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Space Qualification for an Intersatellite Laser Communications System

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SPACE QUALIFICATION FOR AN INTERSATELLITE LASER COMMUNICATIONS SYSTEM

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ABSTRACT

The development of an optical system for space applications requires that careful attention be given to hardware design and testing. A procedure for developing and qualifying a laser intersatellite communications package is presented, along with the derivation of specific levels used in the successful testing of its transmitter assembly. This general approach may also be useful for the development of other high-reliability optical systems.

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1. INTRODUCTION

While optical communication using ground-based fiber has been widely implemented, the technology for high-rate optical satellite crosslinks still remains wholly in the laboratory. In order to move from laboratory demonstrations to deployed operational systems, space-qualified hardware must be developed.

Intersatellite laser communications systems offer many of the same advantages to space communications that fiber links offer to ground-based communications. High data rates are possible using the enormous bandwidth and spatial gain of optical channels. Optical intersatellite links are generally secure, with resistance to jamming and eavesdropping. However, the operational environments and system requirements of satellite laser communications (lasercom) are sufficiently distinct that much new hardware needs to be developed before high-rate optical crosslinks can be established in space.

In this report, Lincoln Laboratory's process to develop and space qualify hardware for a satellite lasercom system is described. The design and qualification testing of the Laboratory's diffraction-limited 30-mW diode laser transmitter for use in a 220-Mbps heterodyne communications experiment will be followed as a design example.

2. SPACE LASERCOM PROGRAM REQUIREMENTS

Many of the subsystems in a space lasercom system are functionally similar to those in terrestrial and undersea links. Data processing and drive electronics, the laser itself, detectors, and demodulator electronics, in particular, are similar in the two systems. In fiber links, fiber loss, dispersion, and scatter influence the choice of wavelength and laser power. In free space, however, where there are no constraints presented by the transmission medium, there is a premium placed on high laser power coupled into a system with low loss and high optical quality. Because the beamwidth of a space lasercom system is typically narrow (4 μrad from a 20-cm aperture at 0.86 μm wavelength, for example), the beam must be pointed toward the receiver with great precision, despite the unwanted micro-motions of orbiting spacecraft.

The lasercom package must withstand exposure to the harsh environment of launch, then operate reliably during its multiyear mission. The data base on which to predict reliability will be very small; the technology is still at the experimental stage, and only a few copies of each hand-crafted unit of a given design will be built. Furthermore, redundancy in the system can be used only sparingly, because weight and power are at a premium in a spacecraft.

3. THE LINCOLN LABORATORY LITE PROGRAM

For the past five years, Lincoln Laboratory has been developing technology for a flight-worthy optical system for satellite-to-satellite communications. Based on proven laboratory hardware, Lincoln Laboratory is building and space qualifying systems for the Laser Intersatellite Transmission Experiment (LITE) [1]. LITE was designed to be part of NASA's Advanced Communications Technology Satellite (ACTS) to be launched on NASA's Space Transportation System for placement in a geosynchronous orbit; thus the launch and orbit survival requirements for the LITE design were dictated by these host vehicles. Table 1 summarizes some of the critical launch and orbit requirements for LITE, which were used to set the environmental testing levels*.

TABLE 1

Launch and Orbit Requirements for LITE

Exposure	Level	Duration
Launch/Deployment Temperature Range	–30 to 60°C	Cycling
Host Interface Temperature Range (Operational)	–5 to 50°C	Cycling
Random Vibration	6.5 *g* (rms)	1 min
Acoustic Noise	140 dB	1 min
Static Loading	20.7 g	At Maximum

The LITE flight package includes an Opto-Mechanical System (OMS) to be mounted on the Earth-facing panel of the host satellite, along with data processing and support electronics mounted remotely [2]. This optical system consists of a bench-like structure supported by a truss network which provides thermal and vibrational isolation from the host. The optical beams are transmitted and received via a large steerable mirror on the earth-facing side of the bench, with a large pointing range for communications with other geosynchronous or low-earth-orbit platforms. A 20-cm-diameter telescope receives a beacon signal for tracking via the mirror and transmits a diffraction-limited 0.86-µm-wavelength beam. The bench also supports the laser transmitter, a laser diagnostics module [3], beam steering and tracking optics, acquisition and tracking detectors, and associated relay optics. The LITE communications system uses heterodyne detection with 4-ary frequency-shift-keyed (FSK) modulation at data rates up to 220 Mbps.

