Tactical Satellite Communications - Project 591 (1965-68)

Background and History: In order to provide improved military beyond-line-of-sight communications, in 1965 the Director of Defense Research and Development (DDR&E) requested the military departments investigate the use of a communication satellite repeater in the military UHF band to support a variety of tactical terminals including aircraft, ships, submarines, and ground vehicles.

The use of a satellite relay for communication to military aircraft was considered in 1960 (Project Steer). The effort was redirected, however, to microwave frequencies for ground terminals (Advent). NASA began experiments with satellite communication in commercial aircraft in the VHF band in 1964 using the command and telemetry channel of Syncom II, and continued the experiments with the ATS series of satellites.

Project 591 was originally authorized by the Department of Defense in 1965 as a low cost demonstration of the feasibility of using low data rate communication via satellite relay between aircraft of the USAF Strategic Air Command. As the program progressed, the Army, Navy, and other Air Force commands were invited to participate.

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.

Feasibility Demonstration: To support the feasibility demonstration, the Aeronautical Systems Division (ASD) and the Air Force Avionics Laboratory (AFAL) were directed in 1965 to develop and fly a UHF airborne terminal that could operate through the LES-5 satellite and determine the reliability of airborne satellite communications. ASD and AFAL contracted with the Electronics Communications Incorporated (ECI) in St. Petersburg FL for a flyable UHF satellite communications system. ASD/AFAL also developed a circularly polarized antenna, called a loop V, housed in a fiberglass radome and installed on top of the fuselage of a B-52 bomber and C-135 tanker. A standard UHF blade antenna was also installed for comparison measurements. Because of the satellites limited transmit power, the communications link would only support 60-word per minute teletype traffic. A Kleinschmidt FGC-80 keyboard, tape punch, tape reader and printer were also installed in the two test aircraft.

Satellite Description: The physical characteristics of the LES-5 are given in Table 1. A descriptive drawing of the satellite, indicating the antenna position as well as the various dimensions is given in Figure 1 and a photograph of the satellite in Figure 2. Power budgets for the uplink and downlink of a typical aircraft-to-satellite link based upon these characteristics are presented in Table 2.

The satellites antenna system receives and transmits signals with nominal Right Hand Circular Polarization (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.

The uplink signals, band centered on 255 MHz, are received and separated by the triplexer from the downlink 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

PHYSICAL CHARACTERISTICS

Weight	225 lb
Size	Cylindrical, 48 in. diam × 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 Hz	
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) -120 dBm (100 kHz)
After 18 Mar. 1968	- 98 dBm (300 kHz) -103 dBm (100 kHz)
Passband ripple (sensitivity variation from that for 225.12 MHz)	
Narrow band (100 kHz)	-1.5 dB (more sensitive) +1.0 dB (less sensitive)
Wideband (300 kHz)	-2.0 dB (more sensitive) +5.0 dB (less sensitive)
Antenna	
Polarization	RHCP
Gain, satellite equator	2.2 dB
Gain, 7 deg off beam	1.7 dB
3 deg beamwidth	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 1 Physical Characteristics of LES-5 Satellite

