IN-FLIGHT THERMAL PERFORMANCE OF THE LIDAR IN-SPACE TECHNOLOGY EXPERIMENT

William A. Roettker*
NASA Langley Research Center
Hampton VA 23681-0001

Abstract

The Lidar In-Space Technology Experiment (LITE) was developed at NASA's Langley Research Center to explore the applications of lidar operated from an orbital platform. As a technology demonstration experiment, LITE was developed to gain experience designing and building future operational orbiting lidar systems. Since LITE was the first lidar system to be flown in space, an important objective was to validate instrument design principles in such areas as thermal control, laser performance, instrument alignment and control, and autonomous operations. Thermal and structural analysis models of the instrument were developed during the design process to predict the behavior of the instrument during its mission. In order to validate those mathematical models, extensive engineering data was recorded during all phases of LITE's mission. This in-flight engineering data was compared with preflight predictions and, when required, adjustments to the thermal and structural models were made to more accurately match the instrument's actual behavior. The results of this process for the thermal analysis and design of LITE are presented in this paper.

Introduction

The Lidar In-Space Technology Experiment (LITE) was the primary payload flown on STS-64 in September 1994. During its 10-day mission, LITE collected over 53 hours of science data that will be used to study the vertical structure of clouds in the atmosphere, determine temperature and pressure profiles, measure the presence of atmospheric aerosols, and improve climate modeling algorithms. In addition to the science data, technology data was obtained to characterize the environment in which LITE operated. Over two hundred temperature, pressure, thermal flux, strain, and acceleration sensors were monitored and recorded during the entire mission: from nine minutes before launch, through ascent to orbit, during ten days of on-orbit operations, and during entry and landing.

Instrument Description

The LITE payload, shown in Figure 1, consists of the following major components: Laser Transmitter Module (LTM), Receiver System, Cold Plate Electronics (CPE), Boresight Assembly (BA), Camera System, Power Distribution Box (PDB), OASIS-1, Active Thermal Control System (ATCS), the Orthogrid Platform, and the Enhanced Multiplexer/Demultiplexer Pallet (EMP).

The LTM contains two solid state lasers and their associated optics and electronics. The total output energy is 1200 mJ per pulse, and the pulse rate is 10 Hz. The LTM is enclosed in an aluminum canister that is pressurized to 110.3 kPa (16 psia) with dry nitrogen. The canister is 1.52 meters long and 0.61 meters in diameter. The LTM weighs approximately 250 kg.

The Receiver System consists of the telescope, aft optics assembly (AOA), aft optics housing (AOH), and telescope support structure (TSS). The telescope was originally built as the flight prototype for the Orbital Astronomical Observatory in the late 1960s and was obtained from NASA Goddard Space Flight Center. The telescope is 1.1 meters in diameter, 1.3 meters long, and has a one-meter-diameter

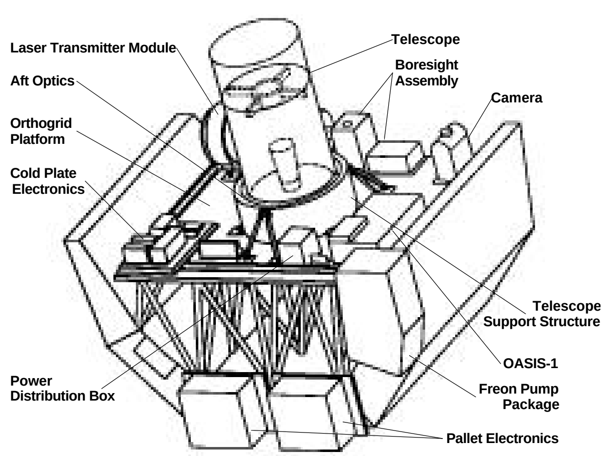

Figure 1. LITE Instrument Overview

* Aerospace Engineer, AIAA Member

beryllium primary mirror. The AOA consists of the optics bench, variable field stop (VFS) mechanism, three movable filter systems (MFS), three science channel detectors, one alignment detector, optical components (lenses, mirrors, beam splitters, color filters) and mounts, and associated electronics. The TSS attaches the telescope and AOA to the orthogrid platform. It allows radial expansion and contraction of the receiver due to temperature changes without inducing large stresses and also uniformly distributes lift-off and landing loads.

The CPE is a collection of electronic components mounted on and cooled by a cold plate. The cold plate is approximately 104 cm long and 72.4 cm wide. The electronic components include the Instrument Controller (IC), Digital Data Handling Unit (DDHU), Ku-band Signal Processor Assembly (KuSP), and Engineering Data System (EDS). The IC controls LITE instrument functions and timing. It provides a command link to and data link from the LITE instrument and functions as a master control unit. The DDHU receives signals from the science detectors in the LITE instrument and conditions those signals into usable data. The KuSP receives data from the DDHU and packages it for transmission through the orbiter Ku-band transmitter. The EDS monitors the many sensors on the instrument which provide engineering data on the status of the instrument.