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* Although the flight program has been suspended, work has continued on an engineering model with critical units being subjected to qualification testing.

The remainder of this report will describe how Lincoln Laboratory incorporates the system, environmental, and program requirements into an optical system design which can be space qualified. In particular, the design, fabrication, and testing of the completed LITE laser transmitter, which has been successfully qualified and operated in the LITE system, will be described.

4. TEST-LEVEL CONSIDERATIONS

In order to determine the test levels for the LITE hardware, the expected conditions during the prelaunch testing, launch, deployment, and operation of the ACTS spacecraft were considered. The lowest level of testing, the acceptance test level, is one to which all flight hardware must be subjected. The acceptance tests are based on knowledge of the orbital conditions, on measurements taken during previous missions, and on computer models of the spacecraft and the expected loads. The acceptance tests are more severe in level and duration than the expected flight conditions to account for uncertainties in the measurements and modeling.

A more rigorous testing program is qualification testing, which is conducted at higher stress levels and for longer durations than the acceptance tests. Qualification testing is employed prior to the construction of flight hardware to ensure that the flight designs have an adequate margin of safety. If the qualification testing is successful, the flight hardware is constructed identically to the qualification hardware and is subjected to acceptance testing to verify adequate workmanship and the hardware's ability to survive launch and operate under orbital conditions.

Each major subassembly should undergo appropriate qualification testing prior to its integration into a larger assembly. The design of the OMS provides significant protection to its subassemblies from large temperature excursions and from high-frequency vibrations. This requires development of test levels specific to each unit. By design, the OMS temperature controller will maintain near-room-temperature conditions throughout the assembly after the spacecraft orbit is established. As part of the qualification testing, each subassembly is operated at temperatures between 10°C above and 10°C below the range predicted by the computer thermal model. Similarly, the levels used for random vibration testing of subassemblies are based on computer models of the dynamic response at the specific mounting location within the OMS. These levels are then banded to account for uncertainties in modeling and loadings.

5. LAUNCH AND OPERATIONAL STRESSES

During the first minutes of a launch, a satellite is subjected to an intense acoustic field. Random and steady-state accelerations from the rocket motor also spread to the satellite via attachment points that secure the satellite to the rocket. Later, after an initial orbit is established, deployment of appendages such as antennas and solar-panel structures is initiated with the firing of pyrotechnic mechanisms that send shock waves throughout the satellite.

Figure 1 shows various qualification-level random-vibration spectra from the LITE program. The input levels applied at the mounting surface of the OMS were specified by the host spacecraft and are based on a banded response of the spacecraft to the launch conditions. A computer model of the OMS was used to predict the response at the transmitter mounting location. By banding this response, the qualification test level for the transmitter is derived. The increase in level introduced by this banding ensures that a successfully qualified transmitter will not exhibit difficulties when the integrated OMS is qualified.

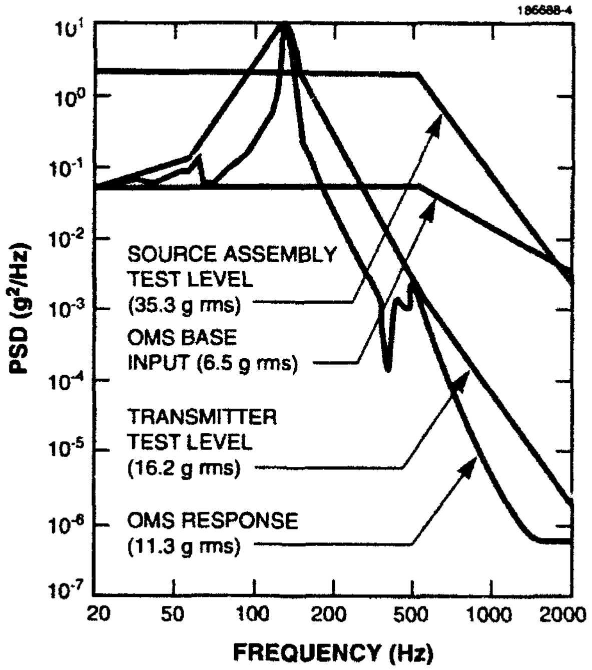

Figure 1. Input and test qualification-level random-vibration spectra.

