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SAMSO TR 69-245

# FINAL REPORT
# TACTICAL SATELLITE COMMUNICATIONS PROGRAM

## PROGRAM 591 AND LES-5 TEST REPORT

BY E. D. ISGRIG, MAJOR USAF
H. F. MEYER
F. E. BOND
ET AL





21 JULY 1969

SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES, CALIFORNIA

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LOS ANGELES AIR FORCE STATION
Los Angeles, California

## FOREWORD

This report summarizes the work performed during the period July 1965 through May 1968 by participating organizations of the U.S. Army, Navy, and Air Force. It was originally published in November 1968 as an Aerospace Corporation Report No. TOR-0200(4133)-4. In addition to the authors shown, the following made significant contributions in the preparation of this report:

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## UNCLASSIFIED ABSTRACT

Testing with the Lincoln Experimental Satellite LES-5 with terminals on board aircraft, ships, submarines, and vehicles demonstrated the feasibility of using UHF repeater satellites to enhance the capability of tactical communication links for world-wide military forces. This report presents a summary of the results of the initial phase of the Tactical Satellite Communication Program (TSCP) involving Tri-Service participation in the technical and operational feasibility tests.

Although the demonstrations were successful, there exists the need to improve terminal equipment with respect to antenna coverage and efficiency, smaller size and weight to meet installation needs, and more convenient message entry and display devices.

Apart from the unexpected "fast fading" phenomenon observed on aircraft, which was easily compensated by the antimultipath diversity system used in aircraft and ship terminals, the characteristics of the propagation medium and sources of natural interference were found to be essentially as predicted. The coverage was generally limited at the horizon by fading at the high look angles by the antenna pattern.

Uplink and downlink measurement RFI indicated general agreement with predicted levels based on known U.S.-controlled ground-based transmitters.

Effective use of simple antennas on aircraft, small ships, and submarines yielded the desired objective of low-cost antennas with broad coverage; communication was maintained despite movement of the terminal. This makes the UHF band acceptable in a large number of applications where SHF operation is not presently feasible.

Frequency division multiple access was successfully demonstrated with terminals not in motion. A small amount of testing with moving terminals (ships) indicated difficulties in maintaining proper uplink power control. The results here are inconclusive.

TABLE OF CONTENTS

| Section | | | Page |
|---|---|---|---|
| | |  |

## TABLES



## FIGURES

SECTION I

INTRODUCTION

## A. BACKGROUND

This report describes results of a program of experiments and analyses concerned with the use of a communication satellite repeater in the military UHF band serving a variety of tactical terminals including aircraft, ships, submarines, and ground vehicles. The report includes a discussion of the objectives, both technical and operational; a description of the equipments used in the tests; and a summary of the test results.

Although the principal program effort involved transmissions through the MIT Lincoln Laboratory LES-5 satellite relay, a significant amount of data relevant to the objectives was acquired by other means, including airborne recording of noise and interference, library research on global frequency allocations in the pertinent part of the RF spectrum, and airborne recording of UHF beacon transmissions from the LES-3 satellite.

## B. SUMMARY OF OBJECTIVES

For a low-cost feasibility demonstration it was necessary to consider installations in existing operational aircraft, ships, submarines, and other vehicles, and the use of existing hardware wherever possible. Other significant factors included the operating environment, the need for compatible communication procedures, and the selection of suitable criteria for evaluating the utility of this new transmission medium.

Since the range to the satellite was approximately 20,000 n mi and its antenna coverage included almost a third of the surface of the earth, it was necessary to account for all potential sources of noise and interference and ensure sufficient radiated power from the various terminals to achieve satisfactory results.

Several factors resulted in preference for relatively simple wide-angle antenna for aircraft, ships, and submarines. For the case of the aircraft, these were the cost of structural modification, drag effects at high speed, and the desire to avoid the expense and problems of a tracking mode; for the Navy vessels, these factors included the cost of installation, the need to maintain communication at various sea-states, and lack of space. The use of a low-gain antenna together with the modest effective radiated power of the satellite transmitter made all potential sources of noise and interference to the terminal receiver of vital concern.

The measurement of the quantitative behavior of the propagation medium and its effect on specific types of modulation and transmission systems was also required. The factors considered included multipath fading due to aircraft or ship motion, scintillation fading, Faraday rotation of the plane of polarization, and ducting. After the program was expanded to include the use of vehicular ground terminals, the measurement of attenuation through foliage was addressed.

Other required data included satellite coverage (how low on the horizon the satellite relay was usable); the effect of antenna patterns; the possible interference to other services caused by the satellite and terrestrial transmitters; and performance with various types of traffic, such as teletype, voice, and data.

## SECTION II

## PARTICIPATING AGENCIES AND MAJOR CONTRIBUTIONS

Table I is a summary of agencies participating in the tests, together with major activities, types and locations of terminals, etc. Table II shows typical test circuit locations. In addition to those organizations directly involved in testing (listed in Tables 1 and II), others made significant contributions toward the success of the program. These organizations and their major activities are shown below. Any omission of significant activities of other agencies is an oversight of the editors.

| | |
|---|---|
| Oklahoma City Air Materiel Area (OCAMA)<br>Tinker AFB, Okalahoma | Installation of terminal equipment in SAC operational B-52s, KC-135s |
| US Noal Electronics Command<br>Washington, D. C. | Coordination and management of Navy tests and measurements |
| USAF Communications Service<br>Scott AFB, Illinois | Controller of LES-5 test network, April 1968 |
| Air Weather Service<br>Scott AFB, Illinios | Participation with RADC and USASCA in weather facsimile tests |
| Electromagnetic Compatibility Analysis Center (ECAC)<br>Annapolis, Maryland | Interference measurements and studies at Andrews AFB, Maryland, and McClellan AFB, Sacramento, California |
| Federal Aviation Agency (FAA)<br>Washington, D. C. | Technical liaison and supply of pertinent data from ATS-1 tests |

In addition to the above, at least two industrial contractors conducted internally supported test activities:

| | |
|---|---|
| Electronic Communications, Inc.<br>St. Petersburg, Florida | Testing with 1 kW transmitter and high gain antenna; support via phone patch to U. S. STRIKE COM for test link to Middle East. |
| The Boeing Company<br>Commercial Airplane Division<br>Seattle, Washington | Recording Faraday rotation and fading on LES-3; CW recording on LES-5 in cooperation with NELC |

## TABLE 1. PARTICIPATION IN LES-5 TESTS

| Agency | Activities | Types of Terminals | Terminal Locations |
|---|---|---|---|
| SAMSO/Aerospace Crop. Los Angeles, Calif. | Program management & system coordination | | |
| | Design & Construction of RFI radiometers | | |
| | Reduction of RFI data | | |
| | Satellite integration launch, & orbital support | | |
| MIT Lincoln Laboratory Lexington, Mass. | Design & construction of LES-5 satellite | | |
| | On-orbiting testing | Fixed | Lexington, Mass. Camp Parks, Calif. |
| | Airborne noise measurement | C-135 & C-131 aircraft | Eastern U. S. Atlantic Ocean & Caribbean Sea |
| | Airborne propagation measurement with LES-3 beacon | JC-135 | Based at ASD, WPAFB; measurements taken at Pacific & Antarctic |
| | RFI investigations | EC-135 | Westover AFB, Mass. |
| | | Destroyer | Newport, R. I. |
| Naval Electronics Lab Center (NELC) San Diego, Calif. | Technical communication testing | Shore terminal | San Diego |
| | Propagation measurements | "Jeep" class Aircraft Carrier (LPH-2) Iwo Jima | Ships based at San Diego |
| | | Cruiser Oklahoma City | Ships based at San Diego |
| | | USS Eldorado AGC-11 | Ships based at San Diego |
| Naval Air Test Center (NATC) Patuxent, MD. | Technical communication testing | (2) P-3A aircraft | Based at Patuxent, Md. |
| | Operational feasibility testing (airborne) | Shore station | Point Lookout, Md. |
| Navy Underwater Sound Labs (NUSL) New London, Conn. | Technical communication testing | Shore station | Fishers Is., N. Y. |
| | | "Guppy" class Submarine Sea Leopard | Based at Norfork, Va. |
| Rome Air Development Center (RADC) | Technical communication testing | Fixed station | Floyd Test Site Rome, N. Y. |
| | Support for operational feasibility testing | | |

## TABLE 1. PARTICIPATION IN LES-5 TESTS (Cont'd)

| Agency | Activities | Types of Terminals | Terminal Locations |
|---|---|---|---|
| U. S. Strike Command (STRIKE)<br>MacDill AFB, Fla. | Operational feasibility testing | (2) Transportable shelters | Florida |
| | | Fixed (ECI operated) | Middle East |
| USAF Strategic Air Command (SAC)<br>Hq. Offutt AFB, Nebr. | Operational feasibility testing | (6) EC-135C | Based at SAC Hq., Offutt AFB, Nebr. |
| | Network controller for all; communication tests for first nine months | (3) Bombers B-52H | Based at K I Sawyer AFB, Mich. |
| | | (3) Tankers KC-135A | Deployed at Ileson, Alaska; based at K I Sawyer AFB |
| Aeronautical Systems Division (ASD)<br>Air Force Avionics Lab (AFAL)<br>Wright-Patterson AFB, Ohio | Procurement of USAF feasibility terminal equipment | Experimental Bomber NB-52C | Based at WPAFB |
| | Technical communication testing with specially instrumented aircraft. | Experimental Tanker JC-135A | Based at WPAFB operated world wide |
| | Airborne measurement of propagation phenomena & RFI | | |
| U. S Army Satellite Communication Agency (USASATCOMA)<br>Ft. Monmouth, NJ | Technical communication testing | (2) 1/4 ton trucks<br>(2) 3/4 ton trucks | Ft. Monmouth, N. J.<br>Eastern U. S.<br>Ft. Huachuca<br>Panama<br>Canada<br>UK and Western Europe<br>Puerto Rico |
| | RFI testing | Van (semifixed) | |
| | Operational feasibility demonstrations with U. S. Army Air Defense Commands, and Army Components of Unified Command | | |
| | Coordination of NATO participation | | |
| USAF Cambridge Research Station (CRL)<br>Lexington, Mass. | Measurements of scintillation fading | Fixed | Lexington, Mass. |

