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The K_a-Band Communication Systems of the Lincoln Experimental Satellites LES-8 and LES-9

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This paper presents a description of component and system techniques necessary for a high-reliability solid-state millimeter-wave communication satellite system. This includes the use of hermetically sealed active devices and thorough testing over temperature of the components and systems. The performance of the system in orbit has been verified to be the same as on the ground.

Introduction

LINCOLN Experimental Satellites LES-8 and LES-9 are a pair of experimental communication satellites designed and built to operate in a synchronous ecliptic orbit and to communicate on a crosslink from satellite to satellite as well as with surface terminals.

At synchronous-orbit altitude, each satellite has a ground-visibility area about 8000 miles in diameter. With crosslink communication between two satellites spaced thousands of miles apart, a single pair of satellites could provide communications among terminals anywhere in an area covering more than 3/4 of the surface of the Earth. Communication links are possible at both UHF and K_a-band at approximately 37 GHz.

Figure 1 shows a cutaway drawing of LES-9. The side facing the Earth is the forward platform, which is used for mounting and precision alignment of the K_a-band antennas and the Earth sensors. The K_a-band receiver diplexer filters and front ends are mounted as close as possible to the diplexer polarizer mounted on each antenna. The K_a-band transmitter power amplifiers are mounted on sections of the internal decagon adjacent to the forward platform to minimize the length of the waveguide runs to the antennas.

LES-8 and LES-9 each utilize two independent K_a-band communication systems (see Fig. 2). The K_a-dish system uses a fixed paraboloidal reflector in conjunction with a steerable flat reflector to provide a narrow beam, tracking antenna for crosslink or uplink/downlink communications.[1] The K_a-horn system includes a fixed horn to provide a wide-beam antenna coverage. Local oscillator requirements for both systems are provided by a single K_a-band local oscillator. Each receiver subsystem features a broadband low-noise mixer utilizing Schottky-barrier diodes to achieve a typical system noise figure of less than 8 dB. Each transmitter includes an array of solid-state amplifiers which utilize IMPATT diodes, and delivers 0.5W of power to the antenna. The transmitter signal is modulated at a lower frequency and is upconverted to K_a-band using a mixer similar to that used in the low-noise receiver.

This paper will discuss the K_a-band systems carried on LES-8 and LES-9, which were built to demonstrate component and system techniques necessary for a high-reliability solid-state millimeter-wave satellite communication system.

K_a-Band Local Oscillator

The K_a-band local oscillator signal for each satellite is generated by a frequency multiplier chain which is driven by a high-stability 5 MHz master oscillator.

A picture of the portion of the LES-9 multiplier chain containing the last four varactor doublers is shown in Fig. 3. This particular multiplier chain is driven at 2.25 GHz and has its output at 36 GHz.

The sections of the multiplier chain between the 5 MHz master oscillator and the 2.25 GHz interface use transistor frequency multipliers. The entire K_a-band chain uses approximately 12 W of dc power to produce about 100 mW of rf power at 36 GHz.

The varactor section of the multiplier chain along with an attenuator and the waveguide power dividers are mounted on the forward platform of the satellite to minimize the lengths of the waveguide runs to reach each of the four mixers.

K_a-Band Receivers

The K_a-band receiver front ends of each satellite are identical. They consist of a two-diode balanced mixer followed by a low-noise bipolar transistor amplifier (see Fig. 2). The outputs of the two front ends on each satellite may be interchanged between the uplink and crosslink receivers via a coaxial transfer switch. This permits use of the high-gain dish antenna with either the uplink receiver or crosslink receivers.

The heart of the receiver and upconverter mixers is a diode which is mounted in a hermetically sealed package.[2,3] The package consists of two gold-plated copper studs soldered into a copper-ceramic annular sleeve. A cutaway drawing of the diode package is shown in Fig. 4. The semiconductor chip is soldered to one copper stud and a gold-plated tungsten whisker is soldered to the other stud. The total length of the diode package is about one-half inch.

A millimeter-wave packaged diode was developed because the high reliability required for a space communication system makes it mandatory that the semiconductor diode chip be protected from contamination during fabrication and ground test. The performance of a mixer using this diode is as good or better than has been reported in the literature with unpackaged devices. In addition to the LES-8/9 mixers, this packaged diode has also been used in a number of mixers including several which operated above 100 GHz.

