	20 ft	Low density traffice	USASCA*	Mid-'73
LT	8 ft	Contingency & special user support	Not awarded as of mid-'71	Not awarded as of mid-'71

*United States Army Satellite Communications Agency

The military satellite communication system that has been designed will satisfy the varied and changing user requirements over the next 5 years. The system will evolve from an analog system (almost total) into a digital system (almost total) during this period. Additionally, the initial groundwork will be laid for moving into a time division multiple access (TDMA) system. The satellites developed will provide steerable narrow coverage antennas which will greatly enhance the flexibility and operational capability of the system. Ground assets developed primarily for the Phase II DSCS will include militarized pulse-code modulation (PCM) and time division multiplex (TDM) equipments, error correcting coders/decoders, high data rate phase shift keyed (PSK) modems, and new highly-reliable ground terminals.

17.2 SYSTEM DESCRIPTION

The first Phase II satellites are scheduled to be launched in late 1971 and the system will be implemented in three distinct periods, each providing different communications capabilities. In the first period (denoted as Stage 1a), Phase II will operate in the frequency division multiple access (FDMA) and code division multiple access (CDMA) mode and will provide a point-to-point operational capability by mid-1972 after completing essential on-orbit satellite tests. In the second period (denoted as Stage 1b), Phase II will operate in the FDMA mode to provide a multipoint network satellite communications capability and the CDMA mode to provide point-to-point protected (i.e., jam-resistant) communications for vital traffic. During the final period, the Phase II system will employ time division multiple access (TDMA) and CDMA to provide a total network capability. The latter state will be denoted as Stage 2.

In Stage 1a, the point-to-point terminal linking arrangement results in an operational system similar to that of IDCSP. However, in this case, many links will be handled simultaneously by each satellite. During this initial stage of the Phase II DSCS only the upgraded IDCSP terminals will be included in the system. The traffic will range from one analog voice channel between AN/TSC-54 terminals to 12 analog voice channels between AN/MSC-46 terminals. A few selected links will provide a wideband digital traffic capability to support such requirements as wideband digital data and digitized voice signals. These digital links will be time-shared with FM voice circuits. The baseband and modulation equipment (i.e., FM modems, multiplex, digital modems, etc.) will be those which are presently in use in the IDCSP.

A protected traffic capability (i.e., circuits resistant to RF jamming) will be provided during Stage 1a on a terminal-to-terminal basis using existing CDMA (spread spectrum) equipment. These links will be dedicated lines between selected users and will pass designated vital traffic only. Communications control of the system during Stage 1a will consist of scheduling with system coordination and discipline maintained by a controller. One controller will be established for each satellite.

Initially, it is intended to launch two satellites. Three to four satellites may be needed to supply a complete global capability providing connectivity among the geographical locations dictated by military requirements. However, a decision on placing more than two satellites in orbit has been deferred to a later date.

A limited number of AN/TSC-54 terminals will be equipped to provide a contingency capability in Stage 1a. These terminals will be self-contained in that they will be provided with FM modems, multiplex, and ancillary equipment to handle 12 voice channels. The FM modems will be capable of modulating an RF carrier with up to 72 voice channels delivered to the terminal in a baseband form from a separate technical control facility. Operation of contingency terminals during this stage will be via the satellite narrow beam antennas.

Stage 1b will utilize multiple receive and transmit carriers at selected locations (nodes) to support links in a multipoint network operating via a single satellite. Traffic will range from 12 voice channels on the AN/MSC-46 pairs to three voice channels between the AN/MSC-46 and AN/TSC-54 terminals. Initially, a few links will be used to provide wideband digital traffic between selected areas in support of imagery data and digitized voice requirements as in Stage 1a. As the time division multiplex (TDM) and pulse code modulation (PCM) equipments become available, the system will phase from an almost all-analog system into a hybrid (part analog, part digital) and finally into an all-digital system. Access to the satellite in Stage 1b will be FDMA. During this stage the new MT and HT terminals will become available and will be integrated into the system. Control of the DSCS in Stage 1b will continue to be on a schedule and discipline basis as described for Stage 1a.

AN/TSC-54 terminals will be available for contingency operation as described for Stage 1a. In Stage 1b a larger number of AN/TSC-54 terminals will have been modified for contingency operation through the satellite narrow beam. They will be provided with URC spread spectrum equipment to achieve electronic survivability (i.e., an anti-jam capability). Note that operation with the satellite narrow coverage antennas, in itself, provides jammer rejection when the beam can be placed so as not to include the jammer.

In Stage 2, the system will operate using time division multiple access (TDMA). All links will be established on a time base (rather than frequency) allowing each terminal to function as a multiple link, or nodal, terminal. A full complement of modified IDCSP and newly-procured terminals will be available for use during this stage.

Protected traffic will continue to be provided using spread spectrum equipment. However, the modems employed will be of an advanced model specifically designed to meet the Stage 2 system requirements.

