PREFLIGHT TESTING SYSTEM FOR AN OPTICAL SENSORS PAYLOAD

A Major Qualifying Project Report
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Abstract

The MIT Lincoln Laboratory High Power Missile Alternative Range Target Instrument program will test an Optical Sensor Module (OSM) payload onboard an expendable rocket. This project presents the design of a mechanical system and the testing procedures for the preflight testing of the OSM payload. The system includes a support structure that rotates the OSM under an attached optics bar that excites the OSM sensors. Analysis of the light sources and collection optics used on the optics bar is presented. Finite element heat transfer analysis provides the effects on the optics bar and the OSM due to heat from the lights, and establishes the heat-safety procedures during testing. Finite element structural analysis provides the static and dynamics response of the testing system.
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<td>Chemical Oxygen iodine Laser</td>
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<td>FEA</td>
<td>Finite Element Analysis</td>
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<td>HEL</td>
<td>High Energy Laser</td>
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<td>HP</td>
<td>High Power</td>
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<td>LL</td>
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<td>LP</td>
<td>Low Power</td>
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<td>MARTI</td>
<td>Missile Alternative Range Test Instrument</td>
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<td>MDA</td>
<td>Missile Defense Agency</td>
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<td>OSM</td>
<td>Optical Sensor Module</td>
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<td>SHEL</td>
<td>Surrogate High Energy Laser</td>
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Chapter 1 Introduction

Defending the United States, allies, and friends has always been a high priority for the United States Government. Advanced ballistic missile technologies developed by foreign countries have influenced the U.S. Missile Defense Agency to focus efforts on a layered missile defense strategy. There are approximately 5,900 ballistic missiles in countries other than NATO, China, Russia, or the U.S., and the number of ballistic missile producing countries continues to increase (U.S. Department of Defense, 2009). The United States Government is developing the capability to counter ballistic missiles in all stages of flight. The Airborne Laser (ABL) Program is an ongoing project between the U.S. Missile Defense Agency, Boeing, Lockheed Martin, and Northrop Grumman that is part of the layered missile defense strategy. The project’s main objective is to develop a laser system with the capability of detecting and destroying ballistic missiles during the early flight stages. In order to evaluate the ABL’s effectiveness on ballistic missiles, a testing instrument was designed by MIT Lincoln Laboratory (LL) called the Missile Alternative Range Target Instrument (MARTI). This instrument is organized as two distinct projects; the High Power (HP) and the Low Power (LP) modules, with each having many different kinds of sensors to test the different lasers associated with the ABL program.

Proper functioning of the sensors relates directly to the outcome of the Airborne Laser test. Malfunctioning sensors will lead to inconclusive results therefore, wasting time, money, and the optical sensor modules. Currently there is no standard or easy method of testing the optical sensors on the modules before the final rocket assembly and launch. Ideally, the preflight optical sensor evaluation would be fast, able to effectively determine if the sensors are functioning correctly, and used as a final check of the OSM’s before the final rocket assembly.

The goal of this Major Qualifying Project (MQP) is to design, fabricate and test a preflight optical sensor evaluation system for MARTI. With the completion of this project, Lincoln Laboratory will be able to accurately test all sensors on the OSM’s and determine if the sensors are working properly prior to launch. The major objectives of this MQP are:

1. Perform necessary heat transfer calculations
2. Select suitable optoelectronics
3. Design the system
4. Fabricate, build, and test the system
The heat transfer analysis is important in order to determine the effects on our system. If the system becomes too hot for operators to handle, then heat safeguards will have to be added. High Power sensors need a higher irradiance level than the Low Power sensors and the lighting schemes will need to adjust to satisfy both requirements. Heat transfer and optoelectronic analysis is an important part in order to ensure that enough light is emitted to excite the various sensors. The selected lights will allow us to complete the design and move forward with the manufacturing and testing phases. The primary considerations for design and implementation are effective safeguards, transportability of the system, easily accessible, usable power source, and suitable light sources to excite the sensors. The most important considerations for completion of this project are to ensure that the mechanical and heat transfer analysis are completed accurately and in a timely manner—allowing us more time to optimize our design framework and successfully test and adjust the system.

1.1 Ballistic Missile Defense

Ballistic missile defense is important for the United States to remain competent and well positioned when engaged in war or armed conflict. The Missile Defense Agency (MDA) has been working for over twenty years in researching and deploying defense mechanisms to protect the United States from ballistic missiles. The MDA’s main objectives include the following (Welch & Briggs, 2008):

- To defend the United States, deployed forces, allies, and friends from ballistic missile attacks of all ranges in all phases of flight.
- To develop and deploy, as directed, a layered ballistic missile defense system (BMDS).
- To enable the fielding of elements of the BMDS as soon as practicable.
- To provide capability in blocks, improving the effectiveness of fielded capability by inserting new technologies as they become available.

