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Thirty Years of Research and Development in Space Communications at Lincoln Laboratory

The goal of Lincoln Laboratory's program in space communications is the development of reliable, affordable systems for military communication. These systems must function dependably — even in the presence of natural or hostile interference.

A broad, total-systems approach has characterized the program since its inception. Lincoln Laboratory has designed, built, tested, and operated communications satellites and their corresponding terminals in real-world environments.

Some of the techniques that have been developed to meet the requirements of military space communications have had or will have important, sometimes unanticipated, applications in the civilian sphere.

Nowadays we take the ready availability of worldwide high-capacity communications circuits for granted. Communications satellites and undersea cables bring us information (such as live television) from almost anywhere.

It was not always this way. In the mid-1950s, for example, trans-Atlantic communications relied on several teletype cables, a few dozen voice channels via cables equipped with vacuum-tube repeaters, high-frequency (HF) radio (roughly 3 to 30 MHz), and physical transport of messages by plane or ship. The rest of the world was not even that well equipped.

The HF medium has always challenged communications engineers. Under favorable conditions, it provides worldwide communications (that is, from a specific point to another specific point, at a specific time) by the use of relatively small, low-power transmitting and receiving terminal equipment. However, natural phenomena often interfere with HF links. And in time of war (cold or hot), they become targets for jamming. Nevertheless, HF was the only game in town in the 1950s. Thus the communications for the command and control of U.S. strategic forces worldwide left a lot to be desired.

Lincoln Laboratory's program of research and development in space communications has accomplished much in its 30-year history. The initial objective of the program was simply to make long-range military communications *routinely available,* first for large, fixed terminals and then for small, mobile ones. After that goal was reached, the emphasis shifted toward making the communications systems *electromagnetically and physically survivable,* capable of functioning despite the most determined efforts by an adversary to interfere with them by jamming or by physical attack.

The job is not finished. The successes achieved in making communications systems available and survivable must be followed up by equally noteworthy breakthroughs in making the technologies *affordable,* so that both tactical and strategic users can benefit from reliable communications.

Project West Ford

The immediate impetus for Lincoln Laboratory's first work in space communications came from the HARDTACK series of high-altitude nuclear tests, which were carried out in the Pacific Ocean near Johnston Island in August 1958. The first of these thermonuclear detonations destroyed the ionosphere over a vast area around the test site, and thus interrupted a great many HF radio communications links (because HF radio signals travel by means of reflections off the lower surface of the ionosphere and the surface of the earth).

The loss of HF radio halted commercial trans-

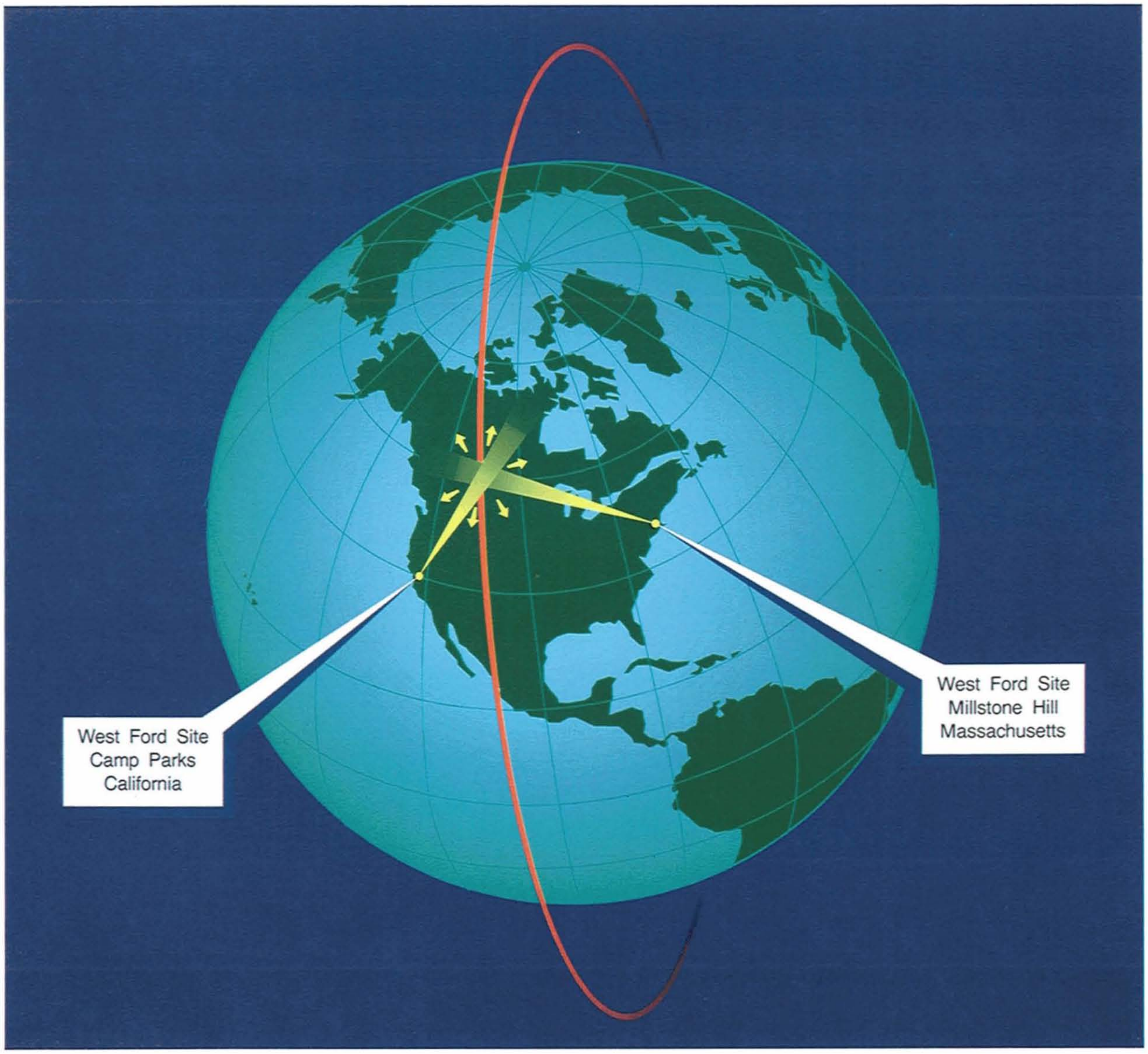

Fig. 1 — The orbiting belt of West Ford dipoles made possible the demonstration of survivable scatter communications across continental distances.

Pacific air transport. The military implications of a failure in HF radio communication at a critical time were obvious. How could radio communication be maintained?

Walter Morrow, of Lincoln Laboratory, and Harold Meyer, then at TRW Corp., considered the problem of HF radio communication failures during the Army's Project Barnstable Summer Study in 1958. They suggested that, if the ionosphere became unavailable to serve as a natural reflector (due to such natural phenomena as solar storms or due to thermonuclear detonations), an orbiting artificial reflector could replace the ionosphere. Both the U.S.S.R. and the United States had recently demonstrated the capability of placing satellite payloads into orbit, so the idea had become feasible.

Morrow and Meyer proposed the construction of an artificial reflector that consisted of a pair of belts (one circular polar, one circular equatorial) of resonant scatterers in orbit a few thousand kilometers above the surface of the earth. The scatterers in each belt would be conducting objects (e.g., lengths of wire) that would resonate at the system's operating wavelength and therefore reradiate RF signals. The smaller the objects, the shorter the wavelength, and the easier their distribution from an orbiting dispenser. If the objects were too small, however, construction of adequate transmitting and receiving terminals would become excessively difficult.

Lincoln Laboratory proposed an experiment to demonstrate transcontinental communications by sending full-duplex (i.e., simultaneously in both directions) transmissions between terminals in Camp Parks, Calif., and Westford, Mass. The orbiting scatterers would act as half-wave dipoles and resonate at ≈8 GHz; the communications would be transmitted at 7,750 and 8,350 MHz (Fig. 1). Each scatterer would be a 0.7-in length of #53 AWG copper wire (0.0007-in diameter). The experiment would require that about 480 million of these 40-μg dipoles (19 kg of copper) be distributed into circular polar orbits at an altitude of about 3,600 km. The average separation between dipoles (Fig.2) would be roughly 0.3 km. Sixty-ft (diameter) paraboloidal antennas would be fed by transmitters with 20-to-40-kW average power (Fig. 3). Maser receivers would provide what was then the lowest attainable system noise temperature at that wavelength, approximately 60 K. The waveforms for modulation and demodulation, multiple-frequency-shift keying (MFSK) spread over a bandwidth of 4 MHz, were designed to satisfy the requirements of communication via forward scatter off the orbiting dipoles, and to probe the characteristics of the belt via radar back scatter and forward scatter.

Recognizing that a proposal to place vast numbers of *anything* in orbit would be controversial, Lincoln Laboratory designed the proposed experiment, Project West Ford, to ensure that the experimental belt would not endure. The pressure of incident solar radiation on the orbiting dipoles would change their orbits so that the perigee of each revolution would move steadily down. Before long, the orbits would start to dip into the thin upper atmosphere of the earth, and the resistance of the atmosphere would slow the dipoles enough that they would fall back to earth. Thus the belt would be removed from orbit within a few years after its launch.

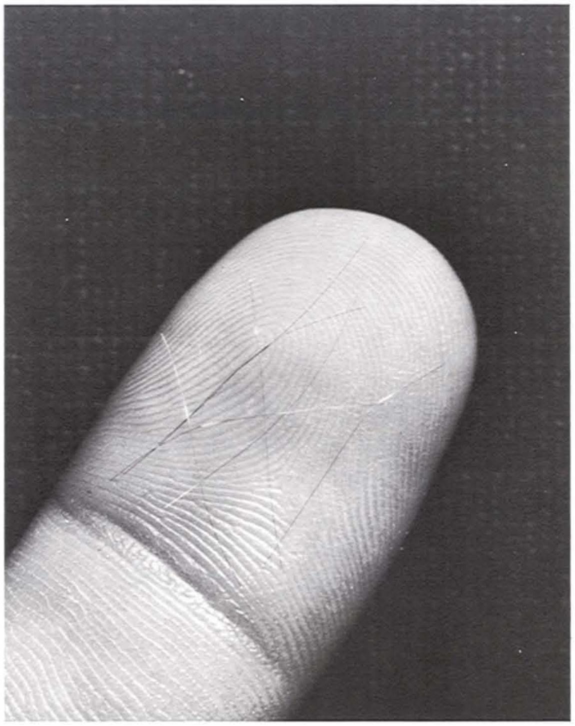

Fig. 2 — The Project West Ford orbiting dipoles were hairlike segments of copper wire. The finger has not been identified.

After planning this responsible method for concluding the experiment, Lincoln Laboratory unveiled Project West Ford in 1960 — in virtually complete detail, even though the planned experiment was originally secret. Of particular importance was allaying the concerns of optical and radio astronomers and other scientists who perceived the experimental belt as potentially harmful: capable of interference with scientific observations and a precursor of worse experiments to come. The electropolitical conflict that greeted the West Ford announcement is chronicled in Ref. 1; it and Refs. 2 and 3 describe the project in detail. The orbital-scatter-communications experiment had originally been called

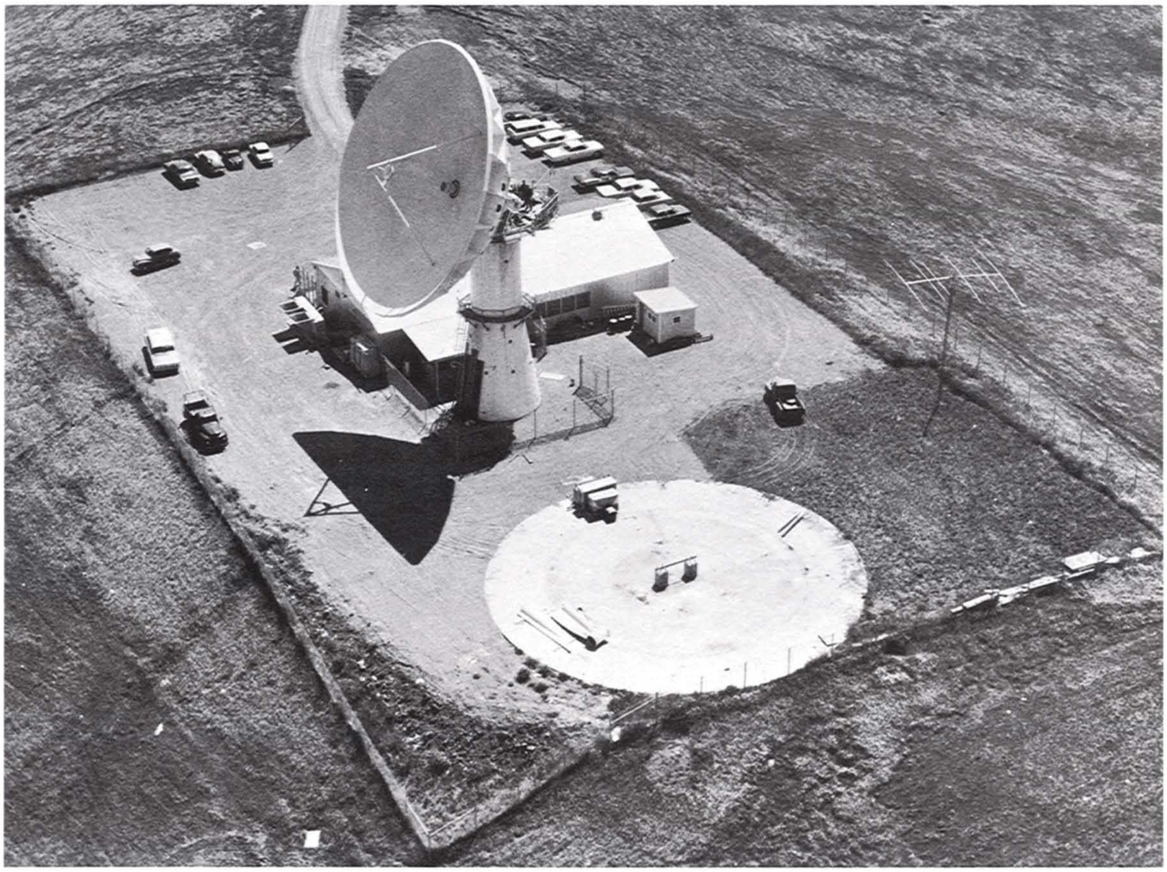

Fig. 3 — The West Ford communications terminal at Camp Parks, near Pleasanton, Calif., including special circuitry for modulation and demodulation of signals, a large steerable antenna, a high-power transmitter, and a sensitive receiver.