17.3 SPACECRAFT

The spacecraft characteristics for the Phase II DSCS satellites are displayed in Table 17-3. A block diagram depicting the communications transponder is shown in Figure 17-1.

The communication subsystem consists of a multiple channel repeater with the channels crosslinked, receive and transmit EC antennas, and two NC antennas each capable of receiving and transmitting simultaneously. Each NC antenna will be capable of being independently steered.

Table 17-3. Phase II Satellite Characteristics

<table>
<tr><th colspan="2">TYPE</th><th>X BAND MECHANICALLY DESPUN HORN</th><th colspan="2">X BAND MECHANICALLY DESPUN PARABOLIC REFLECTOR</th><th>S-BAND BICONICAL HORN FOR TT&C</th></tr>
<tr><td rowspan="3">ANTENNAS</td><td>Number</td><td>1</td><td colspan="2">1</td><td>1</td></tr>
<tr><td>Beamwidth</td><td>Pencil Beam - 18°
(Earth Coverage)</td><td colspan="2">Pencil Beam nominal 2.5°</td><td>Toroidal 32° wide</td></tr>
<tr><td>Gain (dB)</td><td>Xmit. 16.8 (Edge)</td><td colspan="2">Xmit. 33 (Edge)</td><td>3 (Peak)</td></tr>
<tr><td rowspan="12">REPEATERS</td><td>Configuration</td><td>EC–EC*</td><td>EC–NC*</td><td>NC–NC*</td><td>NC–EC*</td></tr>
<tr><td>Type</td><td colspan="4">Single conversion with each of 4 channels operating in a linear, quasi-linear, or hard-limiting mode as selected by ground commands</td></tr>
<tr><td>Bandwidth (1 dB)</td><td>125 MHz</td><td>50 MHz</td><td>185 MHz</td><td>50 MHz</td></tr>
<tr><td>Number</td><td>One</td><td>One</td><td>One</td><td>One</td></tr>
<tr><td>Receiver</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Type Front End</td><td colspan="2">Tunnel Diode common to EC–EC & EC–NC channels</td><td colspan="2">Tunnel Diode common to NC–NC & NC–EC channels.</td></tr>
<tr><td>Front End Gain</td><td colspan="2">No Data</td><td colspan="2">No Data</td></tr>
<tr><td>System Noise Figure</td><td colspan="2">8.3 dB</td><td colspan="2">12.8 dB</td></tr>
<tr><td>Transmitter</td><td></td><td colspan="2"></td><td rowspan="5">This channel shares a transmitter with EC–EC channel</td></tr>
<tr><td>Type</td><td>TWT common to EC–EC &
& EC–NC channels</td><td colspan="2">TWT common to EC–NC &
NC–NC channels</td></tr>
<tr><td>Gain</td><td>No Data</td><td colspan="2">No Data</td></tr>
<tr><td>Power Out</td><td>20 Watts</td><td colspan="2">20 Watts</td></tr>
<tr><td></td><td>EIRP</td><td>28</td><td colspan="2">40 (Each of 2 antennas)
43 (1 antenna)**</td></tr>
<tr><td rowspan="9">GENERAL FEATURES</td><td>Stabilization</td><td colspan="4"></td></tr>
<tr><td>Type</td><td colspan="4">Spin stabilized – nominal 50 RPM with hydrazine thrusters for stationkeeping and attitude corrections</td></tr>
<tr><td>Capability</td><td colspan="4">Pointing accuracy of despun platform ±0.14° That of NC antenna ±0.2°. East–West stationkeeping to within ±3° of designated subsatellite point for 5 years</td></tr>
<tr><td>Power Source</td><td colspan="4"></td></tr>
<tr><td>Primary</td><td colspan="4">Right cylindrical array of solar cells, capable of providing 520 watts at launch and 357 watts after 5 years</td></tr>
<tr><td>Supplement</td><td colspan="4">Three nickel cadmium batteries</td></tr>
<tr><td>Communication Power Needs</td><td colspan="4">235 watts</td></tr>
<tr><td>Size (feet)</td><td colspan="4">diameter 9; height 13</td></tr>
<tr><td>Weight (lb)</td><td colspan="4">1100</td></tr>
</table>

*Denotes uplink and downlink antennas that channel interconnects.