The packaged diode approach also permitted extensive diode characterization and burn-in independent of the final microwave circuit assembly. About 400 flight-type diodes were fabricated for life tests and to provide a pool from which to select flight devices. Table 1 lists diode selection criteria.

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A number of early devices went back "to meet their maker" before satisfactory circuit and handling techniques were developed. These techniques included the design of a bias circuit to insure isolation of the diode from power supply or static-induced transients during subsystem tests, as well as antistatic handling precautions when working with the diodes out of the mixer.

Figure 5 shows a schematic diagram of the K_a-band receiver mixers. A mixer with two diodes was chosen for reliability reasons to provide some redundancy in case of diode failure. This arrangment also simplified the design of a reactively terminated image mixer. The signal and local oscillator are fed to the mixer diodes via the E- and H-plane arms, respectively, of a reduced-height matched magic T (see Fig. 6). The diodes are placed across the A and B arms as shown in Figs. 5 and 6. The IF outputs are combined with a Wilkinson hybrid. Also contained within the 2 GHz Wilkinson hybrid portion of the assembly is a bias-decoupling network which permits independent current-source biasing of the mixer diodes. Current-source biasing of the diode makes the mixer conversion loss and noise figure (NF) relatively insensitive (± 0.5 dB) to local oscillator power variations and temperature variations (see Fig. 7). The local oscillator power supplied to each of the mixers is about 7 mW.

The mixer is mounted directly on the receiver arm bandpass filters of the diplexer so that phase can be set for an optimal reactive termination at the mixer image frequency. The conversion loss of the low-noise mixer assembly including the diplexer filter and IF hybrid is under 4 dB. The excess noise

Table 1 Selection criteria for K-band mixer diodes

Electronic characteristics:	
Junction capacitance (zero bias)	$8\ \mathrm{fF} \le C_{j0} \le 20\ \mathrm{fF}$
Series resistance (at 10 mA)	$R_s \le 15\ \Omega$
Forward voltage (at 10 mA)	$V_F \le 1.1$ V
Reverse breakdown voltage (at 100 nA)	$V_R \ge 7.0$ V
Exponential ideality factor	$n \le 1.15$
Conversion loss (at 55 GHz)	$L_x \le 5.5$ dB
K_a-band impedance vs bias	similar for matched diodes
Semiconductor chip:	
Device diameter (measured optically)	$\ge 3\ \mu$m
X300 magnification photographs brightfield and darkfield	contacted device has no visible defects
Package:	
Visual inspection	no voids in solder-seals; no excess solder on sides
600 *g* pull test	no change in V-I characteristics; no motion of package components
Burn-in test:	
Changes in V-I characteristics after one month	ΔV_F (10 mA) < 30 mV; ΔV_F(100 nA) < 20 mV; ΔV_R(100 nA) < 2.0 V

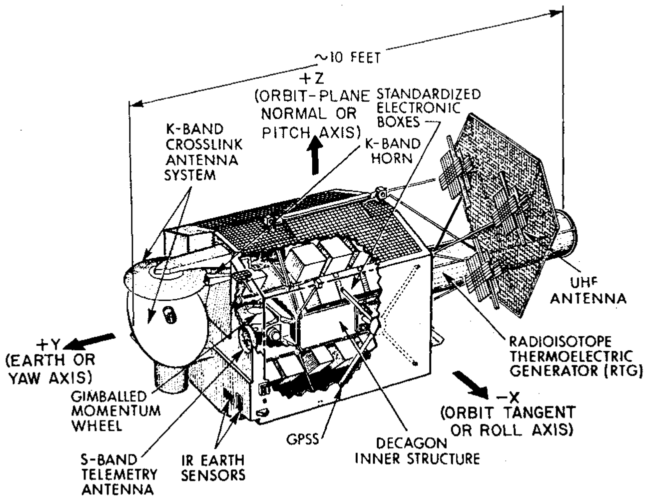

Fig. 1 Cutaway of LES-9.