Project Needles, but giving it the more benign name of West Ford did little to still the clamor from both sides of the Iron Curtain (Fig. 4) [4]. Ultimately, reason prevailed and presidential approval was given for West Ford launches, though limited to the bare minimum, to demonstrate the concept of orbital scatter communications.

On 21 October 1961, the first experiment was launched, piggyback on another payload, into circular polar orbit from Vandenberg AFB, Calif. It was unsuccessful; the dipoles did not deploy as planned. On 8 May 1963, a second launch, in the same manner but with improved dipole-dispensing arrangements, achieved a substantial degree of success. The belt formed and closed over a period of about 40 days; its estimated density was 5 dipoles per cubic km. The effectiveness of the scatterers proved greater in the early stages of belt formation, when the dipoles were less spread out, than later on. The dipoles' density in the common volume illuminated by the two beams of the terminal antennas was higher earlier, allowing communication at data rates of up to 20,000 bits/s.

As the months and years passed, the belt became less effective for scatter communications, testimony that it was indeed cleaning itself out of orbit. By early 1966, the removal process was essentially complete [5]. At the conclusion of the measurements and demonstrations, the two communication terminals were converted to other uses.

Project West Ford was an undeniable success, but it had little impact in terms of operational employment. Communication via passive

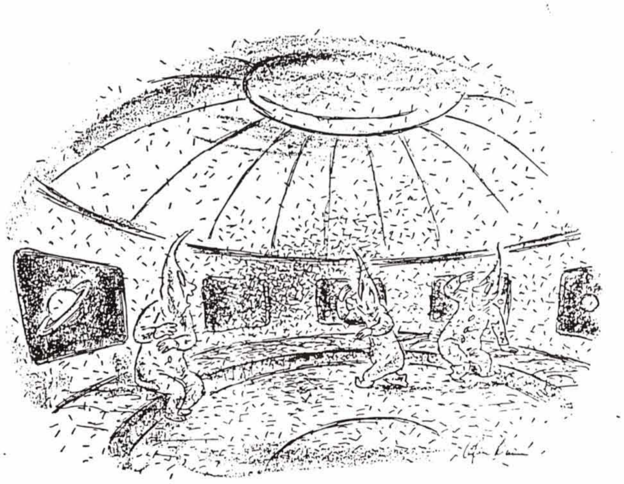

*Fig. 4 — "Close that window!"
Drawing by Alan Dunn; ©1961, 1989 The New Yorker Magazine, Inc.*

satellites such as the West Ford dipoles required users to make large investments in complex terminals and provided only limited capabilities. The success and burgeoning availability of active communications satellites, beginning with AT&T's TELSTAR-1 in 1962 [6], have swept the field. In fact, today's extensive commercial and military applications of satellite communications depend on the technology of active satellites.

Now and then the vulnerability of conventional satellite communications to radio-frequency interference (RFI), whether intentional or not, is brought forcibly to everyone's attention [7]. Furthermore, most satellites in orbit are fragile and thus vulnerable to physical attack. Therefore, Lincoln Laboratory has focused its work in active-satellite space communications on the development of robust systems that function reliably in the face of formidable levels of interference. But the lesson of Project West Ford — that point-to-point scatter communications at limited data rates can be extremely survivable — should not be forgotten.

Space Communications at Super-High Frequency

After showing with Project West Ford what could be done for military communications by using passive satellites, Lincoln Laboratory embarked on a program to improve the design of active satellites.

In most cases, the downlink signal (from a satellite to a surface terminal) is the "weak link" in satellite communications; an uplink can be strengthened by increasing the power of a surface transmitter. By contrast, a satellite downlink must be strengthened by maximizing the effective isotropically radiated power per unit mass in orbit — a more difficult task. To address the downlink problem in space communications, Lincoln Laboratory set out to develop high-efficiency spacecraft transmitters in the downlink frequency band. Improved antennas offered an additional benefit: if the spacecraft attitude-control system associated with a high-gain spacecraft antenna could position the antenna within its required beam-pointing tolerance, downlinks and uplinks would both benefit. These and other spacecraft-related technologies were addressed by a series of Lincoln Experimental Satellites (LES), which were launched between 1965 and 1976.

Capitalizing on high-efficiency systems of modulation and demodulation, together with recent advances in encoding and decoding signals for detection and correction of errors, promised significant advantages for communication terminals. Also needed were interference-resistant, multiple-access signaling techniques that would permit simultaneous use of a satellite by tens or hundreds of users, some of them mobile, without invoking elaborate systems for synchronization and centralized control. These and other terminal-related problems were addressed by a series of Lincoln Experimental Terminals (LET) that went hand in hand with the LESs.

Lincoln Laboratory's post–West Ford space-communications program got under way in 1963 with a charter to build and demonstrate space-communications systems that addressed military needs [8, 9]. The initial program objective was to build, launch, and field a LES and a LET that would work together as a system and demonstrate practical military satellite communications (MILSATCOM). The availability of Project West Ford's advanced RF technology at super-high frequency (SHF) — 7 to 8 GHz

— contributed to the decision to design LES-1 and LET-1 for that band. The Department of Defense's (DoD) concurrent procurement of a series of SHF satellites and terminals, commencing with the Initial Defense Communications-Satellite Program (IDCSP) [10], meant that lessons learned from LES-1 and LET-1 would find an additional application.

LES-1 and its twin, LES-2 [11, 12], were each built as a small polyhedron with a mass of 37 kg (Fig. 5), solar-powered, and spin-stabilized. The satellite's communications transponder acted as a bent pipe in the sky: it translated signals received at the uplink frequency to the downlink frequency after passing the signals through a 20-MHz-wide filter at intermediate frequency (IF) and a hard limiter. In response to measurements by visible-light sensors of the earth's position, an autonomous electronic antenna-switching system would connect one of eight SHF horn antennas on the corners of the polyhedron to the transponder. A magnetic attitude-control system (pulsed electromagnets working against the earth's magnetic field synchronously with sensor outputs) kept the satellite's spin axis oriented perpendicularly to the line of sight to the sun, and thus avoided thermal problems.

Fig. 5 — Andy Howitt inspects Lincoln Experimental Satellite (LES)-1 near the end of its fabrication.

Fig. 6 — Lincoln Experimental Terminal (LET)-1 — a complete, self-sufficient, transportable terminal for SHF space communications — ready to roll.

The Titan III-A boosters, which would carry LES-1 and -2, were still under development. The boosters were capable of carrying the satellites to inclined circular orbits at altitudes of about 2,800 km. To reach a higher altitude (which would allow tests that would better represent operational MILSATCOM systems), LES-1 and -2 were each equipped with a perigee kick motor, a solid rocket that would place the satellite in an inclined elliptic orbit with 15,000-km apogee.

LES-1, launched from Cape Canaveral on 11 February 1965, accomplished only a few of its goals. Apparently because of ordnance-circuitry miswiring, the satellite never left its circular orbit and ceased transmitting in 1967. LES-2 did much better: on 6 May 1965, it achieved its planned final orbit. Operation with LET-1 [13] was successful, commencing the morning after launch.

LET-1 (Figs. 6–8) was a complete, self-contained, air-transportable ground terminal equipped to test and demonstrate evolving space-communications techniques in realistic environments. The terminal included a modula-

Fig. 7 — LET-1 set up for operation with LES-1.

tion/demodulation system based on 16-ary frequency-shift keying (FSK), frequency-hopped over a 20-MHz-wide band at SHF. This set of features, tailored to match the characteristics of LES-1 and -2, provided protection against interference — whether by happenstance or by intention — and was applicable for communication over dispersive channels that used orbiting scatterers such as the moon or the West Ford dipole belt.

LET-2 and -3, each consisting of only a signal-processing van, were built at about the same time as LET-1. One of these terminals was used with the SHF West Ford terminal at Westford; the other was transferred to the Army Signal Corps for service with SHF terminals at Camp Roberts, Calif., and at Fort Monmouth, N.J. The signal-processing features of LET-1, -2, and -3 included advanced vocoders for speech compression and reconstruction, and convolutional encoders and sequential decoders for detecting and correcting errors in the received data stream. The incorporation of cooled varactor-diode parametric amplifiers, which provided a system noise temperature of about 55 K, improved the sensitivity of LET-1's receiving system [14].

The next step in Lincoln Laboratory's program in space communications was to push a satellite out to a geosynchronous orbit. LES-4 (Fig. 9) was built to fulfill that mission. The satellite was an outgrowth of LES-1 and -2; the 53-kg satellite had a greater number of solar cells and an enlarged array of sun and earth sensors [11, 15]. The SHF transponder on LES-4 was essentially identical to the ones on LES-1 and -2, although its electronically despun SHF antenna system was more sophisticated [16]. LES-4 carried an instrument for measuring spatial and temporal variations of the energy spectrum, in five energy ranges, of trapped electrons encountered in orbit. This instrument

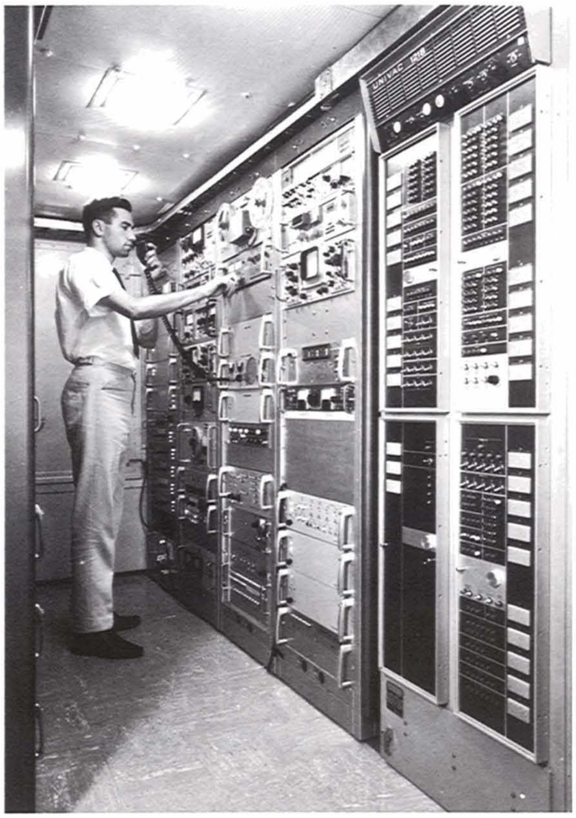

Fig. 8 — Steve Russell operating LET-1.

was added to provide information both for scientific interest and to aid the design of future spacecraft.

A Titan-IIIC booster was to carry LES-4 and its companion, LES-3 (described below), to a near-geosynchronous altitude and deposit them in circular, near-equatorial orbits with eastward drift in subsatellite longitude of about 30 deg/day. These satellites did not have on-board propulsion systems. The satellites would be visible to any given terminal for about five days, then disappear in the east to reappear six days later in the west. Unfortunately, the booster failed to finish its job, leaving these satellites stranded in their transfer ellipses. This disappointment, however, had its bright side: LES-4's repeated trips between perigee (195 km) and apogee (33,700 km) gave it many opportunities to measure the radiation environment over a wide range of altitudes [17]. LES-4's communications system appeared to be working as well as it could under the handicap of being in the wrong orbit. Ultimately, as with the West Ford dipoles, the pressure of solar radiation caused the perigee of LES-4's orbit to descend into the upper atmosphere, and it burned up.