**With 2 NC antennas employed TWT output power is split. With 1 antenna full power goes to that antenna.

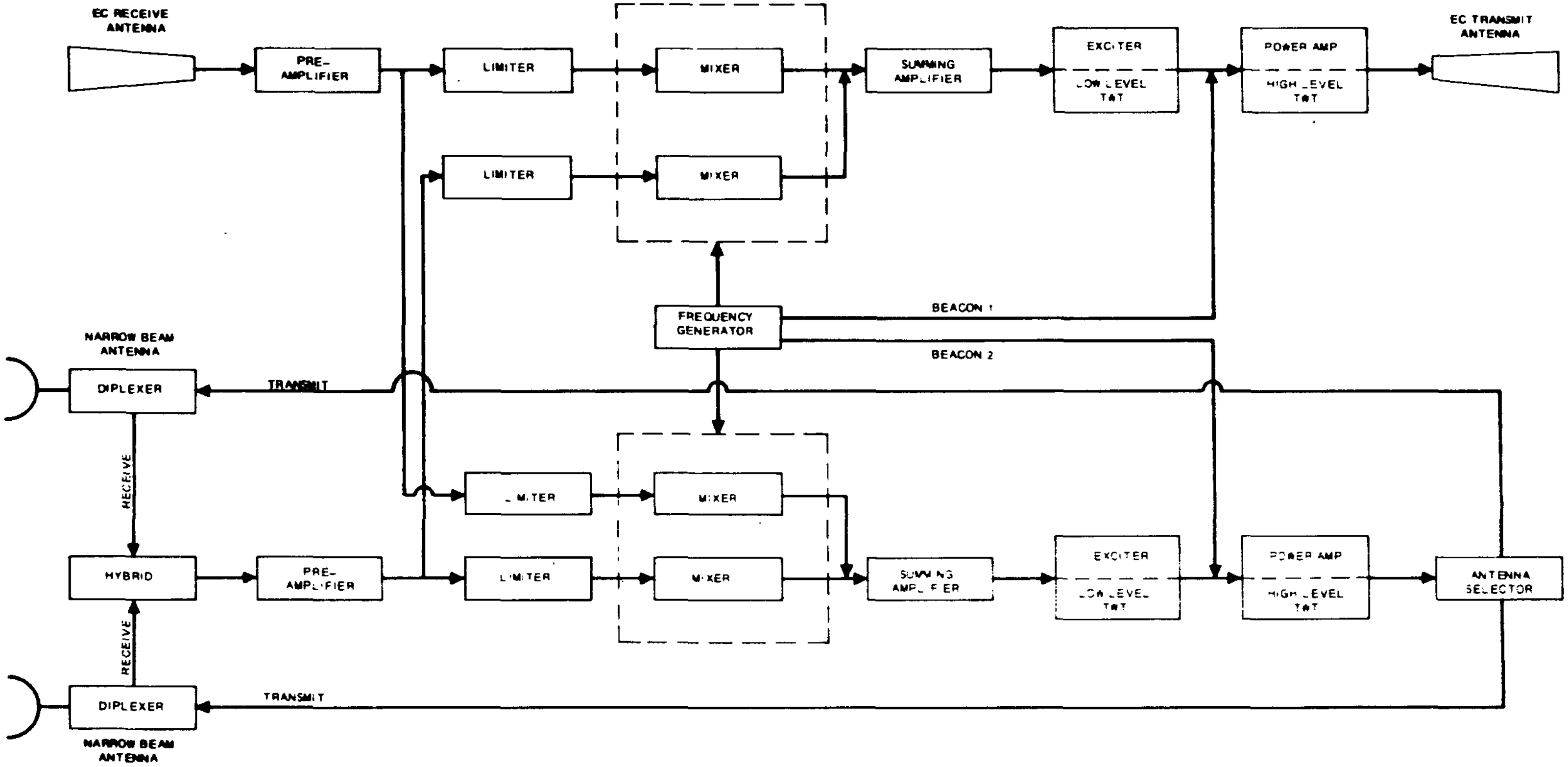

Figure 17-1. Phase II DSCS Communications Transponder

The uplink frequency transmitted by a DSCS earth terminal determines which of the four signal channels will be used. This assumes that an earth terminal planning to use either the NC-NC or NC-EC channels is within the geographical area covered by one of the NC antenna patterns. Satellite receive frequencies are in the 7900-8400 frequency band. These input frequencies are translated in frequency, amplified, and retransmitted in the 7250 to 7750 MHz band. A simplified frequency plan is presented in Figure 17-2 which relates the various channel modes together with their related frequency translations and satellite antennas. Both the EC-EC and NC-EC channels share the output power of a 20-watt TWT amplifier using the earth coverage antenna. Likewise, the NC-NC and EC-NC channels are combined and transmitted via a second 20-watt TWT amplifier using either one or both of the narrow coverage antennas. The bandwidths of each channel are presented in Figure 17-2 and represent 410 MHz of usable bandwidth.

All active components within the communications subsystem are redundant. Selection of any active component, together with the narrow coverage antenna switching, is accomplished by ground command. In order to achieve maximum in-orbit usage of the Phase II satellite, all onboard systems have been sized to provide a minimum 5-year operational lifetime. Each channel within the satellite can be commanded to operate in either a linear, a quasi-linear or a hard-limiting mode.

