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# An opto-mechanical subsystem for space based coherent optical communication*

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## ABSTRACT

This paper provides an overview of the opto-mechanical subsystem (OMS) for the Lincoln Laboratory Laser Intersatellite Transmission Experiment. The OMS contains the telescope, relay optics, and beam steering mechanisms. The optical, mechanical and thermal aspects of the OMS design are discussed and the predicted design performance is presented.

## 1. INTRODUCTION

Space-borne coherent optical communication systems based on semiconductor lasers offer the potential for higher data rates and greatly reduced package size and weight when compared to conventional technologies.[1] However, the integration of an optical communication system onto a satellite provides a number of challenges not encountered in the microwave and millimeter wave domain.

The Laser Intersatellite Transmission Experiment (LITE), being carried out by the Massachusetts Institute of Technology Lincoln Laboratory is aimed at demonstrating the technology for high speed optical intersatellite data links. In its original conception, the LITE program had two phases. First, a transmit only package was to be integrated onto the NASA ACTS satellite to transmit to an earth-based coherent optical receiver. In the second phase, the receive segment of the package would be flown in low earth orbit, thus providing space demonstration of all aspects of the required technology. The LITE package also was to play host to a NASA full duplex direct detection experiment, the Direct Detection Laser Transceiver (DDLT) experiment. The current goal of the LITE program is to produce an engineering model of the OMS.

This paper will describe the design of the LITE optomechanical subsystem (OMS), which was to be placed on the ACTS satellite. A substantial fraction of the OMS was designed to Lincoln Laboratory specification by the Perkin Elmer Corporation.

## 2. OPTOMECHANICAL SUBSYSTEM OVERVIEW

The LITE OMS consists of the optical train, relay optics, including telescope, the acquisition and tracking optics, receivers, and servo systems, and thermal control system.

The OMS also serves as a platform for the LITE semiconductor laser transmitter module[2] which contains four redundant lasers and collimators, the LITE beam diagnostics module [3] which performs the diagnostic functions of wavelength power and modulation monitoring, and the NASA direct detection transmit and receive modules.

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The functions of the OMS may be simply described as 1) To select the desired source, 2) align the selected optical source with respect to the OMS optical train and the spacecraft, 3) perform acquisition and tracking of the target receive terminal, and 4) perform the above while maintaining high optical quality and throughput in the face of a time varying thermal and vibrational environment.