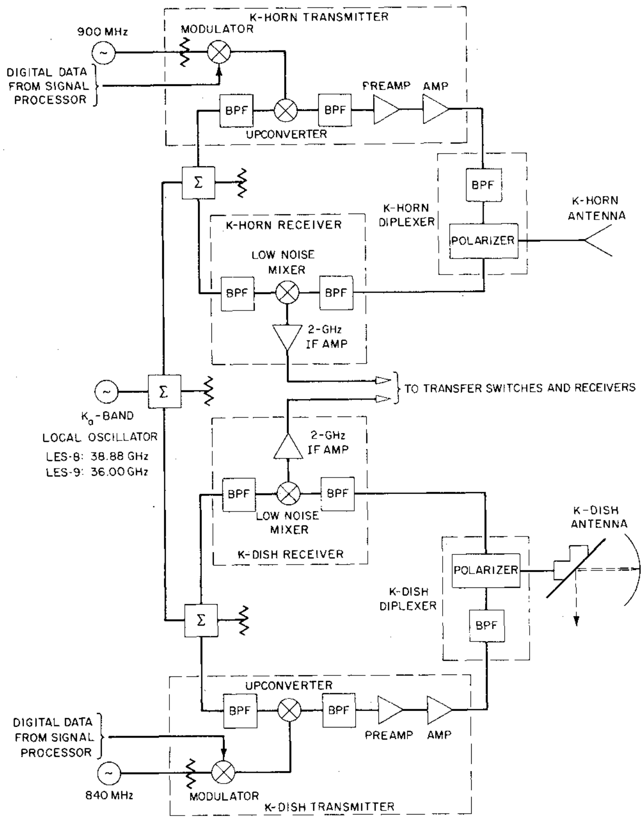

Fig. 2 Block diagram of K_a-band system.

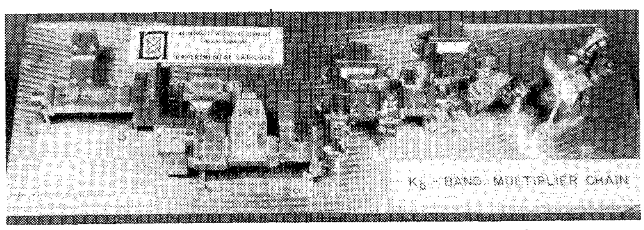

Fig. 3 LES-9 K_a-band multiplier chain showing the four varactor doublers.

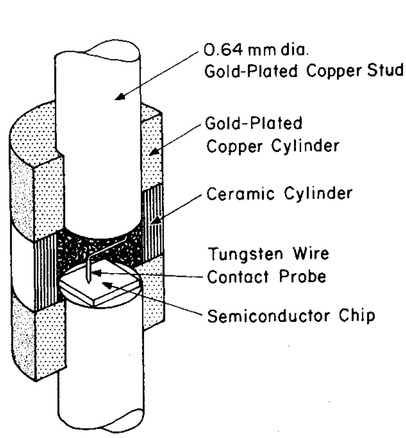

Fig. 4 Cutaway of mixer diode.

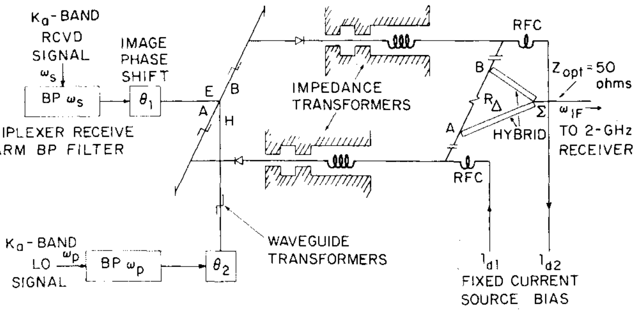

Fig. 5 LES-8/9 K_a-band receiver mixer schematic diagram.

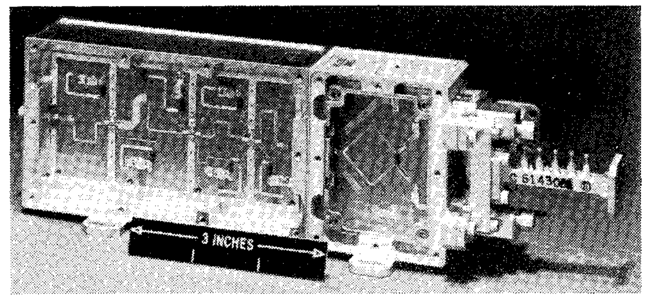

Fig. 8 RF circuit view of K_a-band receiver front end.