The BA is a closed-loop control system that turns an incoming laser pulse from the LTM 90 degrees and maintains the laser pulse's collinearity with the LITE Receiver System. The Camera System provides visual identification of the scene that the LITE instrument views during daytime data taking operations. The PDB distributes incoming orbiter power to the various LITE subsystems.

The Orbiter Autonomous Supporting Instrumentation System (OASIS-1) measures and internally records pertinent environmental data during ascent, on-orbit, and descent. During ascent and descent, OASIS measures acceleration, acoustics, strain, temperature, pressure, and thermal flux. On orbit, it measures temperature and pressure.

LITE's ATCS is integrated into the EMP ATCS and provides Freon-114 cooling to the LTM and CPE. A schematic diagram of the ATCS is shown in Figure 2. The Freon is supplied by the EMP at a mass flow rate of 1211 kilograms per hour (± 10%) and at a temperature of 8°C ± 7°C.

The orthogrid platform is a support structure to which components of the LITE instrument are mounted. The orthogrid platform consists of four orthogrid panels, 52 struts, and hardpoint fittings. The Enhanced Multiplexer/Demultiplexer Pallet (EMP) is the unpressurized payload carrier for the LITE instrument. The EMP provides the mechanical, electrical, thermal, command, and data interfaces from the LITE instrument to the orbiter.

More detailed descriptions of the hardware can be found in the Johnson Space Center (JSC) document *STS-64 Cargo Systems Manual: LITE* (JSC-26143).

Thermal Requirements

LITE's thermal requirements are defined to ensure successful operation of the LITE instrument during its mission. LITE must be able to withstand the space shuttle ascent and entry environments and operate in a low Earth orbit environment.

Temperature constraints for LITE subsystems are listed in Table 1. Subsystems must remain within the operating temperature limits whenever that subsystem is powered, and must always remain within the non-operational temperature limits listed in the

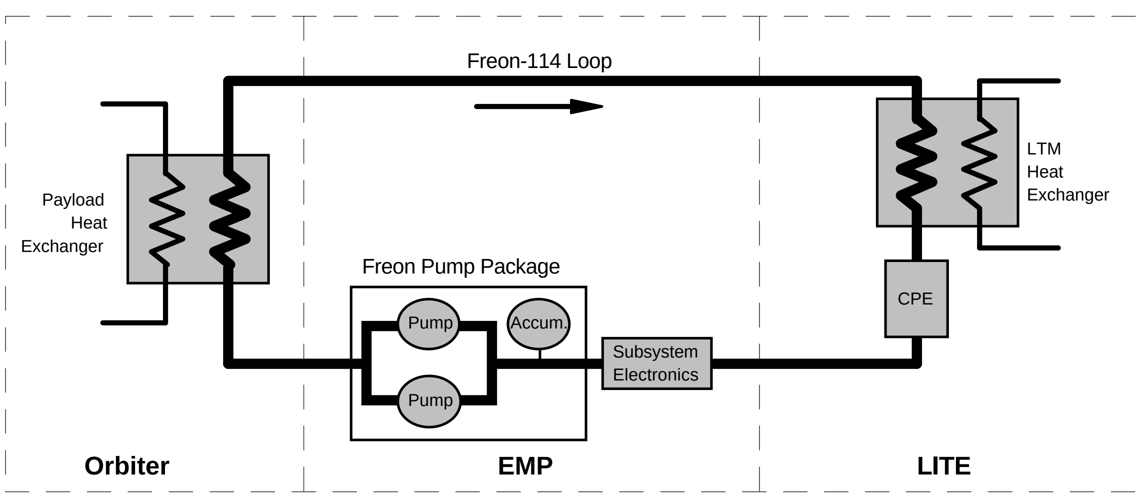

Figure 2. LITE Active Thermal Control System

table. These temperature limits apply to all phases of the LITE mission.

Component	Operational Limits (°C)		Non-operational Limits (°C)	
	Min.	Max.	Min.	Max.
LTM	0	60	0	60
Receiver System	8	40	-28	50
Cold Plate Elect.	-40	85	-55	125
Boresight Assy.	-9	65	-40	90
Camera System	4	45	-55	125
Power Distr. Box	-35	85	-55	125
OASIS	2	55	-	-

Table 1. LITE Temperature Limits

LITE uses both active and passive thermal control techniques to dissipate heat generated by the instrument. The ATCS provides active cooling to the LTM and CPE. All other LITE subsystems rely on passive means (conduction and radiation heat transfer) to dissipate their heat loads. Power dissipation of all subsystems in each of LITE's operating modes is summarized in Table 2. Note that this table does not include EMP subsystems or the High Data Rate Recorder; these components were not included in the LITE instrument thermal analyses.