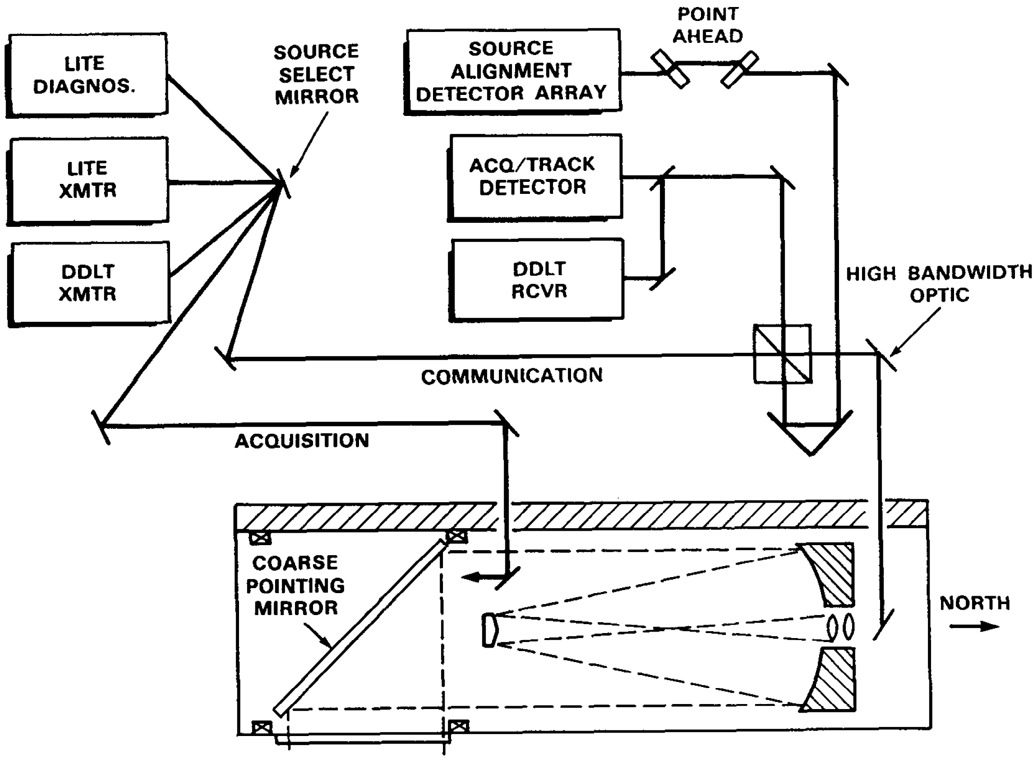


*Figure 1:* OMS Schematic

A schematic of the OMS is shown in Fig. 1. Light from the desired source is selected by the source select mirror (SSM), a two axis mirror, and directed down one of the three possible paths, the communication path, the acquisition path, or to the diagnostics module. In the communication mode, light from the SSM is relayed to the high bandwidth optic (HBO) which is a two-axis mirror with closed loop bandwidth of 1 kHz. From the HBO the light goes out through the telescope where it is expanded from a 5 millimeter diameter beam inside the OMS to the 20 cm (4 μrad far field divergence) transmit beam. From the telescope the light exits the system off a coarse pointing mirror (CPM) which provides large angle, low bandwidth, pointing to the beam. During the communication mode, a small amount of signal (2%) is leaked off of a polarization diplexer and directed to the source alignment detector array (SADA). The SADA consists of four detectors and an image splitter which monitor the position of the source, and by feeding back to the SSM, maintain source alignment. Two tilt plates are in the SADA path which can be used to provide two axes of pointing bias, for point ahead, to the transmit beam. The receiver terminal transmits a tracking beacon which is incident upon the telescope, travels to the HBO, and then, by virtue of its orthogonal polarization, is split off to the acquisition and tracking detecter (ATD). The ATD consists of four avalanche photodiodes and an image splitter. The position of the received signal is monitored and errors are fed back to the HBO. Since the transmit signal also reflects of the HBO, it is automatically directed back along the path of the received beacon (plus any point ahead angle) and the effects of platform motion are compensated for.

Because of uncertainties in the attitude of the lost spacecraft, an acquisition procedure must be undertaken prior to a communication session. Initially, the OMS can only be pointed to approximately 1 mrad. Hence, to ensure that receive terminal is illuminated, the transmit beam is broadened to 1 mrad. far field divergence. This is accomplished by switching, via the SSM, the output of the transmitter through an acquisition path which bypasses the telescope. The acquisition process will be discussed in detail later.

Also, prior to communication, the transmit wavelength, power and modulation quality are set by interaction with the diagnostics module.

A listing of some of the major OMS requirements appears in Table 1, and a more detailed schematic is shown in Figure 2.

*Table 1*

*Major OMS Requirements*

| | |
|---|---|
| Optical Throughput Loss | -3.9 dB |
| Wavefront Quality | $\lambda/15$ |
| Communication Beamwidth | 4 $\mu$rad |
| Tracking Jitter | 0.215 $\mu$rad/AXIS |
| ATD Bias Error | 0.086 $\mu$rad/AXIS |
| RMS Pointing Error | 0.1 $\mu$rad |
| Weight (including contingency) | 96 lb. |
| Power (operational with no sun) | 91 W |