Lincoln Laboratory's accomplishments in SHF space communications opened up a part of the electromagnetic spectrum that remains heavily used today. In fact, succeeding generations of SHF satellites now form the space segment of the Defense Satellite Communications System (DSCS).

Space Communications at Ultra-High Frequency

LES-1, -2, and -4 and LET-1, -2, and -3 showed the capabilities of SHF for reliable communications between fairly massive terminals. These technologies, however, were not immediately available to small tactical units such as vehicles, ships, aircraft, and specialized ground troops, all of which needed direct, dependable communications. Only a large command-post airplane or a sizable ship could be equipped with an SHF terminal that could work with the DSCS satellites in orbit and those planned for the immediate future.

High levels of RF power at SHF could not be

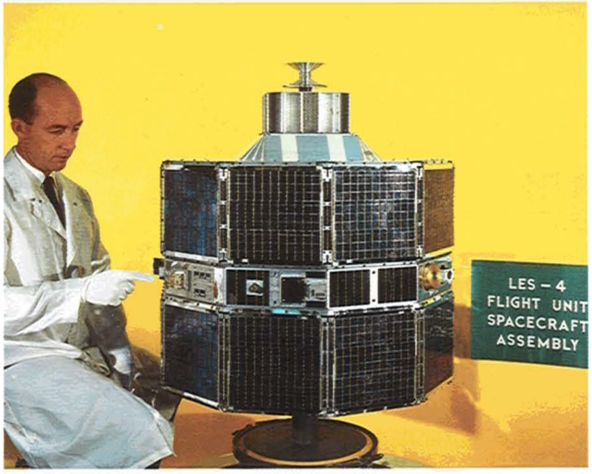

Fig. 9 — Andy Howitt again, checking a sun sensor on LES-4.

generated in the satellites, so the downlink continued to limit system performance. Each terminal's antenna aperture had to be large enough to capture the downlink signal, and the price for a large antenna aperture at SHF was a narrow, high-gain antenna beam that had to be pointed directly toward the satellite. Small tactical units could not accommodate such complex antenna systems, particularly if the platform carrying the terminal would be in motion.

Communications links at much lower frequencies (in the military ultra-high-frequency [UHF] band, 225 to 400 MHz) solved the downlink problem. Solid-state circuits could generate substantial amounts of RF power at UHF in a satellite [18, 19]. A relatively uncomplicated low-gain terminal antenna could provide a broad beam (simplifying the task of pointing an antenna in the direction of the satellite), and a sizable receiving area, which permitted closing the link. Such antennas were particularly appealing for aircraft installation [20]. UHF terminals promised to be comparatively simple and inexpensive, and they could be readily produced in large numbers.

The feasibility of active-satellite communications at longer wavelengths — although not seriously in question — was demonstrated at VHF by Hughes Aircraft Co. on 8 May 1964. The company used teletype-rate signaling (60 wpm) through the SYNCOM-2 [21] satellite from one ground terminal to another nearby. A 148-MHz telecommand and a 136-MHz telemetry link were used for the uplink and the downlink, respectively [22]. On 27 January 1965, teletype-rate satellite communication to and from an airplane in flight was demonstrated by using the SYNCOM-3 satellite [21], operating in the same mode as SYNCOM-2, and a ground terminal at Camp Parks [23, 24]. NASA's ATS-1 satellite [25], launched in December 1966, also participated in experiments of this sort.

The linear polarization of the satellites' and the airplanes' VHF antenna systems handicapped these airborne tests. As the radio waves traversed the ionosphere, their planes of electromagnetic polarization were rotated by the Faraday effect (interaction of the earth's magnetic field with free electrons). When a net misalignment between the orientations of the two antennas occurred, the level of the received signal was consequently reduced.

In 1965 the DoD established Tri-Service Program 591 (Tactical Satellite Communications) to enable the Army, Navy, and Air Force to evaluate the potential usefulness of satellite communications in the military UHF band. Lincoln Laboratory was chosen to provide the satellites essential to the test program. LES-5 was to be built and launched as soon as possible; LES-6 would incorporate improvements on LES-5 and would be launched a year later. The three military services would procure test terminals that would work with LES-5 and -6 and would arrange for their installation in ships and aircraft.

Lincoln Laboratory carried out two programs to measure the characteristics of the UHF environment. In the first program, receiving equipment was installed in aircraft and flown over representative cities and varied terrains, and the ambient RF noise was measured [26–28]. In the second program, propagation phenomena between satellites and airborne terminals were examined. For this program, LES-3 was built in haste, using technology from LES-1, -2, and -4, and was launched along with LES-4 on 21 December 1965.

LES-3 (Fig. 10), with a mass of 15.5 kg [11, 29], was essentially a signal generator in orbit. It radiated a signal near 233 MHz that was biphase-modulated by a 15-bit maximal-length shift-register sequence at a clock rate of 100,000 bits/s. Correlation of the signal received in an aircraft with a replica of the known sequence brought out time-delay structures in the propagation path. Multipath propagation effects were expected, and they were observed [30]. Given the degree of smoothness of the earth's surface relative to the 1-m free-space wavelength of 300 MHz (the middle of the military UHF band), much of earth's surface is mirrorlike, and electromagnetic waves were able to be propagated between the satellite and the airborne terminal by more than one path. By knowing the likely parameters of the signal delays, the communication-system designers were able to construct modulation and demodulation circuits that would not be confounded by multipath-propagation effects.

As mentioned, booster problems trapped LES-3 and LES-4 in transfer ellipses, although circular, equatorial orbits at a near-geosynchronous altitude had been planned. The actual orbit of LES-3 did permit the gathering of multipath-propagation data over a wide variety of terrains, and it gave the Lincoln Laboratory test team a reason to fly to exotic destinations to receive LES-3 signals reflected by representative types of terrain. Like LES-4, LES-3 ultimately re-entered the atmosphere and disintegrated.

LES-5, launched by a Titan-IIIC booster on 1 July 1967 [31], and LES-6, launched in the same way on 26 September 1968, share a strong family resemblance (Figs. 11–13), with masses of 94 and 169.4 kg, respectively [32, 33]. Each satellite is powered by solar cells and is spin-stabilized around an axis nominally perpendicular to the near-equatorial orbit plane. LES-5 has no onboard propulsion system; its spin axis is kept erect by an attitude-control system based on pulsed electromagnets interacting with the earth's magnetic field [34]. LES-5 is in a near-circular, sub-synchronous orbit (a period less than a sidereal day) and drifts eastward about 33 deg/day. LES-6 has a workhorse ammonia propulsion system for attitude and orbit control and a backup magnetic attitude-control system.

The central feature of each of these satellites is a broadband, hard-limiting, frequency-translating UHF-to-UHF transponder. To avoid problems due to the Faraday effect, each satellite has a circularly polarized antenna system. LES-5's antenna gain pattern resembles a fat doughnut placed around the waist of the satellite [35]; LES-6's antenna pattern is a directive beam that is automatically aimed at the earth, regardless of the satellite's spin, by a system that includes optical sensors and electronic RF switches [35].

To make a long story short, satellite commu-

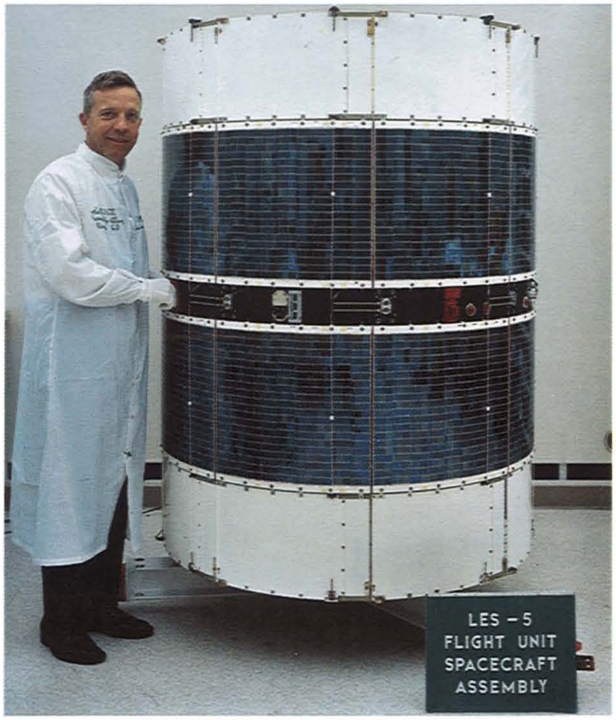

Fig. 11 — Claude Gillaspie points with pride to the viewband of LES-5.

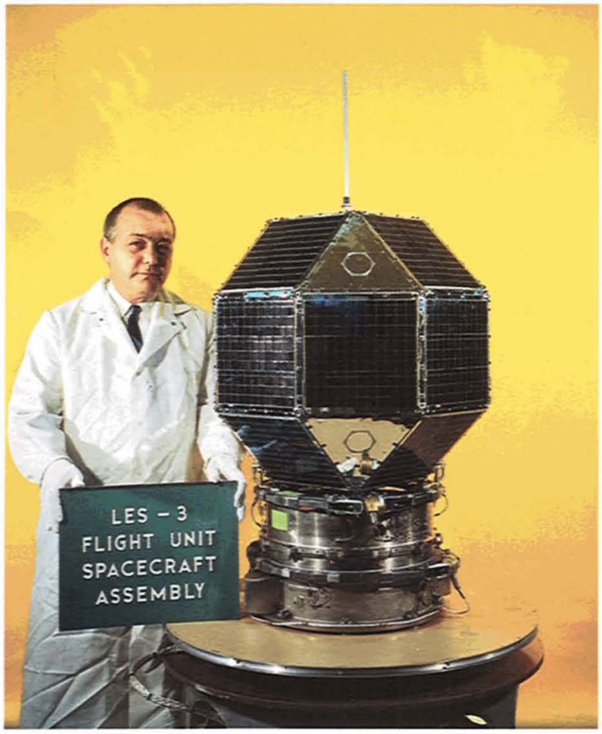

Fig. 10 — Joe Marapoti has LES-3 ready for launch.

Fig. 12 — Joe Palmer (left) and Howard MacDonald (right) tighten a screw on LES-6. What is wrong in this picture?

nications in the military UHF band worked well. The Tri-Service terminals in ships and aircraft and in the field communicated readily through LES-5 in orbit. To enhance satellite-communications at UHF to and from mobile platforms, Lincoln Laboratory developed a special anti-jam/multiple-access system of modulation and demodulation based on frequency hopping and MFSK [36]. The TATS (Tactical Transmission System) that worked with LES-5 was completed at the last minute, "after the launch but before the insertion into orbit." TATS met its performance goals and was put into production by the DoD. The LETs for UHF (Fig. 14) were much smaller than SHF terminals. The components of a representative UHF airborne terminal are shown in Fig. 15.

LES-6 and the Hughes-built UHF/SHF TACSAT (Ref. 37, launched 9 February 1969) placed substantial communications resources in geostationary orbit, and the DoD procured large quantities of UHF terminals. Since more than two satellites were needed for worldwide coverage, a series of satellites, including Gapfiller (MARISAT, Ref. 38), FLTSAT (FLTSATCOM, Ref. 39), and LEASAT [40], were launched. A new series, UHF Follow-On (UFO) satellites, is now under development.

Use of the UHF spectrum for MILSATCOM is by no means limited to the U.S. DoD. The U.S.S.R. has announced a series of Volna ("Wave") satellites that incorporate UHF uplinks and downlinks [41], and the United Kingdom has included UHF provisions in its series of SKYNET-4 satellites, the first of which was launched on 10 Dec. 1988 [42]. As will be discussed, it is very difficult to defend a communications satellite with a UHF uplink against a determined jamming attack. Nevertheless, since the relative simplicity and comparative cheapness of UHF MILSATCOM terminals make this part of the spectrum highly attractive, it is likely to remain in use for a long time.

Experience with UHF satellite communications soon revealed that transmissions are sometimes subject to amplitude scintillation due to propagation through turbulent electron-density fluctuations in the ionosphere [43]. Extra-strong received signals cause no problems, but weak signals may break communications links. These effects occur most often for terminals near the geomagnetic poles and the geomagnetic equator. To characterize scintillation effects on a link that included the Pacific Gapfiller satellite, and to provide a flexible test environment, Lincoln Laboratory measured transmissions from Hawaii to Guam and used these measurements to design and test a time-diversity communications system for mobile terminals [44].