1.2 Airborne Laser Program

The Airborne Laser Program is a project that has developed a laser system to detect, track, and destroy threat ballistic missiles in their early stages of flight (Access Intelligence, 2007). The program began in 1996 when the US Air Force awarded Boeing with a contract to
transform a Boeing 747-400F aircraft into what is now the Boeing YAL-1 Airborne Laser weapons system (Perram, Marciniak, & Goda, 2004). It has been an ongoing project between the U.S. Missile Defense Agency and industries partners in Boeing, Lockheed Martin, and Northrop Grumman. “Since 2004, the program has made continual and significant progress, which is an amazing achievement for a program of such complexity,” said Greg Hyslop, Boeing’s ABL vice president and program director (Access Intelligence, 2007). Figure 1 shows a Boeing 747 equipped with the Airborne Laser.

The ABL’s engagement sequence includes six infrared sensors that detect missile launches, a beam control / fire control system that targets and determines the type of missile, a beacon illuminator laser to specify and adjust for any atmospheric differences between the 747 and the targeted threat missile, and finally a chemical oxygen iodine laser that acts as the high-energy source to destroy the missile. After creating the Airborne Laser System, the U.S. Defense Agency and industry partners needed to test its accuracy and irradiance levels on a target instrument that could mimic a threat ballistic missile.

1.3 Missile Alternative Range Target Instrument

In collaboration with the NASA Sounding Rocket Operations Contract (NSROC), MIT Lincoln Laboratory has created an instrumented target missile called the Missile Alternative Range Target Instrument (MARTI) to determine and evaluate the effectiveness of the ABL lasers and related systems. The main purpose of the MARTI is to “quantify the laser performance of
the Airborne Laser (ABL) during a simulated missile engagement” (Chadwick, Blanchard, Wilson, & Gass, 2008). There are two forms of the MARTI; low powered (LP) and high powered (HP). The LP-MARTI tests the low power targeting and acquisition lasers of the ABL. These lasers include the Beacon Illuminator Laser (BILL), the Track Illuminator Laser (TILL), and a low powered version of the COIL or the Surrogate High Energy Laser (SHEL). The HP-MARTI only tests the functionality of the high-powered COIL or the High Energy Laser (HEL). Both HP and LP-MARTI consist of a nose cone, a telemetry module fitted with antennas and GPS, and three MARTI optical sensor modules (OSM).

For each HP OSM there are 512 HEL optical sensors; for each LP there are 512 SHEL sensors, 128 BILL sensors, and 32 TILL sensors. Both the HP and LP-MARTI are designed to acquire data from the lasers hitting the sensors and quickly transmit the information to a source on the ground before the modules fall into the ocean or are destroyed by the ABL.

In order to complete these tasks, the ABL completes a number of operational sequences. First it detects the exhaust plume of the boosting missile by using six infrared sensors. After the target is detected, a Track Illuminator Laser walks up the missile from the exhaust plume to the tip of the nose. This kilowatt-class solid state laser is used to not only track the missile on its trajectory, but also to determine what type of missile it may be. By determining what type of missile is being targeted, the ABL can detect the location of the missile’s fuel tank, which is the primary target in order to destroy the missile. The structure of MARTI is shown in Figure 2.
1.4 Laser Technology

Laser technology in recent years has provided breakthroughs in many military and defense applications. Programs ranging from the Airborne Laser program (ABL), the Tactical High Energy Laser program (THEL), and the Large Aircraft Infrared Countermeasures program (LAIRCM) are all military programs using advanced laser technology (Perram et al., 2004). In order to understand Light Amplification by Stimulated Emission of Radiation or LASER’s, one must comprehend the science and technology behind them.