Component	Heat Dissipation (watts)	
	Standby	Data Take
LTM	186	1869
Receiver System	81.9	86.7
Cold Plate Elect.	205.3	205.3
Boresight Assy.	27.9	77.1
Camera System	18	18
Power Distr. Box	37.7	37.7
OASIS (standby)	32	32
TOTAL	**588.8**	**2325.8**

Table 2. LITE Power Dissipation

The LTM and Receiver System have specific thermal requirements applicable only to those subsystems. The LTM should transfer less than five watts conductively through its kinematic mounts. This helps reduce thermal distortions of the orthogrid platform. The temperature of the harmonic generator ovens within the LTM must be kept within 0.1°C of their operating temperature to prevent fluctuations in the output energies of the lasers. The LTM must thermally stabilize within two hours of its initialization. Alignment of the laser components within the LTM must be maintained over a wide range of external temperatures.

The Receiver System is required to maintain alignment throughout operational thermal environments. The allowable despace between the telescope's primary and secondary mirrors is 0.05 cm (0.02 inches) from the aligned position. Optical mounts within the AOA are designed to withstand temperatures as low as -27.8°C without affecting their optical elements.

Thermal Design Characteristics

The LITE ATCS is integrated with the EMP ATCS and provides Freon-114 cooling for the LTM and CPE. The temperature of the Freon delivered to the LITE instrument will be 8 ± 7°C, and the mass flow rate will be 1211 ± 121 kilograms per hour.

All other LITE subsystems rely on passive thermal control techniques to regulate their temperature. Multi-layer insulation (MLI) with an outer layer of beta cloth is used on the exterior of the LTM, Receiver System, CPE, BA, Camera System, and OASIS to limit the amount of heat gained from or lost to the environment. All components mounted on the orthogrid platform, with the exception of the Receiver System, use a thermal isolation system to limit the amount of heat transferred between the components and the orthogrid platform. Placed on top of the orthogrid platform is a cover that acts as a light block, preventing solar radiation from passing through the cutouts in the orthogrid platform and striking the struts and pallet structure below. The bottom surface of the orthogrid platform and the 52 orthogrid struts are iridited.

LITE components not covered with MLI are painted white to maximize heat transfer away from those components. The TSS and AOH essentially act as radiators for the AOA. The PDB housing is also painted white.

The interior surfaces of the telescope, AOH, and AOA are painted black to minimize light reflections within the Receiver System. This has the added benefit of enhancing radiation heat transfer across the interior of the telescope, reducing temperature gradients and decreasing thermal deformations in the telescope tube.

In order to protect the LITE instrument during cold attitudes, critical components have survival heaters incorporated in their design. The AOA has an 80 watt heater bonded to the back of the optical bench that turns on at 4°C and turns off at 21°C. This heater will prevent the AOA's optical mounts from reaching their cold design temperature limit of -28°C. The BA has two survival heaters: a 15-watt heater located on the upper gimbal assembly, and a 30-watt heater located on the lower gimbal assembly. These heaters will keep the encoders located within the BA above their minimum non-operating temperature. The BA heaters turn on at -10°C and turn off at 0°C. The Camera System survival heater is a 50-watt heater that turns on at 4°C and turns off at 21°C.

OASIS has its own internal thermal control system. If the temperature of the tape recorder within OASIS drops to 1.7°C, OASIS turns itself on to generate enough heat to warm itself above that temperature.

Thermal Models

TRASYS model

A 397-surface TRASYS model of the LITE instrument, EMP carrier, and orbiter payload bay was developed to calculate radiation conductors and absorbed heating fluxes used in the LITE instrument thermal math model. For components such as the LTM and CPE mounted on the orthogrid platform, only the exterior surfaces of thermal blankets were included in the instrument-level TRASYS model. Individual TRASYS models of subsystems were developed when needed to determine radiation conductors among components underneath the thermal blankets.

The TRASYS model of the LITE instrument is shown in Figure 3; the instrument in the orbiter payload bay is shown in Figure 4.

In order to calculate the absorbed heat fluxes on the LITE instrument, TRASYS needs information about the thermal environment and orbit parameters in which LITE will operate. Table 3 lists the environment and orbital parameters used to describe the nominal, hot, and cold cases in the TRASYS model. The nominal case uses LITE's preferred orbit altitude of 259 km (140 nm) and historical average values of the solar flux and Earth infrared emitted flux. A low altitude of 194 km (105 nm) and high solar and Earth flux values were used for the hot case. The cold case assumed a high altitude (296 km or 160 nm) and historically low solar and Earth fluxes.