As the number of UHF satellite-communications terminals grew, so did the importance of increasing the utilization efficiency of the UHF satellite transponders. Lincoln Laboratory developed a demand-assigned time-division multiple-access (TDMA) system that accomplished this goal by improving the ground terminals. The laboratory demonstration of the Terminal Access Control System (TACS) [45] led to the

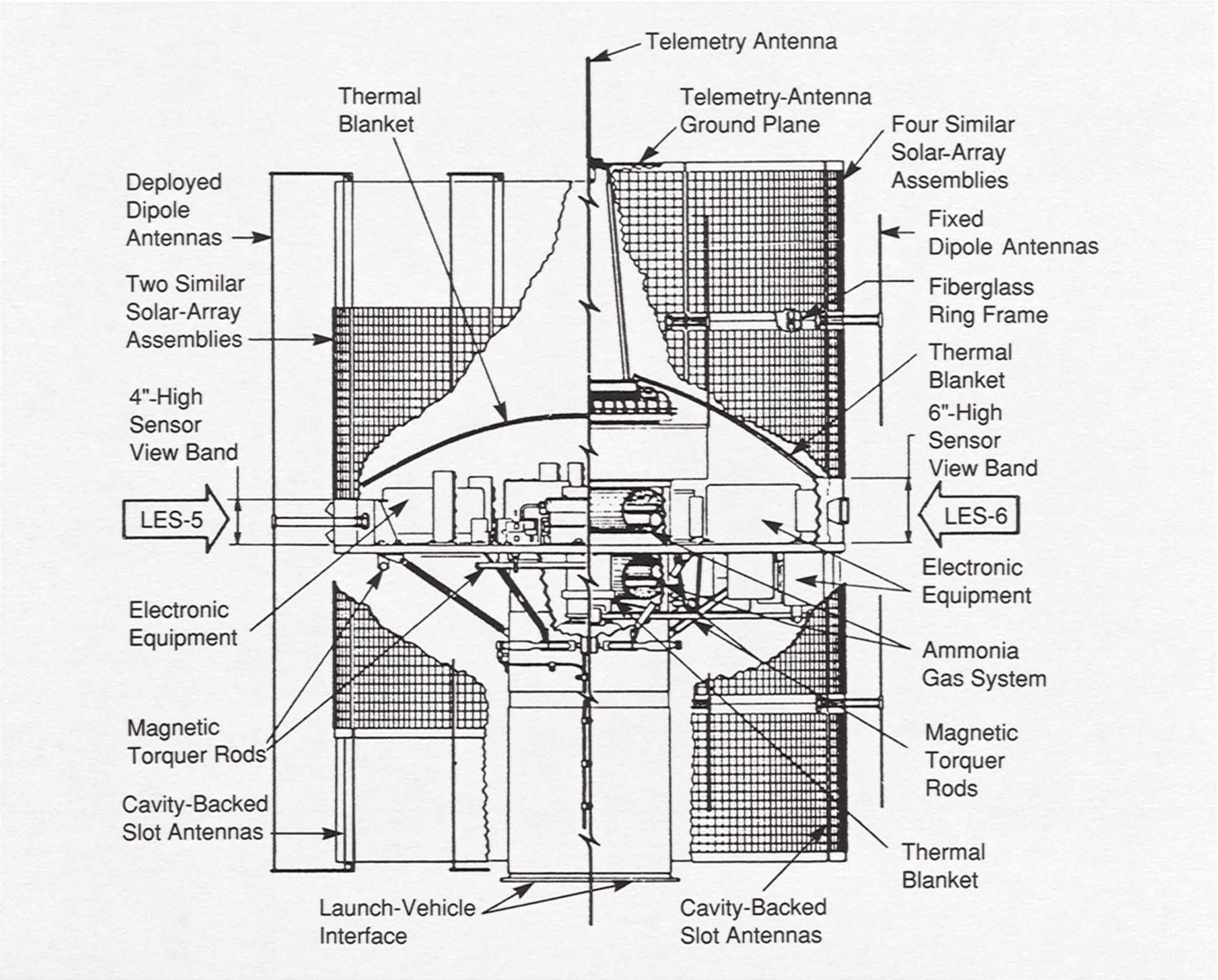

Fig. 13 — The prominent features of the generally similar satellites LES-5 and -6 are shown here for comparison.

Navy's procurement of demand-assigned multiple-access (DAMA) terminal-control equipment for some of its UHF satellite-communications systems.

LESs have often accommodated space-technology experiments. LES-6 carries a set of solar cells for measurement of degradation effects, a detector for measurement of particle radiation (similar to the one on LES-4), a pulsed-plasma-thruster system for orbit control [46], and a system for automatically stationkeeping the satellite in longitude [47]. The Aerospace Corporation provided LES-5 and LES-6 with automatically scanning UHF receivers that serve as spectrum analyzers in the sky and repeatedly sweep their receiver passbands across separate 15-MHz-wide windows.

The characteristics of the RF environment near the altitude of geosynchronous orbit have been measured and telemetered to Lincoln Laboratory for analysis [48]. These tests have demonstrated that observations in orbit can give very different results from predictions based on listings of frequency allocations and authorizations. Some entities request frequency allocations but rarely use them. Other entities radiate interfering signals, usually unintentionally, toward the satellite corridor; these signals can be nuisances. As the use of the electromagnetic environment increases, the importance of locat-

Fig. 14 — Lou Hallowell is about to take off with LET-4, a mobile terminal for UHF satellite communications.

ing and mitigating sources of uplink RFI is becoming increasingly important.

After LES-6's test program was successfully completed, it began a long period of operational communications support. The satellite was placed on reserve status in March 1976, when the first Gapfiller was launched. A condition check of the LES-6 communications transponder, carried out on 14 October 1988, showed that, after 20 years in space, it still worked. The satellite's output power and receiving sensitivity were found to be significantly poorer than they were during the years just after launch. However, LES-6 is still available for limited communications support if needed; its stalwart endurance testifies to the extremely long, useful lives of spacecraft systems. The next scheduled condition check of the LES-6 communications transponder is planned for 1993.

Space Science

During the early years of Lincoln Laboratory's program in space communications, the builders of LESs worked side by side with the builders of scientific instruments that were flown on spacecraft orbiting the earth and on others orbiting the sun. In 1967, Lincoln Laboratory–built plasma-probe instruments were working aboard the spacecraft EOGO-1, EOGO-3, Mariner-4, Pioneer-6, and Pioneer-7, and a Lincoln Laboratory gamma-ray telescope was operating aboard OSO-E. The equipment carried by LES-6 to measure particle radiation was the last such scientific experiment; thereafter the strong program focus on MILSATCOM mission requirements ruled out most side activities.

Although not directly related to MILSATCOM functions, the Lincoln Calibration Spheres

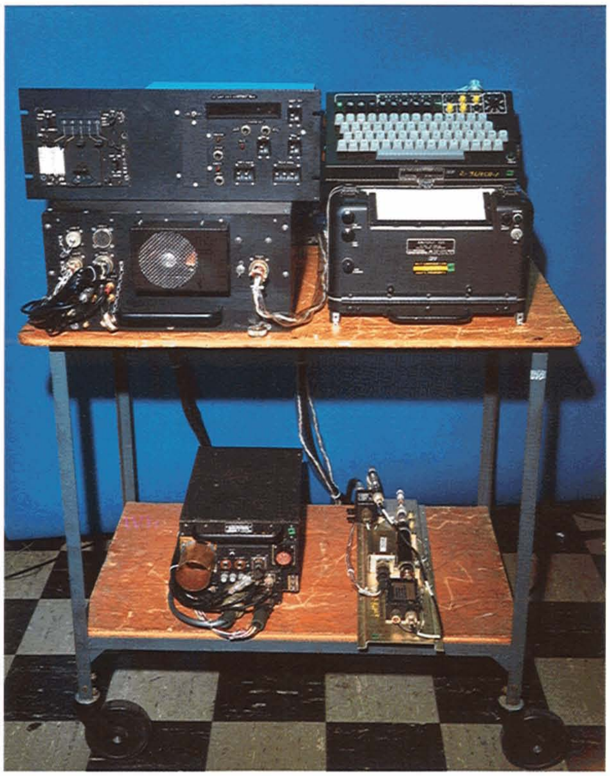

Fig. 15 — These black boxes are the subsystems of a representative airborne terminal for UHF satellite communications. On the top shelf of the cart, the control panel and modem electronics package are at the left; the military teletypewriter (keyboard and printer) is at the right. On the bottom shelf, the transmitter is at the left, the transmit/receive switch for the antenna is at the right.

(LCS) deserve mention [49]. Each sphere (Fig. 16) was a polished, hollow, rigid aluminum sphere with a diameter of 1.129 m, an optical cross section of 1 m^2, and a radar cross section at 1,300 MHz of 1 m^2. These passive satellites, with masses of 34 kg, were designed to be calibration objects for ballistic-missile and satellite-tracking radars and for optical telescopes. LCS-1 was placed in a circular orbit at an altitude of 2,800 km on 6 May 1965 — too high to be very useful, but where the booster was scheduled to dispense its payload. LCS-2 and LCS-3 were lost to booster failures. LCS-4 was placed in a circular, near-polar orbit at an altitude of 850 km on 7 August 1971 and continues to be a useful calibration object.

Multiple-Beam Antennas

LES-1, -2, and -4 and LET-1, -2, and -3 showed that SHF could provide reliable communications within certain limitations. The antenna systems on these satellites were small in terms of wavelength, and their beams were much larger than earth coverage (which is about 18° from synchronous altitude). The next level of sophistication in SHF space communications was a satellite antenna system with a mechanically pointable, less-than-earth-coverage beam. This advancement was achieved through governmental procurement of communications satellites such as the second generation of the

Fig. 16 — A Lincoln Calibration Sphere at Rohr's plant in Chula Vista, Calif. Note in the mirrorlike surface of this sphere the reflection of the man leaning on it, the camera and tripod, the photographer, lines in the parking lot, and surrounding buildings. The man is believed to have been an employee of Rohr; he has not been identified.

DSCS (TRW's series of DSCS-IIs, Ref. 50). Lincoln Laboratory undertook to develop and demonstrate, in orbit, an antenna system that could allow satellite operators to aim the transmit (downlink) power to receivers and simultaneously reduce the receiving (uplink) sensitivity in directions that might include sources of jamming or other interference.

Such an antenna system can be built in two ways. In the phased-array approach, many separate transmit and/or receive modules (each of which has a beamwidth much larger than earth coverage) are controlled individually in amplitude and phase so that the sum of their signals, a result of constructive and destructive interference, approximates the desired transmit or receive antenna pattern covering the earth. In the multiple-beam–antenna (MBA) approach, many separate antenna feeds form a dense set of narrow pencil beams covering the earth. The signals from this collection of beams are adjusted in amplitude and phase ("weighted") and combined to approximate the desired antenna pattern. Each approach has its merits and shortcomings, and the appropriate choice depends on the application.

Lincoln Laboratory began a program to demonstrate, in orbit, a 19-beam MBA for reception at SHF (Fig. 17). An earth-coverage horn was to be used for transmission. The 30-in–diameter aperture of the receiving antenna yielded a nominal 3° resolution throughout the cone subtended by the earth from geosynchronous-satellite altitude. The ground control terminal was to calculate the weights for the individual beams to approximate the desired antenna pattern and to transmit the weights to the satellite by telecommand.

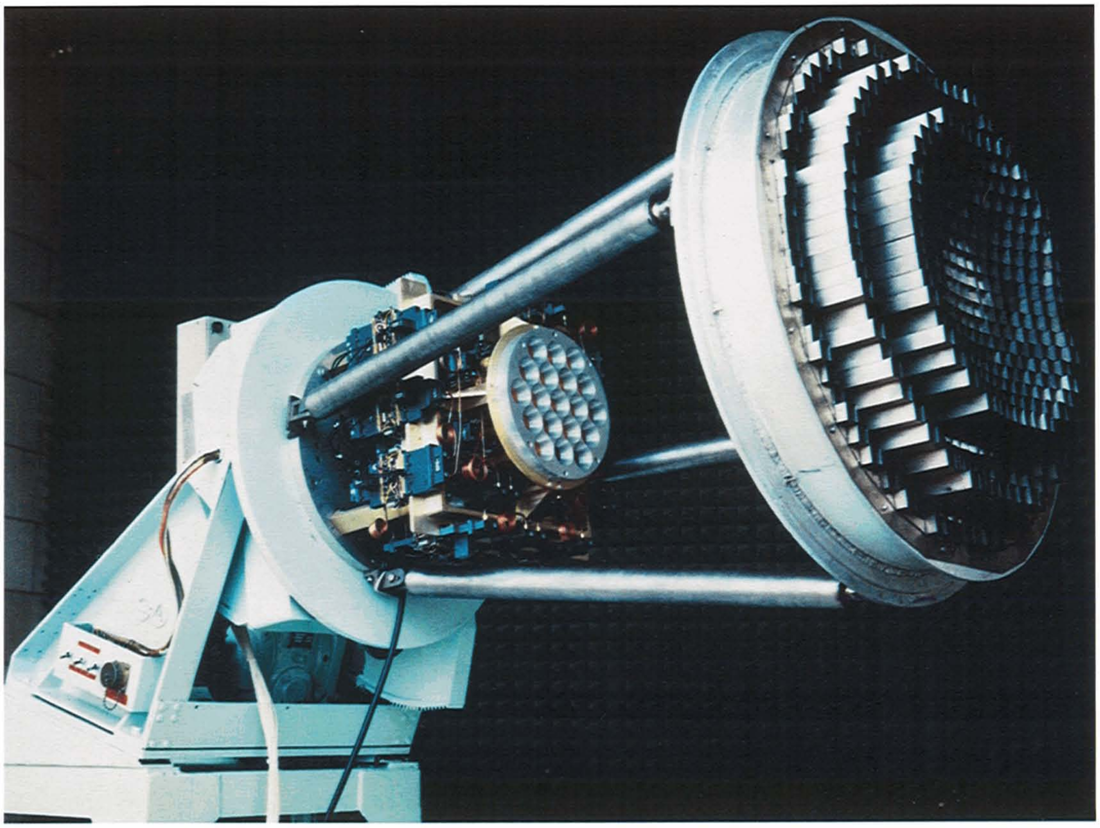

Fig. 17 — RF switch matrix, cluster of 19 feed horns, and waveguide lens (left to right), comprising a multiple-beam antenna such as that planned for LES-7.

