10.6-MICROMETER LASER COMMUNICATION SYSTEM EXPERIMENT FOR ATS-F AND ATS-G

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Summary A laser communication system weighing 30 pounds and consuming 30 watts is to be flown on the ATS-F satellite for a space-to-ground experiment. An identical system proposed to be flown on ATS-G will complete an experimental intersatellite communication link. A 6-inch aperture optical antenna with a 92 dB antenna gain and a 500 mw carrier provide a minimum 23dB carrier-to-noise ratio for a 5 MHz bandwidth system. This experiment will permit analysis of laser Communication system parameters as a base line for future operational system designs, such as could be employed on a Data Relay Satellite. In addition to the NASA ground station, a station prepared by Bell Telephone Laboratories will perform atmospheric propagation experiments on the beam received from the satellite.

Introduction The purpose of the coherent wide-bandwidth spacecraft-to-spacecraft laser communications experiment to be flown on ATS-F and proposed for ATS-G is to use the present laser state-of-the-art to establish the feasibility and value of optical communications. The experiment requires implementation and testing of a highly efficient wide-bandwidth high data rate communication link between the ground and ATS-F and between two geosynchronous satellites, ATS-F and ATS-G. The chosen spectral range, 10.6 micrometers, offers optimum channel capacity per pound of satellite weight and watt of satellite power budget.

The proposed experiment combines Goddard Space Flight Center's capability in relay satellites - the technology of geosynchronizing and stabilizing the orbits of ATS-F and -G - with recent developments in laser communications to provide high-quality transmission from ATS-F to a small, portable laser-receiving station. The simplicity of the proposed flight packages, the use of laboratory-proven components, and the use of existing NASA facilities establish confidence that the experiment goals will be achieved, contingent only upon the normal performance of critical spacecraft subsystems. A high data-rate communications system at 10.6 micrometers (28 THz = 28 x 10^{12}Hz) has been realized over an 18 kilometer ground link (1).

The experiment will include its own telescope and steerable reflector. This 6-inch diameter optical antenna will beam through a small hole in the skin of the earth-viewing module (Figure 1). The experiment must be placed so that its line-of-sight toward the earth and to ATS-G is unobstructed.

The incidence on the satellite of laser radiation received from the earth can be kept as low as 10^{-13} watt per square centimeter throughout the communications experiment; consequently, it will not interfere with infrared equipment in the satellite.

The objectives of the experiment are as follows:

- Establish the feasibility of high data-rate 10.6 micrometer laser satellite-to-satellite communications and evaluate operational performance
- Provide baseline data necessary to design satellite-to-satellite optical links for the Data Relay Satellite and deep-space probes
- Provide information to directly compare microwave and infrared laser systems
- Provide 5 MHz wide, clear-weather, back-up channels between ATS-F and the earth
- Provide 5 MHz wide, earth-to-earth, real-time, all-weather channels via ATS-F and -G, using both X-band and infrared links

The experiment will perform the following functions:

- Measure overall communication parameters, such as signal-to-noise ratio, bit-error rate, and system efficiency
- Measure laser transmitter frequency stability and drift under space environment
- Establish interrelation between receiver noise bandwidth and laser local oscillator automatic frequency control (LO AFC) loop and its dependence on spaceborne laser-frequency stability and Doppler shift
- Measure the noise figure of radiation-cooled infrared detectors/ mixers in space
- Measure background noise presented to the infrared coherent received when pointing at the earth, the sun, and other planets - Measure telescope tracking servoloop parameters.

The following table lists the salient specifications for the proposed laser communication system.