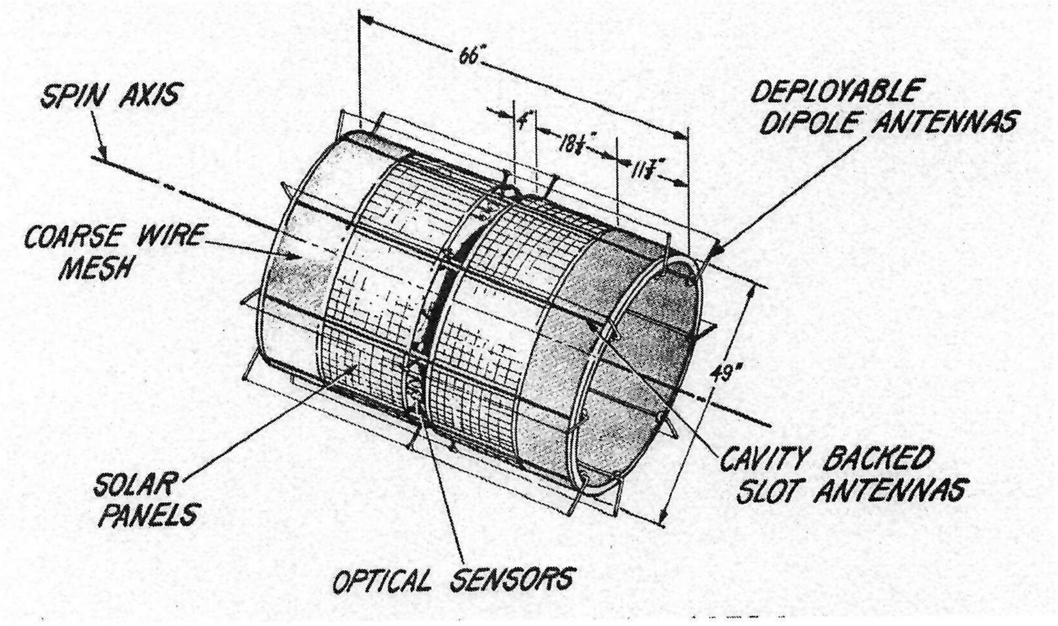


Figure 1 Drawing and Description of LES-5 Satellite

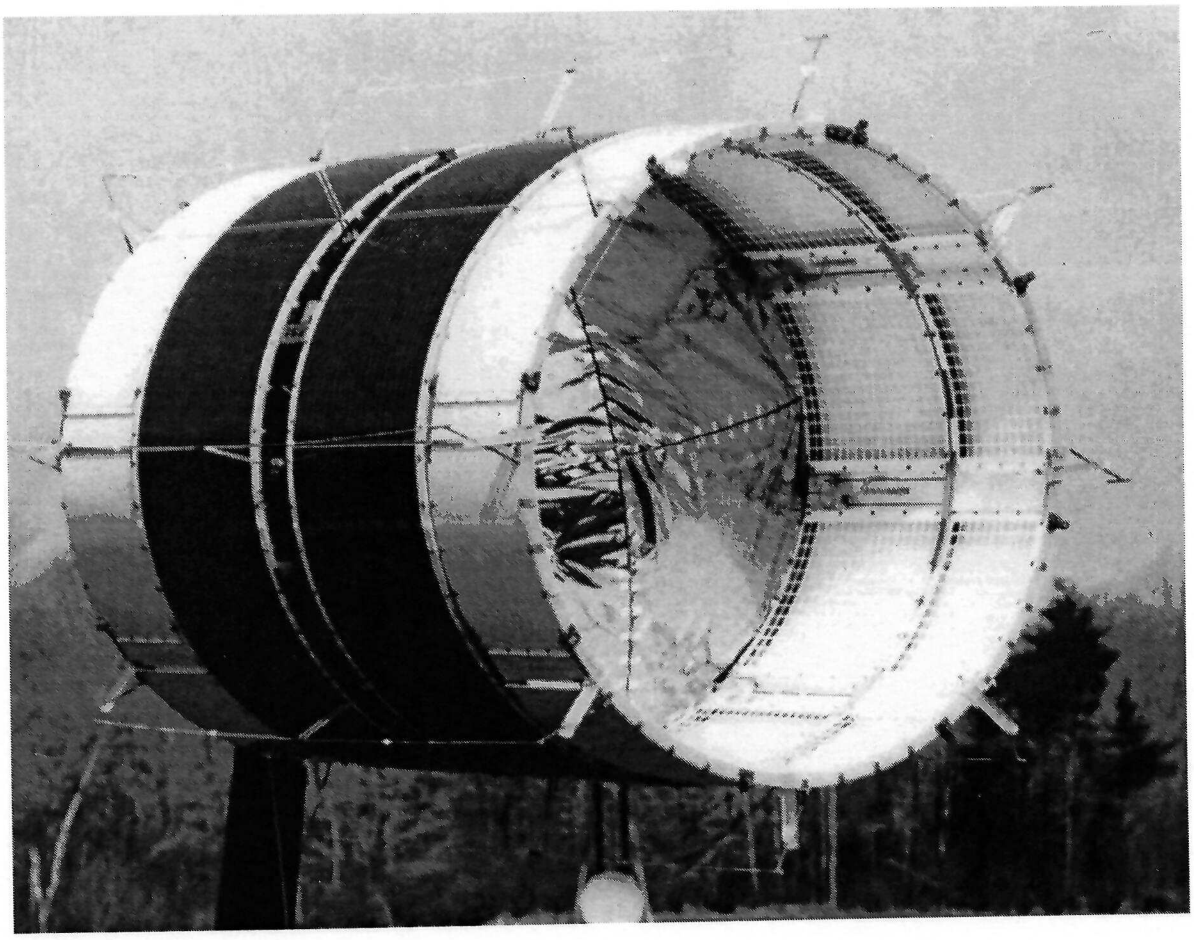


Figure 2 LES-5 Satellite on Test Range at Lincoln Laboratory

PHYSICAL CHARACTERISTICS

Weight	225 lb
Size	Cylindrical, 48 in. diam × 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 Hz	
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) -120 dBm (100 kHz)
After 18 Mar. 1968	- 98 dBm (300 kHz) -103 dBm (100 kHz)
Passband ripple (sensitivity variation from that for 225.12 MHz)	
Narrow band (100 kHz)	-1.5 dB (more sensitive) +1.0 dB (less sensitive)
Wideband (300 kHz)	-2.0 dB (more sensitive) +5.0 dB (less sensitive)
Antenna	
Polarization	RHCP
Gain, satellite equator	2.2 dB
Gain, 7 deg off beam	1.7 dB
3 deg beamwidth	32 deg
Axial ratio, worst case	3 dB

ORBIT CHARACTERISTICS

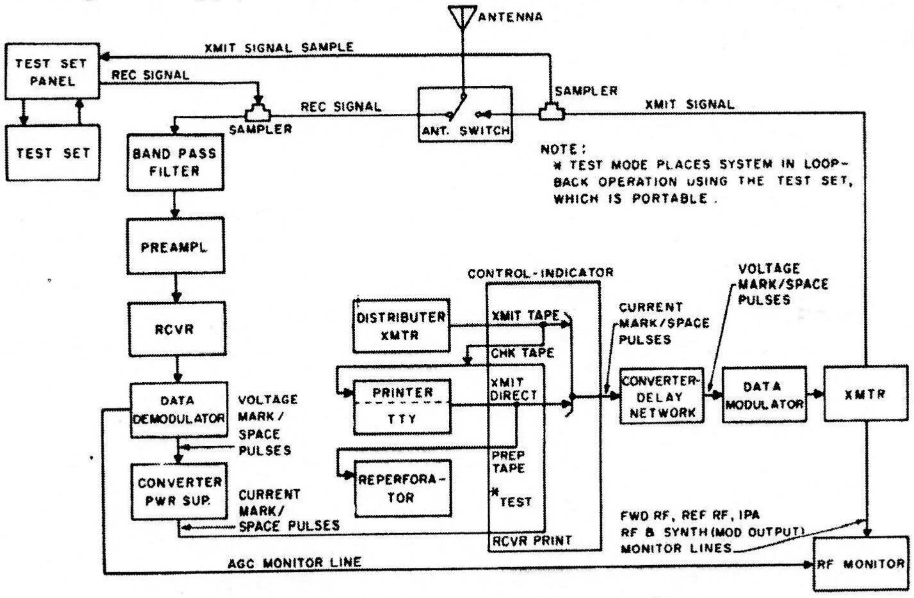
Orbit	~18,000 n mi near circular 7 deg inclination
Drift rate	~32.93 deg per day, eastwardly
Spin rate	Approximately 10 r/min

Table 2 Link Budget for LES-5 Satellite

bandwidth 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.

Terminal Description: The airborne system consists of a teletypewriter (with tape capability), modulator, one kilowatt transmitter, low gain antenna, preselector filter, low-noise preamplifier (3.0 dB), receiver, demodulator, and control panel.

The functional block diagram of the system is shown in Figure 3. A photo of the major components is shown in Figure 4, and the teletype equipment in Figure 5. The HPA is shown on the bottom right. The IPA is on the left with the modulator in the middle. The receiver is shown on the upper left with the demodulator and power supply. The standard UHF blade is shown on the far right.



NOTE:
* TEST MODE PLACES SYSTEM IN LOOP-BACK OPERATION USING THE TEST SET, WHICH IS PORTABLE.