All transmitting antennas will be left-hand, circularly polarized, while the receiving antennas will be right-hand, circularly polarized. The two narrow coverage antennas will be capable of being independently steered through ±10° in each of two orthogonal directions, whereas the earth coverage antennas (transmit and receive horns) will provide coverage to approximately 1/3 of the earth's surface.

The launch profile of the launch vehicle will be chosen so that, with use of the satellite's orbital control subsystem and telemetry and command subsystem, the longitude of each satellite's subsatellite point can be accurately selected. In the same manner, the satellite's orbital control subsystem and the telemetry and command subsystem will be capable of repositioning the satellite once during the operational

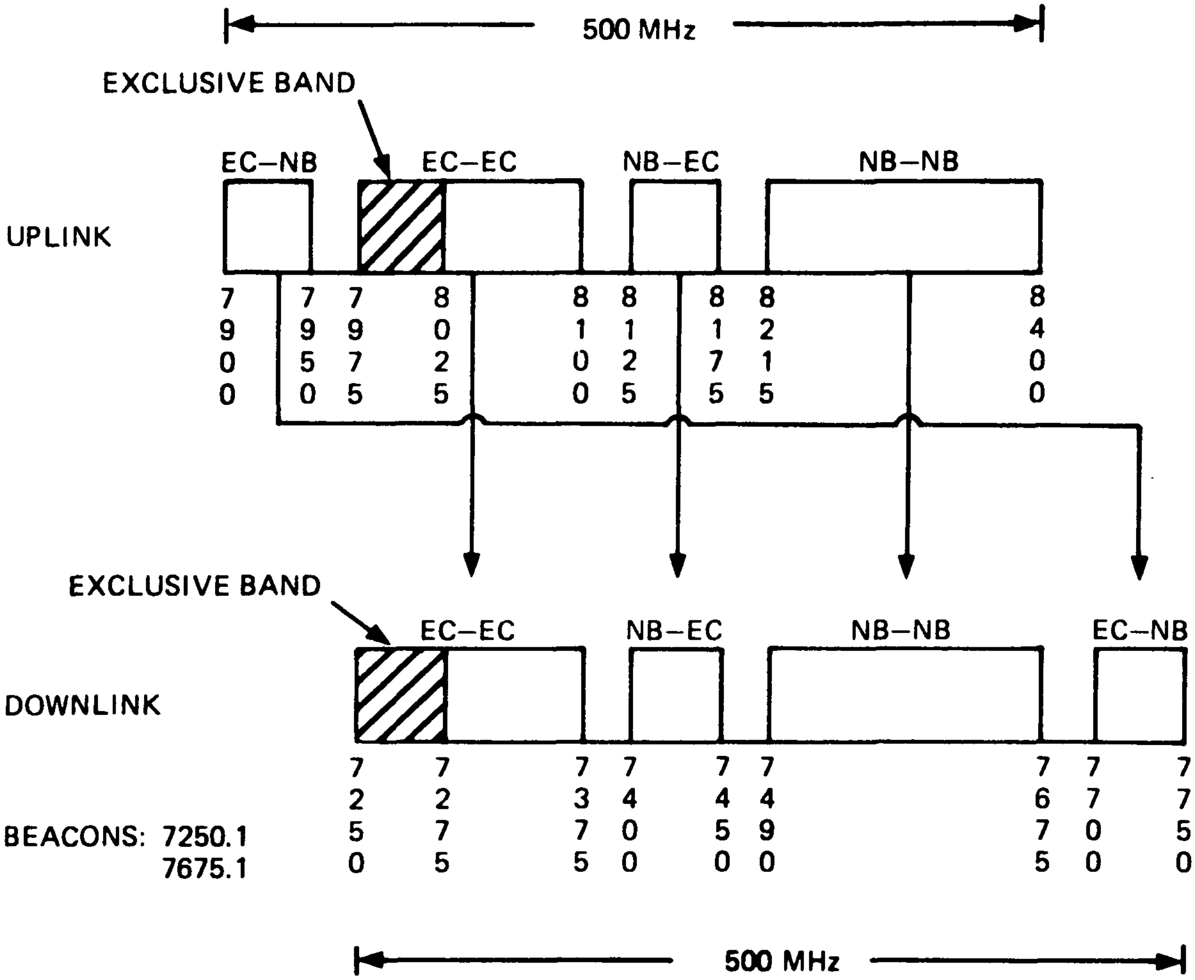

Figure 17-2. Phase II DSCS Frequency Plan

life to any other equatorial point at a rate of at least 15° per day. Over the operational life of the satellite, the East-West excursions of the satellite will be maintained to within ±3° of the designated subsatellite point. The inclination of the satellite orbital plane with respect to the equatorial plane will not exceed ±3° over the operational life.

Electrical power is supplied to the satellite from solar arrays. In addition, batteries are provided for eclipse operation.