Airborne Laser Program’s perceived difficulty accordingly to the Department of Defense Laser Master Plan is labeled green meaning that the perceived difficulty of the project is moderate. Other lasers applications recognized by the DoD can be seen in Table 1.
### 1.4.1 Solid State Laser

Solid state lasers (SSL) are a specific type of laser that uses a gain medium that is a solid crystalline material and is primarily optically pumped (Goldwasser, 2009). “Solid-state lasers include heat-capacity, fibers, and continuously cooled lasers” (Perram et al., 2004). Solid-state lasers have become more efficient, more powerful, and widely used; they are commonly used to measure distances, to aid with surgery, cutting metals, and even in the graphic arts. The primary host material for SSL’s is yttrium aluminum garnet, which is advantageous over other materials since it has a high thermal conductivity and mechanical strength. Two ions used in SSL’s are neodymium (Nd\(^{3+}\)) and ytterbium (Yb\(^{3+}\)), which both have their advantages and disadvantages in respect to absorption bands, quantum efficiencies, waste heat, and cooling capabilities.

The Airborne Laser Program uses two SSL’s: the Beacon Illuminator Laser and the Track Illuminator Laser. “The TILL is a Q-switched, 10-W-class, Yb:YAG laser comprised of four mutually incoherent illuminators sharing a single aperture. The BILL is a kW-class Nd:YAG laser comprised of two laser modules which share an aperture to provide pulses at 5 kHz” (Goda, Marciniak, and Perram, 2004).

### 1.4.2 Chemical Oxygen Iodine Laser

The Chemical Oxygen-Iodine Laser is an infrared chemical laser that is fed with gaseous chlorine, molecular iodine, and a mixture of hydrogen peroxide and potassium hydroxide in an aqueous state. A schematic of a COIL is shown in Figure 3. “\(O_2(a^1\Delta)\) is a two phase reactor governed by the stoichiometry Equation (1):
\[ \text{Cl}_2(g) + \text{H}_2\text{O}_2(l) + 2 \text{KOH}(l) \overset{\Delta}{\rightarrow} \text{O}_2(a^1\Delta) + 2 \text{KCl} + 2 \text{H}_2\text{O} \quad (1) \]

The chlorine and hydrogen peroxide solution get mixed together and produce massive amounts of heat through a chemical reaction and an excited state of oxygen. The energy from the oxygen gets transferred to the iodine and injected into a gas stream creating rapid energy transfer. This form of laser was developed for military purposes in 1977 by the US Air Force, but due to its ability to be easily absorbed by metals it has become useful for industrial processing such as laser cutting.

![Schematic of a Chemical-Oxygen Iodine Laser](image)

**Figure 3. Schematic of a Chemical-Oxygen Iodine Laser (Goda, Marciniak, and Perram, 2004)**

### 1.5 Lighting Sources and Optics

Light sources all carry distinct amounts of energy for any given wavelengths. When we analyzed various light sources for our project, we needed to determine the particular wavelength to get an accurate representation of the energy emitted. Equation (2) shows the direct relationship between energy and wavelength, whereas \( E = \text{energy} \); \( h = \text{Planck’s constant} \); \( v = \text{frequency of light} \); \( c = \text{speed of light} \); and \( \lambda = \text{wavelength} \).

\[ E = hv = \frac{hc}{\lambda} \quad (2) \]
1.5.1 Light Sources

One particular light source is the conventional incandescent bulb. This source emits light by supplying energy through tungsten filament, which heats up and turns a bright white color. The emission of light is a direct result of energy loss. In determining the most suitable light source for the light bar, we are going to have to analyze the energy loss of all light sources and the amount of energy that the source is capable of producing.

Tungsten halogen light sources are also considered an incandescent bulb; however, tungsten filaments are sealed into a compact transparent envelope filled with an inert gas and small amount of halogen. Because of tungsten halogen lamps smaller size, they can advantageously be used more efficiently with optical systems. However, there are certain constraints when using tungsten halogen as a light source in an optical system. The filament has temperature limits and if this temperature is surpassed then the bulb could melt and cause system failure. Tungsten-halogen lamps are available in various shapes and sizes including tubular and conical (See Appendix A Final Light Selection).

The temperature of a standard halogen light bulb can range from 3000 K to 3623 K (Elert, 2003). The temperature of the tungsten filament will transfer heat to the sensors in the OSM through conduction. Varying temperatures, which result in different digital count outputs, are essential in determining the irradiance levels.

Irradiance levels for tungsten halogen bulbs will vary from fluorescent lighting sources. When we selected a lighting source for the optical sensor pre-test system, we analyzed the irradiance differences to determine how much the light is collimating per given area. Irradiance
can be described by Equation (3) where as $\varepsilon =$ emissivity; $\sigma =$ Stefan Boltzmann constant; $T =$ surface temperature and $T_{\text{Room}} =$ room temperature:

$$\text{Irradiance} = \varepsilon \sigma (T^4 - T_{\text{Room}}^4) \quad (3)$$

Fluorescent lighting sources are used in various applications and provide light at several times the efficacy of incandescent lamps (Hammer, 2009). Fluorescent lamps are available in a range of tinted and saturated colors, depending on the chemicals used in production. Technology developments in lighting research and design have helped increase the luminous efficacy of fluorescent bulbs to nearly 90 lumens per watt from 50 lumens per watt. The most common fluorescent light is an elongated round tube that varies in length from 15 cm to 2.4 m. Other shapes include circular, U-shaped, rectangular, and twin-tube.