The MBA, which was kept facing the earth by the attitude-control system, dominated the configuration of LES-7 (Fig. 18). Solar-cell arrays followed the sun to collect energy as LES-7 revolved during its orbit around the earth. Work got underway to develop the satellite bus — consisting of structure and housekeeping systems, power, propulsion, attitude control, thermal control, telemetry, and telecommand — in parallel with the development of the MBA and of the communications system associated with it [51].

By early in 1970, it became apparent that LES-7 was ahead of its time. Since there was not enough support in the DoD for the mission, the funding required for the satellite's development, launch, and evaluation in orbit was not available. Lincoln Laboratory, with considerable regret, put aside the LES-7 flight program. The critical technology of the MBA was carried through development on the bench and at an antenna test range [52]. In time the MBA concept found application — in the third generation of the DSCS. Each GE-built DSCS-III [53] carries two 19-beam SHF MBAs for transmission and one 61-beam SHF MBA for reception (Fig. 19).

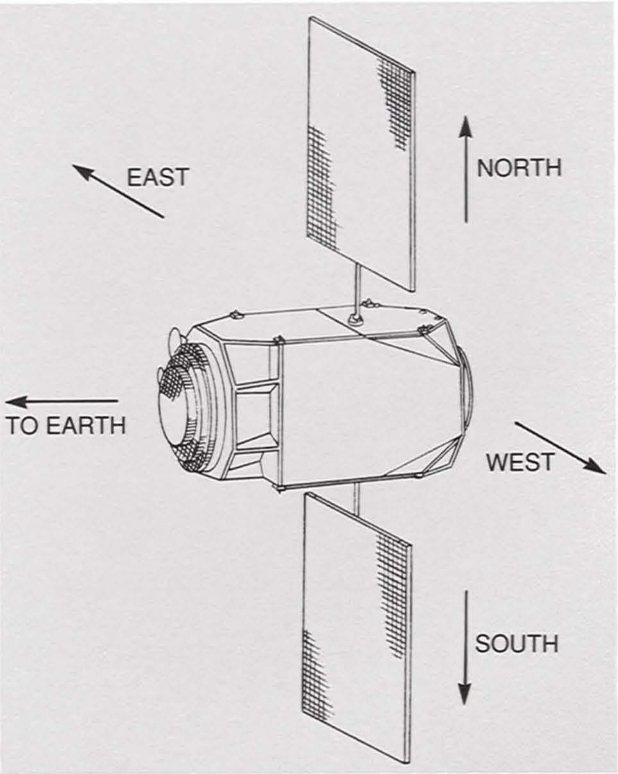

Fig. 18 — Design study for LES-7.

Space Communications at Extremely High Frequency

LES-8 and -9 are a pair of experimental communications satellites that Lincoln Laboratory developed and built for the DoD [54, 55]. They were designed to operate in coplanar, inclined, circular, geosynchronous orbits, and to communicate with each other via intersatellite links (crosslinks), and with terminals operating on or near the surface of the earth. The overall communications system (Fig. 20) provided for assured communications between a limited number of strategic terminals at data rates ranging from teletype (75 bits/s) to vocoded voice (2,400 bits/s) and computer data exchange (19,200 bits/s). The system design incorporated a number of band-spreading and signal-processing techniques for electromagnetic survivability, including encoding/decoding, interleaving/deinterleaving, multiplexing/demultiplexing, frequency hopping/dehopping, and demodulation, crossbanding, and remodulation onboard the satellite.

LES-8 and -9 (masses of 450 kg each) are shown in Figs. 21 and 22; their salient characteristics are listed in Table 1. The military UHF band was augmented by uplinks, downlinks, and intersatellite links at extremely high frequency (EHF). That portion of the spectrum held out the promise of abundant bandwidth to accommodate many simultaneous users and spread-spectrum systems of modulation and demodulation for electromagnetically survivable (i.e., hard, anti-jam) communications links. For reasons of convenience, operating frequencies in the K_a-band (36 to 38 GHz) were selected.

Intersatellite links in the 55-to-65-GHz frequency range would have been desirable, because absorption by oxygen molecules would attenuate signals passing through the atmosphere. However, it soon became apparent that the technology of 1971, on which LES-8 and -9

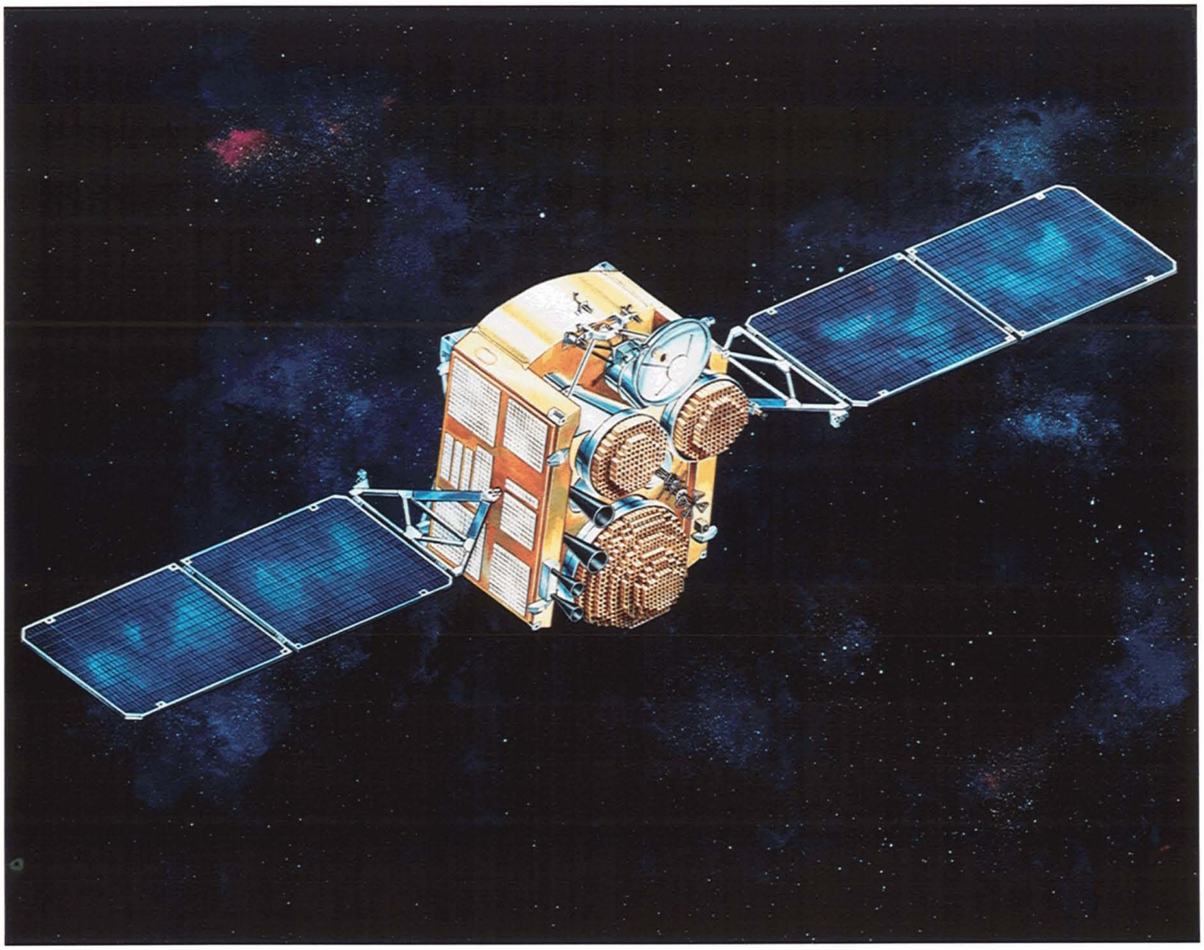

Fig. 19—Artist's concept of the Defense Satellite Communications System (DSCS)-III satellite in orbit. Note the three waveguide-lens multiple-beam antennas.

had to be based, would not support such an enterprise. Very little test equipment was commercially available for frequencies above 40 GHz. Attention, therefore, focused on the development of the needed components and subsystems at K_a-band [56].

One of the strengths of Lincoln Laboratory's program in space communications is that it encompasses the development of terminals and of satellites under one roof. Transmission and reception for satellite links providing substantial anti-jam capability, such as links through LES-8 and -9, are complex when compared to links that rely on unprotected transponders, as do links through LES-1, -2, -4, -5, and -6. It would be very difficult if the space and terrestrial segments of a modern MILSATCOM system were developed separately and their first operating encounter took place after launch. Lincoln Laboratory conducted extensive end-to-end testing of communications links before launch, including the terminals that Lincoln Laboratory developed and those developed by the Air Force and the Navy. The generally smooth course of the communications-link testing in orbit (Fig. 23) owed a great deal to the pre-launch testing at Lincoln Laboratory [57].

The LES-8 and -9 intersatellite links successfully addressed the key technical problems that confront the implementation of satellite-to-satellite communications [58, 59]. LES-8 and -9 were launched together on 14 March 1976. The Titan-IIIC booster placed them in nearly coplanar, circular, geosynchronous orbits with equa-

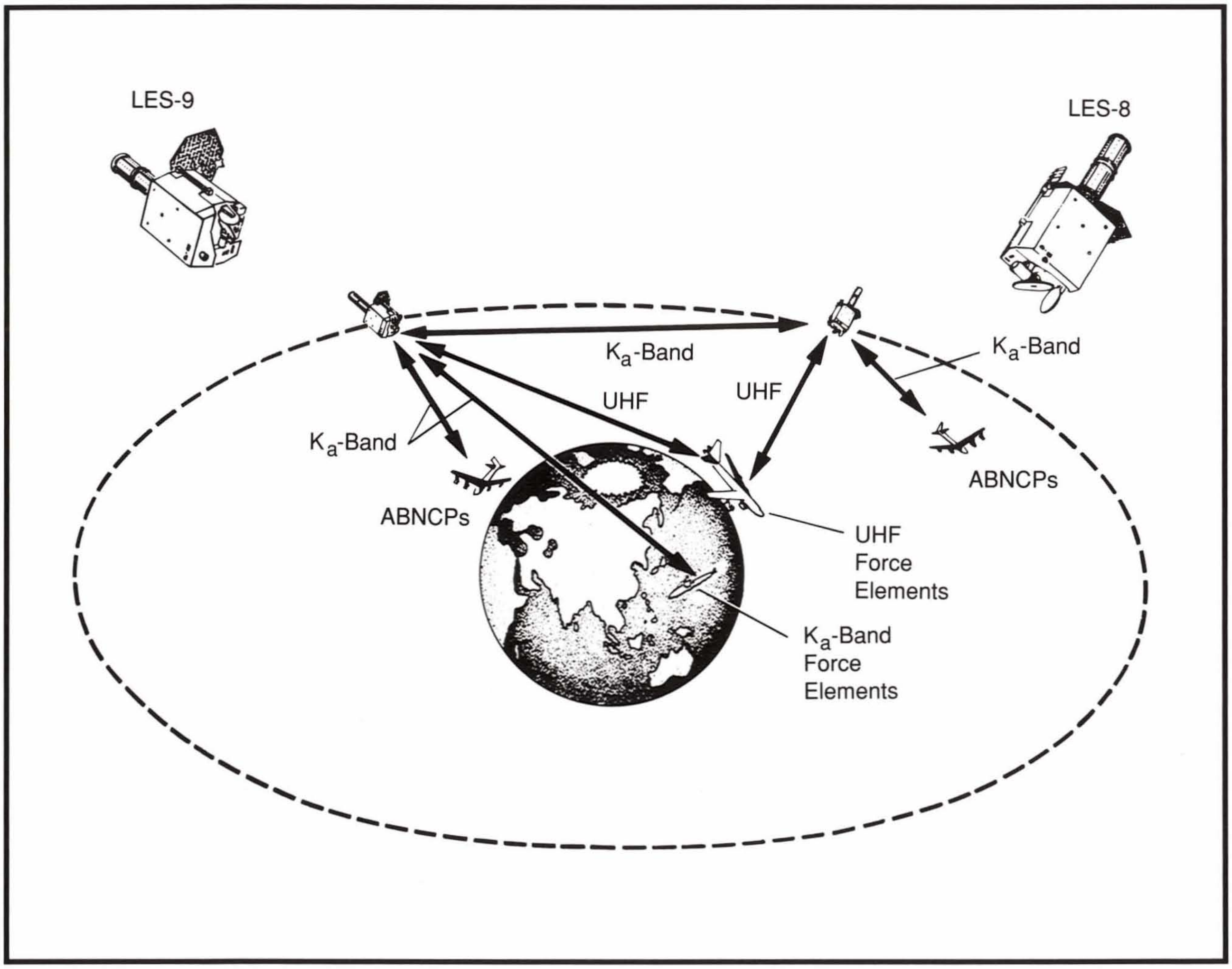

Fig. 20 — Configuration of the strategic communications links that LES-8 and -9 were designed to support.

torial inclinations of about 25°. The time of day for lighting the fuse was chosen so that the orbital planes were near the ecliptic. This orientation was selected to satisfy the launch requirements of the companion Naval Research Laboratory (NRL) SOLRAD-11A and B satellites and to facilitate a measurement of the performance of the ultra-low–drift third-generation gyroscopes from the Charles Stark Draper Laboratory that LES-8 and -9 carried as flight experiments [60]. Accepting final orbits with inclinations about equal to the latitude of the launch site also allowed lofting a more massive total payload than would be possible for an equatorial orbit.