TABLE I - COMMUNICATION SYSTEM PARAMETERS

Carrier Frequency	28 THz (10.6 micrometers)
Modulation Mode	FM
System Noise Bandwidth	10 MHz
Modulation Bandwidth	5 MHz
Antenna Aperture	6 in.
Antenna Gain	92 dB
Prime Power Required	30 w.
Mass	30 lb.
Minimum Detectable Signal per Hz	-164 dBm
Intermediate Frequency	20 MHz
LO Power	50 mw
Transmitter Power	500 mw
Transmitter Efficiency	10%
Carrier-to-Noise Ratio at Optical Mixer Output	23 dB
Range	3.6×10^7 meters
Atmospheric Loss	4 dB
Loss in Optical Components	6 dB

Experiment Description As stated previously, the overall objective of the 10.6-micrometer laser communication experiment is to establish the feasibility of a wide-bandwidth laser intersatellite communication link. The experiment will be conducted in two phases: The first phase, establishing a high data rate link between ATS-F and a ground terminal, will fulfill most of the experiment objectives; the second phase will establish the high data rate link between ATS-F and -G. Most of the technology required to provide a satellite-to-satellite laser communication link can be demonstrated by the first phase. Although ATS-G will not fly until approximately one year later, the ATS-F systems are designed to be operational when ATS-G is in orbit. Satellite lifetimes, which now average two years, are expected to increase to 3 or 3.5 years in the 1972 or 1973 period (2).

The laser communication link will then be established between ATS-F and ATS-G by "cross-strapping" the laser communications signals to the satellite-to-ground radio-frequency (RF) link. Similarly, the RF signals will be impressed on the laser communication link. The cross-strapping of signals will thus provide for the implementation of a real-time data-relay link from a low-orbiting satellite to ATS-G via radio, from ATS-F to -G by laser, and finally from ATS-F to a ground-based data-acquisition facility via RF. This multifunction communications capability is a prototype of the operational functions required of the DRSS.

The laser optical communication equipment consists of two basic parts: two flight packages and the operational ground equipment.

Flight Package The flight package, Figure 2, consists of five parts: (1) The optical subsystem contains a coarse beam-pointing mechanism (slewing mirror), a 6-inch Cassegrainian telescope, image-motion compensator, directive mirrors, and beam splatters. (2) The laser subsystem contains the 500-mw transmitter, the 50-mw laser local oscillator, the frequency stabilization servo, and laser power meters. (3) The infrared mixer and radiation cooler subsystem contains the signal mixer, image motion error sensor, preamplifiers, and radiation cooler. (4) The signal-processing subsystem contains the IF post amplifier, image-motion compensator drive electronics, laser transmitter modulator drive electronics, laser frequency control electronics, beam-pointing mechanism drive electronics, and command and telemetry interface electronics. (5) The power supply subsystem contains the laser high-voltage and modulator power supplies and the low-voltage signal processing and drive electronics power supplies.

Optical Subsystem The optical subsystem (see Figure 2) is designed to scan the transmitted beam and receiver over the acquisition field-of-view, form a narrow transmitted beam, collect energy in the infrared portion of the spectrum, divide it between image-motion sensor and information mixer, and superimpose local oscillator and received radiation to produce heterodyne action.

The coarse beam-pointing mechanism serves to direct the transmitted modulated beam toward the earth-based terminal and to direct the received laser signal into the Cassegrainian telescope. In the initial phase, the coarse pointing mechanism on ATS-F will be positioned to point to any ground station within view of the satellite. In the latter phase, it will be positioned to point to the ATS-G satellite which, for an equatorial trisatellite position, would be displaced from the symmetry axis by ± 30 degrees. This requires moving the coarse pointing mirror over a 30 degree range both east and west and over a nominal 5 degree range in the north-south direction to provide adequate coverage. To effect a desired angular movement of the laser beam, the mirror has to move only half as much. Therefore, to position the mirror within the ± 0.1-degree satellite stabilization uncertainty, a 50-position resolver is required in the north-south direction and a 300-position resolver in the east-west direction.

The bearing on the 6-inch coarse pointing mirror will not experience much motion during the satellite lifetime. Only a few ground sites will be used, and ATS-G will be in a fixed position relative to ATS-F. After acquisition, corrections to the beam direction will be accomplished by a fine-control mechanism; therefore, very little repetitive positional movement is required of the coarse beam-pointing mechanism. This item is the only mechanically rotating device in the system.

The coarse-pointing mechanism mirror is a lightweight mirror consisting of aluminum or beryllium overcoated with Kanegen before optical polishing. Metal mirrors are especially attractive because of their weight, ease of mounting, high modulus of elasticity, and favorable thermal properties. For 10.6-micrometer wavelength, the mirror flatness is not seriously degraded in the expected space environment and can be achieved more easily than in the visible wavelengths.