Figure 1 also shows the test level to which an individual source assembly was qualified. These tests were performed long before the spacecraft test requirements or the final transmitter configuration had been determined and were based on conservative estimates of what could be expected within the transmitter during its qualification process.

The spacecraft also undergoes large variations in temperature, particularly during launch and transfer orbits when the spacecraft moves and out of the earth's shadow and the vehicle's orientation with respect to the sun varies. Until the solar array panels are deployed, the available electrical power is limited to the satellite's battery capacity, which thereby restricts the use of electric heaters. Thus temperature swings within the OMS would range from –30° to +60°C. Although only minimum operation (such as the telemetry of critical data) is required during this period, the thermal stresses are potentially damaging. To verify survivability of the design, qualification testing includes repeated thermal cycling from –40° to +66°C in addition to the operational tests mentioned previously.

Conditions after the satellite has been deployed can also hinder operation. High-frequency vibrations (tens of milli-*g* at several hundred Hz) within the satellite are generated by the momentum wheel assembly, while low-frequency vibrations (hundreds of microrads at several Hz) are generated by the solar array drives and the station-keeping devices. These disturbances can affect the performance of servo mechanisms used to point the communications beam at the receiver. Each subassembly and the optical bench have been designed to have structural resonances which are significantly higher than these disturbances, to avoid unacceptable line-of-sight jitter.

Operating in a vacuum poses additional difficulties. To prevent contamination of critical optical surfaces, material usage must be limited to those which exhibit a very low tendency to outgas. Refractive optical systems which were focused in a standard atmosphere will no longer be properly aligned in a vacuum. Convective heat transfer is no longer possible, making dissipation of waste heat more difficult and changing temperature profiles throughout the assembly.

In addition, phenomena such as cosmic radiation absorption and micro-meteoroid strikes can cause damage to critical electrical or optical components. Careful choice of components and materials ensures that even after years of operation in space, performance requirements will be met. The qualification test program is designed to simulate launch loadings and operational conditions so that the design and workmanship can be verified. Where testing is impractical, analysis must be relied on to ensure satisfactory performance.

6. HARDWARE DEVELOPMENT PROCESS

In order to develop units for operation in the space environment, a multistep design process is followed in which one person follows the entire development of one unit. During the design process, this unit engineer is the focal point for all decision making regarding the unit.

The process starts with a design proposal which considers the expected launch and operational conditions within the lasercom package. For the LITE transmitter, computer modeling predicted conditions such as the temperature of the transmitter's mounting points, the spectrum of the random vibration seen by the transmitter during launch and operation, and the total radiation dose over the mission life.

During the design process, proven components are selected when possible. New components are tested as early as possible to determine their suitability to space operation. For the LITE transmitter, two components which received early qualification testing were the diode laser and its collimator. Their successful qualification allowed the design of the transmitter to proceed.

As the design matures (but before flight-quality hardware is built), breadboard versions are often constructed to test the operation of critical design features. This allows functional performance of the unit to be assessed, particularly when the unit is coupled with breadboard versions of related units in the lasercom package. As an example, breadboard versions of the transmitter and the thermal controller were mated to verify the required temperature stability of ±0.001°C.

Once the design is complete, with changes made as required by the preliminary testing, fabrication of the qualification unit begins. The qualification unit is built to flight-quality standards but is subjected to test levels more severe than flight levels to uncover flaws in design or fabrication techniques.

The flight unit is built identically to the qualification unit but is tested at lower levels representative of launch conditions. These tests are intended to uncover any defects in workmanship without unduly stressing the flight unit.

The final transmitter configuration is shown in Figure 2. The transmitter contains four redundant source assemblies supported by a titanium structure comprising the housing, the support struts, and the prism mounting tray. Two sources are mounted on the top of the structure and two below, with each beam directed toward its own fold mirror. The fold mirror directs the beam to an anamorphic prism pair which circularizes the beam and points it to the beam intersection point located outside the transmitter. A two-axis servo-driven fold mirror located at this point directs the active beam to the proper OMS beam path and corrects angular drift of the transmitter beam.