Figure 3 Functional Block Diagram of Airborne UHF SATCOM Terminal

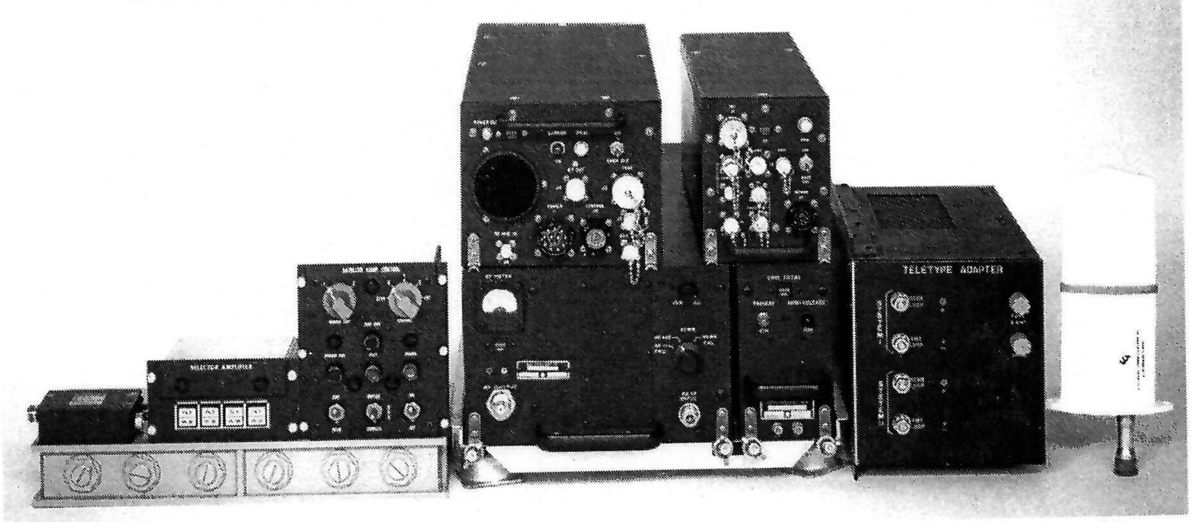


Figure 4 Manor Components of UHF Airborne SATCOM Terminal AN/ARA-64

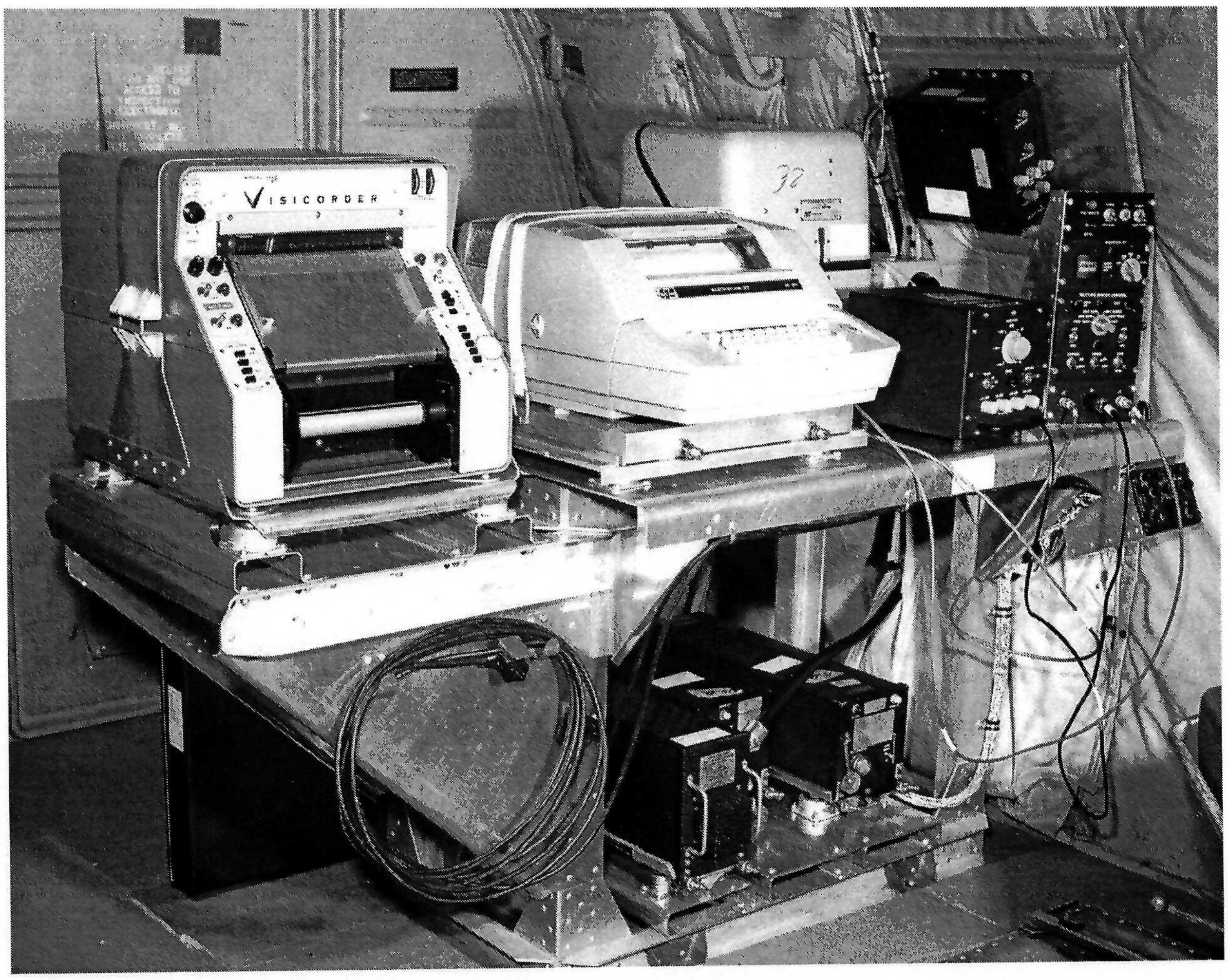
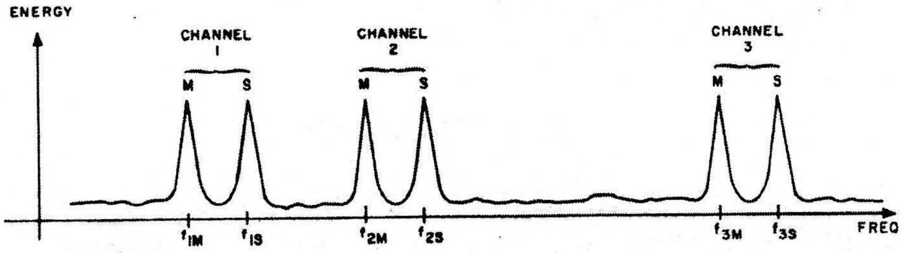


Figure 5 Project 591 Teletype and Instrumentation Equipment Mounted in Test Aircraft

The teletype equipment is a standard unit which is capable of both 60 and 100 words per minute and utilizes a 7.42 or 8 unit code. It also has the capability of punching tape and sending tape at the above mentioned rates. The control indicator also has a test function for demonstrating the complete system, except antenna, is performing properly. The terminal's transmit and receive frequencies are not the same; therefore, it is necessary to perform a frequency translation which simulates the satellite. This is accomplished by the test set, shown in the upper left hand corner of the Figure 3.

The incoming teletype message to the modulator is re-clocked and the 7.42 code is converted to an alternating 7 and 8 code. This results in a uniform bit stream which is split up into three chips, one chip for each channel. Each bit is transmitted on three different frequencies for a duration of one-third of the bit length. The six keying lines are used to key on their appropriate oscillators as shown by the frequency spectrum in Figure 6. The six oscillators have to be very stable to maintain their relationship to allow each frequency to be filtered individually by fixed filters.

The output of the Data Modulator is used to drive a standard UHF airborne transmitter which contains a times four multiplier in the IPA. The Power Amplifier (PA) has an output power of one kilowatt and is tunable over the 225 to 400 MHz frequency range.



(C) FREQUENCY SPECTRUM

Figure 6 Triple Diversity Modulation Scheme

Several antennas were tested, including the standard UHF blade and a circularly polarized loop-vee. The circularly polarized receive antenna was essential in the early phases of the program when the availability of a circularly polarized transmission from the satellite was in doubt. When it was determined that it would be possible to put a circularly polarized antenna on LES-5, it made it possible to use a simple blade on the operational aircraft. The radome that is required for the loop-vee is 155 inches long; this was objectionable to some operational units. The loop-vee with radome is shown mounted on a B-52 aircraft in Figure 7. A standard UHF is shown just in front of the loop-vee on the C -135 aircraft in Figure 8. It can be seen from this example why antenna considerations are important for aircraft terminals.

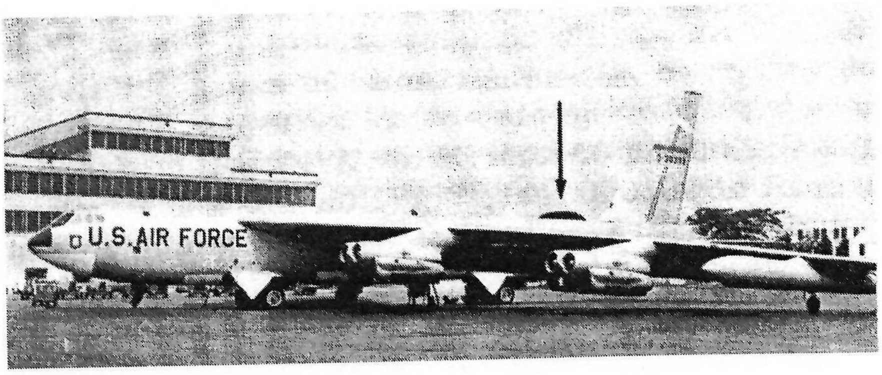


Figure 7 B-52 Test Aircraft with Loop Vee Antenna Radome

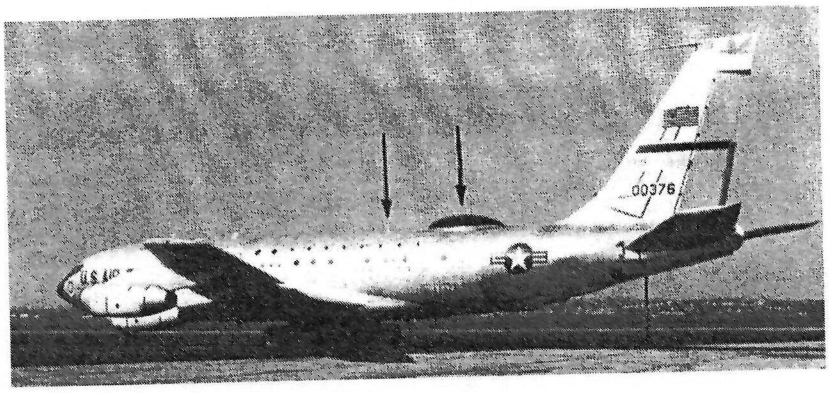


Figure 8 C-135 Test Aircraft with UHF Blade and Loop Vee Antenna Radome

The expected interference and the broadband capability of the low noise preamplifier dictate the use of a good preselector filter. This filter has an insertion loss of approximately 1 dB and provides 75 dB rejection outside the band. The system noise figure was less than 4.5 dB and the preamp has an overload clipper to prevent burnout when a local transmitter tunes across the receive band.