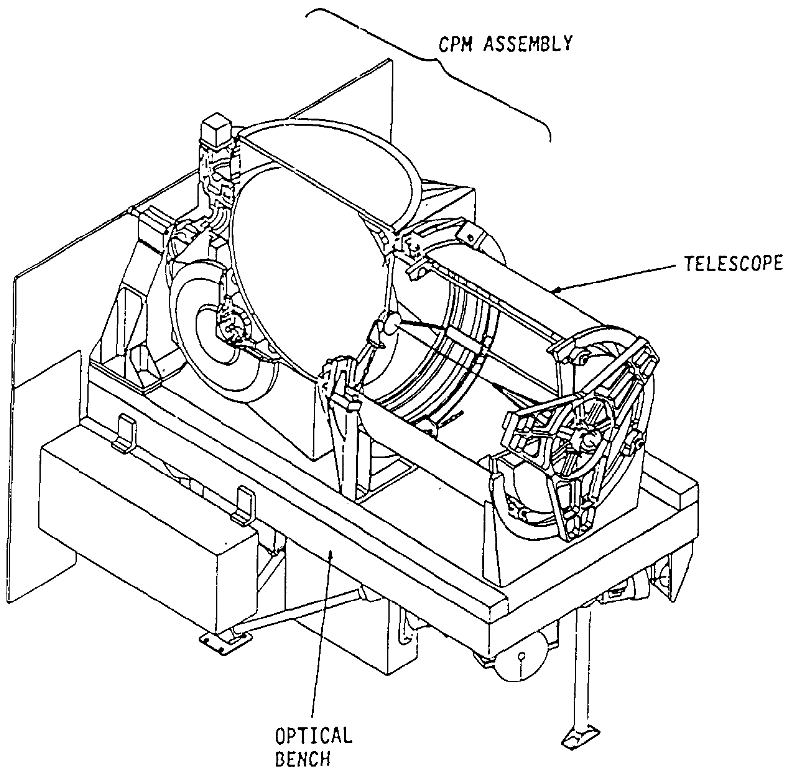


***Figure 2:*** OMS (Top View)

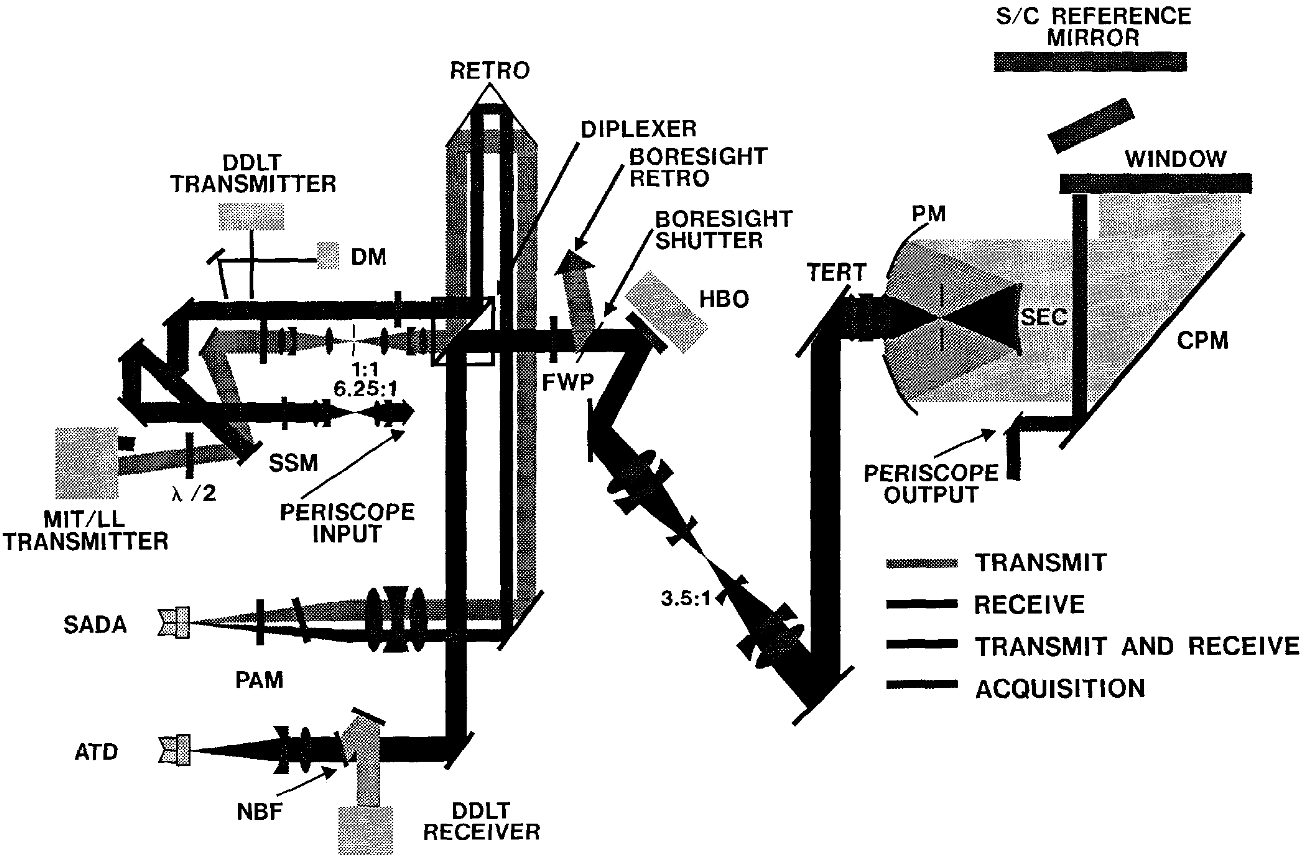


*Figure 3:* OMS Optical Prescription

## 3. OMS OPTICAL DESIGN

The optical design of the OMS is essentially straightforward and is shown in Fig. 3. The telescope is a Dall-Kirkam design with 20 cm. diameter F/1.7 primary. The obscuration of the primary mirror by the secondary is 15%. This is the optimum obscuration ratio for the truncated beam emitted from the transmit module. The system was fairly fast, which was dictated by volume constraints. The increased sensitivities associated with the fast optics impacted the choice of materials, (i.e., super-invar metering rods) and necessitated careful thermal control. Both the primary mirror and the CPM were constructed of frit-bonded ULE for low weight and low thermal sensitivity.

The exit pupil of the OMS is located at the primary mirror, the entrance pupil is at the SSM. The entrance pupil is relayed by two sets of relay optics, a 1:1 relay and a 3.5:1, relay onto the exit pupil. An intermediate pupil is at the HBO. Pupil control is important for maintaining high throughput: the direction of the output of the LITE transmitter module can change by as much as $\pm$ 1 mrad. over life (in 5mm beam space). The location of stops within the OMS is also important. The overall field of view of the system is determined by the 1.5 mrad. stop within the telescope itself. There is a 80 $\mu$rad. stop in the 1:1 relay. The 80 $\mu$rad. was chosen to accomodate up to 60 $\mu$rad. of point ahead angle plus 20 $\mu$rad. of fabrication and assembly