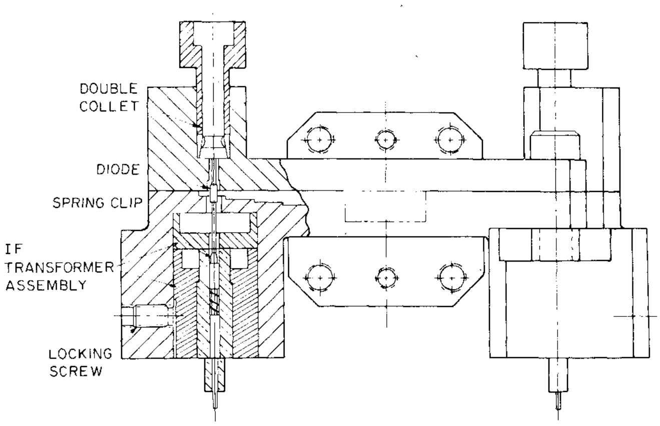

Fig. 6 K-band mixer assembly.

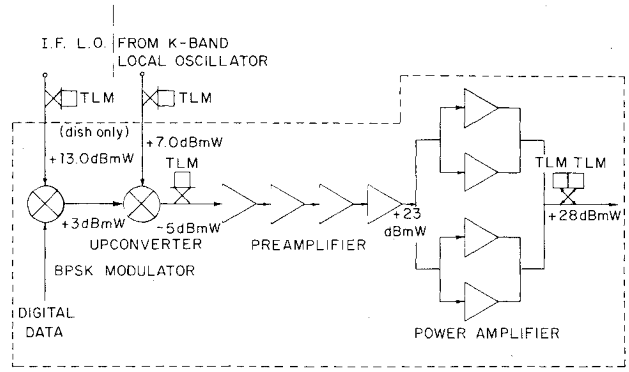

Fig. 9 Simplified K_a-band transmitter diagram.

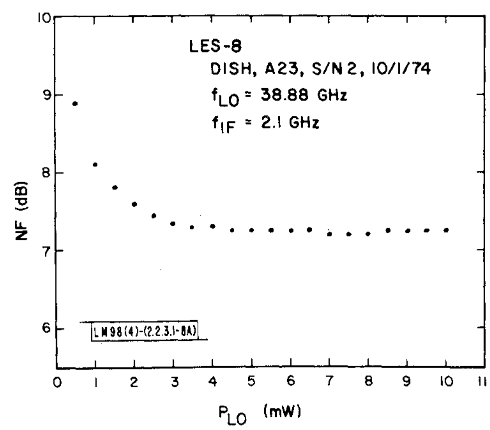

Fig. 7 LES-8 K_a-dish receiver front end noise figure vs local oscillator power.

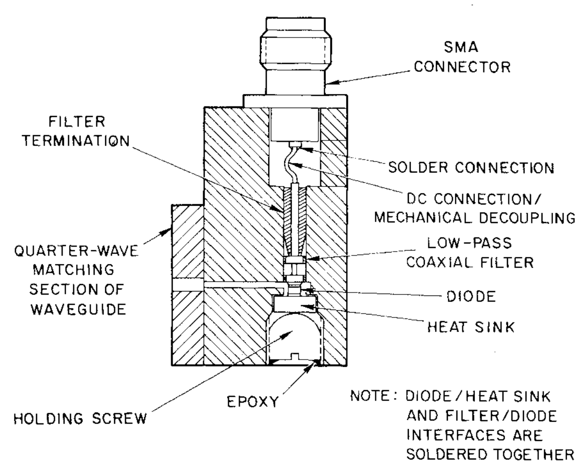

Fig. 10 Amplifier diode mount.

contribution of the diodes to the noise temperature set by the conversion loss is negligible.

The K_a-band receiver mixers are immediately followed by a 2 GHz low-noise bipolar transistor amplifier. The amplifier uses a cascade of three single-ended common-emitter amplifier stages. The amplifier uses a network consisting of a pair of quarter-wavelength microstrip transmission lines for interstage coupling. This structure provides impedance transformation, dc decoupling, and filtering between the amplifier stages.