The telescope (optical antenna) is a 6-inch aperture Cassegrainian system with a 0.2-degree field-of-view. It acts much in the manner of an RF antenna; that is, it focuses the laser output into a high power density beam during transmission and provides maximum power-gathering area during reception.

The telescope is composed entirely of reflective aluminum or beryllium mirrors. After optical polishing, the mirrors are coated with vacuum-deposited aluminum, either pure or in combination with other materials, to provide high infrared but low visible reflectance (3). These films, as well as pure aluminum, provide a reflectance as high as 98% at the 10.6-micrometer wavelength. Special paints and baffles used in the telescope and telescope housing will reduce scattered light and provide temperature control. Because many of the optical elements and associated mounting structures radiate thermally to space, the mirrors will operate at a temperature lower than that of the surrounding satellite.

After the telescope collects and focuses the received energy, the energy passes through a negative lens that also acts as a filter. This negative lens collimates the converging telescope rays into a pencil-thin parallel beam which is then directed into the image-motion compensator, or finepointing mechanism. Selective mirror coatings and lens filter material eliminate the -necessity to shutter the system from direct sunlight.

The image motion compensator corrects instabilities in satellite pointing. The satellite will be earth-oriented and stabilized by a 3-axis inertial-wheel control system to a specified accuracy of ± 0.1 degree, with a jitter rate of 0.0003 degree per second. The required pointing accuracy of the optical system, on the other hand, is approximately ± 0.0003 degree, representing a dynamic control range of only 36:1. Satellite operational fine-guidance systems operate at dynamic range levels as high as 200:1 (200 resolution elements). To implement fine control of optical beams over a relatively narrow field-of-view, new operational techniques are being developed to supplement older, well proven techniques, such as the galvanometer movement that can steer optical beams very precisely without causing large bearing-supported components to be moved.

One technique the Goddard Space Flight Center Optical Systems Branch employs for optical beam steering is based on small piezoelectric bender bimorphs as the active deflection elements (4). A simplified diagram of the optical beam-steerer configuration is shown in Figure 3. By moving one mirror in a direction orthogonal to the movement of the other mirror, an infinite number of beam directions may be obtained to within the resolution of the system. For initial beam acquisition, the coarse beam pointing mechanism is commanded to point to either the ground station or ATS-G. The ground station or ATS-G laser transmitter beam bypasses its 6-inch optical system and is pointed at ATS-F within ± 0.1 degree. By bypassing the transmitter beam around the optical system, a diffraction-limited beam with an angular divergence of ± 0.11 degree is produced. This beamwidth is greater than the angular uncertainty of ATS-F. Therefore, the ATS-F satellite is illuminated by the broad beam. A command is then sent to ATS-F, via the telemetry link, to start the search-scan operation. Once ATS-F has achieved “lock-on”, the ATS-F transmitter is turned on and it serves as a beacon for lock-on by the receiver at the ground station or on ATS-G. The search-scan operations are performed by the application of appropriate voltages to the piezoelectric bender bimorphs.

Laser Subsystem Two prime lasers will be used in the spacecraft package: a 50-mw laser local oscillator and a 500-mw laser transmitter. A modulator crystal, constructed of either cadmium telluride or gallium arsenide, mounted inside the transmitter’s optical resonant cavity provides frequency modulation with a 5-MHz bandwidth. Two approaches can be taken to ensuring the frequency stability of the transmitter and local oscillator lasers; either active or passive stabilization can be employed. A functional diagram of a primarily passive system is shown in Figure 4.

An open servoloop makes it possible to maintain the LO frequency to within 15 MHz ± 1 MHz of line center (of the laser’s spectral line) and the transmitter carrier within 5 MHz ± 1 MHz of line center on the other. To guarantee freedom from interference and crosstalk, in a given transceiver, the local oscillator and transmitter laser will operate on different vibrationalrotational transitions, e.g. the P(20) and P(22) lines.

Infrared Mixer and Radiation Cooler Subsystem The mixer and radiation cooler subsystem has two functions; heterodyne detection of the signal information and heterodyne image motion sensing. Each function is discussed below.