uncertainties. It is desirable to keep this stop as small as possible to limit the amount of solar radiation incident back into the transmit module to 1 mW. during those times when the sun is directly incident upon the OMS aperture. Finally, a 20 μrad. stop is located in the ATD path. This size was chosen as a compromise between having a large field of view (for acquisition) and a narrow field of view (for background rejection) for tracking.

## 4. OMS THERMAL/MECHANICAL DESIGN

The thermal and mechanical design of the OMS was carried out in conjunction with the OMS optical design and an integrated optical/thermal/mechanical computer model was developed as part of the design process.

Although it is beyond the scope of this paper to go into the design details, some important lessons can be stated. It is of paramount importance to understand the nature of the platform to which the optical package will be mounted. The ACTS satellite presented a wide spectrum of vibrational disturbances which perturbed the line-of-sight. The effects of these disturbances on the OMS line-of-sight are shown in Fig. 4. The total system pointing budget is 0.4 μrad. (0.1 beamwidth). Although there are numerous large amplitude, low frequency disturbances, the design was driven most by the high frequency momentum wheel induced disturbances. The design of the mounting struts and optical bench was carefully tuned so as not to amplify these disturbances. The structure provided inherent isolation near 100Hz which was the largest momentum wheel contribution. In addition the structure was designed to withstand the expected launch loads.