TABLE 2. SUMMARY OF TEST CIRCUITS

| Location | Agency |
| --- | --- |
| **I. AIR-TO-AIR LINKS (approx. 1200 hr of testing)** | |
| S. E. Asia - CONUS | ASD |
| Arctic - CONUS | SAC, NATC, ASD |
| Antarctic - CONUS | ASD |
| Europe - CONUS | NATC, ASD |
| Africa & Indian Ocean - CONUS | ASD |
| Alaska - CONUS | SAC |
| South America - CONUS | NATC, ASD |
| Australia - CONUS | NATC |
| Pacific (Hawaii) - Atlantic (Europe) | ASD |
| **II. SHIP & SUBMARINE LINKS (over 1000 hr testing)** | |
| Pacific (San Diego Area) - Atlantic (New London & Norfolk) | NELC, NUSL |
| **III. MOBILE, TRANSPORTABLE, & FIXED GROUND TERMINALS (over 2000 hr of testing)** | |
| Canada, UK, Germany, Belgium, Holland, Italy - CONUS | USASCA, RADC, NELC |
| Middle East - U. S. | STRIKE, RADC |
| Panama - U. S. | USASCA |

SECTION III

DISCUSSION OF OBJECTIVES

## A. ENVIRONMENTAL OBJECTIVES

### 1. Propagation

#### a. Multipath Fading

Results of the early Syncom II VHF experiments with commercial aircraft indicated the presence of severe fading especially when the aircraft was over water. The geometry of the situation is shown in Fig. 1. Transmission between aircraft (or ship) and satellite may be via the direct path L or the reflected path X and Y. Since the aircraft antenna beam is usually broad, energy received from both paths can be nearly equal. This can result in signal enhancement or cancellation depending on the difference in path lengths (in terms of the wavelength $\lambda$). The cancellation may be nearly complete if the reflection coefficient is close to unity. This situation is representative of specular reflection, which may be expected with reflection from water and a small incident angle

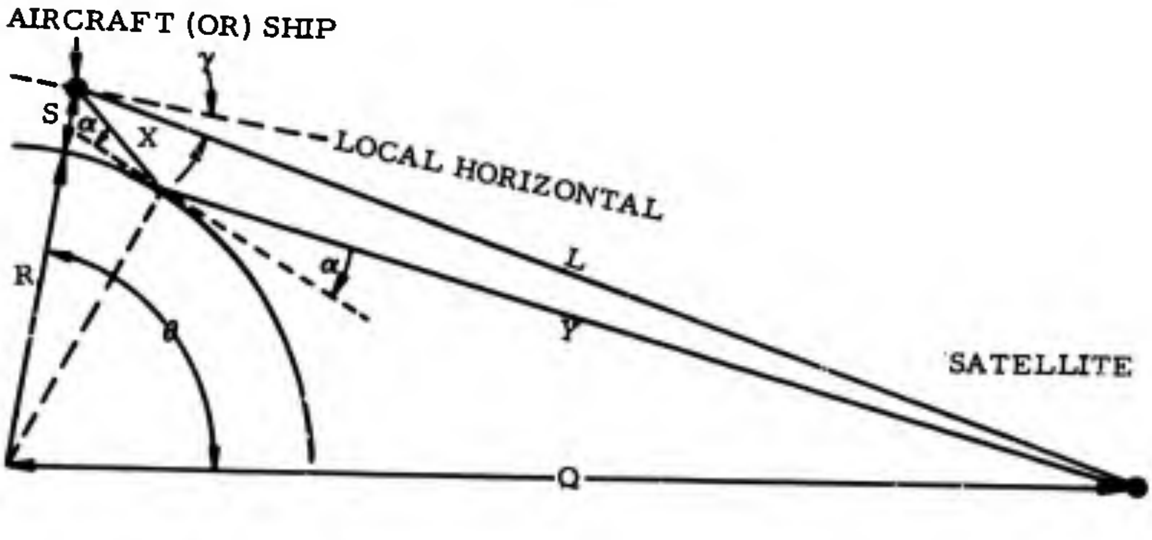


Figure 1. Geometry for Aircraft-to-Satellite Transmission

Under other conditions the reflection may be diffuse, resulting in a variable amplitude reflected ray. For this case, the fading due to cancellation is generally less severe. Hence, the specular case is addressed in more detail. Differential delay and fading rate are the significant factors.

They depend on aircraft altitude S, satellite orbital radius Q, earth radius R, and great circle angle $\theta$ between aircraft and satellite subpoints. The fade rate also depends on the component of relative velocity between aircraft and satellite in the plane of the paper. Figure 2 shows a typical variation with $\theta$. For subsequent convenience the satellite look angle $\gamma$, defined as the satellite position relative to the aircraft local horizontal, is also shown. Figure 3 shows a theoretical calculation of the depth of specular fading plotted against satellite look angle $\gamma$ for horizontal and vertical polarization, assuming smooth sea water reflection and based on theoretical expressions for variations of reflection coefficient $\rho$ with incident angle $\alpha$.

In anticipation of the need for some form of diversity to combat this degradation, one could transmit the same information on more than one frequency. If the frequency separation is the reciprocal of twice the differential delay the fading will be anticorrelated; that is, the amplitude of one transmission frequency will be at a maximum when the other is at a minimum. Since the maximum frequency separation is constrained by the RF bandwidth allocation and the differential delay varies with a number of factors, as discussed above, the amount of protection possible is usually limited. In general, it is not possible to provide diversity at very low look angles (very small differential delay).

The evaluation of the interacting factors discussed above and the performance of the diversity technique was a major test objective and a strong factor in the selection of the modulation and transmission system for the SAC feasibility equipment. In anticipation of the need for preliminary data, Lincoln Laboratory incorporated a UHF beacon transmitter in the LES-3 satellite, launched in December 1965, and recorded the received signal structure on an experimental EC-135 aircraft. The beacon was phase modulated at a 100 kHz rate with a shift register generated digital sequence 15 bits long. Analysis of the received signal spectrum and its variation with time provided an early estimate of multipath and fading behavior.

b. Faraday Rotation

This effect was also strongly evident in the Syncom tests. If transmission from the satellite or aircraft is linearly polarized, the plane of polarization will rotate at a rate dependent on the transmission frequency angle between the earth's magnetic field and direction of propagation, and the integrated electron density traversed by the path. At VHF and UHF, the rotation can cause prohibitive transmission outages if linearly polarized antennas are used at both ends of the link. The ideal solution is to provide circular polarization (CP) antennas at each end.

If CP is used at one end and linear at the other, a 3 dB polarization loss results. The degree of ellipticity in the CP field is also of interest since it results in an amplitude variation.