The optical subsystem directs the incoming infrared signal to the signal mixer. Coherent heterodyne detection is used because it is superior by six orders of magnitude to direct envelope detection in sensitivity and the ability to discriminate against background radiation. Heterodyne detection involves the coherent mixing of the incoming laser signal with the local oscillator in a square-law detector. The emergence of coherent laser technology has now made possible the performance of this function, analogous to RF techniques. The ultimate sensitivity limit for infrared heterodyne detection, termed the quantum limit, is 2hfB or nominally 3.76×10^{-20} watt per cycle of noise bandwidth. Recent measurements by Arams (5), Teich (6), and Mocker (7) have shown that sensitivities within 3dB of the quantum limit are attainable.

The infrared mixer used will be a sensitive, wideband mercury cadmium telluride (HgCdTe) detector which can be operated at temperatures in excess of 100° K. This capability makes possible-the use of lightweight radiation coolers instead of the more cumbersome, limited-lifetime solid cryogens. Further, unlike cryogenic refrigerators, radiation coolers place no burden on the satellite's prime power supply.

The output of the video mixer is supplied to a broadband preamplifier which is connected to a coherent demodulator. The modulated signal may, for example, be then directed to the RF cross-strap. The fine beam pointing error sensor provides the servo signals necessary to operate the image-motion compensator that controls the direction of the transmitted and received rays. Sensor operation can be divided into two modes: acquisition and tracking. The acquisition mode starts when the image motion compensator initiates a scan program; it terminates when the error sensor registers acquisition and sends a command to the scan generator to halt the scanning operation. The tracking mode starts with the acquisition of a signal. After acquisition, the image of the incoming laser beam,is automatically centered on the sensor. Subsequent drifts in the image position result in azimuth and elevation error voltages that cause the image-motion compensator to recenter the image.

While the above discussion broadly covers the acquisition process, the precise form of the error sensor has not been given. Two types are under active consideration and evaluation. The most straightforward is merely a quadrant mixer array employed in a manner analogous to the four feed horns in an RF amplitude-sensing monopulse system. An alternative to the quadrant mixer which places a smaller thermal load on the radiation cooler is the use of a rotating element in front of the signal mixer to produce a nutation of the beam which can be used for angle sensing.

Operational Ground Equipment The function of the operational ground equipment is to provide a self-contained mobile test facility which, when located at an ATS ground station, is capable of evaluating both uplink and downlink experiment performance. It will exercise and evaluate the experiment in a variety of operating modes and collect data for analysis.

Current plans call for the operational ground equipment to be installed at the Mojave ATS ground station during initial satellite tests and then to be moved to Europe after the ATS-F spacecraft assumes its final position over the African continent. In addition to the NASA ground station, a station prepared by Bell Telephone Laboratories will perform atmospheric propagation experiments on the beam received from the satellite.

The operational ground equipment will consist of a standard astronomical dome, the laser heterodyne transceiver, boresight equipment, calibration tower and source, and a vibration-isolated mount for the transceiver. All operating controls, test panels, and data readout instrumentation will be located in the ATS ground station,

Conclusions The ATS-F laser communication experiment is the first effort to develop the technology of laser intersatellite communication systems. In terms of either payload pound or watts of prime power the carbon dioxide laser offers an attractive alternative to microwave or millimeter wave intersatellite communication systems.