The receiver was fixed tuned and highly stable to permit operation at the required low data rates. It had a triple conversion to obtain the proper filtering and provide an output for an external MODEM. The second IF is 10. 7 MHz and has a 100 KHz crystal filter which defines the receiver bandwidth. The second local oscillator is a voltage-controlled crystal oscillator which is part of the AFC loop.

The system frequency uncertainty is greater than the demodulator bandwidth; therefore; it was necessary to perform a frequency scan of ±2 KHz. To add to the flexibility of this equipment as a test device, an external frequency adjust pot is available on the control panel. This allows the sweep to be centered or manual acquisition without the sweep. The AGC is derived from three different sources, external control on the front panel, internal to the receiver, and from the DEMOD. The external AGC is for those applications where the receiver is used as a test instrument and the effects of AGC need to be removed. For noise leveling purposes, the internal AGC is normally applied to one stage of the receiver and can be used on all AGCd stages when no DEMOD is available. The AGC normally comes from the DEMOD where the C/N is sufficient to give a decent error voltage. The third IF frequency was selected to give a good operating frequency for the crystal filters in the demodulator.

At the receiver IF output, the 100 KHz signal spectrum, plus noise, is centered at 342.5 KHz. This spectrum is applied to the DEMOD where there is a matched crystal filter for each of the mark frequencies and each of the space frequencies. These six filters are selected very carefully and are a matched set. Each one has a noise bandwidth of 200 Hz and is designed to give good time response even if the signal is appreciably off the center of the bandpass. This increases the acquisition and tracking range of the system. The outputs of the filters are used to accomplish four different functions. These functions are interrelated and most of them occur simultaneously. The frequency discriminators provide the error voltage for the AFC loop and the AGC detector provides the error voltage for the AGC loop.

Assuming acquisition has occurred and the timing is proper causes the data detectors to be sampled at the right times. Assuming no noise, the outputs of the envelope detectors will occur in a specific pattern, either three marks in a row, or three spaces in a row. The outputs of these detectors are sampled at the proper time and held until all three chips have been sampled. The three marks are linearly combined (as are the spaces) and differentially compared to determine if a mark or space was received. If the system is locked up the output is shaped and sent to the teletype printer.

The hopping pattern goes from M_1 or S_1 to M_2 or S_2, to M_3 or S_3, and back to M_1 or S_1 again. During the time M_1 or S_1 is on, the signal has to be f_{1M} or f_{1S} therefore, if these channels are combined, there will always be an output at that time. The same applies to time slots two and three. This results in a specific hopping pattern, minus information. The bit timing phase locked loop then becomes a simple cross-correlation detector which searches until the proper detectors are sampled at the right time. When the loop is locked up it provides timing to look at the right frequency, as well as the proper time during the chip. The loop also provides the properly phased clock pulse for the output teletype data.

The marks and spaces are also similarly combined for the AGC and threshold detection loop. This results in three 45 Hz waves which is characteristic of this system. The channel filters make the waves nearly sinusoidal, but of different phase. A 45 Hz filter is employed to reduce the effects of signals which do not have this characteristic. The outputs of these filters are detected and the largest signal is used for the AGC loop and the threshold detector. This method has- proven to be very effective against nuisance type interference that has bothered other transmissions.

The threshold detector stops the sweep generator and allows the AFC loop to track the incoming signals. The C/N level is improved by gating on the proper channels when the signal is expected to occur. The six crystal discriminators .are matched to the six crystal filters.

The linear combining gives triple diversity capability when the channels are fading independently and takes the combined energy of all three when the signals are all fading together. This flat fading occurs below five degrees for an aircraft at 30, 000 feet, but it occurs sooner as the altitude is decreased. The linear combining gains 4 dB over selection or switched diversity and is essential for the flat fading situations and provides more margin for multiple accesses to the satellite.

The sweep searches over a ±2 KHz band in less than six seconds. The uncertainties have proven to be nearly an order of magnitude less than this so that the sweep range could be reduced considerably. The short term stability of the system is approximately ± 10 Hz and the long term stability is less than ± 30 Hz.

These systems were installed in B-52s, EC-135's, KC-135's, P-3's, vans, ships, submarines, and ground stations at Rome, New York; St. Petersburg, Florida; San Diego, California; Fishers Island, Connecticut; and Fort Monmouth, New Jersey. At least one of each of the above types of stations contributed significantly to the program. The C-135 stationed at Wright-Patterson (shown in Figure 8) was used to collect the major portion of the data for the airborne tests.

Instrumentation of the ASD/AFAL Terminal: Two ASD/AFAL test aircraft implemented with the Project 591 communications system were instrumented to determine the characteristics of the channel. A special connector on the front panel of the demodulator provided an output of all relevant features of the channel, plus other functions to aid in data analysis. Of primary interest are the outputs of the six envelope detectors which provide an excellent point to monitor the channels. The nature of the signal assures there will be a pulse of signal to obtain an indication of signal strength and an absence of signal for determining the relative noise level. This provides a good means to observe the effects of selective fading and the presence of interference.

The message was recorded to determine the error rate and the distribution of the errors. AGC voltage was also recorded to give a measure of the average signal strength and, when applicable, out-of-band noise was also measured.

The instrumentation system consisted of data amplifiers to condition the outputs of the data demodulator, a magnetic tape recorder for use in computer data reduction, and the Visicorder to allow continuous visual monitoring of the parameters and possible hand reduction of the data. The instrumentation system also contained a time code generator and a gyro package such that airplane attitude parameters and time could also be recorded.

A satellite simulator was built into each system to check system sensitivity. This simulator was also used in some tests when the satellite was not visible and in some cases used in place of the satellite to remove the variables associated with the signal received from the satellite and allow for a much more thorough analysis of other system parameters.

The normal message used in the tests was obtained from a specially designed solid-state teletype simulator. This simulator was synchronized to the clock in the modulator and was used in the tests to obtain a continuous 8-unit teletype code. This simulator would generate four lines (64 characters to the line) and then repeat. The first line started with four Ks, called the preamble, and each line ended with an X, carriage return, letters, and line feed. The message would then be filled in with Alpha-Os, RYs, or spaces at the option of the operator. The use of Alpha-Os was most desirable because of their symmetrical character structure.

To aid in data reduction, data logs were kept by test personnel during test missions and a flight log containing aircraft positions at specific times was supplied by the aircraft navigator.

Summary of Test Results; The ASD/AFAL terminals have flown about 28 flights in the first six-months of testing for a total of 140 hours of data taking time. These tests have covered most types of terrain and a variety of locations around the world. Successful communications have been accomplished from terminals in the United States to our airborne terminal while it was flying over the North Pole, over South Vietnam, and in Europe. Extensive tests have been conducted over the Atlantic Ocean, Pacific Ocean, Arctic and Indian Oceans.

The data collected to date shows that multipath fading can be characterized in general by the simple two-ray multipath model. Multipath fading is almost always encountered on over-water flights when the look angle to the satellite is below 20 degrees. A typical strip chart recordings for flights over water is shown in Figure 9. Flights over polar ice produce results almost identical to over-water flights. Over-land flights produce very little multipath fading, while flights over mountains display no multipath. The fading encountered on over-water flights occurs from the horizon up to angles of 20 or 25 degrees. Above these look angles, the fading is not periodic, predictable, or significant. The level of fading encountered even at low look angles is in general 5 dB or less. Seldom are the fades as great at 10 dB. The deepest fading occurs between a look angle of 10 and 15 degrees. The lack of deep multipath fading is being investigated in greater detail.

