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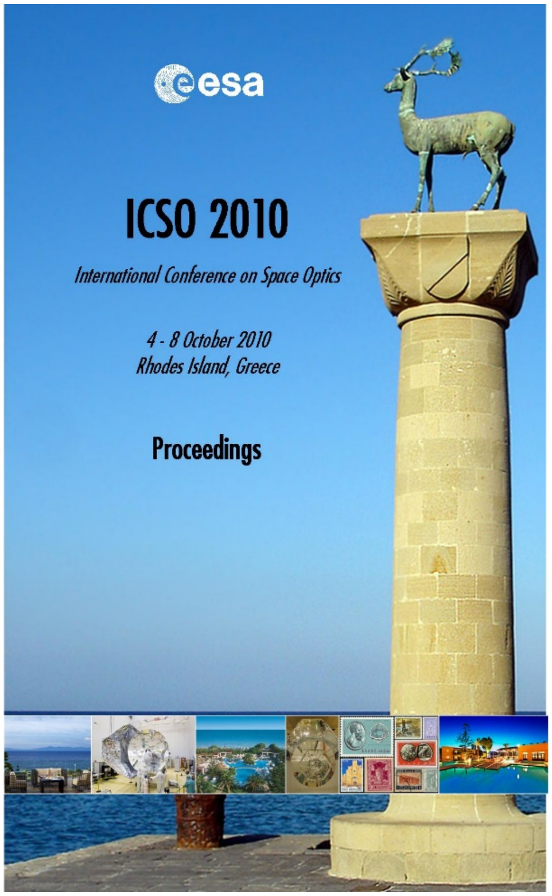

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LOTIS FACILITY SUCCESSFULLY REACHES INITIAL OPERATIONAL CAPABILITY

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I. INTRODUCTION

The Large Optical Test and Integration Site (LOTIS) Facility at Lockheed Martin Space Systems Company in Sunnyvale, CA has been design specifically to accommodate assembly, integration, and testing of optical payloads from as small as 1 meter class apertures to as large as 6 meters. The facility has successfully reached initial operational capability and a basic overview of the LOTIS Facility has been previously reported including wavefront performance [1], its potential for optical payload testing has been previously reported [2]. The facility has been engineered from the foundation up to provide an ideal single location for optical payloads including details such as crane access, clean room space and levels, vibration levels, and atmospheric turbulence levels within the facility especially the interior of the vacuum chamber containing the 6.5 meter collimator. This paper will present and overview of the facility in general and then present results of the vibration isolation bench performance and resulting line of sight jitter of the collimator, as well as atmospheric turbulence measurements within the chamber

II. LOTIS FACILITY OVERVIEW

The overall LOTIS Facility is depicted in Fig.1 and Fig.2. The Receiving and Integration and Test Areas can easily accommodate equipment up to 9 m wide and weighing in excess of 45 metric tons. The configuration of the area-to-area pathways in this facility allows for equipment movement into other areas on air pallets according to processing requirements. A 27 metric ton bridge crane is available for loading and unloading operations in the Receiving Area. From the Receiving area equipment can be cleaned and prepared prior to transfer into the High Bay that measures 660 m^2 and is a class 10,000 clean room. The High Bay incorporates a 32 metric ton bridge crane with a 15 m hook height and an isolated central pad that partially decouples that area from the surrounding building structures for increased stability during integration and test. Adjacent to the High Bay is a 440 m^2 horizontal-flow Low Bay that is a class 10,000 clean room and includes a 4.5 metric ton bridge crane. The overall design of low bay lends itself to component level preparation, assembly, and test.