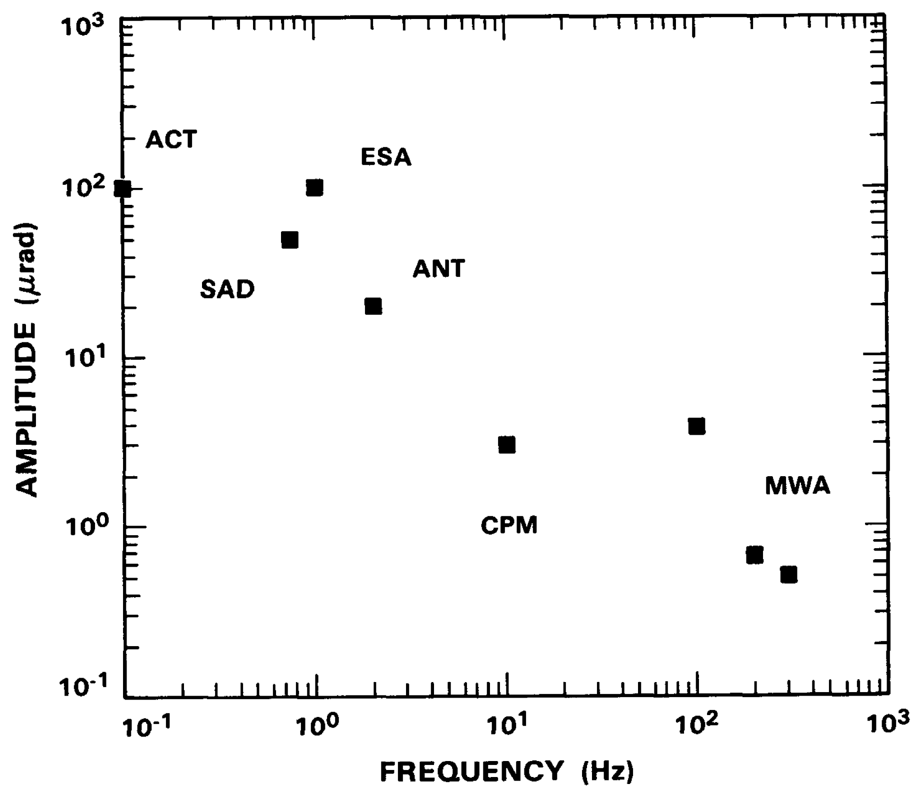


*Figure 4:* ACTS/LITE Angular Disturbance Spectrum (ACT = Attitude Control Tolerances, SAD = Solar Array Drive, ESA = Earth Sensor Assembly, ANT = Antennas, CPM = Coarse Pointing Mirror, MWA = Momentum Wheel Assembly)

Beryllium (Be) was used throughout the OMS because of its low weight and high stiffness. The optical bench is an egg crate structure of brazed Be. The lens housings and mechanisms are also predominantly Be. Be also has a relatively low thermal expansion coefficient and high thermal conductivity; both characteristics are desirable for optical applications.

The job of the OMS thermal control system is to maintain the thermal state of the OMS as constant as possible in the presence of a time-varying thermal environment (See Fig. 5). In order to maintain the wavefront quality and the pointing budget to the required levels, it was necessary to divide the OMS into 24 separate thermal zones, each with its own hybrid heater controller. Each zone was held to its set point to within approximately $\pm 1$ C. at all times. The nominal set point temperatures ranged 20 C.to 30 C. The nominal set points were determined from the worst case solar loading. During conditions of lesser solar illumination, the difference was made up by heater power. Although this approach is somewhat power inefficient (approximately 50 watts of heater power are required under no sun conditions), it was judged to be the most conservative and least risky approach to maintaining optical quality. The thermal design of the OMS was simplified somewhat by the use of a solar window which was highly (90%) transmissive in the signal band and only allowed 20% of the net solar flux into the system. The optical and mechanical design of the window were carried out carefully in order to ensure that it would not contribute excessively to wavefront distortion. The integrated optical/thermal/mechanical analysis alluded to earlier predicts that wavefront quality and pointing will be maintained to acceptable levels at all times.