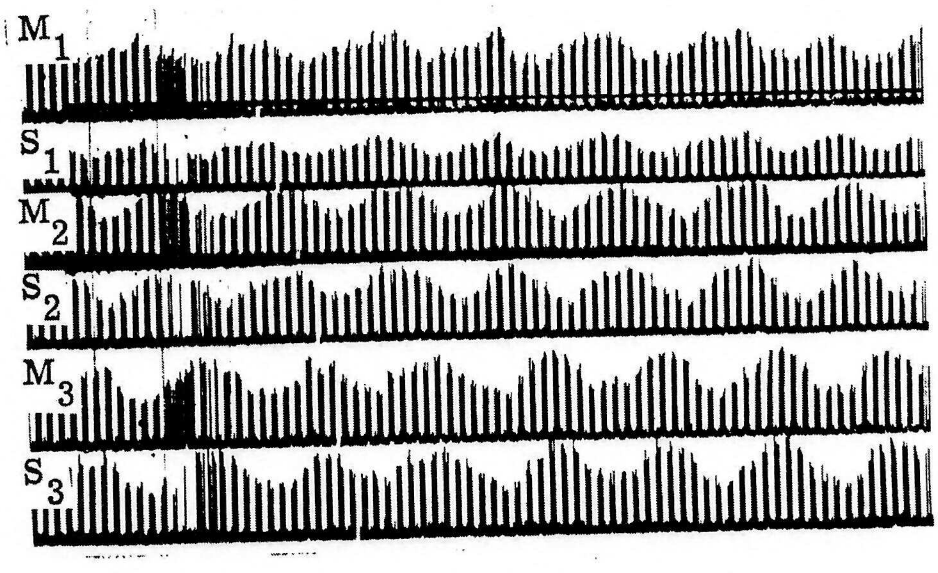


Figure 9 Aircraft's Received Signal Fading over Sea Water

To investigate the validity of the simple multipath model it was necessary to run numerous flights over water at various look angles. The water surface gives the best approximation to the smooth earth model used to calculate the theoretical values. Engineers of Aerospace Corporation calculated expected fade rates and differential delay times for an airborne terminal at 30, 000 feet flying toward the satellite. The fade rate is zero for a satellite overhead (90 degrees look angle) rises to around 0.6 Hz for most look angles and falls rapidly to zero again as the look angle becomes tangent to the earth (-3 degrees look angle).

To get continuous experimental data, the ASD/AFAL airborne terminal was flown from the horizon to a look angle of 55 degrees. The experimental airborne terminal fade rate data agreed very well with the theoretical fade curves.

The differential delay or phase difference of a fade on two different signal frequencies indicates how well a frequency diversity system will work.

Considering the 25 KHz spacing of the Mark 1 - Mark 2 Channel and the 85 KHz spacing of the Mark 1 - Mark 3 Channel, it is possible to determine the expected phase difference of fading on those two pairs. The agreement between predicted and experimental data was good. The Mark 1 and Mark 3 fade together (360 degrees difference), at about a 10 degree angle. The Mark 1 - Mark 2 pair do not reach 360 degrees until about 38 degree look angle. Since coherent fading is seldom encountered above 25 degrees, it is highly unlikely that all three channels would fade simultaneously due to multipath signals at any angle over a few degrees.

The teletype error rate encountered by an airborne terminal is a function of propagation effects, antenna pattern, aircraft maneuvers, and the look angle to the satellite. Therefore, the concept of a single number which defines the error rate for an airborne terminal is not considered meaningful. A dynamic error rate related to the mission profile should be a more useful concept. The following is an attempt to isolate the error rate dependents of each of the variables. Under the most optimum condition, which is normal flight with a look angle between 3 degrees and 40 degrees, the error rate is 10^{-5}. Operating the terminal near the horizon or under conditions of fast fading, the error rate increases to 10^{-3}. During the time when the satellite is in the poor portion of the antenna pattern, the error rate increases to 10^{-2}. Conditions of radio frequency interference produce errors at the rate of 10^{-1}. Under conditions of antenna blockage due to aircraft maneuvers the error rate can go as high as 5×10^{-1}.

Experience to date has shown no noticeable effect on error rate due to time of day, season, latitude, temperature, or altitude. The effect of terrain on error rate has also been minimal. There is a difference in multipath fading with terrain, but seldom does this fading cause errors.

The time-frequency diversity technique adopted for use on this program provides protection against multipath fading above a five degree look angle. Below that angle, the frequency separation is not sufficient to prevent correlated fading. While pretest estimates of the multipath indicated a severe problem for an airborne terminal operating over water, actual test results show only shallow fading to exist. Therefore, it is difficult for any diversity scheme to improve link performance which is already nearly error free. Definite improvement in the error rate is demonstrated under conditions of the unusual fading and radio frequency interference.

Calculations have been made of the mathematical correlation function existing between the six frequencies used in this test. The results show that over a variety of terrain a low correlation exists between the more widely spaced channels. Correlation usually is less than 0.4. However, conversion of this correlation function into an improvement of communication time availability or communication reliability involves other variables. Therefore, the usefulness of this correlation function is questionable.

An evaluation was run on two airborne antennas, one a specially designed, circularized polar antenna (Loop Vee) and the other a standard UHF blade. Both antennas worked well between look angles of 5 degrees and 50 degrees. On the horizon or over 50 degrees, both antennas had less than the 0 dB gain desired. However, due to the system margin, the antennas do provide sufficient gain to allow acceptable communications on the horizon. Again, because of the system margin, the loop vee antenna allows acceptable communication from 50 degrees to 65 degrees. Above 65 degrees the gain is down to a point where communication is not possible. Because of the scalloping of the overhead pattern which the blade antenna displays, its performance above 50 degrees is unpredictable.

Tests were run to investigate the interference or spectrum congestion encountered by an airborne UHF terminal in South Vietnam during the active Vietnam Conflict. A total of seven hours of testing was accomplished on four different days. On two of the days, the satellite was not visible and had to be simulated with the loop tester. On the other two days, the satellite was used; once in a duplex mode communicating with ourselves and on the other day communicating with a ground terminal in California. The spectrum congestion on all four days appeared to be similar and agreed with what had been seen on a radiometer test early in 1967. However, the effect on the specific satellite down frequency differed each day. On the first day one hour of bad interference occurred, which caused complete loss of signal or high error rates. On the second day only one short burst of interference occurred, which caused less than one second of errors. On the third day no interference was experienced at all. On the fourth day there were several minutes of interference, but no errors were experienced due to this interference. These results have shown that the problem of interference in a tactical environment is indeed real. The exact effect of this interference is both time and location sensitive. A larger amount of data will need to be collected if a statistically meaningful evaluation is to be performed, but these results are encouraging.

Occasionally during these flight tests, a fast fading occurred which has a rate one-hundred times faster than the maximum predicted by the two-ray multipath model with reflections from a smooth earth. These fades will affect a single teletype chip while leaving the adjacent chip unaffected. Following is a list of their characteristics:

1. Fast fade can wipe out a single chip.
2. They are frequency selective.
3. They do not appear cyclic.
4. Signal enhancement, as well as degradation, occurs.
5. Switching antennas will often change the fading characteristic.
6. Fading has occurred with both the loop-vee antenna and the blade.
7. Fading is noticed only over water.
8. It has always been encountered at look angles of greater than 25 degrees.
9. It has occurred only within 30 degrees of the equator.
10. Have often flown high look angle flights over water and not seen fast fading.
11. It usually appears slowly, builds up to a maximum and then dies out.
12. It has never occurred for more than two hours.
13. Except for a few minutes when fast fading is at its maximum, the diversity techniques provides error-free copy.

14. Minor directional changes of 10 or 20 degrees do not seem to affect it, but major directional changes of 90 degrees do.

Many theories have been advanced as to the cause of the fast fading. However, to date it is not felt that sufficient information is available to draw conclusions as to the source of the problem. Future tests are planned to specifically investigate this area.

A number of the ground terminals have experienced severe fading due to ionospheric scintillation. Prior to the end of Project 591 in 1968, the airborne terminal had not experienced fading which could be identified as scintillation. Flights into the northern auroral region had been made and no noticeable effect to communications was encountered. However, flight times on those missions did not coincide with any enhanced auroral activity. Testing during the follow-on SATCOM program confirmed that ionospheric scintillation can cause severe fading of the airborne UHF SATCOM link when operating in the equatorial and polar regions.