The transistor selected for use in this amplifier represents the optimum in noise performance obtainable in the 2 GHz band from a device which would pass the stringent qualification requirements for the LES-8/9 program. The overall amplifier noise figure is about 3.5 dB.

Figure 8 shows the RF circuit board side of the K-band receiver front end package. At the extreme right is the receive diplexer filter which is mounted directly on the mixer. This is followed by the IF hybrid and the 2 GHz amplifier.

K_a-Band Transmitters

Each of the K_a-band transmitters includes a binary phase-shift keying (BPSK) modulator, a K_a-band mixer/upconverter, and a solid-state amplifier, as shown in Fig. 9. The BPSK modulation is accomplished at UHF frequencies. This modulated signal is then upconverted in a K_a-band mixer by the K_a-band local oscillator to obtain the required transmit frequency. The mixer output drives an amplifier array consisting of four series-connected stages driving four parallel stages.

The RF circuit in the modulator is constructed using microstrip techniques. The modulator includes a resistive pad to set the drive level to the upconverter and also a diode-switched phase shifter to perform the modulation. The phase shifter in the modulator consists of a branch-line coupler with diode-switch reflection modules on two of the ports. The diode switches use computer-type diodes (IN4148). These diodes were used since they are inexpensive and were available in a flight-qualified version. The loss through the modulator (excluding the pad) is less than 1 dB.

The modulated IF signal is upconverted with the K_a-band local-oscillator signal in a broadband balanced mixer, which uses Schottky-barrier diodes. The mixer and diodes are very similar to those used in the receiver. A larger-area diode is used and the IF circuits of the mixer are slightly different. The conversion loss of the upconverter mixers is about 8 dB. Power output to the amplifier array is -5 dBmW.

The design of the amplifier array is based primarily upon the added power capability of the silicon IMPATT diode (available in 1973) when operated at a reliable junction temperature. A maximum operating temperature of 185 °C was selected on the basis of life testing of 140 devices which predicted an MTTF on the order of 5×10^6 hours at this temperature.[4] For this constraint, typical added powers of 0.15 to 0.20 W at 4% rf to dc conversion efficiency are available. Since the transmitter output power requirement appreciably exceeds this level, power combining techniques are required. The amplifier array of Fig. 9 is obtained by using a configuration optimization procedure based on diode added power capability and circuit losses to minimize the number of stages and maximize overall power-added efficiency.[5] Low-loss power combining is achieved by using matched H-plane tees and output amplifier stages which are matched in gain and phase.

Each reflection amplifier stage includes a packaged IMPATT diode mounted in a reduced-height waveguide circuit, a circulator, and both input and output isolators. The negative resistance properties of the diode transformed into the waveguide environment provide the reflection power amplification. Incident and reflected waves are separated by the three-port Y-junction circulator.

The details of the amplifier circuit are shown in Fig. 10. The packaged diode is soldered to a copper cylinder which contacts the circuit block to provide a good thermal path. The diode is biased through a low-pass coaxial filter. The filter reactance is used together with the length of the short-circuited waveguide to provide a suitable load impedance for amplifier operation of the IMPATT diode. The circuit is characterized in terms of available added power with respect to diode junction temperature rise.[6] Additional gain control is achieved with simple quarter-wave matching sections of reduced-height waveguide, and phase control is provided by the length of waveguide from the face of the circuit to the diode.

The amplifier circuit is fabricated by soldering an electroformed copper cylinder, which houses an aluminum mandrel of reduced-height waveguide, into a copper block. The block is then machined as required and the aluminum mandrel is chemically etched away. This procedure yields high-quality finishes on the waveguide surfaces and facilitates accurate machining of circuits.

The circulators and isolators are incorporated into a single split-block machined unit as shown in Fig. 11. They utilize the properties of nickel-zinc ferrite to provide ≥20 dB isolation over 10% bandwidth with <0.1 dB insertion loss. The isolator consists of a circulator with one port terminated in a matched load which is also included in this unit. In addition, waveguide impedance transformers are included between the reduced-height waveguide of the amplifier mount and the circulator waveguide, and between the isolators and the external waveguide connections.