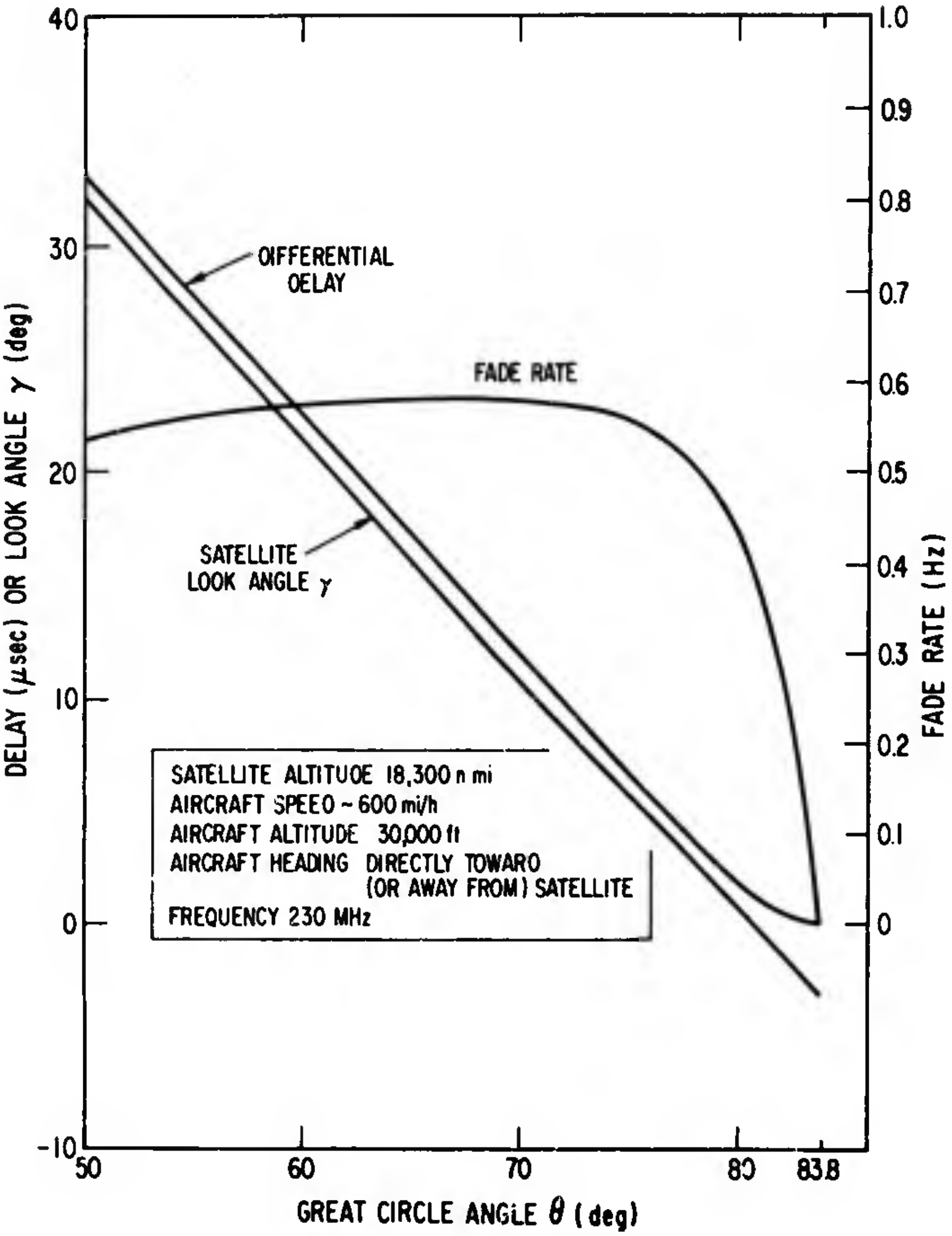


Figure 2. Two Ray Multipath Fading Rate and Delay

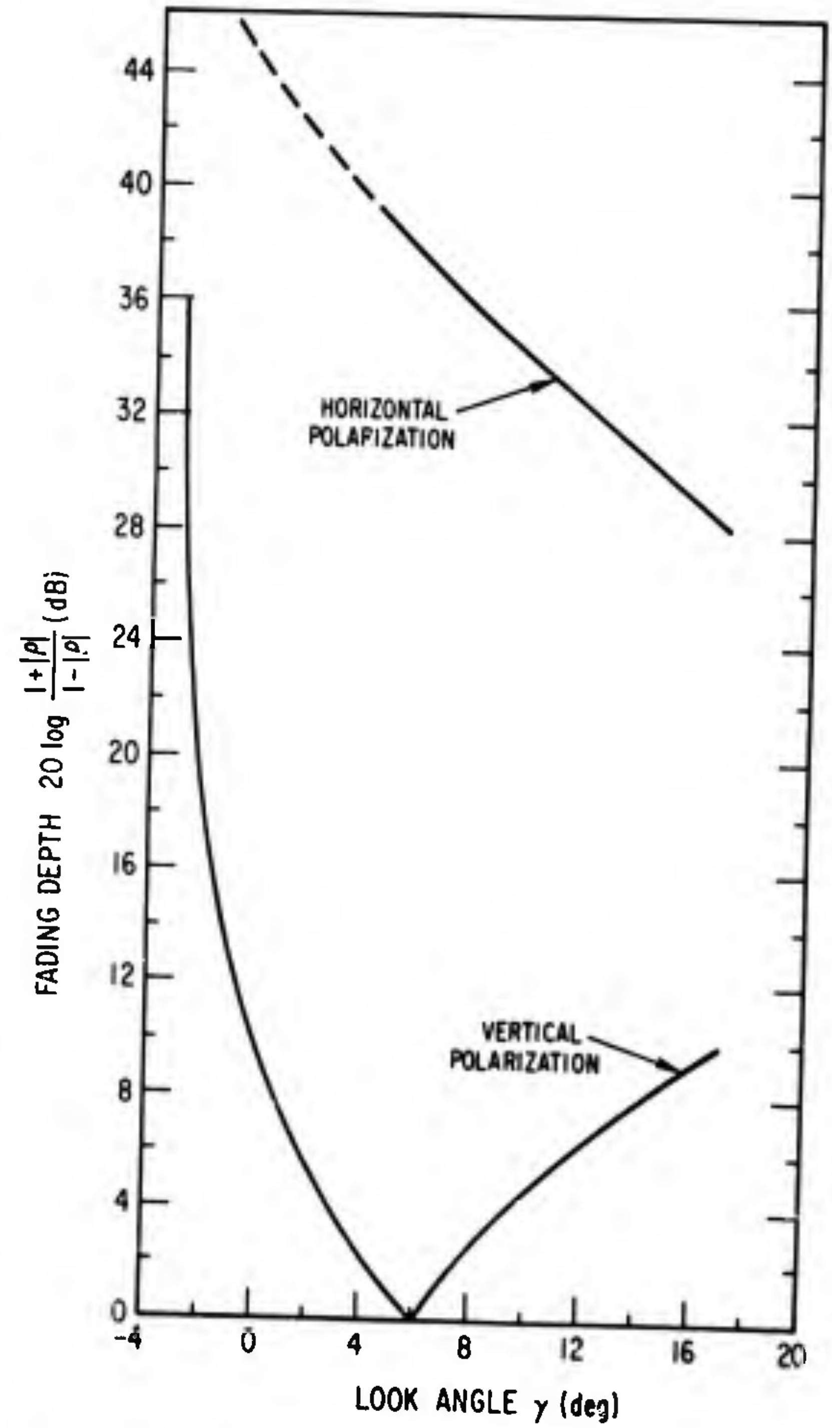


Figure 3. Fading Depth vs Satellite Look Angle, Specular Reflection (Smooth Sea Water).

c. Ducting

The ducting effect is well known in air and ground communication. It is caused by the presence of an inversion layer in the atmosphere or troposphere, which results in a trapping or waveguide effect, sometimes extending the transmission range well beyond line of sight and often resulting in severe fading.

d. Scintillation Fading

This is a fluctuation in amplitude believed to be caused by variations in ionosphere structure. It is dependent on radio frequency, geographic position, and geomagnetic conditions.

e. Satellite Horizon Fading

The motion of a near-synchronous satellite should provide a slow, deep, multipath type of fading when it is "rising" or "setting." The effect of the geometry is similar to that discussed in Paragraph a. This is of particular interest for ground stations attempting to utilize the satellite at a very low look angle.

f. Foliage

The attenuation of heavy foliage (especially the wet, dense variety found in jungle areas) at UHF and VHF imposes a severe limit on ground transmission range. For air- or satellite-to-ground transmission, the problem is less severe since the propagation path encounters less foliage. Data on this type of path was very scant when the program started.

2. Noise

A number of sources of natural noise are potential contributors to both the satellite and aircraft receivers. For convenience, the levels may be specified in terms of absolute temperature (degrees Kelvin), and the temperatures of the multiple sources may be summed to obtain the resulting level. As a reference point, a $000^{\circ}$K noise temperature corresponds to 198.6 dB below 1 W/Hz.

Noise generated in the receiver front ends (assuming a 4 dB noise figure) is about $450^{\circ}$K at 250 MHz. The earth is a radiating source at about $300^{\circ}$K. The contribution of each of these two sources to the satellite and aircraft receivers depends on the antenna beamwidths.

Three additional external noise sources are potentially troublesome to the airborne receiver. Noise bursts due to lightning discharges can be several thousands of degrees at close range. Precipitation static, generated by discharges from aircraft structure (e.g., wing tips), can be serious, but the use of modern discharge devices and care in the design and location of the antennas can reduce it to a negligible amount. Large urban areas act as a distributed source of broadband noise. Probably most of it is traceable to electral apparatus. This problem will, of course, diminish with altitude and antenna pattern discrimination.

3. Radio Frequency Interference

The military UHF band (225 to 400 MHz) is heavily populated with air-to-ground and air-to-air communication circuits. The U.S. Air Force and U.S. Navy are the largest users. The band is also employed for ground and shipborne radar equipments, telemetry, civil point-to-point radio circuits, radio astronomy, and other scientific applications. Although the majority of users are regulated by official allocation and frequency assignment, there is no global control. Thus, a very important question in the program was what a satellite receiver (with an official experimental frequency assignment and thus presumably a clear channel) might encounter at near-synchronous altitude. A similar question existed as to what an aircraft at 30,000 ft with an essentially omnidirectional antenna might encounter at various geographic locations. The problem was approached first with analysis and estimate and then with actual measurements. Estimates of interference level versus frequency at both aircraft and satellite altitude were synthesized from all known reliable sources of information on allocations, assignments, or actual transmission. A scanning radiometer was designed for measurement and recording (or transmission by telemetry) of the peak and average RF level over approximately 25 MHz. Radiometer measurements were made both in orbit and in an experimental aircraft covering a number of significant locations around the world including the Vietnam area.

Other sources of interference may exist on the aircraft itself. For example, some aircraft already include five 1000 W UHF transmitters and a 1 kW HF transmitter. A potential source of on-board downlink interference on Navy ships is the UHF search radar, such as the SPS-43 with a 180 kW peak power in the 205 to 224 MHz range. Obviously each type of terminal installation may have its own peculiar brand of local RFI problem. This on-board interference is not a new problem, but it becomes more pronounced because of the high sensitivity of the receivers required for the satellite link.

The question of interference from the satellite or terminal transmitters to equipments not involved in the program was also considered. The frequency allocations for the experiment were on a noninterference basis. Of particular interest was the effect of spread spectrum transmission in reducing the spectral density of the emitted energy to an insignificant level as received by conventional systems.

## B. OPERATIONAL FEASIBILITY OBJECTIVES

A number of factors were considered in the design of the experiment to evaluate operational feasibility in aircraft. The crew-equipment interface was designed for minimum operator training. Automatic acquisition of the received signal and automatic hard copy teletype printout were to be incorporated. Off line transmit operation was chosen as a means to permit the operator to prepare the message using "hunt and peck" on the teletype keyboard and then to check its accuracy prior to pushing the button for automatic transmission at constant speed. Use of standard teletype equipment in fleet aircraft would require compromises in the location of the equipment so that the designated crew member could operate it without an untenable degree of awkwardness.

It was desired to evaluate the time required to prepare the message, the number of repeated transmissions needed, and received message accuracy in terms of error rates. Operational procedures were to be evolved and checked to permit net operation.