17.4 GROUND TERMINALS

The two major classes of ground terminals to be employed in the Phase II DSCS include modified Phase I, IDCSP, terminals and new terminals presently under development. The major characteristics of the IDCSP ground terminals are presented in the description of Phase I DSCS ground terminals (see Table 17-4). Modifications being made to these terminals, their background, and major characteristics of the new terminals are as follows:

17.4.1 Modified IDCSP Terminals

17.4.1.1 AN/FSC-9 Terminals

The AN/FSC-9 is a large fixed terminal employing a 60-ft. antenna. There are two of these terminals, one at Fort Dix, New Jersey, and one at Camp Roberts, California. The AN/FSC-9 terminals were originally designed and procured under the Advent Program. Initially they operated with the SYNCOM satellites, but they were later modified for operation in the military satellite communications band and used with the IDCSP Phase I satellites. These two terminals were rehabilitated and upgraded, during 1970-71, by STRATCOM under contract to the Philco-Ford Corporation. These modifications ensure compatibility with the Phase II, Stage 1a DSCS. Further modifications to at least one of the AN/FSC-9 terminals are planned in order to provide a multiple transmit and receive carrier capability, a 500-MHz receive bandwidth and a 100-MHz transmit bandwidth. These modifications will allow the terminal to function as a Stage 1b DSCS nodal terminal.

Table 17-4. Characteristics of New DSCS Ground Terminals

TERMINAL FEATURES		TERMINALS	
		HT	MT
ANTENNA	Type	Nominally Parabolic	4 Cassegrain dish array
	Aperture Size	60 ft. Dia.	20 ft. Dia. (effective)
	Receive Gain	60 dB*	50 dB*
	Efficiency	No Data	No Data
	Receive Beamwidth	0.16° @ 3 dB pts.*	0.5° @ 3 dB pts.*
RECEIVE SYSTEM	Type Preamplifier	Cryogenically cooled	Uncooled
	Bandwidth	500 MHz	500 MHz
	Noise Temperature	No Data	No Data
TRANSMIT SYSTEM	Type Amplifier	2 – LPA (Low Power Amplifier) 1 – HPA (High Power Amplifier)	1 – LPA 1 – HPA
	Bandwidth	LPA – 500 MHz HPA – 170 MHz	LPA – 500 MHz HPA – 170 MHz
	Amp. Power Out	LPA – 3 kW HPA – 8 kW	LPA – 3 kW HPA – 8 kW
TRACKING	Type	Automatic	Automatic
	Accuracy	No Data	No Data
TOTAL PERFORMANCE	G/T (dB/°K)	39	27
	EIRP (dBm)	127	117
POLARIZATION	Transmit Feed	RHCP	RHCP
	Receive Feed	LHCP	LHCP
INSTALLATION	Radome	None	None
	Type Facility	Fixed	Transportable

*Derived values for typical antennas of the size indicated

17.4.1.2 AN/MSC-46 Terminals

The AN/MSC-46 is a relocatable terminal consisting of three vans and a transportable 40-ft. antenna and pedestal. The entire terminal including the antenna and pedestal is air transportable. The existing 14 AN/MSC-46 terminals were designed, developed, and placed in operation during the 1963-67 period. The total weight of the AN/MSC-46, in a transport configuration including the diesel generators, is approximately 125,000 pounds. The AN/MSC-46 terminal was designed to be capable of being assembled in 18 hours by a crew of 8 men. In practice, the time required for installation and checkout prior to achieving operational readiness has been considerably longer than 18 hours.

Present planning calls for crystal oscillator modifications to all 14 AN/MSC-46 terminals prior to Stage 1b. Up to seven of these terminals will be provided with a multiple transmit and receive carrier capability, a 500-MHz receive bandwidth and a 100-MHz transmit bandwidth in order to allow them to function as Stage 1b DSCS nodal terminals.

17.4.1.3 AN/TSC-54 Terminals

The AN/TSC-54 was designed as a highly transportable terminal which could be transported in a single military aircraft of the C-130 type. The total weight of the existing AN/TSC-54 terminal type, including spare parts, a single prime power unit, and fuel sufficient for 72 hours of operation, is approximately 25,000 pounds. The 13 AN/TSC-54 terminals were designed, developed, and placed in operation during the 1965-68 period.

The AN/TSC-54 terminals will be modified and equipped to fulfill two missions during Stage 1. They will be equipped to handle up to 12 voice channels for DSCS trunking, using the earth coverage satellite repeater channel. Additionally, with the necessary modifications, they will be used as contingency terminals utilizing the satellite narrow beam channel. These contingency terminals will include 12 channels of self-contained multiplex equipment but will be able to handle a baseband consisting of up to 72 voice channels.

The modifications and equipment additions to the AN/TSC-54s will more than double the weight and volume of these terminals. The latest weight estimates for the AN/TSC-54 contingency terminal complex in a transport configuration is 68,000 pounds.