The complete transmitter assembly is shown in Fig. 12 including the modulator, the upconverter, and the amplifier array. Amplifier input, output, and reflected powers are monitored by germanium back diodes mounted in waveguide circuits similar to the amplifier mounts. Input power is sampled by a matched magic T; output and reflected powers are detected using a dual crossguide coupler. Individual constant current supplies for each amplifier are located in the boxes adjacent to the amplifier arrays. Thermal control is

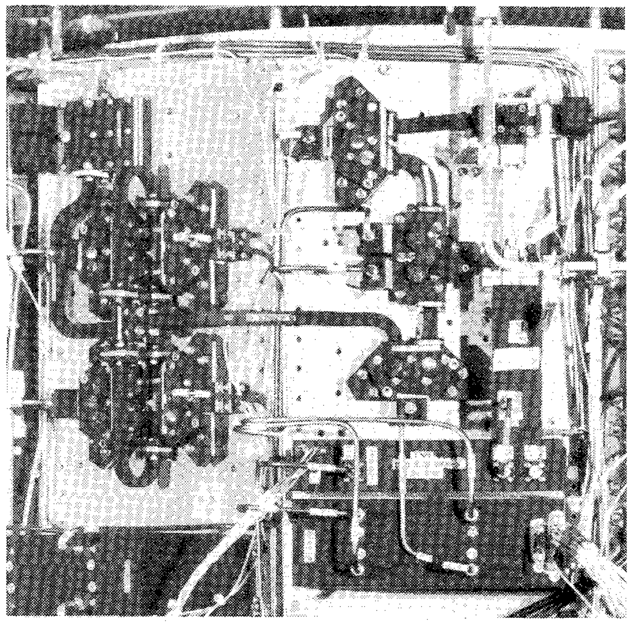

Fig. 12 LES-9 K_a-horn transmitter assembly during communications system tests.

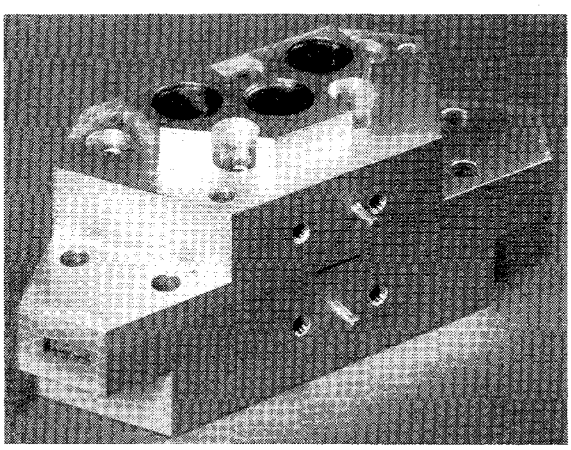

Fig. 11 Amplifier port of circulator assembly.

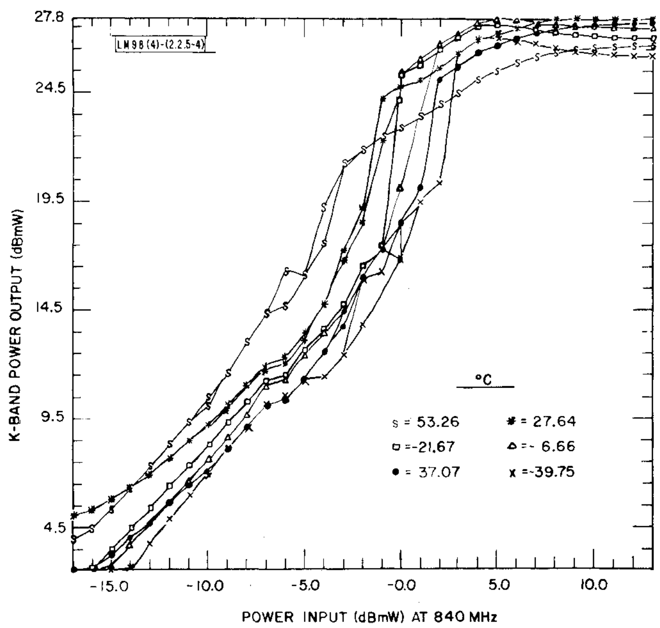

Fig. 13 LES-8 K_a-dish transmitter output.