The transmitter's design must allow the sources to be operated anywhere in the 10° to 30°C range so that the laser can operate at the desired wavelength. To achieve this, the transmitter's support struts were designed to provide high thermal isolation and rigid attachment to the OMS. Waste heat is dissipated by the thermal radiator, which is attached to the sources by flexible thermal straps.

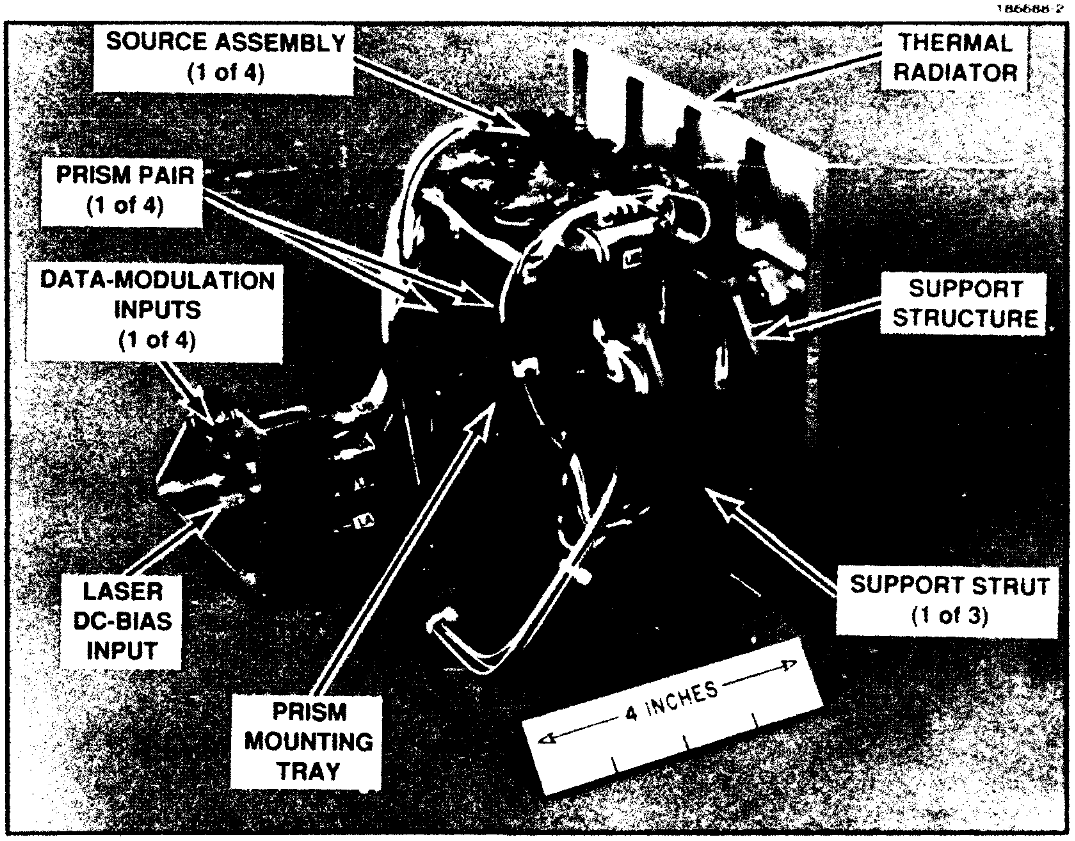

Figure 2. The LITE transmitter.

7. TESTING PROGRAM

Before an entire lasercom package is subjected to qualification testing, individual units should be qualified. The testing of the LITE transmitter, which was typical of that seen by other critical units, will be presented as an example.

Prior to completing the LITE transmitter design, qualification testing was performed on the source assembly, which contains the diode laser, its collimator, electronics, and part of a thermal control system (see Figure 3). This testing showed that the electro-optic, thermal, and mechanical design of the source assembly was satisfactory.

The source assembly testing included random vibration testing for two minutes in each of three axes at up to 35 *g* (rms) and repeated thermal cycling from −30° to +66°C. This testing was performed while the unit was unpowered, as it would be during launch. Shock testing of the source assembly was not warranted at this stage because of the high attenuation provided by the OMS support struts. Shock testing would be performed during OMS qualification.