Performance was to be evaluated as a function of satellite look angle, aircraft attitude, aircraft heading, aircraft altitude, noise conditions, and interference conditions. Since such performance parameters can only be qualitatively assessed with fleet aircraft performing their regular missions, it was decided to augment these tests by means of the ASD (Aeronautical Systems Division/AFAL) experimental aircraft with adequate instrumentation.

The need for compatibility with operational aircraft caused several problems. Existing installed equipment was unsatisfactory for the experiment because of the type of modulation (AM), poor receiver noise figure (>15 dB), inadequate power output, inadequate stability, and antenna location. A top-mounted, circularly polarized antenna with a good pattern would have been highly desirable, and efforts were made to incorporate such an antenna. It was finally determined, however, that available antenna types were not suitable for installation on the operational aircraft and a top-mounted, linear-polarized blade antenna would have to suffice. Tests with other types of antennas would then be made aboard the ASD experimental aircraft.

It was found necessary to install a low noise preamplifier directly below the antenna and to include various RF filters to reduce interference from other on-board transmitters. In the B-52 aircraft, because of space limitations, the high power (1 kW) transmitter was installed in the unpressurized portion of the aircraft.

## C. OTHER FEASIBILITY OBJECTIVES

The performance of other modulation and transmission techniques was evaluated by various participating organizations. Spread spectrum equipments using different techniques were tested. Additional techniques evaluated included conventional radioteletype, voice frequency teletype, FM voice, and single sideband.

The feasibility of communication with other types of terminals was explored, including U.S. Navy ships, submarines, and aircraft mobile terminals, Army ground vehicle terminals, and various fixed terminals.

Operation of a Tri-Service net was another objective, necessitating a common modulation system. Since the SAC feasibility experiment imposed particular constraints, it was decided that the modulation technique to be used for the interservice net would be that of the SAC aircraft.

## D. CHOICE OF OPERATIONAL FEASIBILITY TECHNIQUE AND TERMINAL EQUIPMENT

Equipment makeup for the SAC feasibility experiment was dictated by severe limitations on time and funds. These constraints required minimum development of new hardware and maximum use of available equipment, modified as necessary.

Frequency shift triple time-frequency diversity modulation at 60 WPM was chosen to allow operation under predicted multipath fading conditions and to provide some protection against narrow band interference. In this method of modulation, each bit is broken into three chips, which are transmitted sequentially, each over one of the three frequency diversity channels. Time-frequency diversity was chosen rather than straight frequency diversity to allow operation with Class C terminal transmitters and a hard limiting satellite repeater without intermodulation problems (single access). Two of the channels needed sufficient separation for diversity at low look angles in the presence of predicted specular multipath fading. The third channel was needed for diversity at high look angles in the presence of predicted specular multipath fading where the two end channels could fade together. The end channels are separated by 85 kHz, with the middle channel located 25.5 kHz from the low channel. For each channel the mark and space filters are located 5 kHz apart, i.e., large enough for automatic acquisition without severe frequency stability requirements and small enough for "coherent" fading of the mark and space channel.

A top-mounted blade antenna was selected. A modified ECI transmitter with 1 kW CW output provided power for the uplink. In order that adequate uplink power was ensured in the face of unfavorable aircraft aspect and in the presence of interference, the maximum practicable transmitter power was employed. A 3.5 dB preamplifier with 25 dB gain was installed directly below the antenna. The modem, designed and built by ECI, includes a highly selective receiver with automatic frequency search and track; triple time-frequency diversity detectors, chip and bit synchronization, and diversity combiner; and a triple time-frequency exciter with sufficient power to drive the 1 kW amplifier. A standard Kleinschmidt teletype printer, keyboard, tape punch, and transmitter distributor equipment was selected for input-output devices.

## SECTION IV

## DESCRIPTION OF EQUIPMENT

### A. TERMINAL CHARACTERISTICS

Characteristics of the terminals used in the tests by the various participants are summarized in Table 3.

### B. SATELLITE

The physical characteristics of the LES-5 are given in the first section of Table 4. A descriptive drawing of the satellite indicating the antenna position as well as the various dimensions is given in Figure 4; a functional block diagram of the LES-5 transponder is given in Figure 5. The various communication characteristics of the transponder and its antenna are given in Section 2 of Table 4. Power budgets for the uplink and downlink of a typical aircraft-to-satellite link based upon these characteristics are presented in Table 5.

#### 1. LES-5 Antenna System

The antenna system recieves and transmits signals with nominal RHCP. The component of E parallel to the spacecraft is provided by eight center-fed dipoles, which are deployed from their stowed position. The orthogonal component of the E vector is provided by eight cavity-backed slot pairs. (The members of each pair lie above and below the sensor view band.)

#### 2. LES-5 Transponder

The uplink signals, band centered on 255 MHz, are recieved and separated by the triplexer from the down link and telemetry signals. After amplification and filtering, they are mixed with the 222.5 MHz local oscillator to obtain an IF of 32.6 MHz, where two crystal bandpass filters with nominal bandwidths of 100 kHz and 300 kHz are command selectable.

After linear amplification and bandwidth selection at IF, the received signals enter an IF variable gain amplifier and hard limiter. The limited and filtered IF output is mixed up to RF at the downlink carrier (centered on 228.2 MHz). It is then linearly combined with the narrow band beacon, power amplified, and passed to the antenna by way of the triplexer.

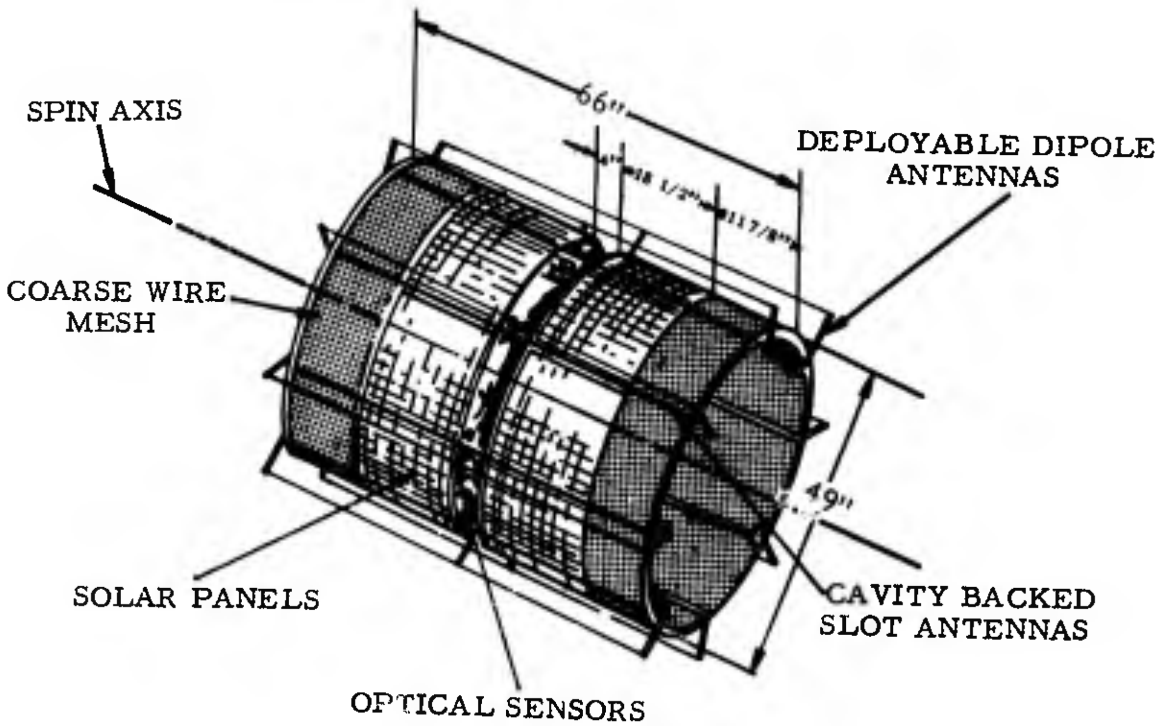


Figure 4. Basic Size Description of LES-5.