LES-8 and -9 are powered by radioisotope thermoelectric generators (RTG) and have no solar cells or batteries [61]. The Department of Energy and its contractors did not create the RTGs easily, because the hot-shoe temperature of the thermocouple array surrounding the plutonium-238 heat source is about 1,000°C at the beginning of the mission, which posed challenging materials problems. The design of the RTGs had to assure their physical integrity in the event of a launch failure, so that the potential environmental hazard would be acceptable. During compatibility tests and preparations for launch, Lincoln Laboratory had to develop special procedures and pay scrupulous attention to health-physics factors to ensure that workers would not be overexposed to particle radiation.

The RTGs were well worth the effort, however; they have performed superbly. They provide continuous electrical power through the 70-min eclipses of the sun by the earth that LES-8 and LES-9 experience every day. The compatibility of these rugged power sources with complex signal-processing circuitry has been well established. These RTGs are similar to the ones that power the NASA/JPL Voyager-1 and -2 spacecraft, which have been exploring the outer planets and distant space since 1977. In fact, the measures that were taken to assure the success of the RTGs in LES-8 and -9 contributed directly to the success of the Voyager missions.

The daily latitude excursions of LES-8 and -9 (now between 20° North and 20° South) are very different from the behavior of most commercial communications satellites, which are stationkept in subsatellite latitude and longitude to a small fraction of a degree. Such precise stationkeeping enables commercial satellites to serve customers who own terminals without a satellite-tracking capability. What might seem, at first, to be a handicap is actually a blessing, however. The motion of LES-8 and -9 relative to ground-based terminals provides a good way to test the motion-compensation circuitry of terminals that operate on moving platforms. Moreover, the daily north/south excursions yield long intervals of visibility from sites in the Arctic and in the Antarctic. The U.S. Naval Support

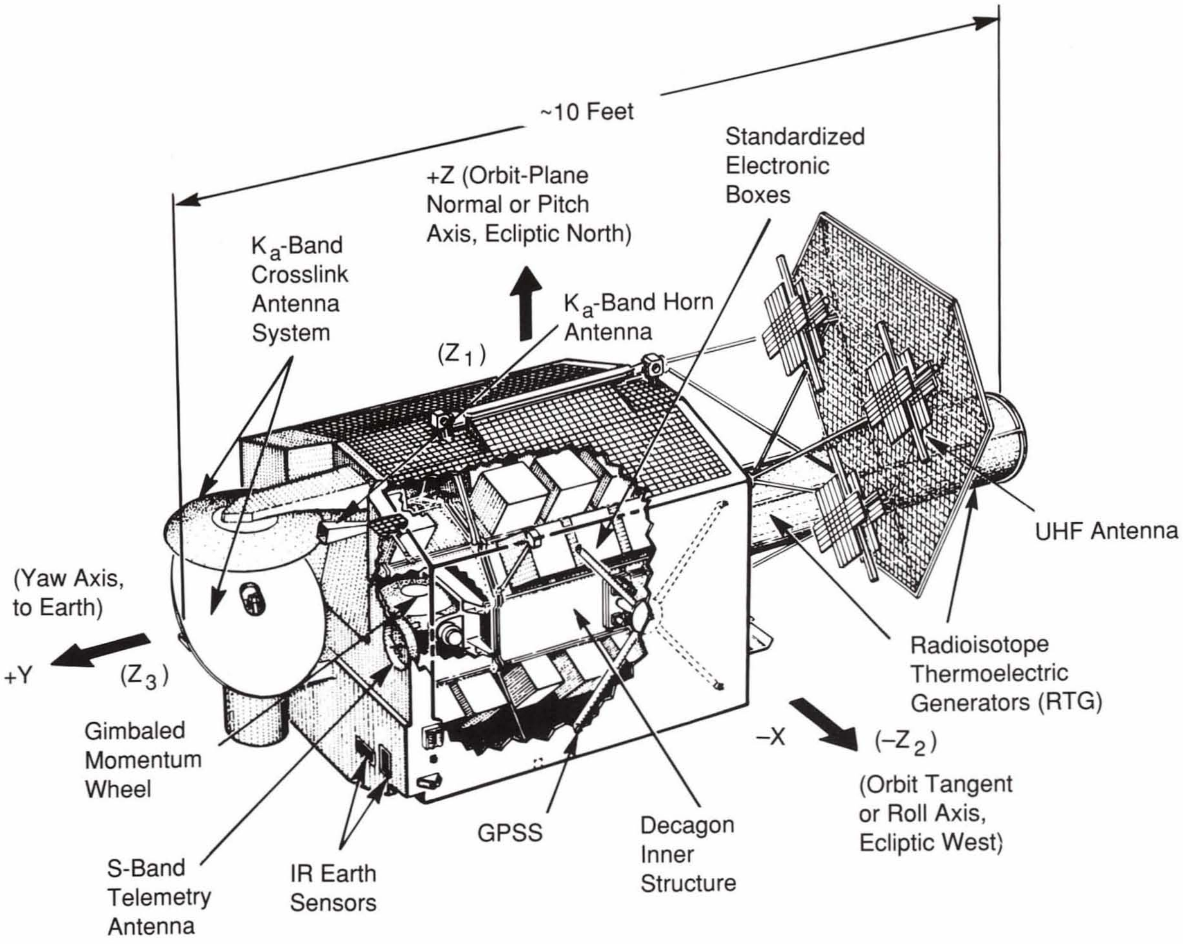

Fig. 21 — Internal construction and external features of LES-9. LES-8 is similar.

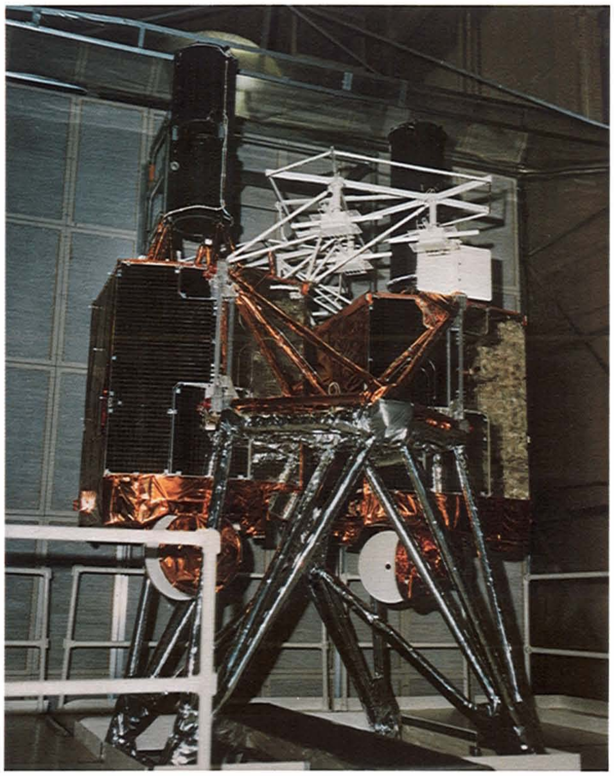

Fig. 22 — LES-8 (left) and LES-9 (right) assembled at Cape Canaveral, Fla. This assembly was hauled over the road from the Satellite Assembly Building to Launch Complex 40 for integration with the Titan-IIIC booster and launch.

Force Antarctica has a regular daily schedule of access time to LES-9, during which business is transacted and people stationed on the Ice can talk with the folks back home. Thanks to LES-8 and -9, the vagaries of HF radio do not limit communications with the polar regions.

LES-8 and -9 represent the high-water mark to date of Lincoln Laboratory's program in space communications. In addition to the complex communications system, these satellites have systems and subsystems for housekeeping functions, including attitude control [62], onboard (secondary) propulsion [63], telemetry [64, 65], and telecommand.

Lincoln Laboratory continues to be responsible for the upkeep of LES-8 and -9. The Lincoln Experimental Satellite Operations Center (LESOC) operates and maintains these satellites, and will continue to serve them as long as they remain useful [66]. By relying on computerized monitoring of data telemetered from the satellites and on human-engineered arrangements to facilitate their control, the commitment to LES-8 and -9 has been met with a minimal number of people (Fig. 24).

During the prolonged gestation of LES-8 and -9, faint-hearted observers sometimes asked whether so complicated a satellite could ever work. However, both the Laboratory's confidence and the strenuous days that went into LES-8 and -9 have been justified by the satellites' success.

After a few years in orbit, the complexity of LES-8 and -9 proved to be a benefit: the satellites' many features, alternatives, and backup modes gave them capabilities that were neither advertised nor appreciated before launch. For example, the hopped local oscillator in the uplink receiver can be set by telecommand, so the satellite can listen to nearly any frequency over a broad stretch of the military UHF band. Instrument-quality power-measurement circuitry in the uplink receiver then gives readings that are telemetered to LESOC. Reduction of an extended collection of that data yields a statistical analysis of spectrum occupancy at the measured frequency by terrestrial terminals, a technique that is a significant advancement over the less flexible RFI-measurement experiments of LES-5 and LES-6 [48].

For another example, consider LES-8's contributions to radio astronomy. The radio telescopes needed for millimeter- and submillimeter-wave observations have to be large and to have highly accurate reflecting surfaces. These surfaces are usually made up of a number of precision replicated panels, each a portion of a paraboloid of revolution. The assembly of the primary reflector presents a problem. How can one know when the panels are positioned relative to one another so that they best approximate the desired overall reflector shape?

Techniques have been developed to measure the local shape of a reflector by holographic analysis of signals received from a distant, monochromatic RF source [67, 68]. The K_a-band transmitting systems of LES-8 — pointed toward an antenna under test — are well suited to

Table 1. LES-8 and -9 Program

SPACECRAFT

- ~1000 lb (Mass) Each
- 3-Axis-Stabilized to Earth
- Circular, Synchronous, Near-Ecliptic, Coplanar Orbits
- RTG Power Supplies
- K_a-Band/UHF Communications
- Spacecraft-to-Spacecraft Cross Linking (K_a-Band)
- Flexible Onboard Signal Processing
- Spread Spectrum (Frequency Hopping) for Anti-Jam
- Autonomous Attitude Control and Stationkeeping
- Cold-Gas (Ammonia) Onboard Propulsion
- Comprehensive Telemetry and Telecommand

TERMINALS

- LL Airborne-Command-Post Terminal — 4-ft Antenna (K_a-Band)
- LL Ship Report-Back Terminal — 18-in Antenna (K_a-Band)
- LL Force-Element Terminals (UHF)
- Air Force and Navy Terminals (K_a-Band, UHF)
- LESOC, Lexington, Mass.

this purpose. Three radio-astronomy observatories in North America have made use of this service and found that using LES-8 to map their reflector surfaces at 38 GHz and then adjusting the panels for a better fit to the desired overall shape yields improved performance at frequencies many times higher (e.g., 230 GHz).

As LES-8 and -9 complete 13 years of fruitful operation in orbit, they have clearly earned their keep many times over. The technologies of onboard signal processing and of EHF transmission and reception successfully demonstrated in the LES-8 and -9 Joint Test Program have been incorporated in subsequent MILSATCOM procurements. The single-channel transponders on the DSCS-III satellites and the Milstar communications system itself (see below) have flowed directly from LES-8 and -9.

Switchboards in the Sky

Following the launch of LES-8 and -9 in 1976, Lincoln Laboratory intensively addressed the problem of providing affordable anti-jam communications to many small, mobile users. LES-8 and -9 and their associated terminals demonstrated that UHF and EHF communications systems could be crossbanded in signal-processing satellites and serve the needs of a limited number of small, mobile terminals. It was tempting to try to extend the approach to meet the needs of a large number of users, because the relative simplicity and cheapness of UHF terminals made that part of the spectrum attractive.