Fig.1. External View of LOTIS Facility Entrance at Lockheed Martin Sunnyvale, CA

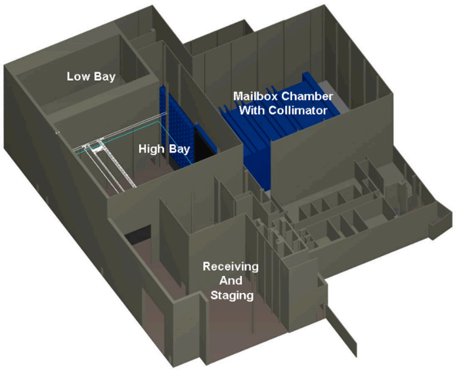


Fig.2. Internal Layout of LOTIS Facility

The LOTIS Vacuum Chamber (LVC) is rectangular with a usable volume of approximately 11 m wide x 25 m long x 11 m high. Figure 3 shows the chamber open and the collimator. The chamber door allows at-grade access from the High Bay into the LVC onto its VIB. The specific design of this chamber enables optical measurements and tests in air or vacuum under highly controlled thermal conditions for accuracy and stability. At atmospheric pressure, the LVC is a class 10,000 clean room fed by a separate air plenum When vacuum operations are required, a combination of roughing, turbomolecular, and cryo pumps can take the chamber to 5 x 10^{-6} Torr in as little as 8 hours. Thermal stability of the chamber, both at atmospheric pressure and vacuum, is maintained at a set temperature within a range of 15º - 25º C to within ± 0.5 Cº at any location within the LVC by recirculating water shrouds that cover the four walls and the roof of the chamber. A 4.5 metric ton bridge crane normally parked in the High Bay adjacent to the door of the LVC and can be moved inside the chamber for equipment positioning and Collimator maintenance. Although this crane is not operable under vacuum, it offers user flexibility for reconfiguration activities within the LVC test environment.

A recessed pit runs the length of the LVC and holds the LOTIS Vibration Isolation System main components. There are three major components in this system, The Vibration Isolation Bench (VIB), an array of active and passive pneumatic actuators beneath the VIB, and a closed-loop control system for the actuators and VIB to actively control pitch, roll, and elevation. The VIB, visible as the floor of the LVC in Fig. 3, is constructed from polished stainless steel and measures 1.1 m thick and 9.1 m wide x 25 m long with a weight of 230 metric tons. It provides a highly stable optical testing platform that can support approximately 110 metric tons of additional equipment.

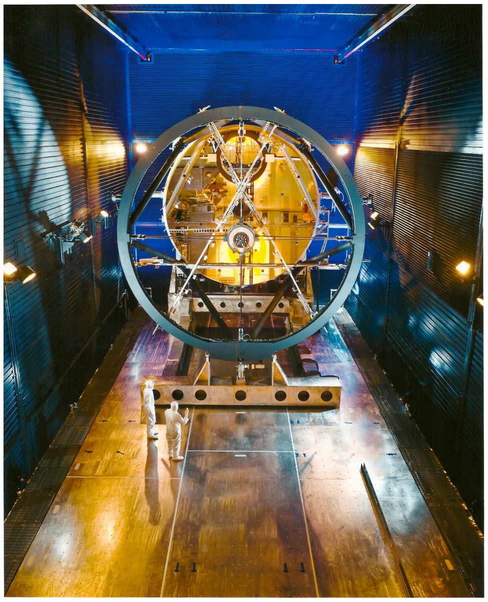


Fig.3. Collimator in LOTIS Vacuum Chamber Atop Vibration Isolation Bench

The heart of the unique optical testing equipment in the LOTIS Facility is a 6.5 meter diameter aperture collimator. This unit was designed and constructed as a joint effort of Lockheed Martin Space Systems Company and the Steward Observatory of the University of Arizona. It is a highly corrected horizon-pointing Ritchey-Chrétien telescope that is operable in either air or vacuum without external alignment references. In astronomical telescope installations star are used as alignment references, but several special subsystems attached to the LOTIS Collimator System to allow a high degree of correction autonomously without such external references. The Flat Mirror Positioner or (FMP) can move into position a 1.8 m test flat in front of the collimator to verify this alignment using a Fizeau interferometer. This method of alignment has been published previously [3]. The overall telescope design offers a nominal field of view of 1.5 milliradians at f/15 over a typical wavelength range of 0.4 to over 5 micrometers.

III. ATMOPSHERIC TURBULENCE LEVELS

Though the LOTIS Collimator is housed in one of the world's largest high-vacuum chambers it is desirable to conduct optical testing in air as well. The test environment within the chamber is controlled with a thermal shroud to produce nearly isothermal conditions for both in-air and vacuum testing. Low turbulence and low vibration levels provide an opportunity to conduct precision optical tests over 6.5 meter apertures while at standard pressure at 10,000 K clean room levels with easy access to optical payloads.