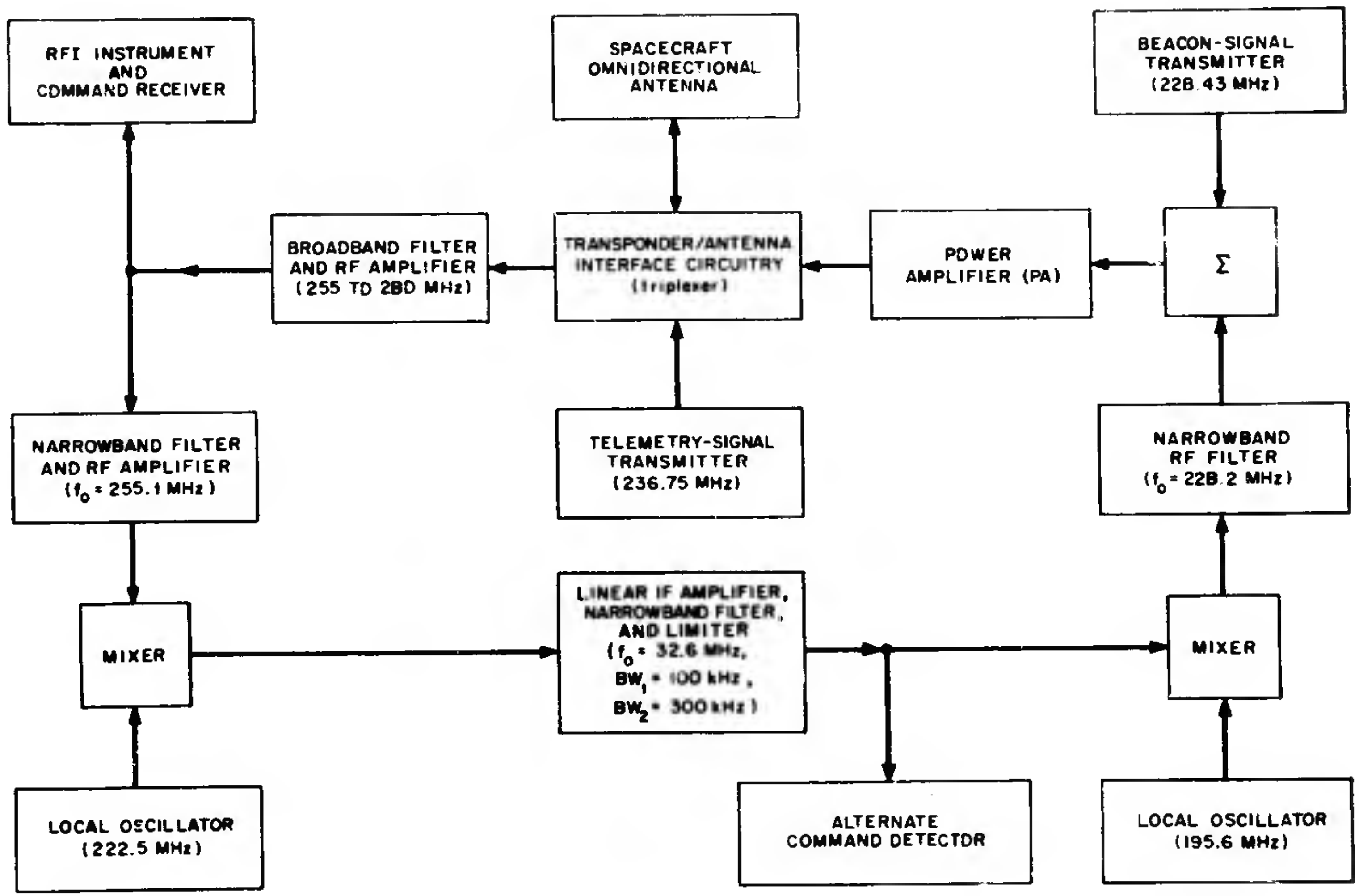


Figure 5. LES-5 Transponder and Associated Subsystems.

# TABLE 3. SUMMARY OF TERMINAL CHARACTERISTICS

| Agency | Terminal Types | $P_0$ (dW) | Antenna Type | Antenna Gain (dB) | Antenna ERP (dBW) | System Noise Temperature, Est. (K) | Modulation Systems |
|---|---|---|---|---|---|---|---|
| Lincoln Laboratory | Mobile LET-4 | 1 | Helix antenna | 12 | 42 | For both 650 min. est. value; however system generally operated in high RFI environment | Digital |
| | Lexington Terminal | 1 | 30 ft. paraboloid | 24 | 54 | | |
| Aeronautical Systems Div. Air Force Avionics Lab ASD/AFAL Wright-Patterson AFB, Ohio | NB-52C exp. bomber | 1 | Blade and loop vee | 0 | 30 | 1200 | Common (60 WPM frequency/time-diversity TTY) |
| | JC-135A exp. tanker | 1 | Dorne Margolin crossed-slot | 0 | 30 | 800 | |
| Rome Air Development Center (RADC) Rome, N.Y. | Fixed | 10 | 33-ft diam parabolic reflector | 25 | 65 | 650 | a. Common<br>b. CW<br>c. FM voice<br>d. 100 WPM TTY<br>e. Facsimile |
| USAF Strategic Air Command (SAC) Offutt AFB, Nebr. | EC-135C | 1 | Blade | 0 | 30 | 1200 | Common |
| | KC-135A tanker | 1 | Blade | 0 | 30 | 1200 | |
| | B-52H bomber | 1 | Blade | 0 | 30 | 1200 | |
| U.S. Army Satellite Communication Agency (USASCA) Ft. Monmouth, N.J. | Truck 1/4 ton | 0.100 | Crossed yagi | 12 | 32 | 1500 | a. Common<br>b. FM voice<br>c. 100 WPM TTY<br>d. Facsimile |
| | Truck 3/4 ton | 1 | Helix | 15 | 45 | 1500 | |
| | Van (semifixed terminal) | 1 | Quad helix | 22 | 52 | 1500 | |

TABLE 3. SUMMARY OF TERMINAL CHARACTERISTICS (Cont'd)

| Agency | Terminal Types | $P_0$ (dW) | Antenna Type | Gain (dB) | ERP (dBW) | System Noise Temperature Est. (K) | Modulation Systems |
|---|---|---|---|---|---|---|---|
| Navy Electronic Labs Comd. (NELC) San Diego, Calif. | Shore station | 1 | 28-ft dish | 23 | 53 | 920 | a. Common<br>b. FM voice<br>c. CW<br>d. Facsimile<br>e. 75% modulated AM voice |
| | | | Helix | 14 | 44 | 1000 | |
| | Iwo Jima aircraft carrier | 1 | Helix; stacked-dipole; conical log spiral | 14 | 44 | 1000 | |
| | Oklahoma City cruiser | | | | | | |
| | USS Eldorado | 1 | Stacked, pole conical log spiral | 8 | 36 | 1000 | |
| U.S. Naval Underwater Sound Lab (NUSL) New London, Conn. | Shore station | 1 | Helix | 12 | 42 | 920 | a. Common -- submarine to shore<br>b. CW shore<br>c. SSB (AM) shore<br>d. Simultaneous CW & SSB |
| | Sea Leopard, submarine | 1 | Loop vee | 0 | 30 | 945 | |
| | | | Phased array | 12 | 42 | | |
| Naval Air Test Center (NATC) Patuxent, Md. | P-3A aircraft | 1 | Loop vee and Dorne Margolin | 0 | 30 | 945 | Common |
| U.S. Strike Command (STRIKE) MacDill AFB, Florida | 3/4 ton truck terminal with modified AN/TRC-24 equipment | 0.150 | 6-ft 20-element CP yagi array | 12 | 34 | 1000 | a. 100 WPM TTY<br>b. FM voice<br>c. Common |

## TABLE 4. PHYSICAL, COMMUNICATION, AND ORBIT CHARACTERISTICS OF LES-5

| | | |
|---|---|---|
| **PHYSICAL CHARACTERISTICS** | | |
| Weight | 225 lb | |
| Size | Cylindrical, 48 in. diam x 66 in. length | |
| **COMMUNICATION CHARACTERISTICS** | | |
| Downlink | Transponder | Beacon |
| Center frequency | 228.2 MHz | 228.43 MHz |
| Frequency translation or offset | --- | ~-100 Hz |
| Before 24 Jan. 1968 | ~-150 | |
| After 24 Jan. 1968 | ~+1700 Hz | |
| Nominal bandwidth | 100 or 300 kHz (switchable) | 800/sec biphase modulation of carrier |
| RF power | 45 W | 3.5 W |
| Antenna | | |
| Polarization | RHCP | RHCP |
| Gain, satellite equator | 2.5 dB | 2.5 dB |
| Gain, 7 deg off beam | 2.0 dB | 2.0 dB |
| 3 dB beamwidth | 37 deg | 37 deg |
| Axial ratio, worst case | 3 dB | 3 dB |
| Telemetry power | 28.6 dBm (0.72 W) | |
| Antenna gain @237 MHz | -0.5 dB | |
| ERP | 28.1 dBm (0.64 W) | |
| Uplink | Transponder | |
| Center frequency | 255.1 MHz | |
| Receiver sensitivity | | |
| Before 18 Mar. 1968 | -115 dBm (300 kHz)<br>-120 dBm (100 kHz) | |
| After 18 Mar. 1968 | -98 dBm (300 kHz)<br>-103 dBm (100 kHz) | |
| Passband ripple (sensitivity variation from that for 225.12 MHz) | | |
| Narrow band (100 kHz) | -1.5 dB (more sensitive)<br>+1.0 dB (less sensitive) | |
| Wideband (300 kHz) | -2.0 dB (more sensitive)<br>+5.0 dB (less sensitive) | |
| Antenna | | |
| Polarization | RHCP | |
| Gain, satellite equator | 2.2 dB | |
| Gain, 7 deg off beam | 1.7 dB | |
| 3 deg beam width | 32 deg. | |
| Axial ratio, worst case | 3 dB | |
| **ORBIT CHARACTERISTICS** | | |
| Orbit | ~18,000 n mi near circular 7 deg inclination | |
| Drift rate | ~32.93 deg per day, eastwardly | |
| Spin rate | Approximately 10 r/min | |

TABLE 5. TYPICAL LES-5 LINK AND MARGIN CALCULATIONS (AIRCRAFT TO SATELLITE)

| | |
|---|---|
| **UPLINK** | |
| Airborne terminal ERP | 30 dBW |
| Path loss @ 255 MHz (extreme range) | 172.5 dB |
| Satellite antenna gain | 2 dB |
| Polarization loss | 3 dB |
| Noise power density $N_0$ (1000°K) | -198 dBW/Hz |
| Signal-to-noise ratio prior to limiting (100 kHz bandwidth, no fading) | 4.5 dB |
| Estimated S/N after limiting, no fading | ~6 dB |
| **DOWNLINK** | |
| Satellite ERP (nominal) | 17 dBW |
| Path loss (extreme range) @ 225 MHz | 172 dB |
| Airborne antenna gain | 0 dB |
| Polarization loss | 3 dB |
| Noise density (1000°K) | -198 dBW/Hz |
| Incidental losses: Antenna pattern<br>Antenna feeds<br>Equipment degradation | Not considered |
| Received power $P_R$ (expected) | -158 dBW |
| Received power (measured) | (-156 to -165 dBW) |
| $P_R/N_0$ (expected) | 40 dB ref to 1 Hz |
| $P_R/N_0$ (actually obtained) | (33 to 42 dB ref to 1 Hz) |
| Theoretical $P_R/N_0$ required for $10^{-3}$ error rate (triple time frequency division 100 WPM TTY, no fading) | 30 dB ref to 1 Hz |
| $P_R/N_0$ demonstrated to achieve $10^{-3}$ error rate, no fading | 31 dB ref to 1 Hz |
| Required fade margin, triple diversity assuming "Ricean" fading with equal power in both paths | 2 dB |
| Available margin with "Ricean" fading (ignoring uplink degradation) | 0 to 9 dB |

## SECTION V

## TEST RESULTS

### A. GENERAL

The basic objectives of the program have been achieved in nine months of testing. The technical and operational feasibility of using a UHF repeater satellite for tactical communications has been demonstrated by the use of LES-5. In addition, useful data has been obtained (through testing with LES-5, analyses, nonsatellite testing, and component development) in the areas of propagation, noise, interference, and equipment characteristics that have been and will be of value in the design of follow-on TACSAT systems and components.