Unfortunately, communications systems in the military UHF band (225 to 400 MHz) are not convincingly robust, because military UHF does not have enough available bandwidth to provide required levels of anti-jam protection. Not even the proposal of a satellite with a very large UHF antenna and autonomous adaptive nulling sufficed. (Adaptive-nulling antennas are used to obtain additional jammer suppression beyond that achievable by spread-spectrum techniques [69, 70]). Thus under Lincoln Laboratory's new approach, all space-communications links intended to be survivable were

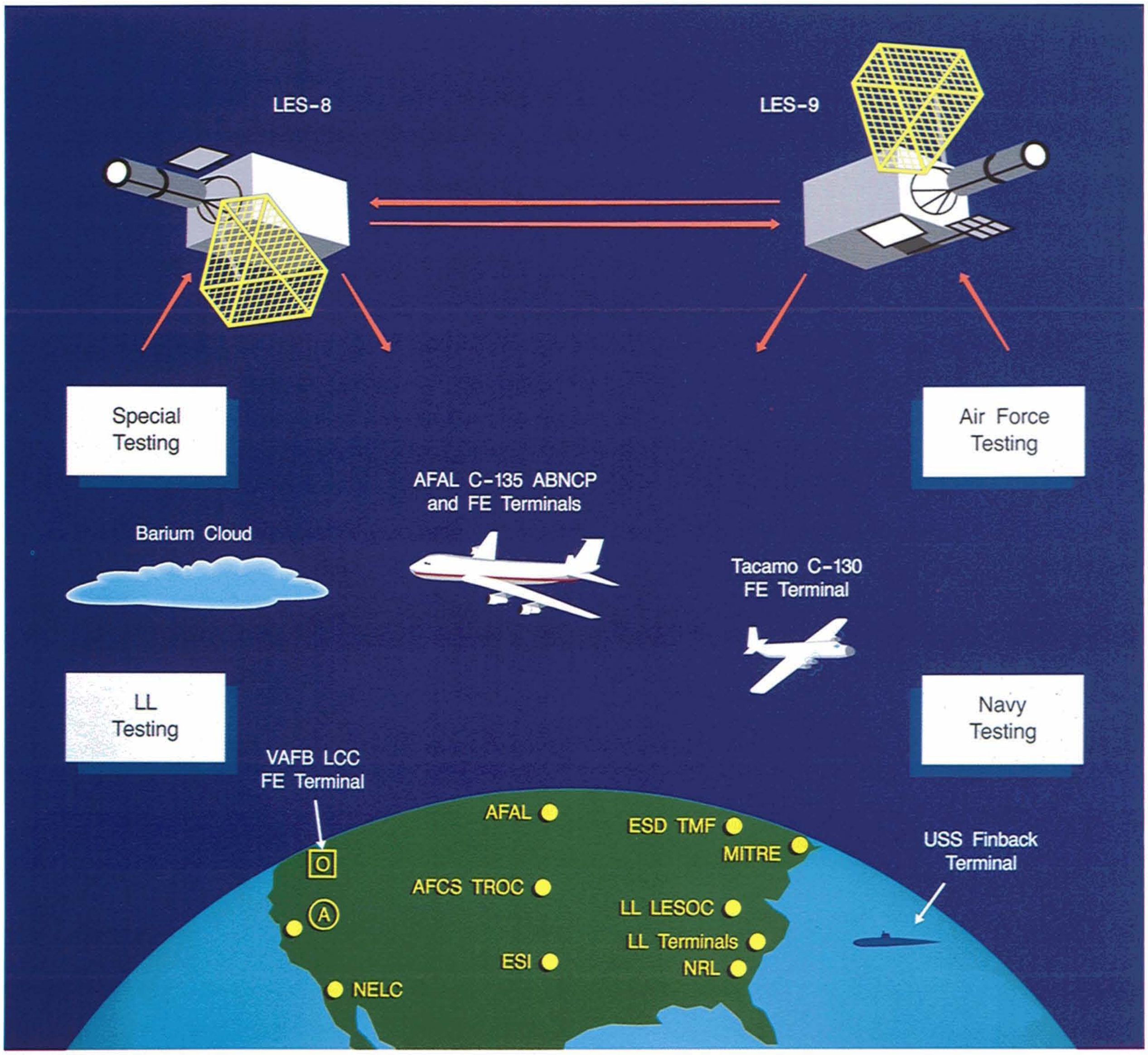

Fig. 23 — LES-8 and -9 communications-system testing in orbit.

assigned to the EHF domain.

The arguments for and against EHF are well known [71, 72]. It has been recognized for some time that the use of the EHF bands can overcome the frequency-congestion difficulties affecting both civilian and military systems at lower frequencies. However, the major advantage to military users is that EHF also supplies the bandwidths necessary to implement robust, anti-jam systems based on spread-spectrum technologies. By using advanced spread-spectrum techniques and uplink-antenna beam discrimination, extensive onboard signal processing, and downlink-antenna beam hopping, a modest-size satellite can simultaneously serve large numbers of small, mobile users with highly jam-resistant communication channels. The probability that covert transmissions from terminals that wish to remain unnoticed will be intercepted is also reduced at EHF. On the negative side, the effects of rain attenuation on link operation at EHF require that — to minimize

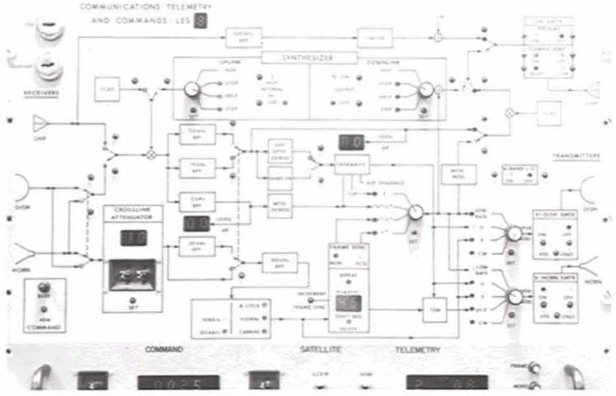

Fig. 24 — This communications-system status panel in the Lincoln Experimental Satellite Operations Center (LESOC) displays data telemetered from LES-8 or -9. System-reconfiguration telecommands can be sent simply by pushing buttons on the block diagram.

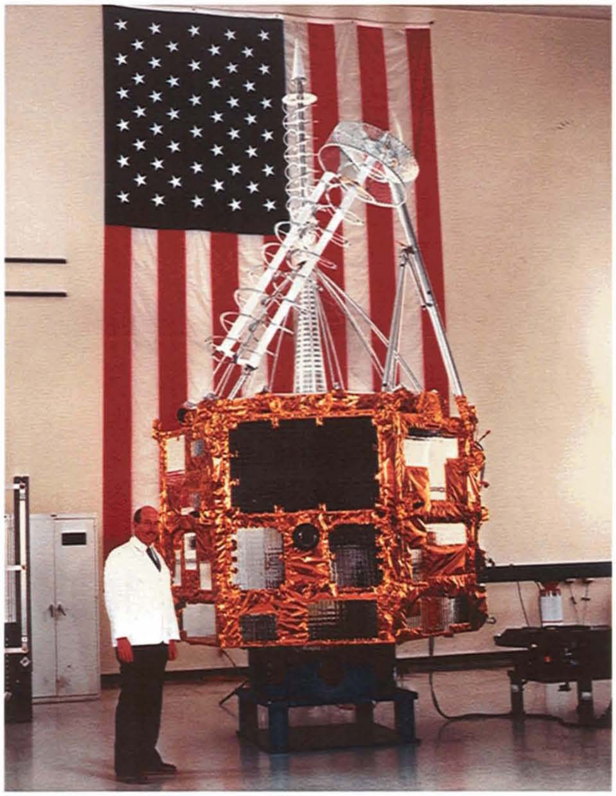

Fig. 25 — Andy Howitt still on the job, after the integration of FLTSAT-7 and its Lincoln Laboratory-built FLTSAT EHF Package (FEP) at TRW's plant in Redondo Beach, Calif.

outage — the minimum elevation angle of the satellite relative to the terminal must be significantly higher than for lower-frequency systems.

In consultation with its sponsors, Lincoln Laboratory conceived a strawman EHF system and built a test-bed satellite with terminal hardware that incorporated the features mentioned above and served as a focus for the in-house technology-development program. The groundwork for this EHF system concept was laid during the successful development and demonstration of K_a-band components, subsystems, and systems in LES-8 and -9. The essential features of the strawman EHF system were demonstrated on the bench at Lincoln Laboratory in 1980 and 1981 in the combined operation of the test-bed satellite with its test-bed terminal.

The EHF system concept and the associated technologies in development at Lincoln Laboratory served as a point of departure for thinking about EHF systems within the DoD MILSATCOM community. In December 1981, the DoD decided to go ahead with a new enterprise, Milstar (formerly military strategic tactical and relay satellite), that incorporates many technical features of Lincoln Laboratory's strawman EHF system in its own system and in its Common Transmission Format.

Lincoln Laboratory was asked to support Milstar development by building two FLTSAT EHF Packages (FEP). The communications capabilities of a FEP, which is an appliqué, or add-on, to TRW's FLTSAT UHF/SHF communications satellite (Figs. 25–27), are a subset of those of a full Milstar-satellite payload [73]. These packages have been completed. The first was integrated with FLTSAT-7 and was launched by an Atlas/Centaur booster from Cape Canaveral on 4 December 1986; the second will be part of FLTSAT-8, to be launched late in 1989. The electronics and antenna assemblies of each FEP were built by Lincoln Laboratory under very tight power (305-W) and mass (111-kg) constraints so they would be compatible with the existing FLTSAT satellite design. The FEP has facilitated the early operational test and evaluation of the Milstar EHF/SHF terminals being developed by the Army, Navy, and Air Force.

The FEP's uplink and downlink frequency bands, near 44 GHz (EHF) and 20 GHz (SHF), conform to the allocations set at the 1979 World Administrative Radio Conference. The FEP's

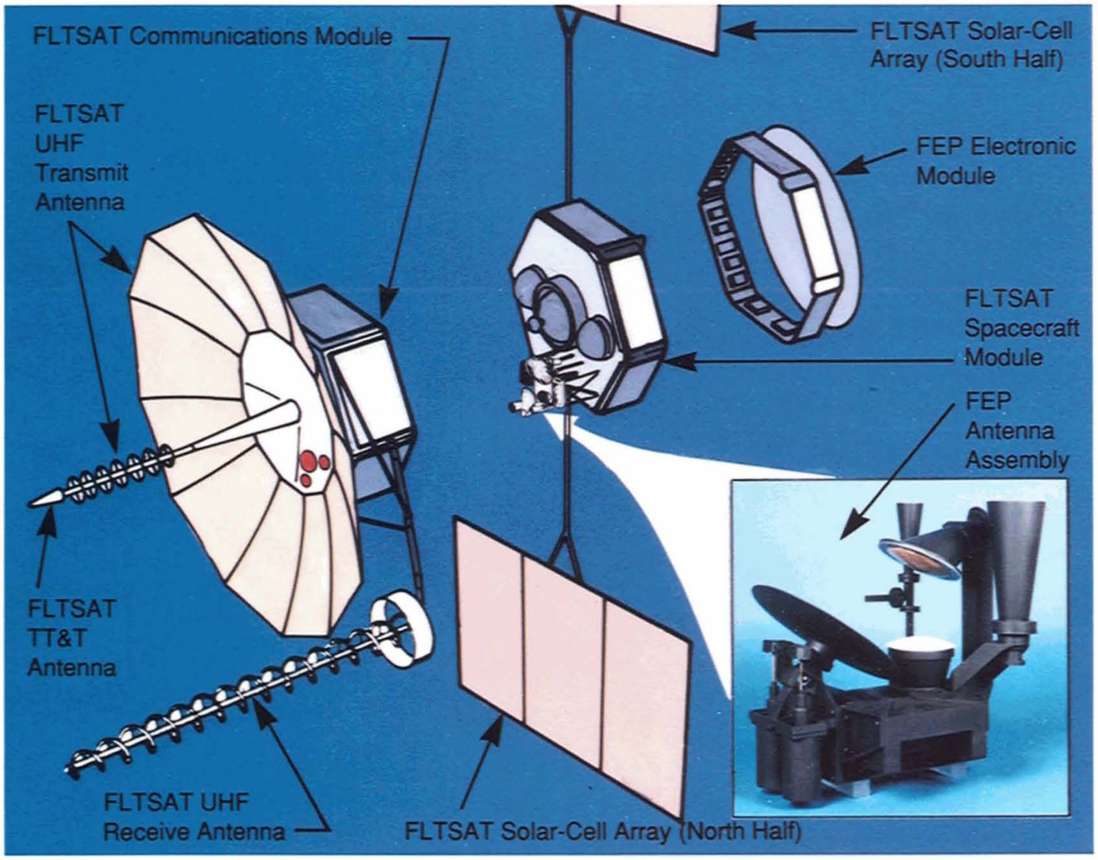

Fig. 26 — Exploded view of FLTSAT-7 (or -8) and its FEP.

antenna assembly provides an earth-coverage beam and a mechanically steered ≈5° spot beam in both the uplink and downlink bands. Lincoln Laboratory has put aside its historical preference for all–solid-state circuitry in this instance and incorporated a traveling-wave–tube amplifier (TWTA), plus a spare, in the downlink transmitter, time-shared between the two antennas. It has worked well.