17.4.2 New Terminal Developments

17.4.2.1 HT/MT Terminals

A contract was awarded in June 1970 for the design, development, and testing of one prototype HT and MT terminal, respectively. Final acceptance testing of the two prototype terminals should be completed by mid-1972. Major characteristics of each terminal are given in Table 17-4. The emphasis in the HT/MT designs was in the following areas:

- High availability obtained by the use of extensive redundancy and sophisticated fault location and automatic switchover circuitry
- Multiple transmit and receive carrier capability including a high level of immunity to the intermodulation products resulting from multiple carrier operation
- Wide bandwidths, linear phase and amplitude characteristics, flexible frequency control, and dual IF interface frequencies of 700 MHz and 70 MHz in order to ensure compatibility with the variety of modems anticipated during the 15-year design life of the HT/MT terminals.

The HT and MT terminals are nearly identical except for the antenna subsystems. The HT will use a 60-ft. antenna which can be erected and subsequently removed from a permanent foundation. The MT terminal design employs the previously developed AN/TSC-54 18-ft. cloverleaf type antenna. It is anticipated that in any production versions of the MT that might be procured, the 18-ft. cloverleaf antenna will be replaced by a parabolic dish antenna approximately 35 ft. in diameter in order to increase the communications capacity of this terminal.

The total weights of the development models of the HT and MT terminals are estimated at 400,000 and 100,000 pounds respectively, including the maintenance and service vans and the prime power units. The weight of the production version of the MT would, of course, increase should it incorporate the larger antenna design.

17.4.2.2 LT Terminals

The Light Transportable (LT) terminal is presently in the definition stage; a contract award is not anticipated before 1973. Further information is unavailable at this time.

17.5 EXPERIMENTS

The Phase II DSCS will be an operational system; no experiments are presently planned. A wide range of tests are scheduled for both checkout and evaluation of performance.

17.6 OPERATIONAL RESULTS

Satellites have not been launched as of mid-1971.

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SECTION 18 - TELESAT

18.1 INTRODUCTION

Telesat Canada was established on September 1, 1969 by an Act of the Canadian Parliament to provide domestic communications service in Canada by satellite. It is a corporate instrument to own and operate on a commercially profitable basis the domestic satellite communications system of Canada as a mixed government, commercial common carrier, and public business venture. Before the establishment of Telesat Canada, some advanced technical planning had been carried out by the Prime Minister's Task Force on Satellites, a project group set up by the Canadian government and headed by Dr. J. H. Chapman. The group concluded that a geostationary satellite system would be the most economical way to satisfy Canada's composite needs for Arctic communication service, remote television service, and additional heavy route television and message traffic service along the U.S./Canadian border.

Design work was initiated in 1969 on a satellite capable of being launched by the thrust-augmented Thor-Delta series of NASA launch vehicles. The spacecraft was to provide six RF channels, each capable of transmitting one color TV signal or the equivalent in message traffic. Early in 1970, however, Telesat received a proposal from the Hughes Aircraft Company for a spacecraft design also capable of being launched by thrust-augmented Thor-Delta series, but which provides exactly twice the communications capacity of the previous design. Telesat is now proceeding on the basis of this new design and expects the satellite to be launched in the last quarter of 1972. The initial system will use two satellites in orbit, the second acting as an in-orbit spare. A third satellite will be available for launching either to replace a failed satellite or to accommodate system growth. The second satellite will be launched about 4 months after the first launch.

The major contribution of this system to satellite communications technology is that it will be the first operational domestic satellite system, and as such is the forerunner of future domestic systems. Additionally, it will develop and demonstrate earth terminals suitable for unattended operation under climatic conditions, including those existing in Arctic regions.

18.2 SPACECRAFT DESCRIPTION

The Canadian domestic satellite, officially named "Anik" (thé Eskimo word for brother), is an all microwave, fixed gain, 12-channel transponder where each channel is essentially an independent amplifier with a bandwidth of 36 MHz. The transponder configuration is shown schematically in Figure 18-1. It receives signals sent from ground stations in the 5925-to 6425-MHz band and down-converts these to 3700 MHz to 4000 MHz for retransmission to other stations. The only active equipment common to all communications channels is a wideband receiver which establishes the system noise temperature, translates the 6-GHz carriers to 4 GHz, and amplifies the 4-GHz carriers to an intermediate power level before channelization. Separation of the FDM-FDMA channels is accomplished by two multiplexers for the even and odd number channels, each of which consists of a bank of six circulator-coupled waveguide filters. A 37 percent efficiency TWT amplifier with a saturated output power of 5 watts is provided in each channel for final power amplification. After power amplification, the channels are summed by two low loss multiplexers, again odd and even, each of which consists of a bank of six waveguide filters. The receiver and driver portions of the repeater are redundant, with a switch at the input selecting the chain for processing inputs. Two spare channels are available since the satellite is sized for 10-channel operation at the end of the 7-year mission life.