Operational testing of the transmitter's source assembly included a measurement of wavefront quality over the temperature range of 10° to 30°C. This range was chosen to ensure that each laser could maintain the proper wavelength as it ages. The results of this testing, shown in Figure 4, indicate that there was minimal loss of focus over the temperature range. Other operational testing included measurements of wavefront quality in vacuum, modulation-port input impedance, and pointing accuracy. All source assembly tests were concluded satisfactorily.

The qualification testing of the entire transmitter included random vibration and thermal cycle testing, at up to 16.2 *g* (rms) and from −30° to +66°C, respectively. Because the design includes survival heaters set to operate at −20°C, it was unnecessary to test the transmitter below −30°C.

The principal characteristics examined before and after transmitter qualification were the beam pointing and wavefront quality. These two parameters are the most sensitive to any changes of the optical path during testing. A change in the transmitter's beam pointing leads to a walk of the beam on the telescope's primary mirror, thereby causing beam truncation. A degradation of beam wavefront quality reduces the power available to the receiver satellite by broadening the beam. Either of these errors could be caused by sub-micron-level shifts in position of any of numerous mechanical or optical components.

Because there are four redundant source assemblies on the transmitter, the characterization included measuring the beam pointing and wavefront quality of each of the four beams. The results show that high beam pointing and wavefront quality were preserved, although there was a small change in the average value of each due to the testing. Figure 5 shows the beam pointing data, along with circles of equal loss. The average wavefront quality was $\lambda/26$ before testing and $\lambda/23$ after testing [4].

In addition to the transmitter, other units which have passed their qualification testing include the laser diagnostics module, the high-bandwidth steering mechanism, the point-ahead mechanism, and several optical assemblies [5,6]. Photographs of four of these other units are shown in Figures 6, 7, 8 and 9.

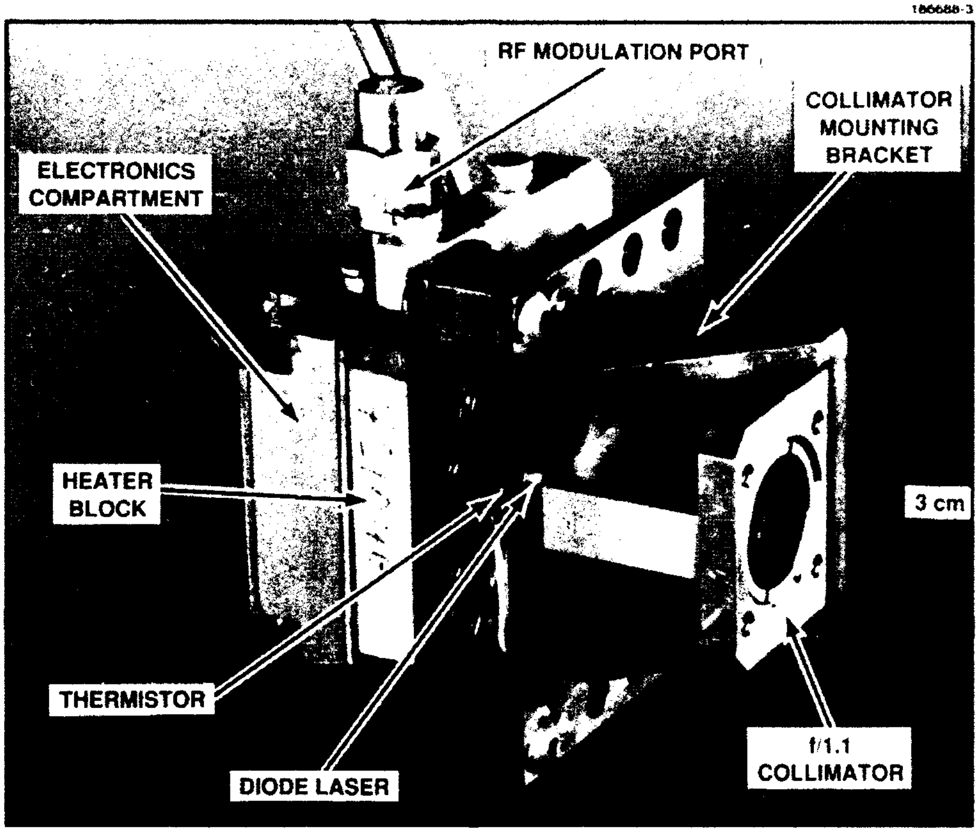

Figure 3. A source assembly from the LITE transmitter.