The LES-5 satellite was put into orbit with a communication bandwidth of 100 KHz. After about four-months of testing, this bandwidth was switched to 300 KHz for wideband tests. Since the airborne terminal is not saturating the satellite receiver, the effect of the bandwidth change was to introduce 5 dB more noise power into the satellite receiver. Satellite transmitter redistributed its effective radiated power and the relayed information is therefore 5 dB weaker. If a ground station excites the satellite, they are still able to saturate it and keep the majority of the ERP concentrated in the retransmitted intelligence. The communication system margin is sufficient to make this 5 dB change unimportant at good look angles. However, on the horizon the previous 10 dB fade margin is now cut to 5 dB.

Occasional intermittent operation is now experienced on the horizon. With the satellite overhead, the airborne terminal was previously able to operate up to 75 degrees look angle with regularity. After the bandwidth increase, communications above 60 degrees were unreliable.

Conclusions: The feasibility of utilizing satellite relay to provide beyond-line-of-sight communication capability of operating commands has been conclusively demonstrated. Low data rate transmission is a potentially useful communications mode for aircraft, ship, submarine, and other vehicle application.

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.

The characteristics of the propagation medium and sources of natural interference were found to be essentially as predicted. Coverage is generally limited at the horizon by fading and at the high elevation angles by the terminal antenna pattern. The "fast" fading phenomenon observed on airborne terminals was a surprise. A further discussion is contained in Johnson's 1981 Reference. The effects of the fast fading appear to be easily compensated by anti-multipath diversity systems. The medium is compatible with a large variety of types of modulation and transmission.

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.

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.

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.

References:

Bond, Fred E. and Hal F. Meyer; **Fading and Multipath Considerations in Aircraft/Satellite Communications Systems**; AIAA 1st Communications Satellite Systems Conference; Washington DC, June 1966.

Bond, Fred E.; **Precise Results for Differential Delay and Fading Rate for Aircraft/Satellite Link**; Unpublished Memo, Aerospace Corp, El Segundo CA; 3 October 1967.

Ellington, T.D. and Ken W. Kirk; **Air-to-Air Propagation Characteristics at Extreme Ranges;** National Aerospace Electronics Conference, Volume 22; Dayton, Ohio; 1966.

Foshee, James J., Gil L. LaVean, Allen L. Johnson, Richard M. Goode; **Multipath and Propagation Experiment Utilizing VHF/UHF Satellite Communications System**; AIAA 2nd Communications Satellite Systems Conference; San Francisco CA; April 1968.

Goode, Richard M. and Gil L. LaVean; **Tactical Satellite System Design Considerations**; IEEE International Conference on Communications; Minneapolis MN, June 1967.

Isgrig, Elvin D., Hal F. Meyer, Fred E. Bond; **Final Report of Tactical Satellite Communications Program 591 and LES-5 Test Report**; Space & Missile Systems Organization; Los Angeles CA; DTIC AD0857274; 21 July 1969.

Johnson, Allen L. and Richard M. Goode; **Six Month Report of Flight Test Results Program 591**; Air Force Avionics Laboratory; WPAFB OH; 31 January 1968.

Johnson, Allen L.; **Coastal Multipath Fading**; IEEE Transaction on Antennas and Propagation; Volume AP-29, Number 4; Pages 665-668; July 1981.

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

EACH TRANSMITTAL OF THIS DOCUMENT OUTSIDE THE AGENCIES OF THE U.S. GOVERNMENT MUST HAVE PRIOR APPROVAL OF SAMSO (SMR). THE DISTRIBUTION OF THIS DOCUMENT IS LIMITED BECAUSE OF CONSIDERATIONS RELATING TO TEST AND EVALUATION OF COMMERCIAL PRODUCTS.

45.

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

SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
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:

D. G. AVIV
E. B. ARROWSMITH
K. H. HURLBUT
C. J. ZAMITES

This work was performed under the cognizance of the Deputy for Space Communications Systems (SMR), Space and Missile Systems Organization.

This technical report has been reviewed and is approved.

H F Meyer
H. F. Meyer, Director
Tactical Sat Com Programs
Group II Programs Directorate
Satellite Systems Division
Aerospace Corporation

W Sanders
Walter W. Sanders, Col USAF
Deputy for Space Communications Sys.
Space and Missile Systems Org. (SMR)

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

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) Tinker AFB, Okalahoma	Installation of terminal equipment in SAC operational B-52s, KC-135s
US Noal Electronics Command Washington, D.C.	Coordination and management of Navy tests and measurements
USAF Communications Service Scott AFB, Illinois	Controller of LES-5 test network, April 1968
Air Weather Service Scott AFB, Illinios	Participation with RADC and USASCA in weather facsimile tests
Electromagnetic Compatibility Analysis Center (ECAC) Annapolis, Maryland	Interference measurements and studies at Andrews AFB, Maryland, and McClellan AFB, Sacramento, California
Federal Aviation Agency (FAA) 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. 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 Commercial Airplane Division 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) MacDill AFB, Fla.	Operational feasibility testing	(2) Transportable shelters	Florida
		Fixed (ECI operated)	Middle East
USAF Strategic Air Command (SAC) 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) Air Force Avionics Lab (AFAL) 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) Ft. Monmouth, NJ	Technical communication testing	(2) 1/4 ton trucks (2) 3/4 ton trucks	Ft. Monmouth, N.J. Eastern U.S. Ft. Huachuca Panama Canada UK and Western Europe 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) 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 λ). 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

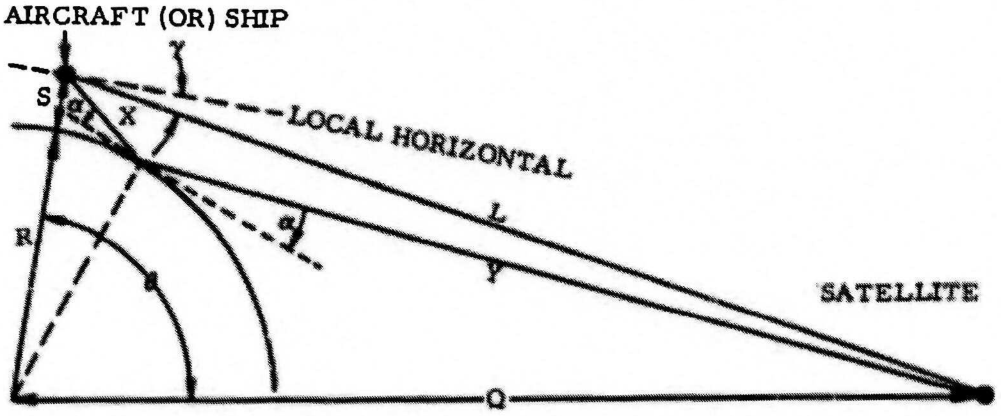


Figure 1. Geometry for Aircraft-to-Satellite Transmission

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 θ 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 θ. For subsequent convenience the satellite look angle γ, 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 γ for horizontal and vertical polarization, assuming smooth sea water reflection and based on theoretical expressions for variations of reflection coefficient ρ with incident angle α.

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.