The mechanically despun communications antenna consists of a 5-foot diameter parabolic reflector and its associated feeds. Antenna despin control is exercised either by ground command or by an on-board pilot signal processor tracking on a ground generated pilot signal. The lightweight reflector is fabricated from a honeycomb sandwich and the reflecting surface is covered with a metal mesh. The latter makes the antenna transparent, thereby reducing what otherwise would be the

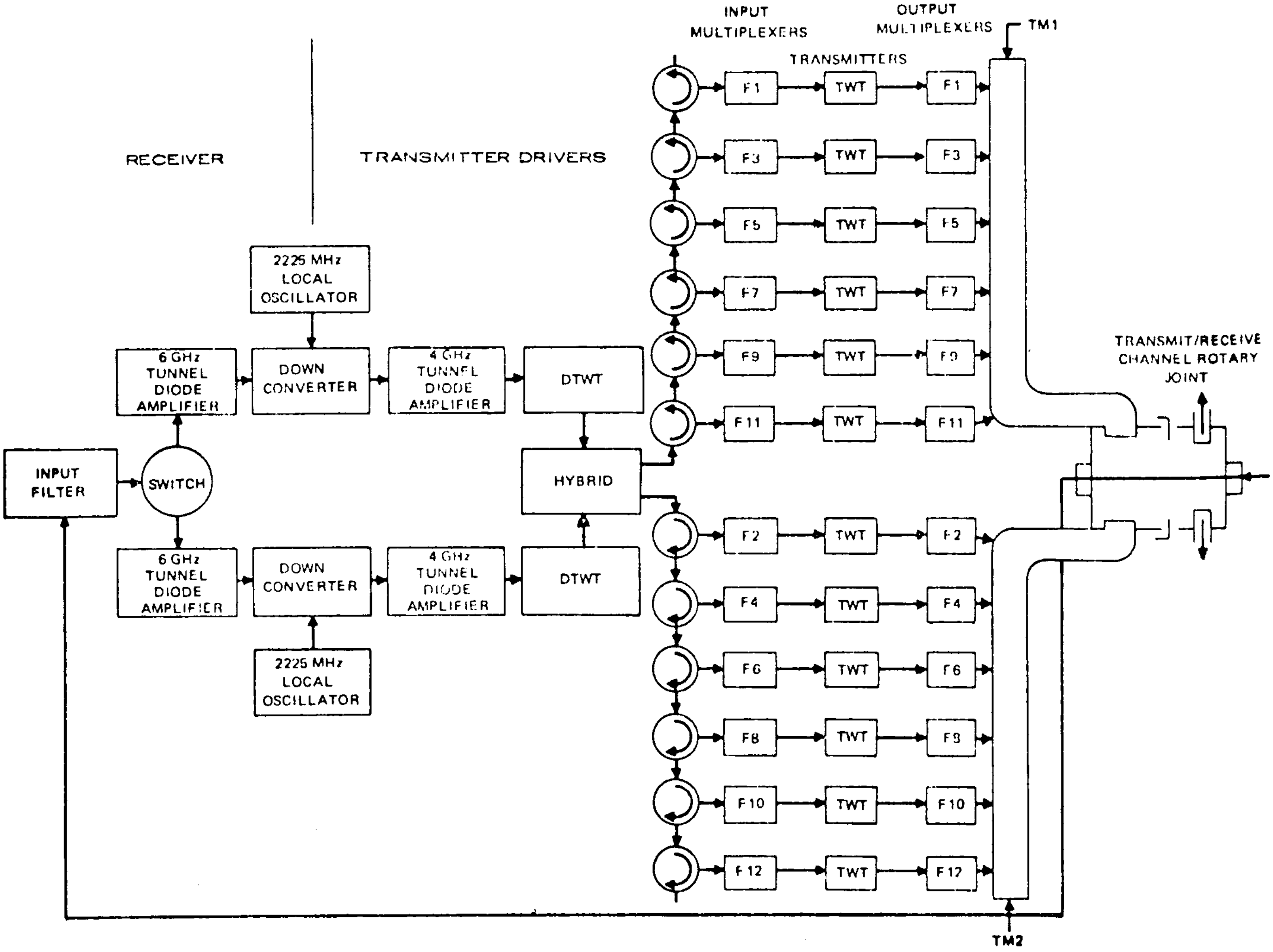

Figure 18-1. Communication Repeater Schematic

significant disturbance of the satellite by solar pressure. The feed assembly consists of a two-horn feed on one polarization for the transmit function, and a three-horn feed plus a planar subreflector for the receive and track functions. The horizontal arrangement of the horns assures that the antenna pattern, roughly 3° x 8°, is wider in that direction than in the perpendicular one. The beam pattern is pointed toward Canada, about 7.6° off the equator. The omnidirectional toroidal beam telemetry and command antennas used during the transfer orbit phase of satellite injection on station are mounted on top the parabolic reflector antenna.