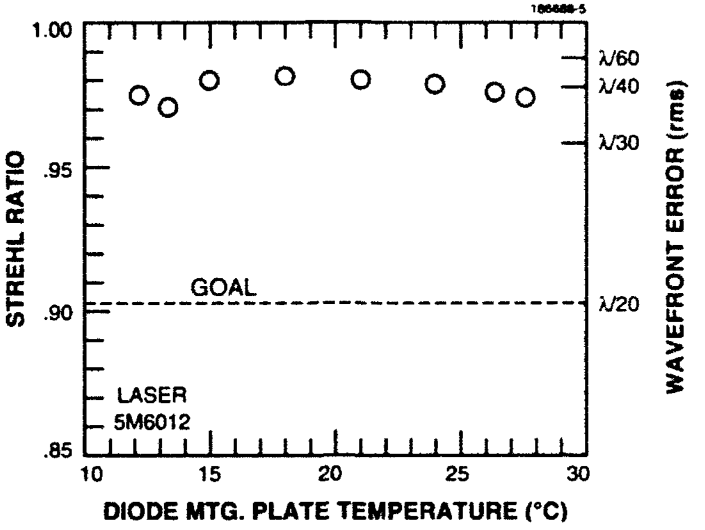

Figure 4. Source assembly wavefront quality over its operating temperature range.

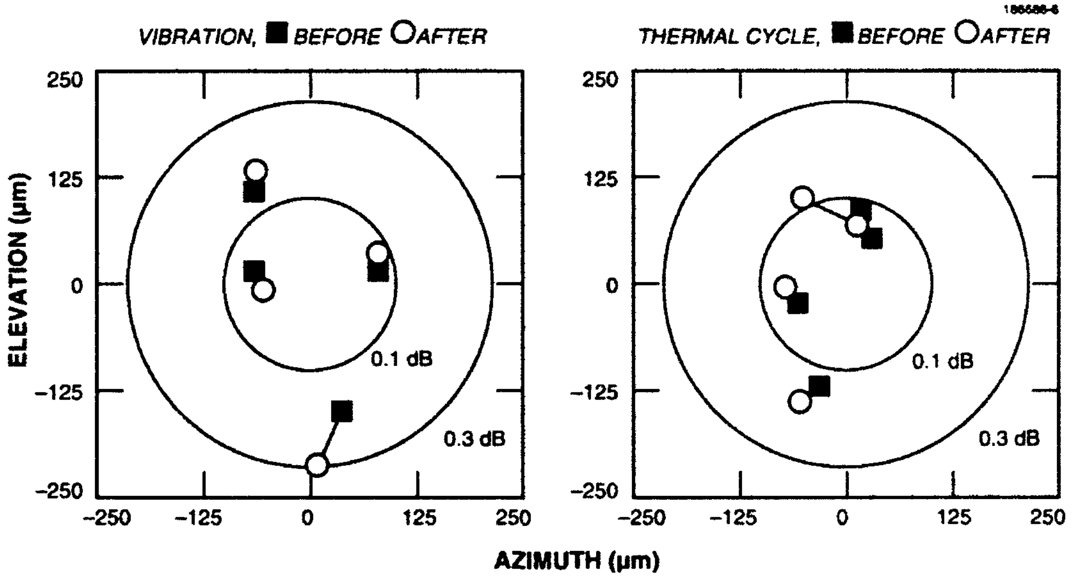

Figure 5. Transmitter beam positions before and after qualification testing.