References

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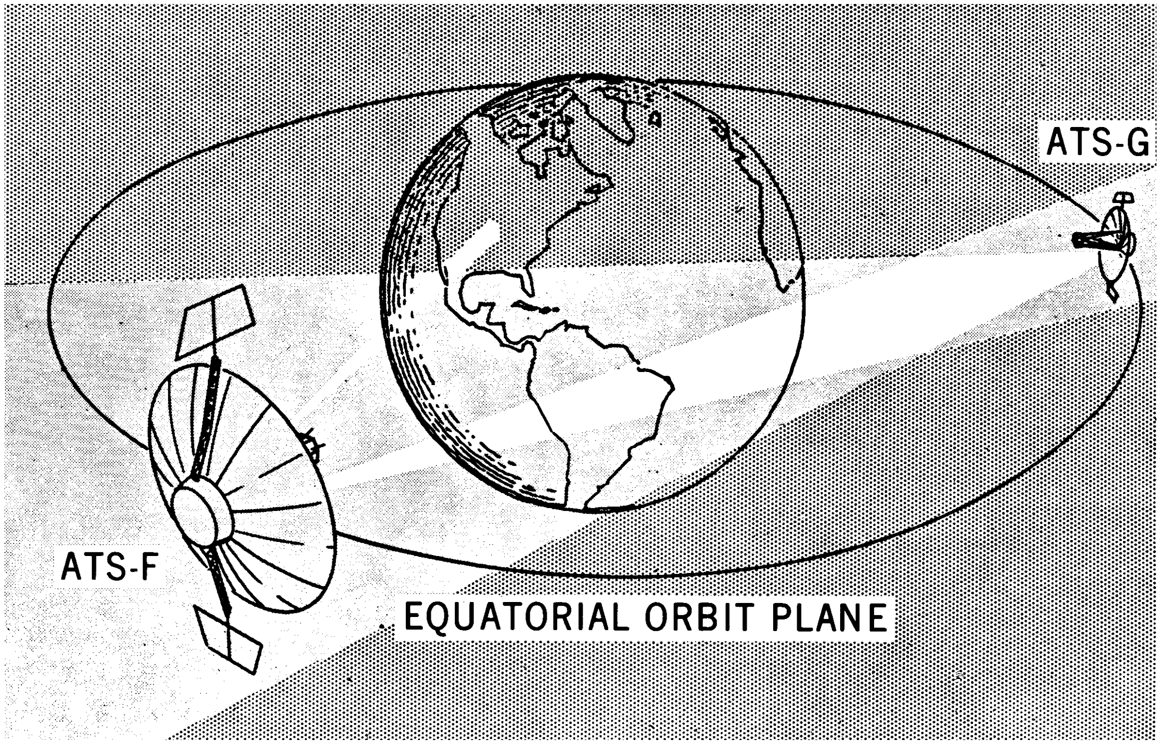

Figure 1. Communication link geometry.