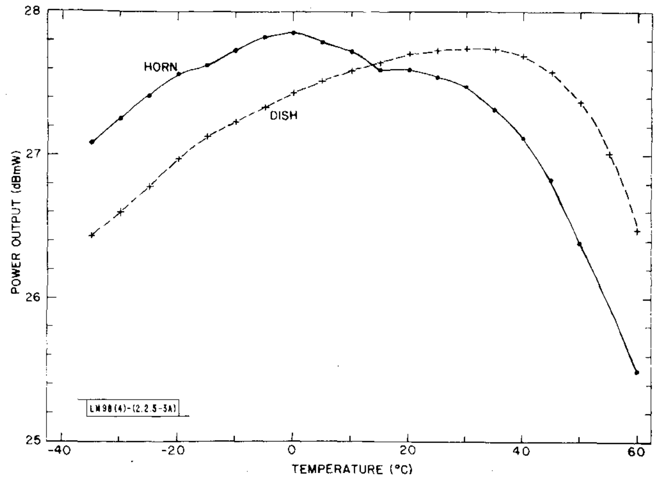

Fig. 14 Power output of LES-8 transmitters vs temperature.

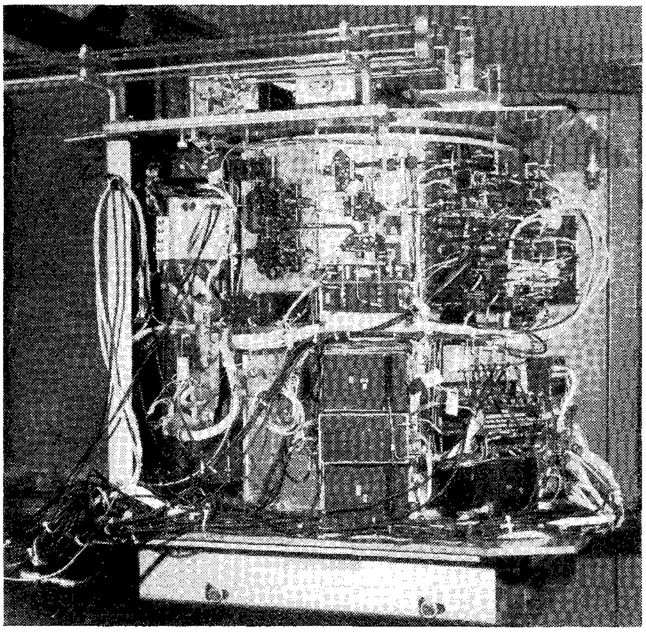

Fig. 15 LES-9 communication system test decagon.

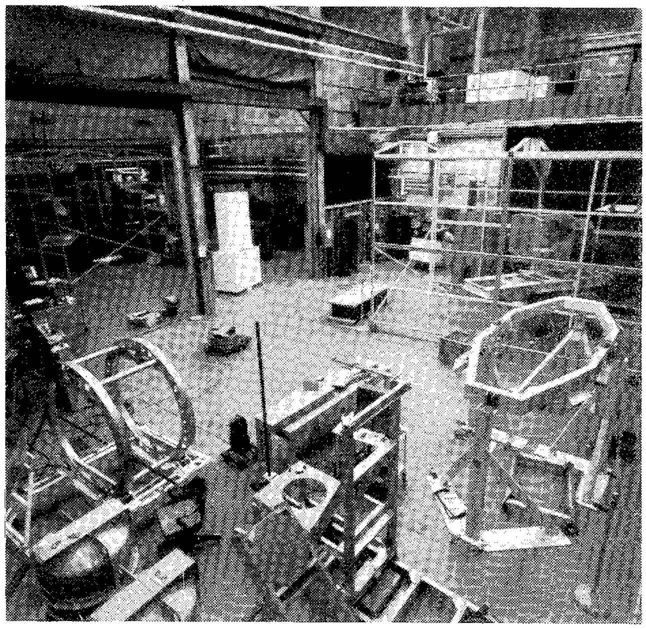

Fig. 16 LES-8 and LES-9 on squint mounts for crosslink tests.

achieved by spreading out the amplifiers over two satellite panels.