Communication tests with LES-5 have been very successful, and the performance of the repeater on orbit has met the predicted values around which the program was designed.

Useful information from the RFI experiment via the telemetry channels has been limited to "night" periods when the earth eclipses the sun at the satellite and the earth sensors view a dark earth disc. At other times, an earth-sensor-associated discrepancy causes serious timing perturbations in the RFI-telemetry subsystems.

On 18 March 1968, after the basic objectives had been achieved, the transponder receiver sensitivity permanently decreased 16 dB. This decrease has been attributed to a transistor stage failure in the preamplifier, which, according to telemetry data, occurred during an eclipse period as LES-5 entered its second eclipse season. As a consequence, no further useful RFI data is expected. Additional air-to-air test data has been accumulated, but with higher error rates as expected. Ground-to-ground or ground-to-air communication with less sensitive equipment is possible where either the ground transmitter radiates sufficient power to override the repeater noise, or the ground receiving antenna has sufficient gain to tolerate the loss in repeater signal power resulting from the power-limited aircraft terminals.

### B. OPERATIONAL FEASIBILITY TESTS

#### 1. Air Force

Operational tests in SAC mission aircraft using regular crew members as operators were reported as generally successful. Analysis of 530 messages transmitted during five satellite passes showed that 318 were received as "good" ($10^{-3}$ to $10^{-4}$ bit error rate), 13 were "acceptable" ($10^{-2}$ to $10^{-3}$ error rate), and the remainder were unacceptable or missed; 95% of the failures were attributed to inadequate equipment maintenance. Negligible operator training was provided or needed. Crew reaction ranged from good to excellent.

The ASD aircraft test results showed that error rates of $10^{-5}$ were obtained for look angles of 3 to 40 deg with level flight and no RFI. From grazing incidence to 3 deg, $10^{-3}$ error rates were obtained which were attributed to fading, ducting, and reduced antenna gain. From 40 to 65 deg error rates of $10^{-2}$ were obtained, and the blade antenna performed better than the loop vee. Above 65 deg, with the link margins available, performance was unpredictable. Above 40 deg, antenna patterns were the chief cause of degradation.

Strike Command modified existing equipment to form Sat Com terminals and successfully demonstrated the passing of four-channel 100 WPM teletype traffic. During an exercise in the MEAFSA area, voice communications via modified radio relay mobile units demonstrated the feasibility of FM voice.

2. Navy

Teletype tests of an operational feasibility nature using the triple time-frequency diversity technique were conducted aboard ship, submarine, shore, and aircraft terminals. Communication of messages were successful for all terminals when interference from shipboard UHF long-range, air-search radars was not encountered. With the aircraft terminal on deck, surface-to-surface tests yielded 99%-error-free messages, while surface-to-air and air-to-air tests resulted in 90%-error-free messages. No significant change in performance was noted as a function of heading or altitude from 500 to 28,000 ft. Operation was successful for look angles from about zero to 55 deg. Dropouts occurred during banks when the aircraft antenna pattern was shadowed. On the other hand, communication at high look angles was restored when the aircraft was banked to avoid the overhead antenna null being directed toward the satellite. Two types of aircraft antenna were tried. Performance of the loop vee antenna appears to be essentiallv as reported from the tests on the ASD aircraft.

In one reported instance during use of the loop vee antenna and operation in the North Atlantic, dropout due to precipitation static occurred as the airplane penetrated the clouds. The Dorne Margolin antenna (Model DMC 34-1) employs two switchable configurations, one for low look angles and the other for high look angles. Antenna pattern tests were conducted for elevation look angles to the satellite between 3 and 85 deg. These tests showed that the combined antenna patterns of the two Dorne Margolin antenna modes provided satisfactory coverage over the upper hemisphere of the airplane in level flight. This coverage is equivalent to that of the loop vee antenna at low look angles and superior to that of the loop vee antenna at low look angles. The on-board HF transmitter in the P-3 airplane produced sufficient RFI to cause dropout in the satellite downlink signal; however, interference from the HF transmission did not occur in the special tests conducted in the C-130G.

3. Army

Successful passing of dummy operational-type full duplex voice traffic between a terminal located in the jungles of Panama and a terminal located in the ZI was demonstrated by the use of directional antennas. Other tests of an operational nature were conducted with terminals located in Puerto Rico, Ft. Benning, and Ft. Bragg. Another test was conducted between terminals in the eastern United States to simulate an emergency backup link for Army Air Defense Command. Although both teletype and voice traffic were successfully passed between terminals, the transmission of PCM data by means of on-off keying was not satisfactory.

## C. TECHNICAL RESULTS

### 1. Satellite ERP and Received Signal Power

Measurements made by MIT Lincoln Laboratory confirmed the expected ERP from prelaunch measurements. USASCA and RADC confirmed these results with independent measurements.

Received signal power to be expected at the input to the preamplifier on the C-135 and B-52 aircraft was calculated to be -158 dBW (+3.5 dB) (-6 dB). These tolerances include (+2 dB)(-2DB) for aircraft antenna patterns and obviously do not take into account extreme antenna losses at very high or very low look angles or aircraft maneuvers shadowing the antenna pattern. Values reported from the ASD KC-135 flight tests indicate -158 to -168 dBW as typical, though the data has not yet been reduced to correlate the various factors with individual measurements.

### 2. Aircraft Multipath Fading

Lincoln Laboratory recorded received signal structure from the LES-3 beacon on an experimental KC-135 aircraft. At an altitude of 26,000 ft, specular fading was recorded at grazing angles up to 20 deg (corresponding to a look angle of about 15 deg). Differential delay was in the order of 5 μsec and varied with look angle as the geometric model predicts. With an aircraft speed of 450 mi/h directly toward the satellite, the specular fading rate was about 0.25 Hz, as expected for this altitude. When fading due to diffuse reflection occurred, the amplitude variation showed significant components as high as 50 Hz. An estimate of the effect of the fading statistics for look angles between 5 and 10 deg showed a 10 dB degradation to frequency shift keying (FSK) teletype at a $10^{-3}$ error rate. Fading below the 2 deg look angle was severe (20 to 30 dB), and tropospheric ducting was suspected. The deepest fades occurred with horizontal polarization over sea water.

The ASD flights using LES-5 were primarily in the region of 30,000 ft with aircraft speed about 550 mi/h. They encountered specular fading below 20 deg look angles over ice and water. Very little was seen when over land. Typical fade range was 3 to 5 dB. The deepest (about 7 dB) occurred at look angles of 10 to 15 deg. This correlates well with the theoretical predictions in Figure 3 for vertical polarization, assuming that the antenna pattern discriminates against multipath reflection at higher look angles. In the 20 to 25 deg region, the fading was generally random and insignificant. The frequency diversity system was effective down to about 5 deg. From Figure 2 this corresponds to a 6 μsec delay and correlates well with the inverse of twice the maximum frequency separation. The measured fading rates and differential delays vs look angle are also in good agreement with the predicted values.

3. Fading Observed by Ground Stations

NELC measured 8 dB fades at both their shore and ship terminals at look angles less than 5 deg.

RADC reported fading greater than 10 dB at look angles below 10 deg and smaller variations (up to 5 dB) at angles up to 35 deg.

Lincoln Laboratory recorded fading on their 30 ft antenna (10 deg beamwidth). It was frequent and often deep at angles below 5 deg. Shallower fades occurred occasionally (typically 3 to 10 dB) at angles between 5 and 40 deg for periods ranging from less than 1 min to more than 1 h. The smaller fades occurred at rates ~1/sec. The deeper fades were much slower (5 to 20 sec duration).

AFCRL recorded fading with an 84 ft antenna and a backfire array with a wide beamwidth. Data was received on both ATS-III (137 MHz) and LES-5. The type of fading that is most likely attributed to scintillation occurred mostly during the night and was four times weaker at UHF than VHF. Except for very low look angles (horizon effects) virtually no deep fades were observed at UHF. Except for very low elevation angles, fades greater than 3 dB occurred about 0.15% of the time and >6 dB only about 0.05% of the time. Typical scintillation fading events had durations of 10 to 20 min.

4. Anomalous Fading Noted on Aircraft

ASD encountered an anomalous "fast" fading on a number of flights. It was characterized by rapid random amplitude variations (sometimes from one TTY chip to the next) and appeared to be frequency selective. It occurred only over water, only within 30 deg of the equator, and usually at look angles greater than 25 deg. It was seen on both the loop vee and blade antennas. It usually lasted for about 2 h or less, building up slowly in amplitude and then dying out. The diversity system was effective in countering it except for a few minutes when it was at its maximum intensity. It was noted that a 90 deg change in heading considerably altered its intensity. Smaller changes had little effect. To the best knowledge of the authors, the cause or mechanism explaining the type of fading is still undetermined.