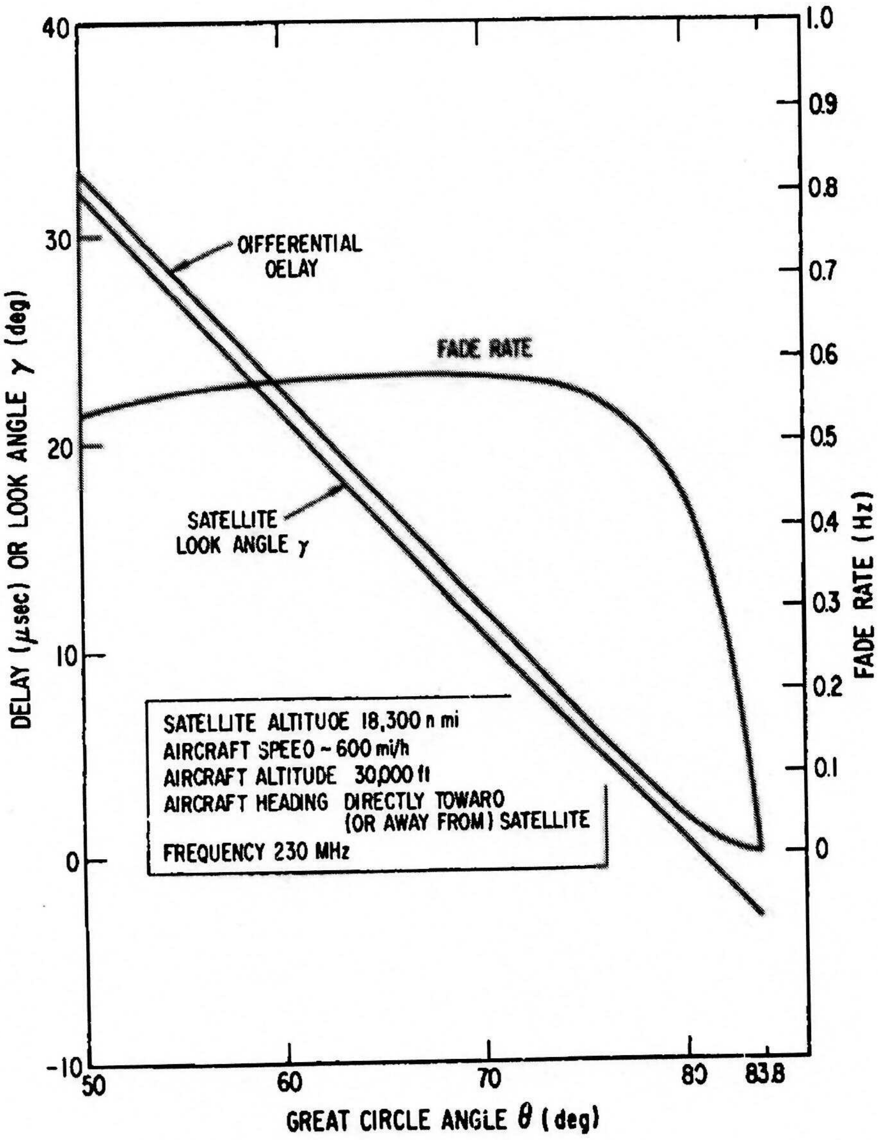


Figure 2. Two Ray Multipath Fading Rate and Delay

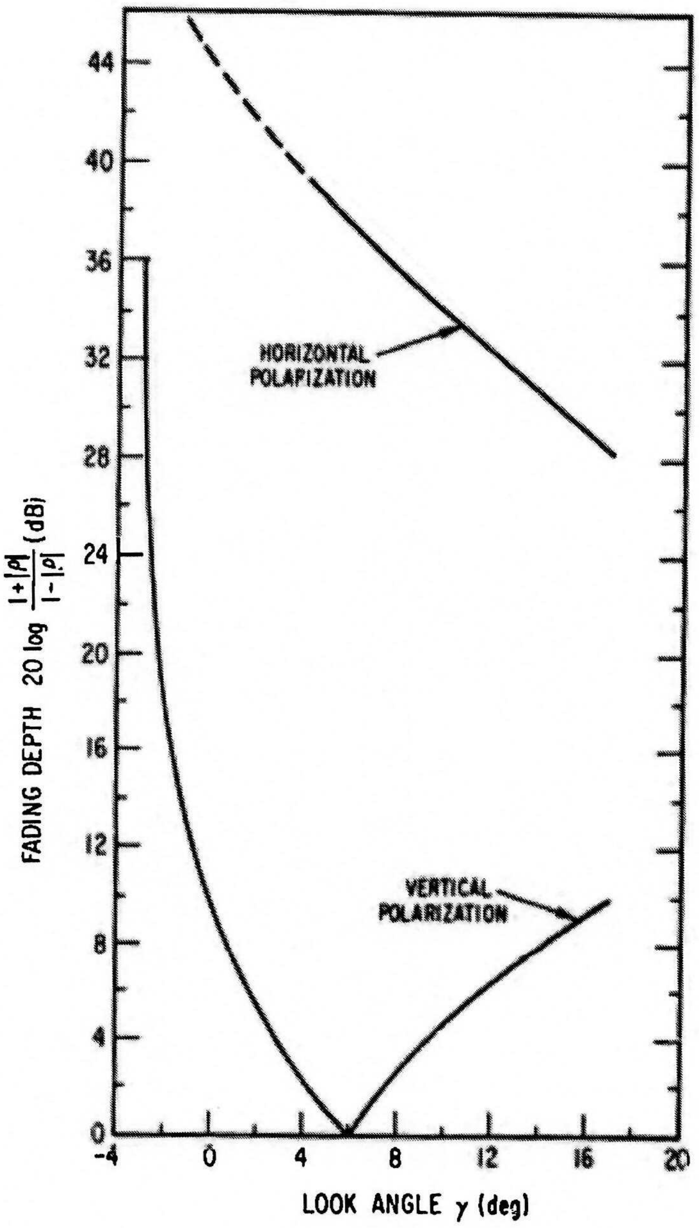


Figure 3. Fading Depth vs Satellite Look Angle, Specular Reflection (Smooth Sea Water).

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°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°K at 250 MHz. The earth is a radiating source at about 300°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.

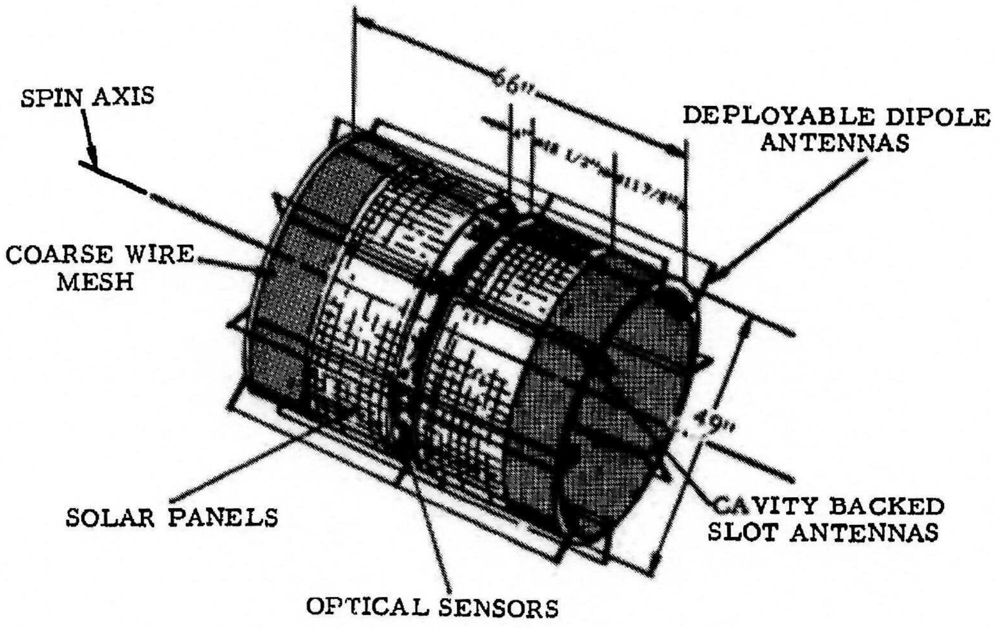


Figure 4. Basic Size Description of LES-5.