The summary of turbulence measurements that is presented here represents single-pass RMS wave front error (RMS WFE) over a smaller 18-inch aperture size and 50-foot propagation distance. Also, approximations to the atmospheric coherence length, r_o , are reported as calculated from the data. Detailed analysis has been previously reported [4].

The chamber was emptied of all hardware and optical testing systems to isolate the effects of only the chamber itself. The clean air system and thermal shrouds were set to 65.0°F (18.3°C) and the chamber operated at ambient pressure of 760.8-torr. The chamber environment was allowed to stabilize for 20-hours before testing began.

A Fizeau interferometer with a circular 18-in (0.46-m) aperture was located horizon pointing along the centerline of the chamber near the position where the Collimator primary mirror would reside. A similarly sized return flat was located at a distance of 50-ft (15.25-m) at the opposing end of the chamber. The interferometer and return flat were elevated to 6-ft (1.8-m) above the floor level where turbulence effects are assumed to be most persistent. The collimated test beam (632.8-nm wavelength) sampled a 50-ft (15.25-m) column of air between the interferometer and return flat in double pass and the turbulence deformations in the wavefront phase. Tilt was intentionally added to the return flat to produce 10 interference fringes on average in a measured interferogram. One non-phase shifting interferogram frame was recorded per data acquisition yielding an integration time of 0.02-sec. Data acquisition was repeated at non-uniform time intervals typically every 25 seconds. Measurements four CAS airflow rates were taken. For each chamber air flow rate, a typical set of measurements set consisted of 65 data acquisitions over a 40 minute period.

The data was used in two ways to access the turbulence level and its impact on optical test planning. First the rms wavefront error of the 18inch aperture is estimated at each CAS setting by assuming the turbulence is normally distributed about the instrument error. This allows the instrument error to be estimated and the rms turbulence characterized. Second the value of r_o is estimated. This method described by Noll [5], assumes Kolmogoroff turbulence which is unlikely within a sealed chamber, it none the less provides a familiar rule of thumb value familiar to many in optical testing but cannot be strictly applied without first considering the assumption. The data is summarized in Table 1.

Table 1. Measured data and calculated estimates of turbulence measurements.

	Measured Total WFE	Turbulence Estimate	Turbulence-Limited Aperture Size
Air System Flow [kcfm]	Average RMS WFE [waves @550nm]	RMS WFE Standard Deviation [waves @550nm]	Atmospheric Coherence Length, r_o @550nm [cm]
35	0.0378	0.0073	76.7
21	0.0346	0.0072	85.4
16	0.0349	0.0069	84.6
0	0.0328	0.0056	91.1

Over the range of air system flow rates measured, the nominal result of Measured Total WFE remained relatively consistent at about 0.035 waves with a Turbulence Estimate of a factor of five lower at 0.007 waves. The results of the calculations of r_o indicate that the lower bound of the turbulence-limited aperture size is about 1-meter. During the next phases of operational tests we look forward to use of the 1.8 m test flat positioned at a variety of locations in the 6.5 m full aperture, to characterize turbulence with the collimator in operation.

IV. ANALYSIS OF THE COLLIMATOR LINE OF SIGHT JITTER

The VIB is a polished stainless steel structure weighing 505,000 lbs and measures 30 feet wide by 82 feet long by 45 inches thick. The VIB is supported from below on a set of 38 airbag vibration isolators. The LOTIS Facility has been designed from the foundation up to eliminate or mitigate vibration disturbances into the vacuum chamber and chamber foundation that support the VIB. This is achieved by designing the building foundation to be physically separated from the vacuum chamber foundation. Structural building elements, building and chamber mechanical systems, process piping, and electrical systems were also kept physically separated or mechanically uncoupled from the vacuum chamber foundation. The VIB provides the vibration isolation for the remaining vibration disturbances from seismic activity, road traffic, and any remaining building mechanical vibrations (such as vacuum pumps), as well as personnel activity within the facility. In addition to passive vibration isolation, the VIB has active alignment control of bench height, pitch, roll, and yaw.

NASTRAN finite element (FE) models of the LOTIS Collimator, VIB, and FMP were assembled into a single FE model. A lumped mass of 80,000 lbs was added to simulate the mass-loading representative of the maximum expected mass of a generic payload or "unit under test" (UUT). The mass was located above the nominal mounting location on the VIB at the optical boresight elevation. No attempt was made to simulate any dynamic characteristics of a UUT.