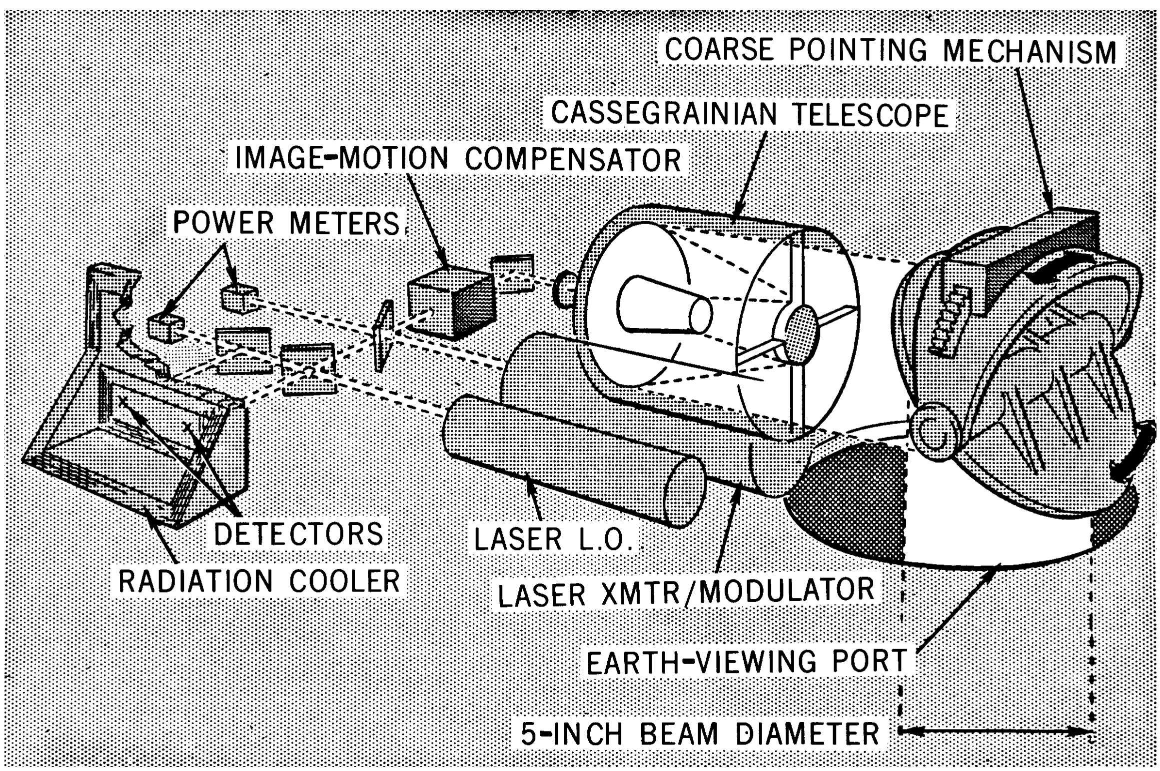

Figure 2. Laser system conceptual diagram.

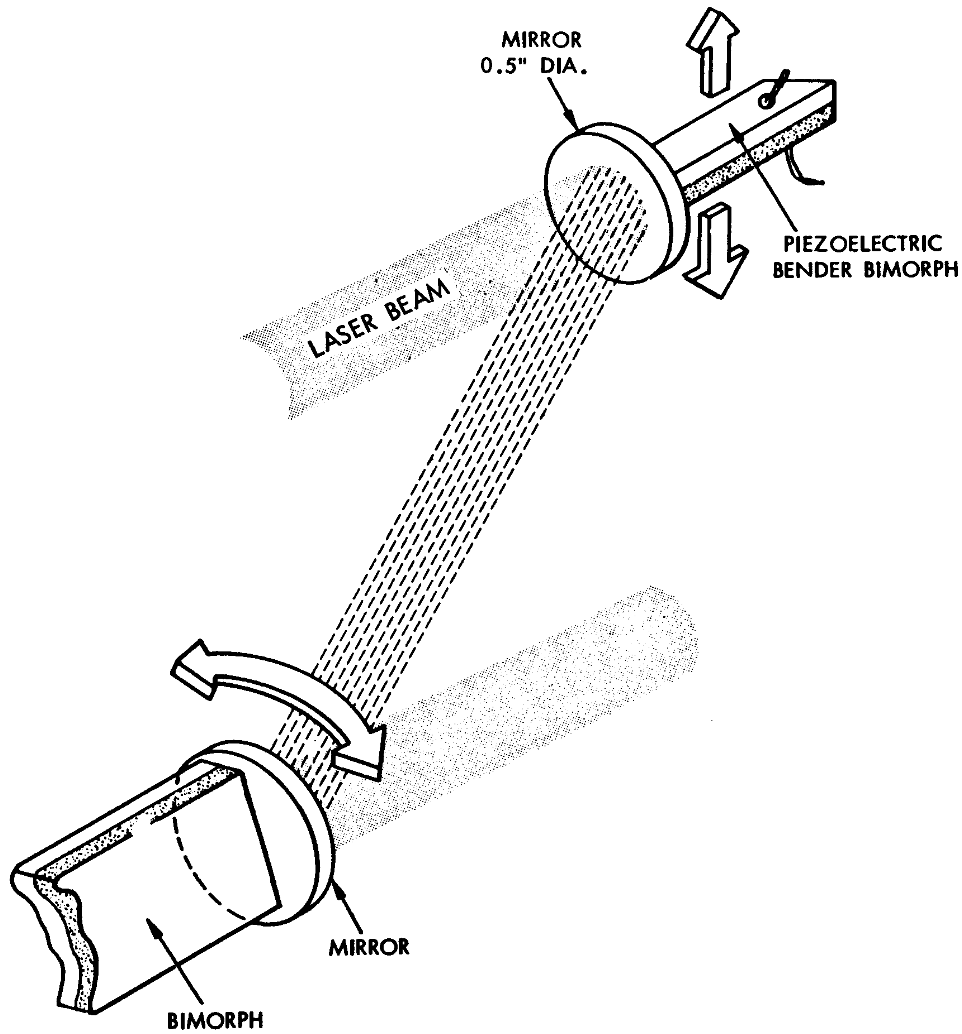

Figure 3. Image-motion compensator, simplified diagram.