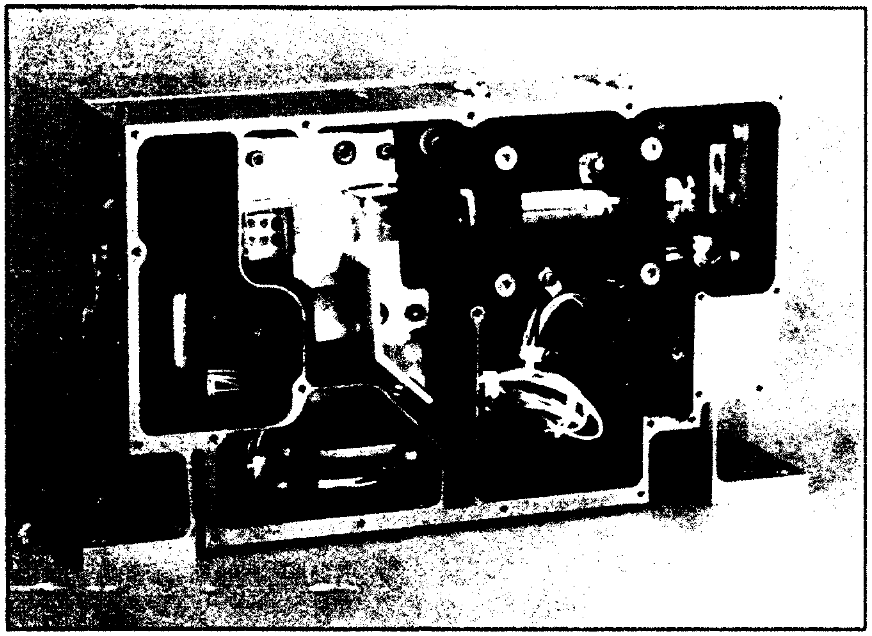

Figure 6. Space-qualified laser diagnostics module (with cover removed).

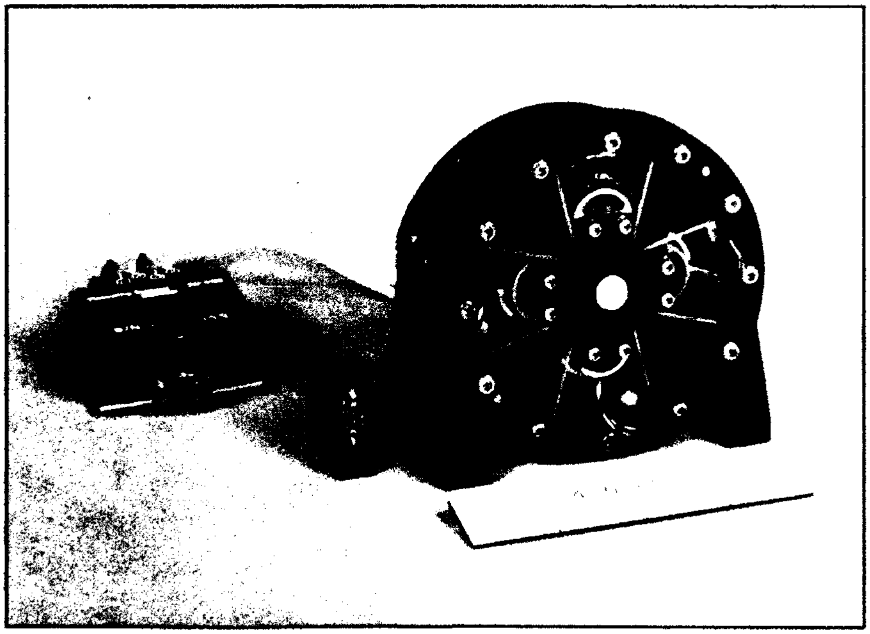

Figure 7. Space-qualified high-bandwidth steering mechanism.

8. SUMMARY

The deployment of an intersatellite laser communications system requires the careful development of hardware which can survive the rigors of rocket launch and which can operate reliably in the space environment. Successful hardware development, in turn, requires a sound design approach and a qualification test program designed to reflect the stresses the package will undergo.

This report has given an introduction to the design and qualification process for a satellite lasercom system, as practiced by Lincoln Laboratory. In particular, the report examines the design and test steps followed in successfully completing the LITE laser transmitter, which produces a 25-mW diffraction-limited FSK-modulated beam at 0.86 μm. Thorough prefabrication analyses and a conservative qualification test regimen should lead to successful space-based lasercom systems.

Figure 8. Space-qualified 1:1 relay lens assembly.

Figure 9. Space-qualified two-axis point-ahead mechanism.

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