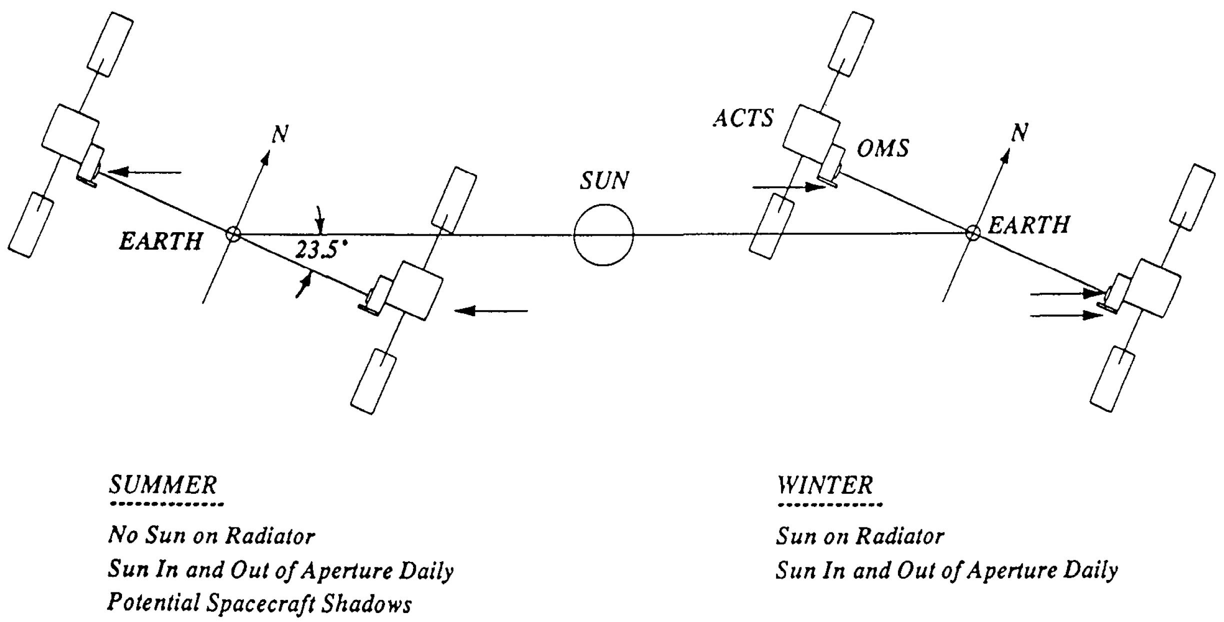


**Figure 5:** Thermal Environment of OMS

## 5. SPATIAL ACQUISITION AND TRACKING

The spatial acquisition and tracking system on the OMS is a direct detection monopulse system centered around four APDs and a 4-way image splitter. During acquisition the four APD outputs are summed, during tracking, angle error information is extracted from differences of the four outputs. The spatial acquisition sequence for an ACTS-to-LEO link is shown in Fig. 6. After stopping the ACTS solar array drives and spoiling the transmit beam to 1 mrad., the HBO begins to execute a spiral scan of the 20 $\mu$rad. field of view of the acquisition and tracking detector across the uncertainty region, searching for the slightly broadened uplink beacon. When a hit is detected, the main scan is stopped and the FOV is returned to where the hit was observed, and a small dither scan is executed until the signal is found, at which time, handover to tracking occurs. The scan may be carried out at a variety of speeds ranging from 2.5 to 160 mrad/sec, and overlaps up to 15 $\mu$rad. This allows the option of building additional acquisition margin by scanning slower and/or overcoming the effects of platform jutter which might cause gaps in the scan platform if insufficient overlap were employed.

In order to meet the system pointing budget of 0.4 $\mu$rad in face of the disturbances shown in Fig. 4 a high bandwidth spatial tracking system is required. The heart of this tracking system is a 1kHz closed loop servo system centered around the HBO. This is nested within a much slower, larger dynamic range loop centered on the CPM. As bias builds up on the HBO, it is sensed by the HBO position sensors (KAMAN sensors) and it is dumped onto the CPM. This allows the HBO to operate always near its null position.