## 5. Fading Connected with Ship's Motion

On board the submarine Sea Leopard, fading ranges of 10 to 14 dB were observed at look angles of 15 deg or less. At higher angles 7 to 10 dB fades were common. The fading seems attributable to a combination of multipath reflection, ship's motion, and antenna pattern effects (antenna beamwidth estimated 25 deg at half power points). When the sea state was at least five (8 to 12 ft peak to peak and 6 sec period) it was possible at times to obtain correlation between recorded amplitude variation and ship's platform motion.

Amplitude variation connected with ship's motion and antenna masking by the superstructure was also encountered on the Iwo Jima.

## 6. Faraday Rotation and Axial Ratio

Lincoln Laboratory measured the axial ratio of the transmitted CP wave from the satellite using a dipole in front of a 3 ft ground plane and found it to be about 2.5 dB, essentially the same as measured at the satellite before launch. Since the transmission was CP, it was not practical to record Faraday rotation with LES-5. The Boeing Company recorded Faraday rotation from the LES-3 beacon. Rotation rates as high as 14 deg/min were recorded, and direction was usually counter-clockwise as viewed from earth.

## 7. Ducting

Very little data was recorded that can be specifically attributed to ducting. It was sometimes suspected when unusually deep fades occurred at low look angles. On several occasions, negative look angle contact was made with the satellite from a shore terminal located at Point Loma. California, 400 ft above the ocean. On one occasion, however, the ASD aircraft flying over Hawaii was able to establish successful communication when the satellite was at a negative 11 deg look angle.

## 8. Foliage Attenuation

During LES-5 tests by the U.S. Army in Panama foliage, using antennas with 12 to 15 dB gain, it was estimated that foliage attenuation was a maximum of 8 dB at a 20 deg look angle and 4 to 6 dB most of the time. Attenuation at 8 deg elevation appeared to be about 2 dB higher.

Prior to the launching of the satellite, Aerospace Corporation personnel conducted field strength measurements at 213 MHz (TV Channel 13 on Mt. Wilson) in California. Measurements in foliage with half-wave dipole antenna varied considerably with small displacements of the antenna. In a pine-tree woods during the dry season at a 3 deg look angle, 8 dB attenuation was typical, though as high as 19 dB in dense areas was observed.

In a botanical garden with foliage from all over the world, the attenuation at a 6 deg look angle ranged from 6 to 14 dB with an average of 10 dB for 15 locations.

Measurements were made by MIT Lincoln Laboratory prior to the launch of LES-5, in dry Massachusetts woods (Ft. Devens) and with a helicopter used as a transmitting terminal at 230 MHz. Results showed an attenuation of ~0.03 dB/ft in groves of oak and pine trees about 50 ft high. This would correspond to approximately 9 dB at a 10 deg look angle.

9. Noise

Noise measurement made on the ASD experimental KC-135 aircraft installation with top-mounted antenna indicated a temperature of 800°K with the aircraft on the ground. Previous calculations had indicated 740°K. Suitable instrumentation was not available for in-flight noise measurements.

MIT Lincoln Laboratory conducted extensive airborne tests to evaluate the levels of galactic and thermal earth radiation, precipitation static, atmospherics, and city noise that would be factors in UHF air-to-satellite communications. Noise temperatures obtained with a top-mounted blade antenna on a C-135 over the Atlantic Ocean resulted in a value of about 150°K. Data taken on a C-131 with downward looking antenna indicated temperature of 250 to 300°K over rural land and 160°K over the Atlantic Ocean. It was concluded that the effects of precipitation static would be negligible with proper static discharges and antenna design. During thunderstorm activity, lightning discharges 10 to 20 mi distant produced bursts of several thousand degrees Kelvin at the rate of 20/min and with a typical burst width of 0.25 sec. Tests with the top-mounted blade antenna over the Miami area resulted in antenna temperatures as high as 1800°K at 226 MHz. Comparing data for actual city temperature with a downward looking antenna measured over a number of cities indicates that the upward looking antenna could see temperatures of up to five times this value depending upon the city, season, and time of the day.

10. Other Tests

a. FDMA Multiple Access

As part of U.S./NATO Tactical Satellite Communication Program, the Army has reported on the results of tests involving terminals in the ZI and foreign countries wherein frequency division multiple access FM was demonstrated. It has been found that dual access is easily achieved with little system discipline. Triple access requires a considerable degree of system discipline to equalize the test tone to noise ratio on each carrier. Quadruple FDMA-FM has been shown to be feasible, but the problems of system discipline have not been determined and evaluated to determine its practicality.

b. FM Voice

Test agencies using this modulation included RADC, USASCA, NELC, and Strike Command. Results were good with the large antennas used for receiving, but became marginal with antenna gains less than about 15 dB.

c. 100 WPM Teletype

Single and multichannel FSK transmission was accomplished by RADC, USASCA, and Strike Command. Successful results were reported.

d. AM Voice

RADC and NELC reported some success in the transmission of 75% AM voice through the satellite with about 21% of distortion resulting from the nonlinear repeater characteristic. It appears that the transmitted signal was not high enough to capture the limiter completely.

e. Facsimile

Cooperative tests were conducted by RADC, USASCA, and NELC on transmission of 8 x 10 black and white pictures. With the exception of occasional disruptions due to RFI, the overall picture quality was considered very good for satellite look angles down to 5 deg.

f. Single Sideband Voice

USNUSL reported the successful loop testing of a single sideband voice transmission at their East Coast shore terminal. With transmitting on loop vee antenna and receiving on the helix, results were acceptable with the transmitter power varied from 1 kW to 25 W. With transmitting on the helix and receiving on the loop vee, satisfactory results were obtained with transmitter power as low as 5 W !! With 1 kW, about 14 dB of clipping occurred in the satellite. Intelligibility was still good.

g. Other Dual and Multiple Access Experiments

USL transmitted single sideband simultaneously with NELC transmitting triple time frequency diversity TTY.

RADC transmitted FM voice and triple time frequency diversity TTY simultaneously.

The NELC shore station and the Iwo Jima tried full duplex triple time diversity TTY. Ship movement and the resultant antenna shadowing made it difficult to maintain the proper power balance and prevent limiter capture.

11. RFI Investigation and Measurement

a. Models Based on Survey of Allocations and Assignments

1.) Electromagnetic Systems Laboratory Study

Electromagnetic Systems Laboratory, Palo Alto, under contract with SAMSO, developed a hypothetical model of interference density to be encountered at synchronous orbital altitude at six equally spaced longitudes. Sources of information for the model included Electromagnetic Compatibility Analysis Center (ECAC), ITU/IFRB, FAA, IRAC, and World Wide Airways maps.

The frequency range was 225 to 400 MHz plotted in 100 kHz intervals. Two cases were considered: The "worst" case assumes all emitting sources to be on simultaneously. The "high duty factor" case assumes that the intermittent sources have a 30% duty cycle and therefore includes only 30% of the total intermittent emitted power.

2.) Electromagnetic Compatibility Analysis Center Study

ECAC, Annapolis, Maryland, performed a study of expected uplink and downlink interference in the 225 to 400 MHz band originating in the CONUS. Sources of data included FAA, NASA, and Weather Bureau, the Treasury Department, and military departments. Mobile equipment was omitted owing to lack of knowledge of locations. Sources of second and third harmonic distortion were included. Sources weaker than those producing the following power density were considered insignificant and ignored:

Aircraft Altitudes (Downlink)

| | |
|---|---|
| In-band interference | $-114$ dBm/m$^2$ |
| Harmonic interference | $-54$ dBm/m$^2$ |

Synchronous Orbital Altitudes (Uplink)

| | |
|---|---|
| In-band interference | $-132$ dBm/m$^2$ |
| Harmonic interference | $-82$ dBm/m$^2$ |

The final data is presented at 100 kHz points across the band for both the "worst" and "high duty factor" cases as defined above:

| "Worst" Case | Orbital Alt. | Aircraft Alt. |
|---|---|---|
| Average over band | -83 dBm/m$^2$ | -32 dBm/m$^2$ |
| Maximum in band | -70 dBm/m$^2$ | -11 dBm/m$^2$ |
| **"High Duty Factor" Case** | | |
| Average over band | -84 dBm/m$^2$ | -32 dBm/m$^2$ |
| Maximum in band | -70 dBm/m$^2$ | -11 dBm/m$^2$ |

b. Airborne RFI Radiometer Measurement

The ASD aircraft flew a modified version of the RFI radiometer designed by Aerospace Corporation for use in the Lincoln Laboratory LES-6 satellite. Data was recorded globally, including specific attention to the Vietnam area where the concentration was found to be the heaviest. The modified radiometer scans two bands: 233 to 250 MHz (low) and 290 to 315 MHz (high). It has a sensitivity of ~120 dBm and a 60 dB dynamic range. It records average RF power (for CW type signals) in each 120 kHz band and peak RF power (for pulse type signals) in each 600 kHz band. Summary of results is presented below, with the blade antenna on the JC-135A:

Global (except for Vietnam area)

| | RF RMS | | RF Peak | |
|---|---|---|---|---|
| | Range of Av RMS over All Scans (dBm) | Range of Max RMS over All Scans (dBm) | Range of Av Peak over All Scans (dBm) | Range of Max Peak over All Scans (dBm) |
| Low band | -84 to -122 | -64 to -82 | -68 to -82 | -48 to -75 |
| High band | -79 to -124 | -52 to -116 | -65 to -89 | -44 to -73 |
| **Vietnam Area** | | | | |
| Low band | -71 to -125 | -66 to -122 | -67 to -94 | -46 to -90 |
| High band | -101 to -125 | -88 to -125 | -81 to -87 | -72 to -81 |

c. LES-5 Satellite Radiometer Measurements

This radiometer is designed to sweep 225 to 280 MHz in 120 discrete steps, in synchronism with the spacecraft timing circuits. It connects to the satellite preamplifier, and its output (RF average and ratio of RF peak to average as discussed above) is telemetered in digital format. Due to difficulties experienced in the timing circuitry, the data is limited. Figure 6 is a plot of a typical run after correction for antenna response.

d. Terminal RFI Discussion

1.) Ship-Borne Radar

Lincoln Laboratory measured local radiation spectrum on two ship-borne radar equipments at Newport, Rhode Island. An analysis of the results indicated a serious downlink RFI problem with a receiving blade antenna located near the radar equipment. It is concluded, however, that a properly designed preselector could alleviate the difficulty.