Electroluminescence is another lighting type applicable to our optical sensor evaluation system. Electroluminescence in the form of light-emitting solid-state lighting uses light-emitting diodes, organic light-emitting diodes, or polymer light-emitting diodes as sources of illumination rather than electrical filaments. This lighting source typically generates less heat when compared with halogen and incandescent bulbs and the light’s shape and small mass provides for greater shock and vibration resistance. Electroluminescence in the form of sheets involves light sources on thin, flexible sheets with an advantage in freedom of size and shape (Boast, 2009).

1.5.2 Light Collimation

There are specific factors when analyzing a light source that can affect its performance and application capabilities. Light bulbs come in all different kinds of shapes as noted in Section 1.5.1 and according to the specific shape; the beam emanating from the lens will travel in various paths. Beam collimation refers to the bulbs ability to focus the light in a parallel manner as seen in Figure 5, which shows an example of an optical collimating lens that helps to focus light intensity on the intended object. The light enters the lens at an angle and exits parallel and uniformly. The light hits the lens and arranges in an efficient manner to increase the irradiance. Figure 6 shows an example of a non-collimating light in which the light is not arranged in an efficient manner, thus losing light that could have been used more effectively.
The shape of the bulb will influence the collimation of the beam and therefore, the amount of light that is exposed to the OSM. A typical M16 tungsten halogen lamp will emit a slightly angled beam anywhere between ten and thirty degrees. Selecting a suitable light source with the correct shape for the optical sensor system was critical in ensuring that the sensors for the module were working correctly. If a light source was selected that could not produce enough digital counts, then additional collection optics would have to be used. Otherwise we would not have been able to determine the pre-flight status of the optical sensor modules.

1.5.3 Collection Optics

Collection optics are lenses or similar materials that focus light to a certain area. A simple example of this is a magnifying lens. Many properties contribute to the capabilities of collection optics such as the thickness of the lens; the primary factor in determining the focal length. The diameter is important so the amount of light or irradiance the lens will absorb and
ultimately magnify. The focal length and the distance from the front of the lens to the object determine the magnification rate. Collection optics are important to a system with a semi-collimated or un-collimated light source. The optics can focus the light to a specific point, and magnify the radiation produced by the light.

When choosing collection optics it is important to look at the magnification rate, focal length, diameter, and distance the lens needs to be from the object; each of which is a design element. Those properties are also important to check tolerances of the lens magnification outputs. Two other material properties that affect the performance of the lens are clear aperture and loss percentage. Clear aperture is the percentage of the lens diameter that is effective, or will focus the light. A majority of lenses we researched have a clear aperture of approximately 90%. Each lens also has a loss percentage, or the percentage of irradiance that will not be transmitted through the lens. This loss is primarily due to reflection and minimally due to absorption.

1.6 Summary

The sensors on the optical sensor module are able to detect light through photoelectric voltage and send a signal through the circuit to produce digital counts. Photoelectric devices give an electrical signal in response to various types of radiation including visible, infrared, and ultraviolet (Chapman, 2009). Once the specific lighting sources that will be tested on the OSM sensors were chosen, we were able to determine which lighting sources to use for the optical sensor test system. Once we were able to select the most suitable light sources and collection optics, we were able to move ahead with the design of the mechanical system.

1.7 Project Objectives and Methodology

The goal of this project is to develop, build, and test a mechanical system that can excite the sensors on the optical sensor module to determine if they are working properly. This test will be used as a final pre-flight check for the sensors to determine functionality.

The objectives and methodology to achieve the goal are:
1. **Perform necessary heat transfer analysis to determine the necessity of heat safe guards and effects on the light and optic bars.**

   There are three main heat transfer tasks: a) determination of the irradiance, size, and digital count requirements for the optoelectronics; b) evaluation of heat effects from the optoelectronics on the system; c) development of any necessary heat safe guards. The heat transfer analysis is performed using theoretical estimations implemented in Microsoft Excel and advanced 3D finite-element simulations using the ANSYS v.12.0.1 software.