Economies in system design have been realized through several steps taken to lessen the satellite's weight and hence its cost in orbit. These steps include satellite attitude determination on the ground rather than by on-board spacecraft hardware, extensive use of thin-walled invar filter waveguides, and affixing the squared solar cells to panels attached to the outer cylindrical body of the spacecraft with rubber cement rather than epoxy.

The design provides for 10-channel operation during sun eclipse periods when the system must be powered by an on-board battery system. During normal sunlight operation only 10 channels would be in operation, with the remaining two channels used for standby operation. The spacecraft is designed for a useful lifetime of about 7 years. Spacecraft characteristics are summarized in Table 18-1.

18.3 EARTH TERMINALS FOR TELESAT

In the Introduction three distinct service requirements were noted for the Telesat system: arctic communication service, remote television, and heavy route communications along the U.S./Canadian border. The equipment complements required to realize circuits of acceptable quality and reliability for each of these services differ considerably, so several earth station configurations have been proposed. The present plans call for two heavy route stations capable of passing all forms of transmission to and from the satellite. The master station, which will also contain the telemetry, tracking and command installation, is planned for Allan

Table 18-1. Telesat Characteristics

Antenna		Type	Dual Mode with shaped beam, Parabolic reflector of 5 foot diameter, plus bicone for telemetry and a cloverleaf for command during the launch and transfer orbit phase.
		Number	One
		Beamwidth	3° x 8° to give coverage of Canada
		Gain	27 dB over coverage area*
Repeater		Frequency Band	C band: 5925 - 6425 MHz (RCV) 3700 - 4200 MHz (XMT)
		Type	Non-linear single conversion
		B.W. (3dB)	36 MHz per channel
		Number	12 RF channels including 2 on standby
	RCVR	Type Front End	Tunnel Diode Amplifier
		Front End Gain	No Data
		Sys. Noise Fig.	Approximately 9 dB*
	XMTR	Type	TWT
		Gain	No Data
		Power Out	5 W
		EIRP	33 to 34 dBW within coverage area per channel
		G/T	-7dB/°K
General Features	Stabilization	Type	Spin with hydrazine jet stationkeeping and attitude control.
		Capability	Stationkeeping to within ±0.1° of 0° orbit inclination and proper longitude.
	Power Source	Primary	20,448 solar cell array providing 300 watts power at launch and 230 watts at end of 7 years.
		Supplement	Two 28 volt nickel-cadmium batteries
		Comm. Power Needs	220 watts
		Size	Total Height = 11.4 ft.; cylinder 75 inch diameter
		Weight	200 lbs. in transfer orbit, 630 lbs. after firing of apogee motor

*Value derived from other data available.

Park, about 70 miles northwest of Toronto. The other heavy route station is planned for Lake Cowichan, 40 miles north of Victoria, British Columbia. They will use 97-foot antennas with uncooled parametric amplifiers to give a minimum G/T of 37 dB/°K.

Five regional network-quality television (NTV) earth stations will be established near Edmonton (Alberta), Regina (Saskatchewan), Winnipeg (Manitoba), Halifax (Nova Scotia) and St. Johns (Newfoundland). These network television stations will be used to receive CBC programs for further distribution by conventional terrestrial means. Approximately 25 remote television (RTV) stations are planned for isolated communities in the northern parts of Canada not served at present by terrestrial microwave facilities. These receive-only stations will be located as close as practicable to the TV rebroadcasting stations they serve. The minimum G/T for the NTV and RTV earth stations will be 28 and 26 dB/°K, respectively. Both the NTV and RTV stations will be capable of unattended operation.

The proposed earth station complement also calls for two northern telecommunications (NTC) earth stations for arctic service. The primary purpose of the NTC stations is to establish two-way communications between the northern localities and the Allan Park main station as well as to receive TV programs for rebroadcasting to the local communities. The stations will be designed for unmanned operation and will be suitable for operation in severe arctic conditions. The first two stations of this type will be located at Frobisher Bay and Resolute Bay in the Canadian Arctic.

At the time of the writing little technical data regarding the proposed earth station configurations of the Telesat have been published. All the available data has been included in the text above.

18.4 EXPERIMENTS

Since the objective of the Telesat program is to establish an operational domestic communications system, few experiments are planned. Testing will, for the most part, consist of satellite in-orbit checkouts and initial evaluations of system performance.

18.5 OPERATIONAL RESULTS

As of mid-1971, the satellites have not been launched. When the system is established, each channel of a satellite will be capable of accommodating a color television program or as many as 960 multiplexed voice channels frequency modulated onto a single carrier. When multiple carriers are employed in an FDMA mode of operation, the voice channel capacities of a single satellite channel will be diminished.

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