The Navy experienced some interference when operating while ship-borne radars were in operation.

2.) Aircraft

Lincoln Laboratory measured interference fields on an Air Force aircraft and found both discrete and continuous spectral components of sufficient level to cause difficulty to the sensitive UHF receiver when the other UHF and HF transmitters were energized. Changing the location of the antennas led to some improvement, but the physical constraints were severe. RFI filters were added in some of the antenna circuits. During actual flight test recordings on board the ASD experimental KC-135, it was necessary to keep the HF transmitter off. The Navy P-3A also suffered interference from the HF transmitter.

3.) Vehicular Terminals

The majority of RFI encountered was identified as being from unauthorized transmissions or confusion in scheduling. On a few occasions locally generated ignition noise from nearby vehicles was troublesome.

4.) RFI to Other Systems Caused by Satellite

Lincoln Laboratory ran tests using CW and spread spectrum transmission from the Lincoln terminal at varying power levels to determine the threshold of interference reached at a UHF AM receiver in the Hanscom Field tower, which was normally used for air-to-ground communications. Results indicate that for spread spectrum transmission at 75 to 2400 bits/sec, a satellite at synchronous altitude with an ERP of ~6 kW will not cause interference.

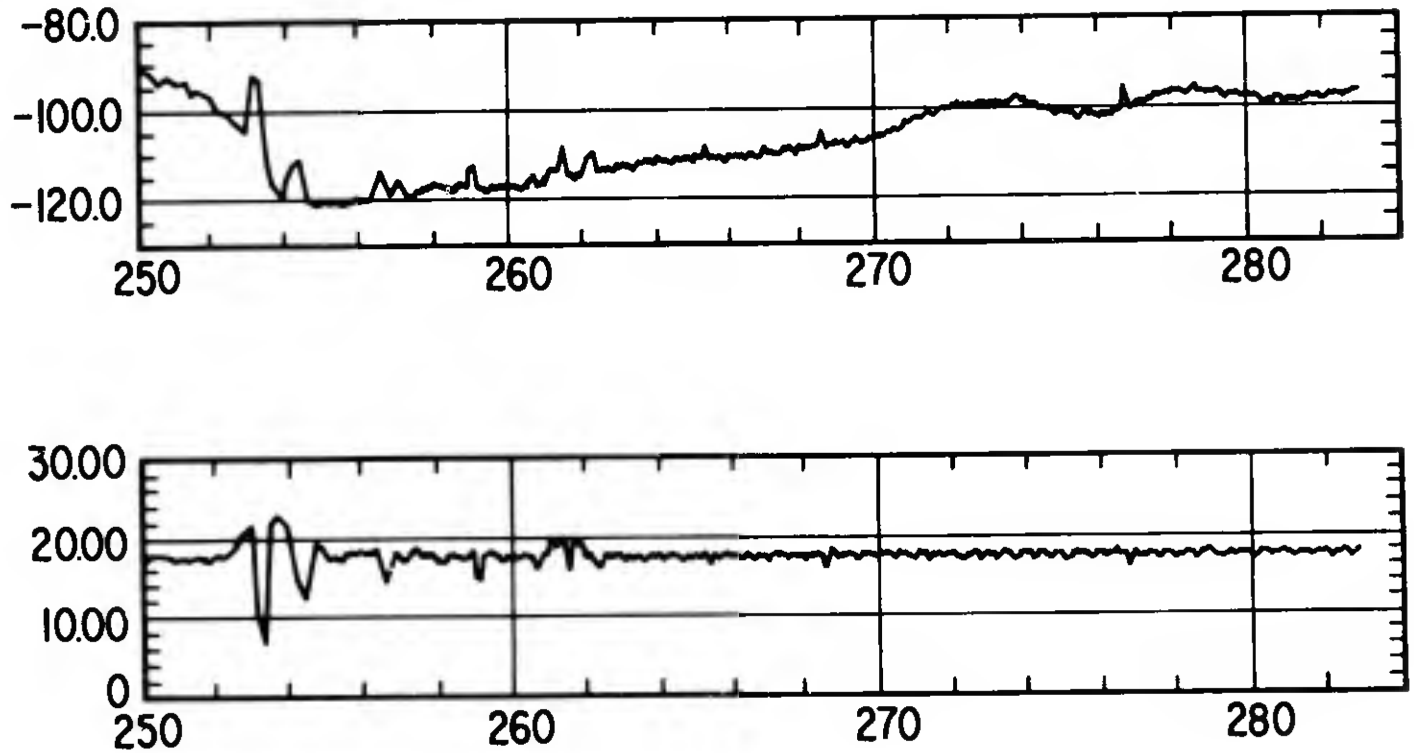


Figure 6. LES-5 Radiometer Amplitide Measurement (Corrected) of Peak-to-Average Power (Top) and Peak-to-Raw-Average Power (Bottom) vs Frequency.

## SECTION VI

## CONCLUSIONS

A. The feasibility of utilizing satellite relay to enhance the communication capability of operating commands has been conclusively demonstrated. Low data rate transmission is a potentially useful communication mode for aircraft, ship, submarine, and other vehicle application.

B. Further refinements in terminal equipments are needed. In particular, they include:

(a) More convenient and smaller message entry and display devices with possible interfaces with on-board computers;

(b) Reduction in size and weight to meet difficult installation problems;

(c) Improved antenna coverage and efficiency.

C. The characteristics of the propagation medium and sources of natural interference were found to be essentially as predicted. Coverage is generally limited at the low end (~ at the horizon) by fading and at the high end by the terminal antenna pattern. The "fast" fading phenomenon observed on airborne terminals was a surprise. However, its effects appear to be easily compensated by antimultipath diversity systems. The medium is compatible with a large variety of types of modulation and transmission.

D. The RFI investigation and test results are generally encouraging. Practically all sources of significant external interference encountered can be identified with terminals under control of the U.S. military establishment. The use of a UHF satellite in a combat area such as Vietnam may require tighter control of frequency assignments than is presently exercised. With regard to the problem of potential interference to other services from a satellite with large ERP, it appears that the use of spread spectrum techniques is a realistic solution. The problems of locally generated RFI in specific terminal installations will continue to require individual attention; however, the experience from the terminals used on LES-5 tests indicates that the required-receiver sensitivities can be realized.

E. The feasibility of frequency division multiple access was demonstrated successfully with terminals not in motion. A small amount of testing with moving terminals (ships) indicated difficulties in maintaining proper uplink power control. The results here are inconclusive.

F. Because of the greatly expanded interest in tactical satellite communications, it appears that the use of SHF should be considered for potential users who are capable of operating in this range, while the use of UHF should be generally restricted to terminals such as aircraft, submarines, and small ships, where SHF operation is not presently feasible.

## SECTION VII

## RECOMMENDATIONS

A. UHF testing should be continued with LES-6 and the same types of terminals. The use of spread spectrum transmission for both interference resistance and multiple access should be stressed, and the investigation of power control problems, especially with ships and aircraft, should be included. Investigation of the fast fading phenomenon should continue.

B. Development should be continued on improved terminal equipment including antennas, message entry and display devices, RF equipment, and modems. Tests of crossed-slot antenna (designed by Lincoln Laboratory) on the ASD aircraft should be continued.

C. Future testing should include all the basic propagation and noise data at SHF in a manner similar to that obtained at UHF, using similar test terminals in applicable tactical environments.

D. Plans for future satellite testing of this type should include standardized test and calibration procedures to ensure accurate correlation of data from many diverse sources.

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| The final Report including LES-5 Satellite Testing conducted under Program 591 | Space and Missile Systems Org.<br>Los Angeles Air Force Station<br>Los Angeles, California 90045 |

13. ABSTRACT
(U) Testing with the Lincoln Experimental Satellite LES-5 with terminals on board aircraft, ships, submarines, and vehicles demonstrated the feasibility of using UHF repeater satellites to enhance the capability of tactical communication links for world-wide military forces. This report presents a summary of the results of the initial phase of the Teactical Satellite Communication Program (TSCP) involving Tri-Service participation in the technical and operational feasibility tests. Although the demonstrations were successful, there exists the need to improve terminal equipment with respect to antenna coverage and efficiency, smaller size and weight to meet installation needs, and more convenient message entry and display devices. Apart from the unexpected "fast fading" phenomenon observed on aircraft, which was easily compensated by the antimultipath diversity system used in aircraft and ship terminals, the characteristics of the propagation medium and sources of natural interference were found to be essentially as predicted. The coverage was generally limited at the horizon by fading at the high look angles by the antenna pattern. Uplink and downlink measurement RFI indicated general agreement with predicted levels based on known U. S. controlled ground-based transmitters. Effective use of simple antennas on aircraft, small ships, and submarines yielded the desired objective of low-cost antennas with broad coverage; communication was maintained despite movement of the terminal. This makes the UHF band acceptable in a large number of applications where SHF operation is not presently feasible. Frequency division multiple access was successfully demonstrated with terminals not in motion. A small amount of testing with moving terminals (ships) indicated difficulties in maintaining proper uplink power control. The results here are inconclusive.

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Satellite Communications | | | | | | |
| Communication Links | | | | | | |
| UHF Communications | | | | | | |