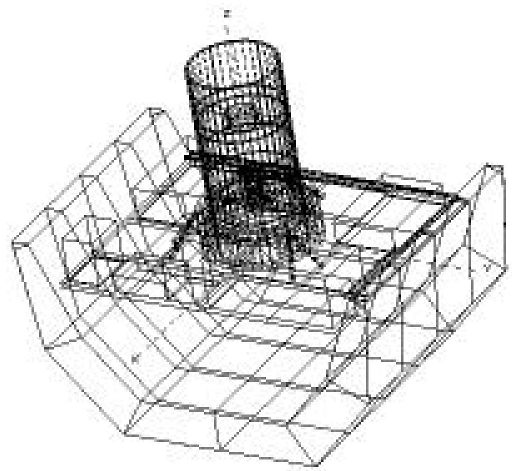

Figure 3. LITE Instrument TRASYS Model.

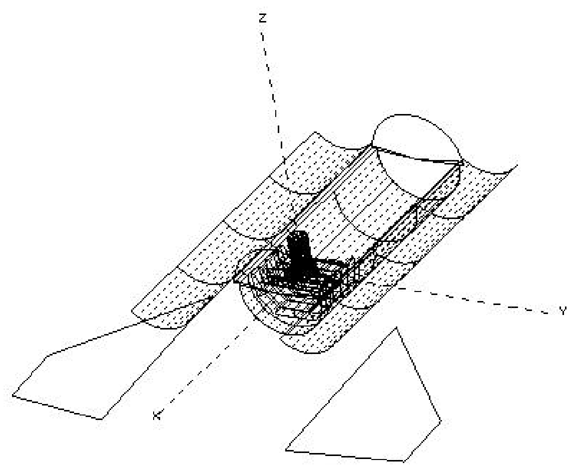

Figure 4. TRASYS Model of LITE in Payload Bay

An important parameter in the thermal analysis of orbiting spacecraft is beta angle (β). Beta angle measures the angle between the spacecraft's orbit plane and the solar vector. Factors that influence beta angle include orbit inclination, time of year of launch, and time of day of launch. Since many of these factors were unknown during the design and analysis of LITE, a range of beta angles was used in the instrument thermal analysis: 0°, 30°, and 66°. Each of the cases listed in Table 3 above was analyzed at each of these

Case	Orientation	Altitude (km)	Solar Flux (watts/m²)	Earth Flux (watts/m²)
Nominal	Earth	259	1367	234
Hot	Sun	194	1423	241
Cold	Space	296	1322	227

Table 3. Orbital Parameters

beta angles. A spacecraft's beta angle will change with time. For short duration missions like a shuttle flight, the beta angle will change only slightly.

SINDA'85 model

The LITE instrument thermal math model was developed using SINDA'85 to characterize the thermal behavior of the entire instrument in the orbiter payload bay. Two thermal math models were developed: an atmospheric, closed payload bay door model used for prelaunch, ascent, entry, and postlanding analyses; and an orbital open door model used to analyze on-orbit cases. Results from these analyses were used to confirm that the instrument's thermal design would meet all LITE performance requirements such as thermal stability and optical alignment.

The LITE instrument portion of the thermal math model was correlated with data from development tests and subsystem thermal/vacuum tests. Reduced thermal math models of each subsystem were incorporated into the instrument-level model. The LTM reduced thermal math model was derived from a model developed by Spectron, the LTM contractor. The OASIS-1 model was taken from a test-verified Lockheed thermal model. The orbiter payload bay was modeled using information from *Simplified Orbiter Thermal Simulator Description* for closed-door and open-door geometries, JSC 19692A and JSC 19540A.

The orbital LITE instrument thermal model contains 391 nodes, 524 linear conductors, and 6224 radiation conductors. The atmospheric model contains 393 nodes, 780 linear conductors, and 5764 radiation conductors.

Preflight Analyses

Extensive thermal analyses were performed throughout the design process. Early analyses focused on parametric studies of design options. After hardware assembly and testing, thermal models were verified against results obtained during thermal/vacuum testing. Analyses during the six months prior to launch focused on mission operations planning.

Thermal model predictions of the temperatures of critical LITE components during various mission phases are indexed in Table 4. Payload Bay (PLB) Opening occurs 1-3 hours after launch. The ascent thermal conditions were biased cold for this case. Standby and Data Take are steady state on-orbit cases analyzed at a nominal 30° beta angle (β). Landing temperatures assume a hot-biased entry profile.