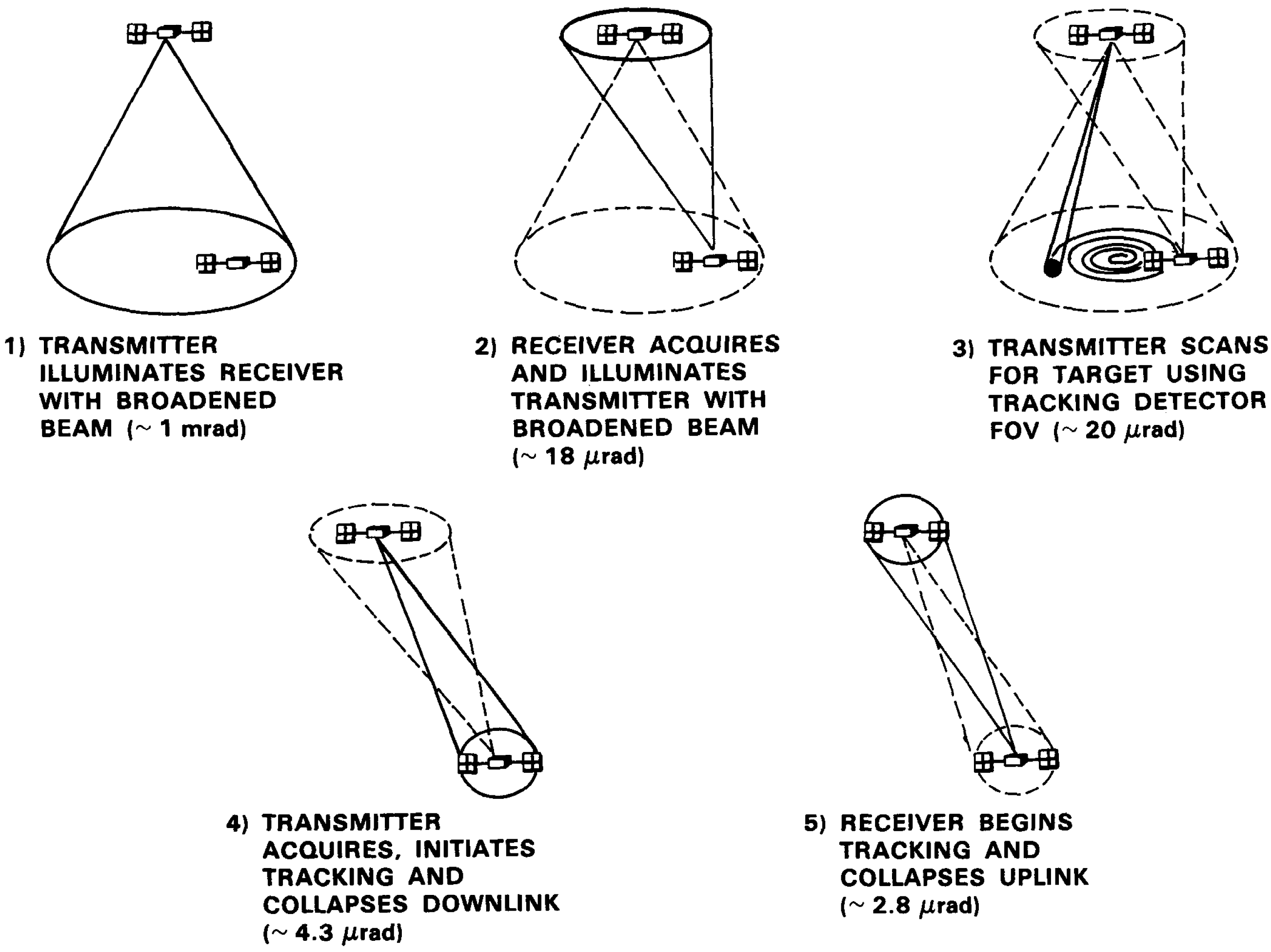


Figure 6: Acquisition Sequence

The overall angular disturbance rejection of the system is shown in Fig. 7. This system provides a factor of 100 rejection of disturbances at 100 Hz (the strongest MWA disturbance) and considerably greater rejection at lower frequencies. At frequencies greater than about 300 Hz, there is very little rejection. Nevertheless, the overall pointing budget was met with margin.