2. **Choose optoelectronics that have the irradiance capability, beam collimation, and focal properties necessary to excite both the high power and low power optical sensor modules.**

   In order to determine the appropriate optoelectronics for the pre-flight system, the correlation between irradiance levels on the optical sensors and the number of digital counts outputted is needed. This analysis provides the type of light bulbs, given specific wattage and voltage that would be able to produce an adequate number of digital counts. The analysis is based on the requirement of twenty amperes current limitation at any one given time. The beam collimation of the light bulbs must ensure that enough light is being focused on the optical sensors for both the high power and low power optical sensor modules. Going along with beam collimation, the focal length measures how strongly the light focuses. This was another consideration used in our determination for which light source to use for the system.

3. **Design the system to meet the following parameters: quick testing of the optical sensors; easily transportable; and no mechanical failure.**

   The mechanical system must allow for quick testing of the optical sensors, transportability, and limited to no mechanical failure. This requires iterations between several drawings and designs to select the best design for functionality and practicality. The design needs to be structurally feasible and meet static and dynamic requirements. Deformation and deflection analysis using ANSYS will enable us to analyze the structural integrity of the design. A general force analysis on the system will show the specific reactions acting on the system.

4. **Prototype and test the design to validate its effectiveness and make any necessary adjustments to meet the design parameters.**

   The light bar and optic bar are designed first to ensure on-time fabrication. Once all of the parts were ordered, machined, and assembled, we were able to prototype the system and
make any necessary changes. The prototype and testing stage of the project allowed us to give recommendations for future development and design.

The flowchart in Figure 8 outlines the methods used to achieve our objectives.

![Flowchart](chart)

**Figure 8. Methodology Flow Chart**

The objectives and methods stated were completed in the timeline outlined in Table 2.

### Table 2. MQP Timeline

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Start</th>
<th>Finish</th>
<th>Duration</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Define Project</td>
<td>8/17/2009</td>
<td>8/21/2009</td>
<td>4.44d</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>Project Proposal</td>
<td>8/17/2009</td>
<td>8/25/2009</td>
<td>1w 2d</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>Proposal Presentation</td>
<td>8/26/2009</td>
<td>8/26/2009</td>
<td>0w</td>
<td>100%</td>
</tr>
<tr>
<td>4</td>
<td>Optoelectronic Analysis</td>
<td>8/19/2009</td>
<td>9/2/2009</td>
<td>2w 1d</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>Design System</td>
<td>8/27/2009</td>
<td>9/24/2009</td>
<td>4w 1d</td>
<td>100%</td>
</tr>
<tr>
<td>6</td>
<td>Order Parts</td>
<td>9/3/2009</td>
<td>9/3/2009</td>
<td>0w</td>
<td>100%</td>
</tr>
<tr>
<td>7</td>
<td>Test Set of Lenses Arrive</td>
<td>9/10/2009</td>
<td>9/10/2009</td>
<td>0w</td>
<td>100%</td>
</tr>
<tr>
<td>8</td>
<td>Full Shipment of Lenses Arrive</td>
<td>9/14/2009</td>
<td>9/14/2009</td>
<td>0w</td>
<td>100%</td>
</tr>
<tr>
<td>9</td>
<td>Full Shipment of Sockets Arrive</td>
<td>9/14/2009</td>
<td>9/14/2009</td>
<td>0w</td>
<td>100%</td>
</tr>
<tr>
<td>10</td>
<td>Test Set of Bulbs Arrive</td>
<td>9/16/2009</td>
<td>9/16/2009</td>
<td>0w</td>
<td>100%</td>
</tr>
<tr>
<td>11</td>
<td>Heat Transfer Analysis</td>
<td>9/14/2009</td>
<td>9/14/2009</td>
<td>0w</td>
<td>100%</td>
</tr>
<tr>
<td>12</td>
<td>Design and Mechanical Analysis</td>
<td>9/21/2009</td>
<td>10/8/2009</td>
<td>2w 4d</td>
<td>100%</td>
</tr>
<tr>
<td>13</td>
<td>Prototype Testing</td>
<td>10/13/2009</td>
<td>10/13/2009</td>
<td>1d</td>
<td>0%</td>
</tr>
<tr>
<td>14</td>
<td>Final Presentation</td>
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<td>10/14/2009</td>
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<td>100%</td>
</tr>
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</table>
Chapter 2 Heat Transfer Analysis