Component	PLB Open	Standby	Data Take	Landing
Pri. mirror	19°C	14°C	15°C	16°C
AOA	18	24	25	26
LTM bench	21	28	29	28
Camera	18	43	44	42
BA	18	46	47	45
Cold plate	19	10	13	19
Orthogrid	17	13	14	29

Table 4. Preflight Temperature Predictions

Flight Results

Two data acquisition systems were used during LITE's mission to record the flight environment: 1) OASIS provided a wide range of thermal, structural, and acoustic information during launch and entry, and snapshots of thermal data during on-orbit operations, and 2) EDS recorded hundreds of thermal, structural, electrical, and performance measurements when LITE was activated on-orbit. Only a small subset of EDS data was available during the preparation of this manuscript, so flight results include a limited number of sensors during a seven-hour period of on-orbit operations. This seven-hour period includes both standby and data taking operations, so both of LITE's primary operating modes are represented.

Mission Timeline

STS-64, carrying LITE as its primary payload, launched from Kennedy Space Center on September 9, 1994 at 6:22:35 PM EDT. The payload bay doors were opened 1 hour and 31 minutes after launch (mission elapsed time [MET] 00/01:31). LITE was first activated at MET 00/03:12. LITE remained activated until MET 09/14:11.

LITE's two primary operating modes are standby and data take. In standby mode, LITE's electronics are powered, temperatures are stabilized, and engineering data is recorded continuously. LITE dissipates 589 watts of heat in standby. From standby mode, LITE can be brought up to data take mode within three minutes. High rate science data is collected during data takes. The mission operation plan called for a series of ten 4.5-hour data takes, and a number of short duration (approximately 15 minutes) snapshot data takes. During data takes, when the laser is firing, LITE generates 2326 watts.

Flight results discussed below cover the seven-hour period of time from MET 01/21:00 to 02/04:00. The shuttle orbiter was oriented in a bay-to-Earth attitude during this entire period. LITE was initially in standby mode. Data Take C (DTC) began at MET 01/22:35 and continued until 02/03:45. The instrument was commanded to standby mode twice during DTC: from 02/00:27 to 02/00:43, and from 02/02:08 to 02/02:17.

Comparisons with Preflight Predictions

Comparisons between the LITE instrument thermal model's preflight predictions and actual flight results are presented in Figure 5 through Figure 11. The thermal model was run for a seven-hour period with standby and data take periods corresponding to the actual flight duration. The flight beta angle was approximately 40° over this duration in the mission, and the thermal model predictions were based on β=40°. Historical average values for solar constant were assumed.

Results for the telescope's primary mirror and AOA are presented in Figure 5 and Figure 6. The thermal model predicted a much lower operating temperature for the AOA than was experienced in flight. The primary mode of heat transfer from the AOA was by radiation to the AOH, then to the TSS, and finally to the environment. High estimates of the emissivity of these surfaces may account for the lower predicted temperatures. Since the AOA faced the back of the primary mirror, its lower predicted temperature was directly related to the low AOA temperature.

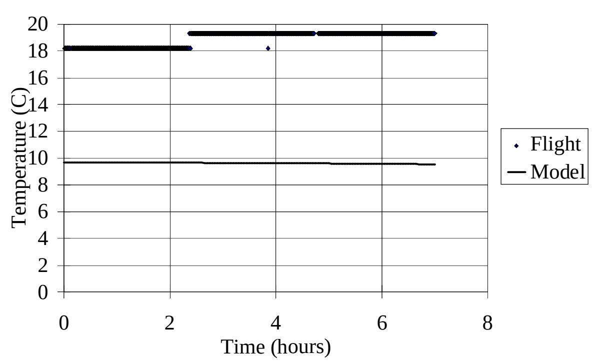

Figure 5. Flight Results vs. Preflight Model -- Primary Mirror

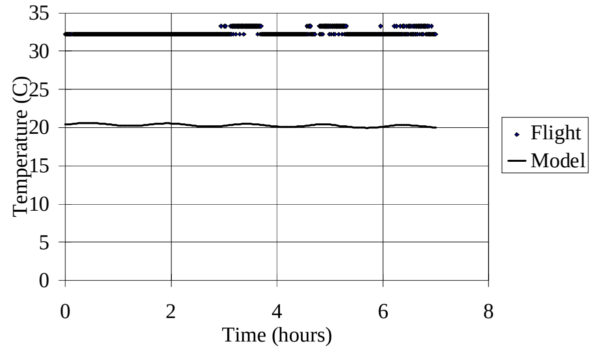

Figure 6. Flight Results vs. Preflight Model - Aft Optics Assembly

The LTM bench temperature comparisons are shown in Figure 7. In this figure, the two different operating modes of the instrument are readily apparent. During the first 1.5 hours, LITE was in standby mode, and the LTM's internal thermal control system was cycling a coolant pump on and off to maintain an internal temperature around 28.5°C. When lasing began, the coolant pump operated continuously and bench temperatures stabilized. Brief transitions to standby mode are indicated by spikes in the LTM bench temperature.