Thirty-eight airbag isolators support the one-half-million pound bench with a suspension frequency of 0.72 to 1.40 Hz when loaded. The FE model of the VIB is composed of approximately 50,000 nodes and 50,000 thin shell elements. The LOTIS Collimator was modeled with 9000 nodes and 12,000 elements to provide sufficient fidelity to capture the dynamic characteristics of the metering truss, penta-prism assemblies, and primary and secondary mirror assemblies. An additional 10,000 nodes and 10,000 elements were used in modeling the Collimator Support Structure that is used to mount the Collimator to the VIB. An additional 4400 nodes and 3400 elements were used to model the FMP. The total assembled model contained 71,000 nodes and 78,000 elements representing a structure weighing over 725,000 lbs., Fig.4.

The first six computed modes of the combined LOTIS system FE model were predominately rigid bench 'isolation' modes ranging from 0.72 Hz to 1.40 Hz. Modes 1 through 6 also exhibited some elastic motion between optical elements, while modes 7 through 12 of the combined FE model were LOTIS Collimator elastic modes. The first two of these elastic modes can be characterized as the primary mirror rotating about the "Y" axis, in a back and forth "no" motion, at a frequency of 3.39 Hz (mode 7) followed by an up and down "yes" mode of the primary mirror at 3.75 Hz (mode 8). Two modes that exhibit significant effective modal mass (modes 11 and 15) are shown in Fig.5. The mode described as, "First Bending Pitch Mode at 4.91 Hz" (mode 11) is also a primary contributor to the total Line of Sight (LOS) jitter response.

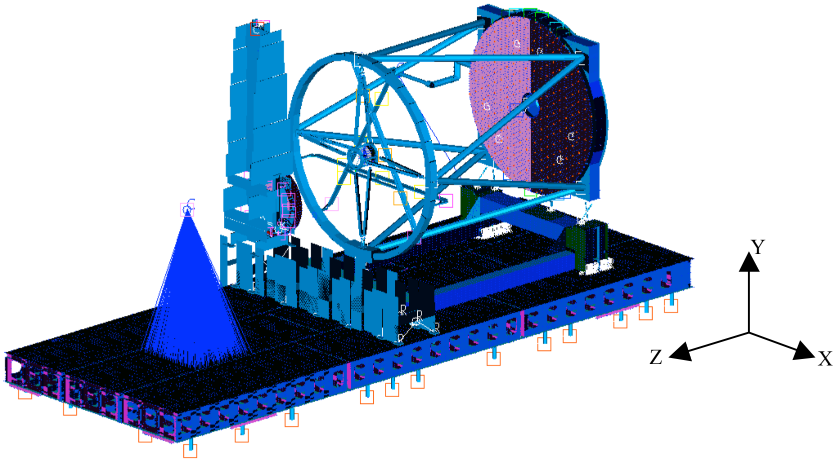
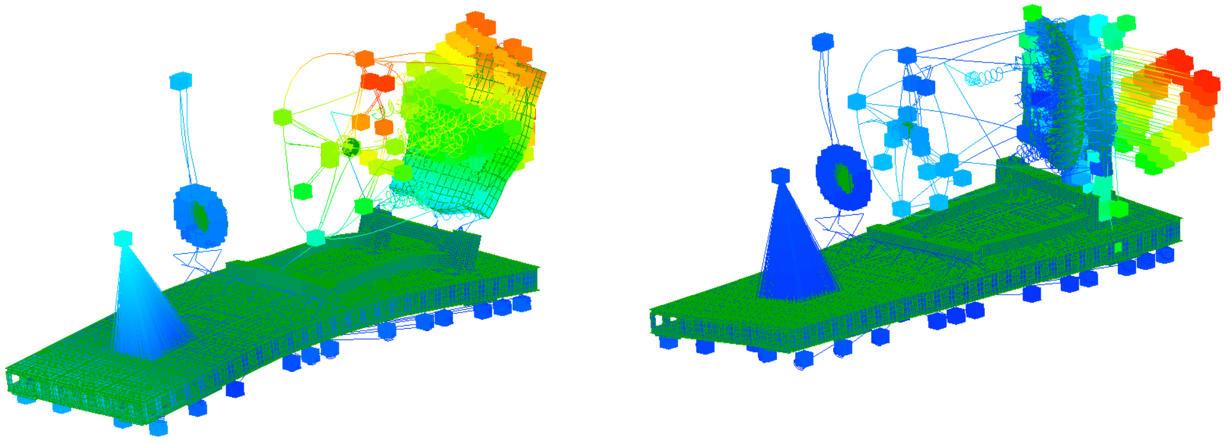