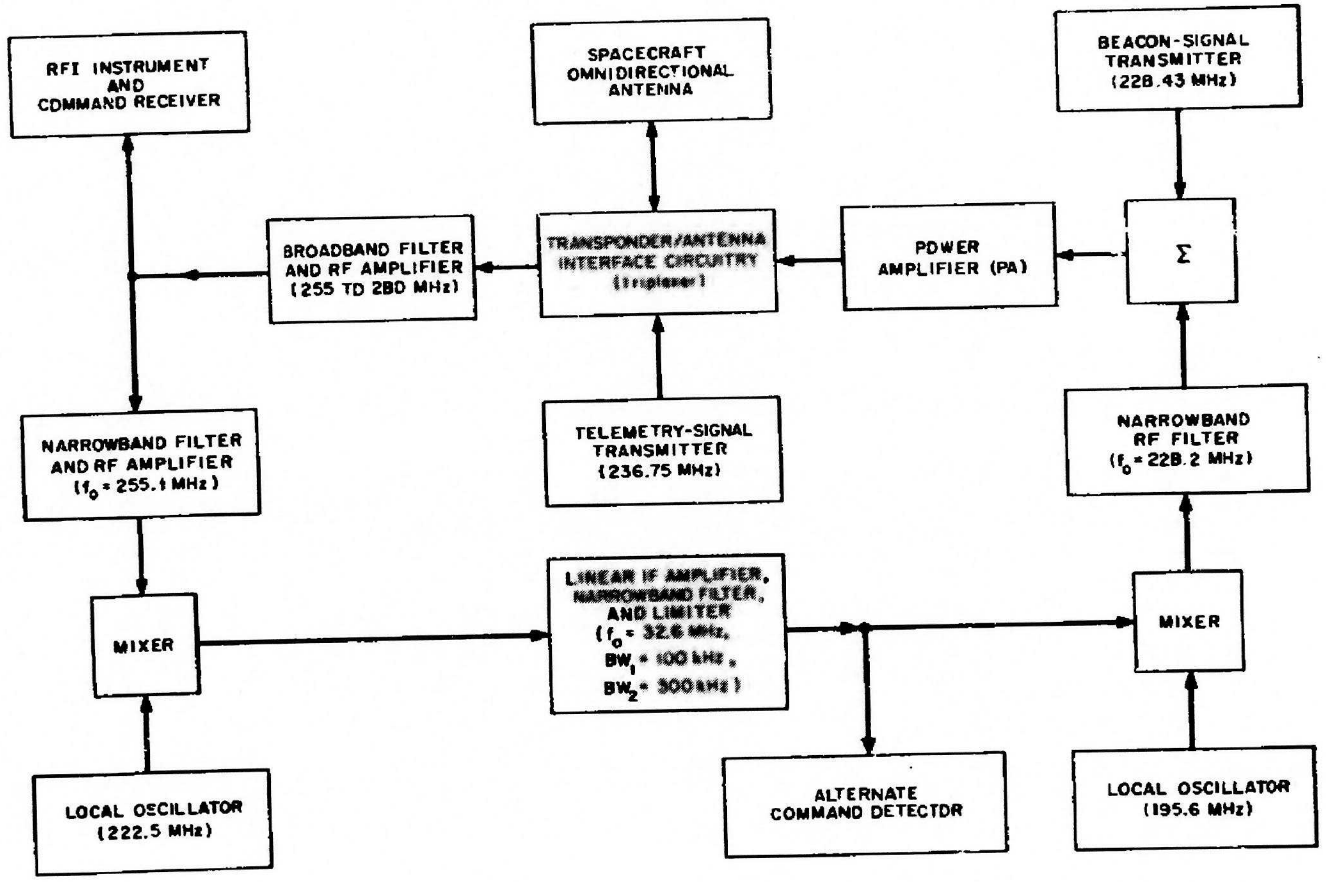


Figure 5. LES-5 Transponder and Associated Subsystems.

TABLE 3. SUMMARY OF TERMINAL CHARACTERISTICS

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

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

Agency	Terminal Types	Antenna				System Noise Temperature Est. (K)	Modulation Systems
		P_0(dW)	Type	Gain (dB)	ERP (dBW)		
Navy Electronic Labs Comd. (NELC) San Diego, Calif.	Shore station	1	28-ft dish	23	53	920	a. Common b. FM voice c. CW d. Facsimile 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 b. CW shore c. SSB (AM) shore 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 b. FM voice 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) -120 dBm (100 kHz)
After 18 Mar. 1968	-98 dBm (300 kHz) -103 dBm (100 kHz)
Passband ripple (sensitivity variation from that for 225.12 MHz)	
Narrow band (100 kHz)	-1.5 dB (more sensitive) +1.0 dB (less sensitive)
Wideband (300 kHz)	-2.0 dB (more sensitive) +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 Antenna feeds 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 essentially 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

	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	-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.

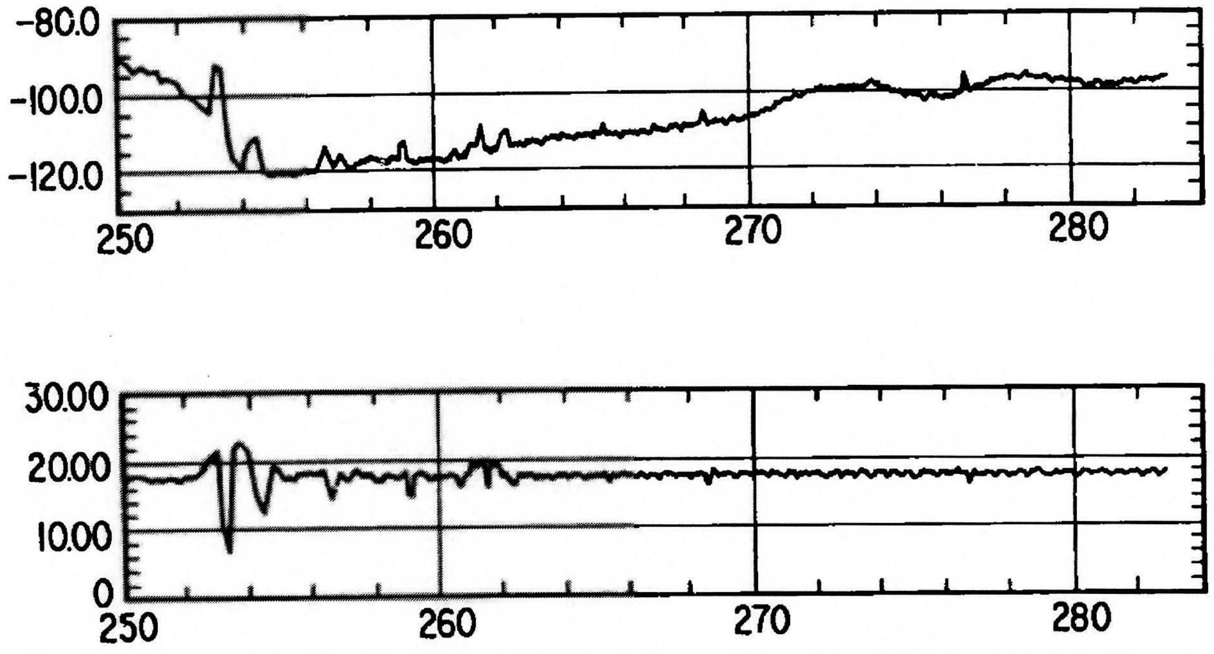


Figure 6. LES-5 Radiometer Amplitide Measurement (Corrected) of Peak-to-Average Power (Top) and Peak-to-Raw-Average Power (Bottom) vs Frequency.

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.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Space and Missile Systems Org. (SMR)
Air Force System Command, Los Angeles Air Force
Station, Los Angeles, California 90045

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP
N/A

3. REPORT TITLE
Final Report - Tactical Satellite Communications Program
Program 591 and LES-5 Test Report

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report July 1965 thru May 1968

5. AUTHOR(S) *(First name, middle initial, last name)*
Elvin D. Isgrig, Major USAF
Harold F. Meyer
Frederick E. Bond ET AL

6. REPORT DATE
21 July 1969

7a. TOTAL NO. OF PAGES
40

7b. NO. OF REFS
None

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.
591

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
SAMSO TR-69-245

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT
Each Transmittal of this Document outside the Agencies of the U. S. Government must have prior approval of SAMSO (SMR).

11. SUPPLEMENTARY NOTES
The final Report including LES-5 Satellite Testing conducted under Program 591

12. SPONSORING MILITARY ACTIVITY
Space and Missile Systems Org.
Los Angeles Air Force Station
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 wer 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						