The thermal model accurately predicted the bench temperature in standby mode, but overpredicted the bench temperature in lasing mode by about 1.7°C.

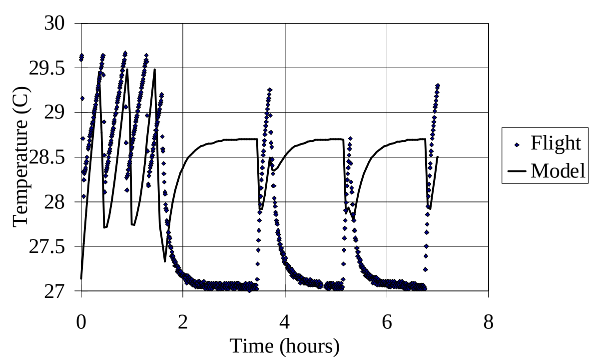

Figure 7. Flight Results vs. Preflight Model -- LTM Bench

From Figure 8 and Figure 9, the thermal model overpredicted the camera temperature by approximately 10°C and the BA temperature by about 12°C. Both the camera and BA were mounted to the orthogrid platform using thermal isolators. The conductivity of the thermal isolators was an important driver in modeling these subsystems. Underestimating the conductivity of these isolators might account for the discrepancy in the temperature predictions.

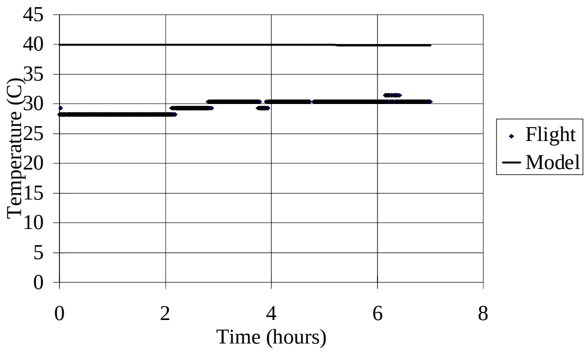

Figure 8. Flight Results vs. Preflight Model -- Camera

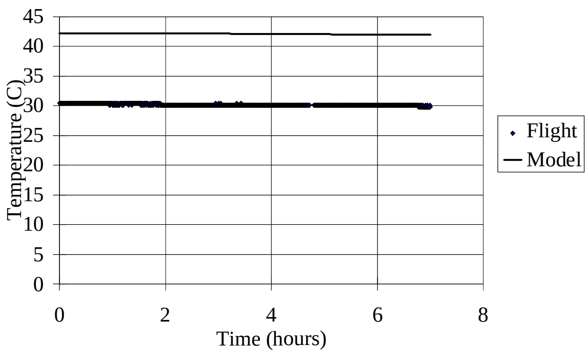

Figure 9. Flight Results vs. Preflight Model -- BA Elevation Gimbal

The LITE cold plate temperature is plotted in Figure 10. As with the LTM bench temperature, LITE's two operating modes are apparent in the temperature profile. During standby mode, model predictions were relatively accurate. In data take mode, the model underpredicted the cold plate temperature by 2.5°C. The thermal model assumed that the temperature of the Freon delivered to the LITE instrument was constant. In flight, the Freon temperature increased during lasing operations as the orbiter's payload heat exchanger struggled to remove the LTM's large heat load from the Freon system. This is the likely reason for the difference between the model prediction and flight results.

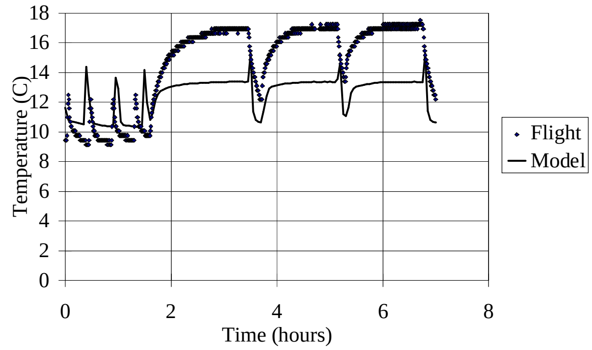

Figure 10. Flight Results vs. Preflight Model -- Cold Plate

The thermal model underpredicted the temperature of the orthogrid platform by 5°C, as shown in Figure 11. One of the greatest uncertainties in the thermal model was the insulating effectiveness of the orthogrid cover. The orthogrid cover was a 5-layer blanket placed on top of the orthogrid used to prevent sunlight from passing through the holes in the orthogrid and striking the pallet and struts below. Since LITE was never subjected to a system-level thermal test, the insulating effectiveness of the orthogrid cover could only be approximated. Adjustments in this value could affect the temperature of the orthogrid platform.