The amplifier is designed to operate at saturated added power level over the expected range of input levels, resulting in a region of hysteresis in the input/output power response. As a result of saturated operation, a 5 to 7 dB decrease in input power level is required to cause a 1 dB decrease in output power. For nominal mixer output levels of 0.3 mW, typical amplifier output powers of 0.6-0.7 W are realized. A typical overall transmitter input/ output power response, including frequency conversion from UHF to K-band frequencies, is plotted in Fig. 13 at several temperatures. The regions of saturated operation, hysteresis, and nearly linear operation are illustrated in addition to the insensitivity to temperature. Temperature variations in the local oscillator supplying the K_a-band upconverter are included in this response. In practice, the transmitters are operated at the maximum UHF input power level (+ 13 dBmW) shown in Fig. 13. For this input level, typical variation in power output is less than 1.0 dB over the operating temperature range of $-20°C$ to $+40°C$ as shown in Fig. 14. Transmitter bandwidth is limited by the upconverter output filter. At nominal operating conditions the power response of the overall transmitter is typically flat with ± 0.25 dB over its passband.

The operating status of the transmitter is monitored via a telemetry link. Mixer diode voltages and IMPATT diode voltages and currents are monitored together with the power monitors mentioned above.

K_a-Band System Testing

Figure 15 shows the LES-9 communication system mounted on a mockup of the decagon and forward platform. The mockup is mounted on a trolley so that it can be rolled into the thermal chamber at the left for tests as a function of temperature. The waveguides at the upper left connect to a switch matrix which permits all satellite receivers and transmitters to be tested and also permits testing of the crosslink between satellites. The K_a-horn transmitter is in the upper center of the photo. To the right of it is a portion of the frequency multiplier chain. On the upper platform are the two receivers' front ends. The K-dish front end is mounted in the brass shield box. The redundant 5 MHz master oscillators and their distribution system are mounted below the transmitter.

The LES-8 mockup for communications system thermal tests was mounted just behind the position of the camera that took this photo. Careful shielding of waveguide joints and the crosslink receiver front ends was necessary to permit exercising the crosslink system between the two satellites at realistic signal levels and at threshold. The shielding required was in excess of 150 dB from the K_a-dish transmitter output at one satellite to the K_a-dish receiver input of the other satellite.

The LES-8/9 systems were each operated during more than 50 temperature cycles. The testing was done over the range of $-40°C$ to $+60°C$. The plots shown in Figs. 13 and 14 are representative of the many computer-controlled temperature tests that were performed in order to verify design margins and provide additional screening against defects. Approximately 250 telemetry points and 30 RF test points were monitored during these tests. In addition to normal RF tests of the communication systems, automatic bit error rate tests were routinely done on all links including the crosslink.

The work with the communication subsystem was concluded with all up tests with the ground terminals and with a mockup of the crosslink system through its antennas. The antennas for the crosslink system were connected to the communication system model through long waveguide runs. The antennas were mounted on other satellite mockups located on squint mount tables in the high bay area (similar to the setup in Fig. 16).

After the testing of the communication system was completed, it was integrated into the spacecraft and then tested with the spacecraft in thermal vacuum. This was followed by an integrated system test with both satellites on squint mounts in the high bay area. A portion of this test setup is shown in Fig. 16. The tents were used to keep dirt and dust off the satellites.

During the integrated system tests with both satellites operating on the squint mounts, tests were again done with the satellites crosslinking and with the ground terminals.[7] During these tests, the output of each transmitter was attenuated by about 50 dB to prevent damage to the opposite satellite's crosslink receiver. The attenuator was implemented near the output of the respective transmitter with a metal pin which was inserted through a hole in the broad wall of the waveguide. The pin was removed for flight and the hole capped.

Operation in Orbit

LES-8/9 were launched March 15, 1976, UTC, from the Eastern Test Range. LES-9 is currently over the Atlantic and LES-8 is about 90° W in longitude.

The receiver system performance in orbit has been confirmed to be the same as measured before launch. All receivers continue to operate normally

Initial evaluation of the satellite transmitter's performance in space by K_a-band ground terminal receivers confirmed the telemetered values of transmitted power within ± 1.0 dB for all four transmitters.

Conclusion

This paper presents a description of component and system techniques necessary for a high-reliability solid-state millimeter-wave communication satellite system. This includes the use of hermetically sealed active devices and thorough testing over temperature of the components and systems. The performance of the system in orbit has been verified to be the same as on the ground.

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The views and conclusions contained in this document are those of the contractor and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the United States Government.

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