Fig.4. Combined LOTIS System (Collimator-FMP-UUT-VIB) Finite Element Model



First Bending Pitch Mode at 4.91 Hz
(Mode 11)

First Torsion and LOTIS Yaw at 6.51 Hz
(Mode 15)

Fig.5. Two LOTIS assembly bending modes that exhibit significant effective modal mass

Following the FE modal analyses, tri-axial seismic accelerometers were placed at four locations on the LOTIS facility foundation and VIB isolator support locations to measure ground vibrations induced by natural and man-made sources. The vibration survey measurements were performed over a period of two days with different combinations of equipment running. Of particular note, three of the six chamber 52-inch diameter cryopumps were in operation during one day of the measurement survey and their effects are included in the overall results. Power Spectral Density (PSD) functions were computed from the ground acceleration measurements. These data appeared to be relatively uniform at each of the locations, and since there was little justification to identify any particular location as a better characterization over another, the maximum excitation was enveloped for all measurement locations, in each direction. The spectral content of the enveloped PSD data was then filtered with a 10 Hz running average window to smooth out excessive peaks and valleys. The smoothed PSD ensures that minor frequency shifts in the FE model does not result in dramatic changes in the overall response.

The Collimator system FE model fixed base normal modes were computed in NX NASTRAN version 4.1 and a Lockheed proprietary solver was used to perform the random base shake analysis. NASTRAN multi-point constraint (MPC) equations were used to create the LOS modal response degrees-of-freedom in the Θ_x and Θ_y directions. This ensured proper phasing of the optical elements for a random analysis. Six modal truncation vectors were computed to augment the eight hundred ten normal modes spanning the frequency range of zero to 125.0 Hz. Modal damping of 0.5% was assumed for all modes except the first six, which used measured test data. The isolator modes had damping values ranging from 1.13% to 3.1%.

A reduction factor was applied to the resultant RMS responses to account for the effect of low frequency modes below 5.74 Hz when assuming the test duration of 100 ms. This reduction factor essentially limits the contribution of low frequency motion to that which would be experienced within the test window duration.

In summary the rms line of site jitter analysis indicates a value of less than 3 nrad. Table 2 lists the Total RMS jitter response and Table 3 identifies the dominant modes with each corresponding jitter contribution. Note that 2.82 nrad jitter represents 95% of the jitter and is attributable to the six identified modes (1, 2, 6, 7, 8, and 11), and 67% of the contribution is specifically attributable to the first mode. The LOS jitter analysis results indicate that the LOTIS Facility and system design exceed the requirements necessary for high accuracy large optical testing.

Table 2; RMS Jitter by Direction

Input Direction	RMS Q_X (nanoradian)	RMS Q_Y (nrad) (nanoradian)	Total RMS Jitter (nanoradian)
X	0.05	2.62	
Y	1.02	0.52	
Z	0.67	0.36	
RSS	1.22	2.70	**2.96**

Table 3; RMS Jitter Contribution by Mode

Input Direction	Mode No. (Q_X)	S (Q_X) (nanoradian)	Mode No. (Q_Y)	S (RMS Q_Y) (nanoradian)	Total RMS Contribution
X	-	-	1(2.0), 6(0.6)	2.6	
Y	11(0.6), 8(0.3)	0.9	7(0.3)	0.3	
Z	2(0.35), 11(0.2)	0.55	-	-	
	RMS Q_X =	1.05	RMS Q_Y =	2.62	2.82

(-) Designates responses with no dominant contributor.

V. CONCLUSION

The LOTIS facility has reached initial operational capability now that the facility is complete and the collimator installed, aligned, and operational in air. The next phase of full operational capability will be accomplished after the collimator is brought to vacuum levels and aligned and operated. Line of sight jitter of the collimator has been calculated at less then 3 nrad based on measured inputs and a full FE model. Measurements of turbulence within the chamber indicate that there is an excellent opportunity to plan precision optical testing despite being at atmospheric pressure and reserving vacuum testing for final test phases of a payload.

VI. REFERENCES

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