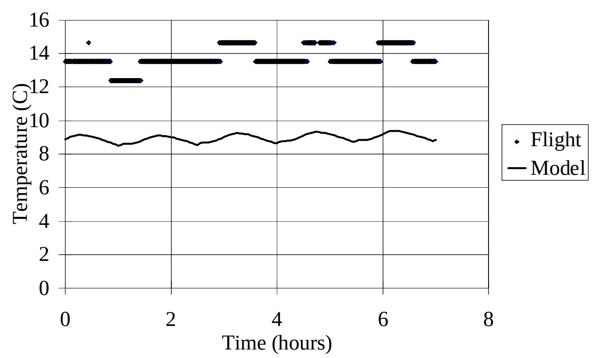

Figure 11. Flight Results vs. Preflight Model -- Orthogrid

Modeling Adjustments

In order to provide more accurate predictions for future flights of LITE on the space shuttle and proposed free-flying operational instruments, some preliminary adjustments based on flight results have been made to the instrument thermal model. Comparisons between the modified postflight thermal model and flight results are presented in Figure 12 through Figure 17.

Only minor adjustments were made to the modeling of the primary mirror and AOA (Figure 12 and Figure 13). The emissivity of black painted surfaces within the telescope was reduced from an optimistic 0.95 in the preflight model to 0.87. This change resulted in slight improvements in the accuracy of model predictions. Predicted AOA temperatures increased from 20°C preflight to 21°C in the modified model, still well below the actual flight temperature of 33°C. Further modifications in the modeling of the AOA will require additional flight data for model verification since the temperatures of the AOH and TSS play such an important role in the transfer of heat from the AOA.

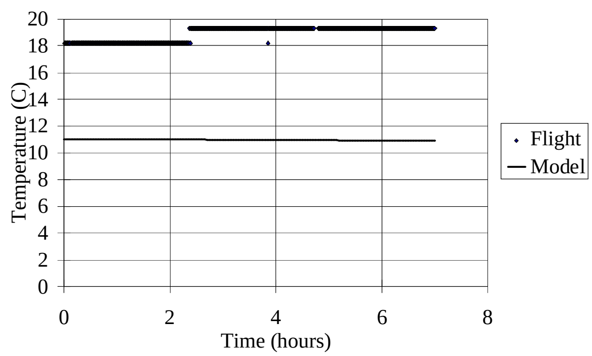

Figure 12. Flight Results vs. Postflight Model -- Primary Mirror

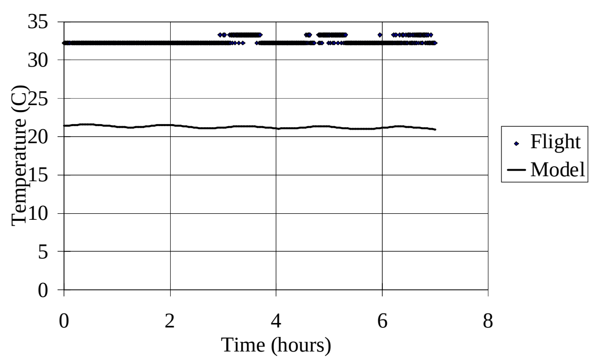

Figure 13. Flight Results vs. Postflight Model -- Aft Optics Assembly

Inaccuracies in the thermal model's prediction of LTM bench temperatures during data takes was traced to a temperature limit in the LTM model's thermal control system logic. When the LTM coolant temperature dropped below a certain limit, coolant bypassed the Freon heat exchanger, allowing the coolant to warm up slightly. In the preflight model, this limit was set at 25°C. By decreasing this limit to 23.3°C in the postflight thermal model, the predicted bench temperature matched the flight results almost perfectly (Figure 14).

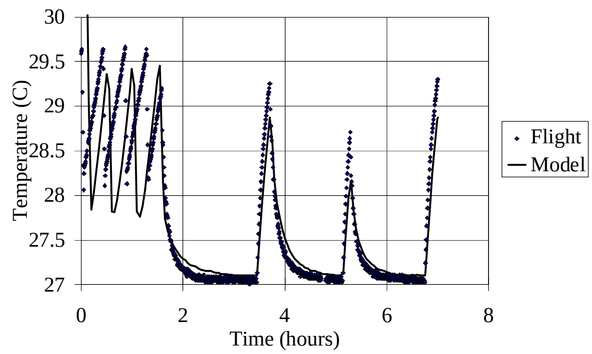

Figure 14. Flight Results vs. Postflight Model -- LTM Bench

The camera and BA models were modified postflight by changing the conductivity of the thermal isolators. In the preflight model, each isolator had a conductance of 0.09 watts/°C. Increasing that value to 0.16 watts/°C in the postflight thermal model produced the results shown in Figure 15 and Figure 16. Differences of 10°C and 12°C, respectively, in the preflight predictions were reduced to approximately 4°C in the postflight model.