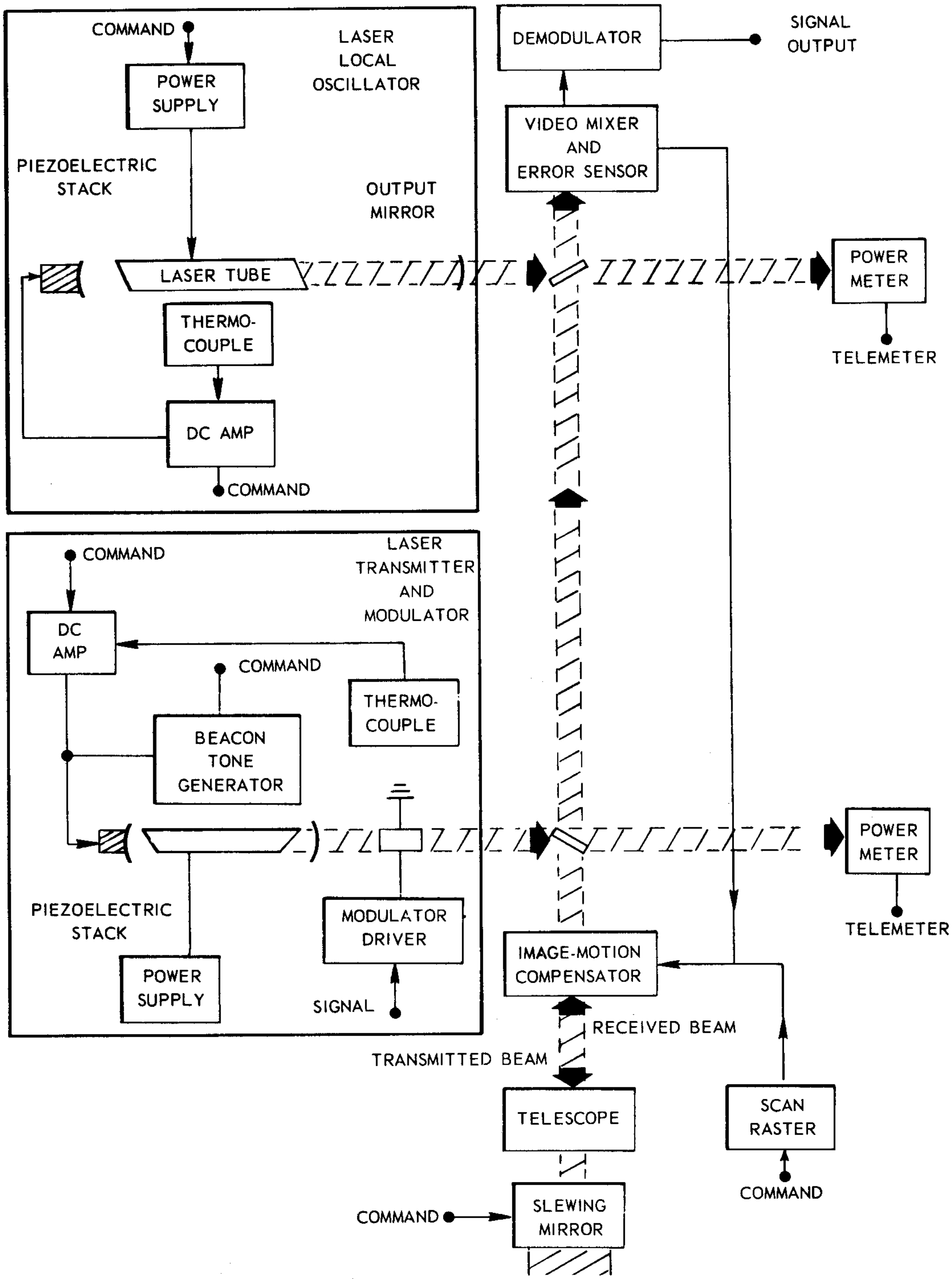

Figure 4. Laser subsystem functional diagram.