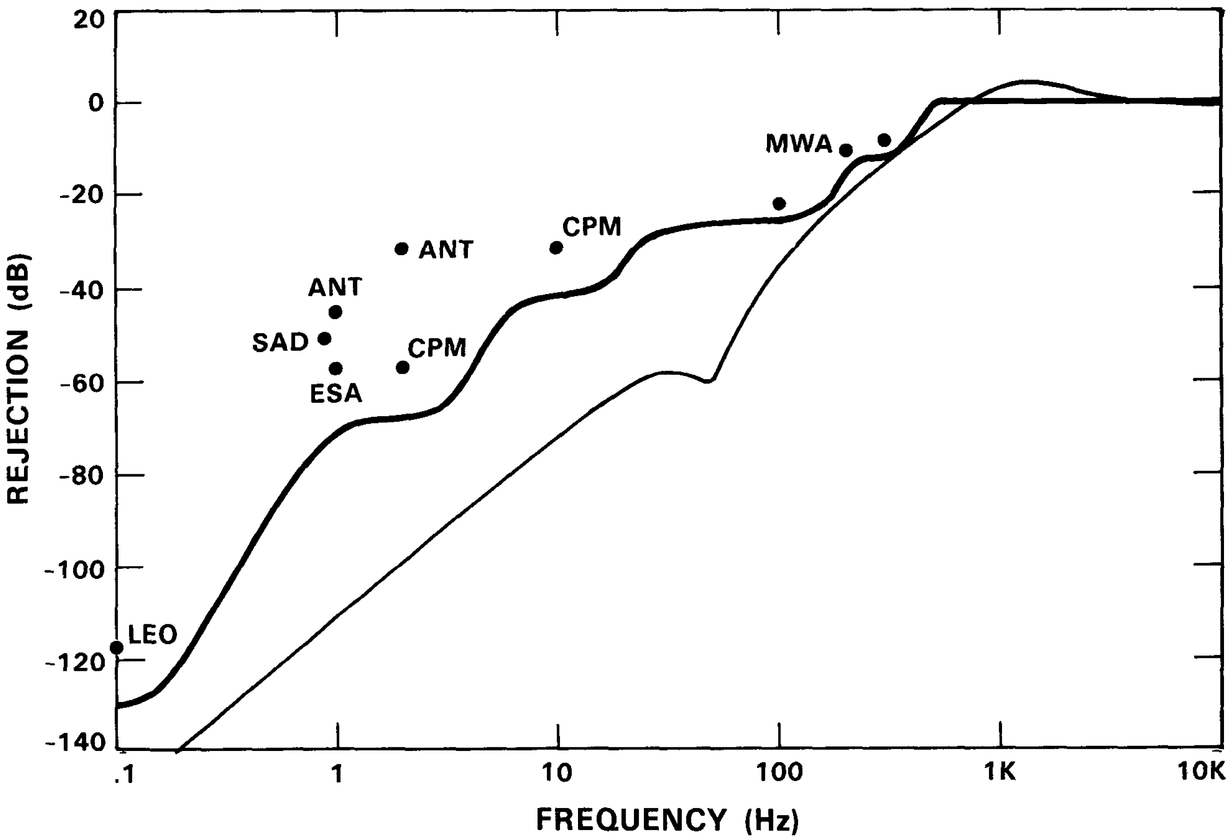


**Figure 7:** Closed Loop Tracking Rejection. Heavy curve represents minimum required rejection. Light curve is actual system rejection.

## 6. SUMMARY

This paper has attempted to give an overview of the design of the LITE opto-mechanical subsystem. The design meets all the requirements listed in Table 1. We have seen that the optical, thermal and mechanical aspects of the system are intertwined in a complex manner, and a successful design requires that they all be accounted for correctly.

## 7. REFERENCES


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