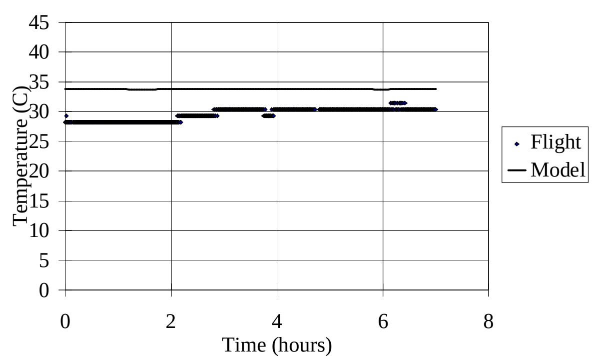

Figure 15. Flight Results vs. Postflight Model -- Camera

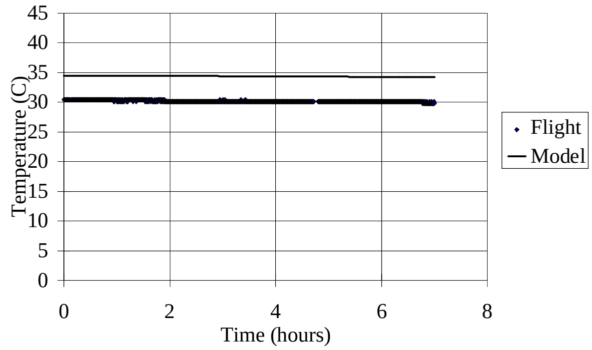

Figure 16. Flight Results vs. Postflight Model -- BA Elevation Gimbal

Since discrepancies between the preflight model predictions of the cold plate temperature and its actual performance in flight may be attributable to higher Freon temperatures during data takes, no modifications to the cold plate modeling have been made. When flight data of the Freon supply temperature becomes available, this theory can be confirmed or denied.

Since the largest uncertainty in the modeling of the orthogrid platform was the effective emissivity of the orthogrid cover, it was decreased from 0.10 in the preflight model to 0.05 in the postflight model. This change resulted in a predicted temperature closer to the flight temperature of 13.5°C: the preflight model predicted approximately 9°C while the modified postflight model predicted 11°C. Since the orthogrid platform was instrumented with more than one temperature sensor, further model modifications will not be done until an analysis of all flight data can be conducted.

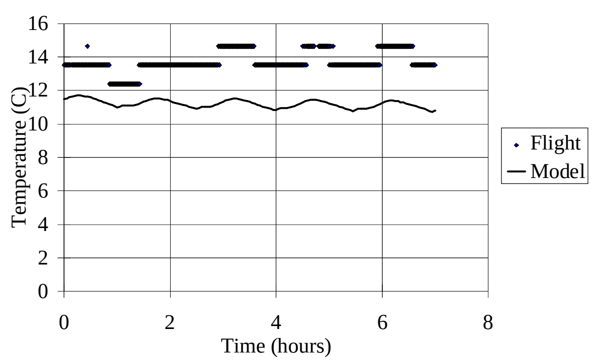

Figure 17. Flight Results vs. Postflight Model -- Orthogrid

Conclusions

Preliminary analysis of a limited set of flight data indicated that preflight thermal models significantly underpredicted the operating temperature of the primary mirror and AOA, and overpredicted the temperatures of the camera and BA. LTM bench temperature predictions were relatively accurate. Cold plate and orthogrid temperatures will require a more detailed analysis of flight data when it becomes available.

Modifications were made to the thermal model to improve the accuracy of its temperature predictions. Camera, BA, cold plate, and orthogrid temperature predictions were improved to within 4°C of flight results. AOA modeling will require more extensive modifications to improve accuracy. Flight data from nearby components, such as the AOH and TSS, will be needed before those modifications can proceed.

Continued use of the LITE thermal models and flight data is anticipated. The effect of the LTM thermal control system on laser performance is a continuing effort. Thermal models will be used in conjunction with structual and optical models to evaluate the alignment of LITE's optical system during flight. Proposed modifications to LITE will be analyzed for their effects on instrument thermal performance. The LITE instrument thermal model may be used as a baseline for studies of a free-flying operational lidar system.

Acknowledgments

The success of LITE's mission is attributable to hundreds of people at Langley Research Center, other NASA centers supporting LITE's development and operation, and TITAN Spectron, who developed the LTM. LITE's thermal control system performed flawlessly, and the contributions to its design and analysis by Dana Gould, Debra Shimek, Brian Killough, and Amy Witsil of Langley Research Center, and Connie Bowen and Karl Reithmaier of TITAN Spectron, are gratefully acknowledged.