Two technological innovations are key to the development of the FEP. First, the application of surface–acoustic-wave (SAW) chirp/Fourier-transformation (frequency-difference-to-time-difference) devices developed and fabricated in Lincoln Laboratory's Solid-State Physics Division has made it possible for the satellite receivers to demodulate simultaneously — with minimum demand for dc input power — the MFSK signals received in many narrowband frequency bins [74]. Had Lincoln Laboratory used the digital technology available at the time that the design choices had to be made, carrying out the demodulation functions would have been prohibitively costly in terms of power and of mass. Because of the rapid advances in VLSI technology, that may no longer be the case.

The second innovation in the FEP is a computer-based resource controller that sets up data channels that operate at different data rates, via different antenna beams and other means, to support individual user-communications needs. User-service requests are received from each user terminal's computer by the onboard access controller. The controller in turn sets up the requested services and informs the involved user terminals' computers of its actions via a downlink order wire. Once a channel has been set up, the FEP converts uplink message formats to downlink message formats and retransmits user data via either or both of the FEP's two antenna beams. The access controller can be reconfigured by command. Although the computer-to-computer dialogs between the FEP and the users' terminals are complex, the required human/machine interactions are user-friendly and are can be easily performed by user-terminal operators. The particulars of the first switchboard in the sky are given in Ref. 75.

The communications-system complexity of a FEP is far greater than that of LES-8 or -9, even though the FEP's parts count is lower. Integrated circuits in the early 1980s, when FEP design choices were made, were more sophisticated than when LES-8 and -9 were designed in the early 1970s. Also, flyable SAW devices became available in time for their use in FEPs.

The experience gained in operating LESOC for the control of LES-8 and -9 in orbit was directly applicable to the task of controlling a FEP in orbit. The greater sophistication of the FEP (compared to a LES-8 or -9) has resulted in a much lower workload in the FEP Operations Center (FEPOC) than in LESOC, where any change in the configuration of the satellite's communications system requires human intervention. The resource controller in the orbiting FEP carries out most of its computer-to-computer transactions with users and would-be users without supervisory intervention. Two FEPOCs have been built: one is installed permanently at Lincoln Laboratory; the other, transportable but by no means mobile, has been installed at a Navy facility in Maine. (The Navy is the operational manager of the FEP

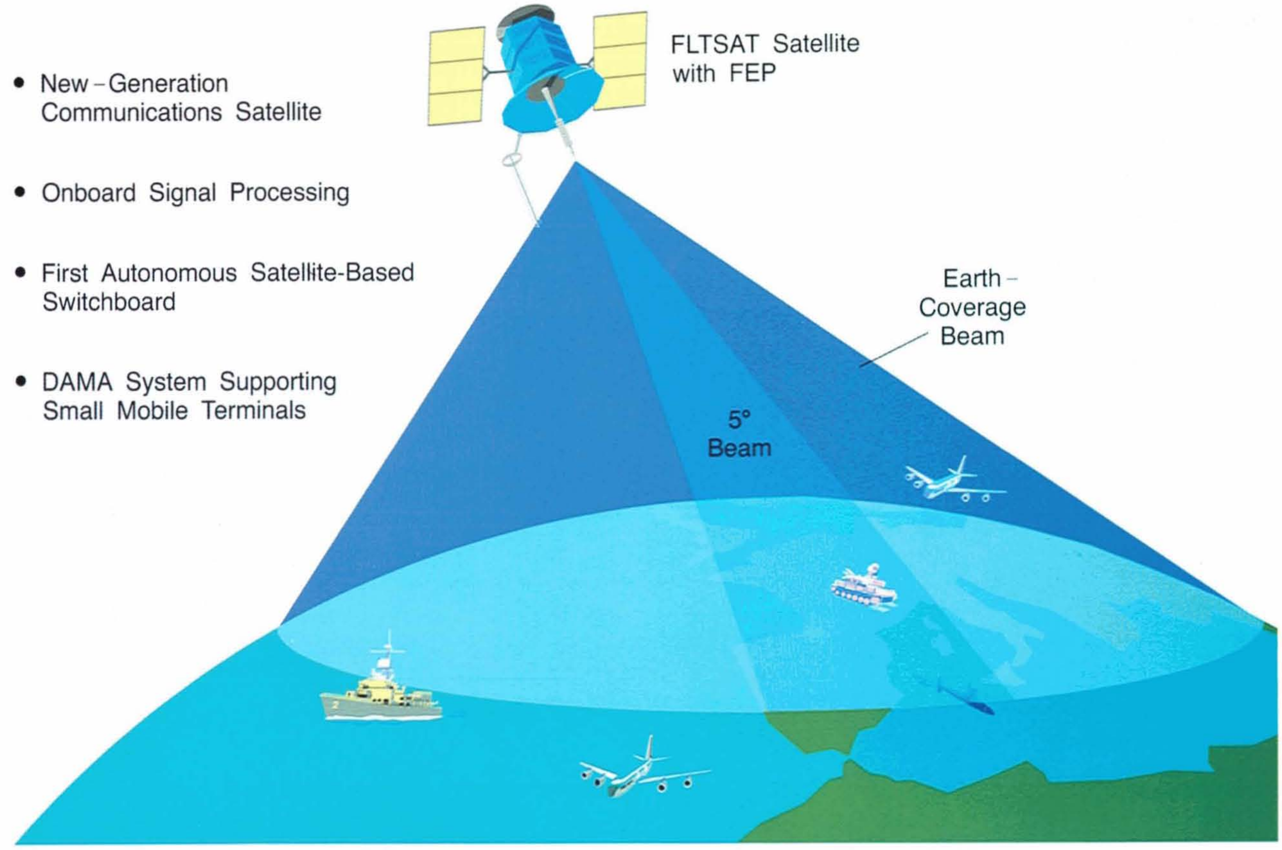

Fig. 27 — Functional features of the FEP.

Communications System.)

During the FEP program, Lincoln Laboratory concentrated on the challenging technologies required for the FEP, taking advantage of the satellite-bus technologies already developed and proven in space by TRW's series of FLTSAT satellites. It has been gratifying that the FEP aboard FLTSAT-7 arrived safely in orbit and has worked well since launch. The success of the FEP program speaks well for Lincoln Laboratory's approach to implementation and quality assurance in building reliable spacecraft.

On the other hand, some of the success of Lincoln Laboratory's program in space communications has to be attributed to plain luck. Consider the case of the FEP carried by FLTSAT-7. The second procurement of FLTSATs was for three satellites and included FLTSAT-6, which carried no FEP, and FLTSAT-7 and -8, each carrying a FEP. The sponsor decided to juggle the launch schedule and interchange FLTSAT-7 and -6 to get an EHF package into orbit as early as possible. FLTSAT-7 was launched successfully on 4 December 1986, as noted above. FLTSAT-6 was launched in the rain on 26 March 1987 and its Atlas/Centaur booster was struck by lightning. After the lightning stroke, the cessation of rocket-engine noise, and a series of muffled explosions aloft, one of the authors of this article, who happened to be at Cape Canaveral at the time of the launch, said to himself, "There but for the grace of God and the United States Navy went the first FEP."

Fig. 28 — Lincoln Laboratory's advanced-development model of the Army SCOTT for EHF satellite communications was installed in an armored personnel carrier and was operated in the field against a satellite simulator by GI crews.

Fig. 29 — Dave Snider shows off the first SCAMP terminal.

Advanced Extremely High-Frequency/Super–High-Frequency Terminals

In another Milstar-related activity, Lincoln Laboratory designed and built SCOTT (Single-Channel Objective Tactical Terminal), the advanced-development model of the Army's Milstar EHF/SHF terminal. In 1983 Army personnel successfully tested this terminal, mounted in a tracked military vehicle (Fig. 28), against a satellite simulator in the field. The Army's production version of SCOTT has many of the features that were first demonstrated in Lincoln Laboratory's advanced-development model.

As an outgrowth of the SCOTT work, Lincoln Laboratory conducted a feasibility study in 1983 that resulted in a conceptual design for a manportable, Milstar-compatible EHF/SHF terminal. The development of the Single-Channel Advanced Milstar Portable terminal (SCAMP) was completed shortly after the launch of the first FEP, and it has operated successfully with the FEP (Fig. 29). There are numerous diverse needs for limited-capability terminals of this class, which offer most of the advantages of Milstar communications without the full range of options.

Optical Space Communications

The success of optical communications for some terrestrial applications is undeniable. The technologies of lasers and of low-loss fiber optics have led to cables that are providing serious competition to communications satellites in the long-haul marketplace. However, optical space communications has been the "wave of the future" for many years. The advent of the laser, with its promise of coherent radiation across the transmitting apertures and correspondingly fine, high-gain antenna beams, has led to very encouraging link-performance calculations. To the best of the authors' knowledge, however, no one has yet demonstrated a nontrivial optical intersatellite link in space.

Lincoln Laboratory once considered putting optical intersatellite links on LES-8 and -9, in addition to the millimeter-wave links. The optical feature was dropped from the satellites' configuration in late 1971 when it became clear that the current state of the art in solid-state laser-diode technology was inadequate for a flight experiment, and that the project's resources could not support an optical link. Progress in available components, coupled with new insights in system design, has since made it attractive to resume work in this area, often called LASERCOM.

Lincoln Laboratory is now developing a technology base for high–data-rate intersatellite links that could be realized with small-aperture, lightweight, low-power optoelectronic packages. The approach taken uses solid-state GaAlAs laser diodes and Si-diode detectors operating in a heterodyne mode [76, 77]. Modulated–continuous-wave transmission and heterodyne detection will be combined in the system design to provide communications significantly superior to the more commonly used systems based on pulsed transmission and direct energy detection (commonly known as the photon-bucket approach). It is projected that the heterodyne approach will result in smaller, lighter LASERCOM packages, with less power demand for the same communications capability.

Although Lincoln Laboratory began to prepare in 1985 for a demonstration of heterodyne LASERCOM technology in orbit, program constraints have ruled it out for the present. The Laboratory is now building an engineering model of a complete heterodyne LASERCOM system, which will address all critical technological areas and issues. When the world is ready for LASERCOM, the technology will be available.

Future Developments in Space Communications

The next goal for reliable MILSATCOM systems is the extension to high–data-rate applications of the robust, jam-resistant technologies for low–data-rate applications that FEP has demonstrated. Considering the large bandwidths that will be required, these new systems will most likely be implemented at EHF, at least for the uplinks and downlinks. The effects of bad weather, even clouds, on optical links between satellites and terminals on the surface of the earth seem certain to rule out LASERCOM for applications in which consistent link availability is important. However, optical links between satellites and airborne platforms flying above the weather may meet specific military needs.

The technology of RF intersatellite links has been amply demonstrated in orbit by LES-8 and -9 and by NASA's tracking-and-data-relay-satellite system [78]. It is only a matter of time, and of continued support, until LASERCOM intersatellite links are similarly demonstrated.

Intersatellite link technologies have not yet found civilian application. The INTELSAT-6 series of communications satellites [79], the first of which will be launched in late 1989, was designed well after the LES-8 and -9 intersatellite links had been demonstrated in orbit. However, it was not found economically justifiable to include intersatellite links in the INTELSAT-6s, nor does it appear to be planned for the next generation, the INTELSAT-7s, now under procurement for launches starting in 1992. Nevertheless, the time for civilian intersatellite links will come.

Conclusions

In the more than 30 years since the U.S.S.R.'s Sputnik-1 launch, space communications has reached a high level of maturity. The mission failures that occasionally besmirch the record of each spacefaring nation cannot obscure the numerous remarkable, and useful, achievements that have taken place. Notable among them are the contributions of space communications, both economically and in terms of increased international stability. Space communications allows national leaders to stay in touch with one another, and it gives them more control over their military resources, thus reducing the possibility of accidental war.

Space communications has changed the way that societies function and interact, and it promises to do far more. To quote the science-fiction writer Arthur C. Clarke (who first suggested the geostationary communications satellite), "What we are building now is the nervous system of mankind, which will link together the whole human race, for better or worse, in a unity which no earlier age could have imagined [80]."

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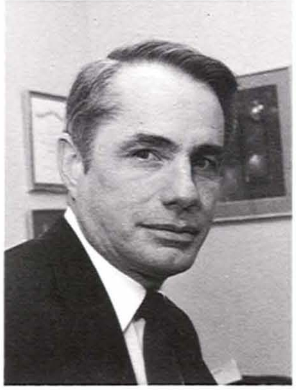

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