The three tasks relating to the heat transfer analysis of the pre-flight optical sensor test system include an assessment of heat safeguards, analysis of the effects of the lights on the optic bar, and the effects on the optical sensor modules. Heat transfer analysis presented in this chapter is performed using theoretical calculations and finite element simulations. These problems were analyzed and solved using the following assumptions:

1. Steady state properties, meaning all thermal and material properties of the system are constant across time change.

2. Energy generated equaled zero ($E_g = 0$) refers to the Energy Balance Equation (4).

   The heat effects from the lights ($E_{in}$) are the only source of energy for the system.

   $$E_{in} + E_g - E_{out} = \frac{\partial E_{stored}}{\partial t}$$ (4)

3. Calculations are at one instant of time ($\Delta t \approx 0$)

4. Effects of powering up the system are negligible when compared to the effects on the fully powered system.

The system analyzed using theoretical and finite element methods in this chapter is shown in Figure 9.

Figure 9. System Geometry
2.1 Heat Safeguards

Safety for the system operators was the primary basis for the heat safeguards. The primary heat safeguard concerns relate with the top of the light bar and the possibility that an operator may touch that area and suffer injury. For the guards, both steady state and transient cases are analyzed via hand calculations and ANSYS. The procedure for the theoretical and ANSYS calculations is as follows. We evaluated the filament temperature and determined the temperature at the top of the light bar. For all of the analysis, input parameters used are shown in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Bulb Filament</th>
<th>Light Bar</th>
<th>Light Bulb</th>
<th>Light Socket</th>
<th>Optic Bar</th>
<th>Collection Optics</th>
<th>OSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissivity</td>
<td>0.4175</td>
<td>0.2</td>
<td>0.8</td>
<td>0.92</td>
<td>0.2</td>
<td>0.93</td>
<td>0.2</td>
</tr>
<tr>
<td>Convection Rate</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>(W/m²K)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (C)</td>
<td>935</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Irradiance (W/m²)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.0846</td>
<td>314100</td>
</tr>
</tbody>
</table>

Table 3. ANSYS Heat Transfer Initial Conditions

The irradiance levels for the optic bar, collection optics and on the optical sensor modules were determined by the bulb properties discussed in Section 3.1.1.

2.1.1 Preliminary Theoretical Safeguard Analysis

A resistance model was used to determine the heat at the top of the bar. This resistance model (Figure 10) was used primarily in the steady state analysis.
Figure 10. Resistance Model

For these calculations it is assumed that the filament heat source (hottest part of the bulb) is in contact with the light bar. This proved to be a bad assumption because it does not take into account the heat transfer resistance through the rest of the bulb and light socket. The light bar is aluminum 6061 and has a thermal conductivity of 167 W/mK. Using Equation (5), across the thermal resistance circuit, the temperature is found to be approximately 950° Celsius.

\[ Q^n = \frac{\Delta T}{\text{Re} \, \text{s} \, \text{i} \, \text{s} \, \text{tan} \, \text{c} \, \text{e}_{\text{total}}} \]  

This simple model considers a point temperature and not the temperature distribution across the bar due to multiple heat sources.

Transient analysis is pursued next. Using the following Energy Balance Equation (6)

\[ \frac{q^*}{E_m} A_{in} + 0 = \left[ h(T - T_{\infty}) + \varepsilon \sigma (T^4 - T_{\infty}^4) + (K/L) (T - T_s) \right] A_{out} = \rho V c \frac{\partial T}{\partial t} \]

In the Equation (6), \( T \) is the temperature after the light bar, and \( T_i \) is the filament temperature. \( \rho \) is the density of the material, \( c \) is the specific heat, and \( V \) is the volume of the system. \( K \) is the thermal conductivity and \( L \) is the length. From our assumptions, \( E_g = 0 \). The integral for of Equation (6) is,
Equation (7) “cannot be integrated explicitly to obtain an exact solution” and instead of using simplified analytical solutions to it (see for example Incropera, DeWitt, Bergman, p.264), three-dimensional numerical simulations were performed using ANSYS.

2.1.2 ANSYS Safeguard Analysis

ANSYS is a finite element analysis program used to model and solve thermal, static, dynamic, and many other problems. ANSYS takes a model, for our cases from SolidWorks, and creates a mesh over the system. The mesh is made up of elements and nodes, the more of those in the model, the more accurate the output will be. The program calculates the heat transfer effects on each element and how those affect the other elements. Then all these finite elements are looked at together, thus showing how the heat would disperse throughout the entire system. This process works for all different types of analyses in ANSYS. The appeal to using ANSYS over hand calculations is that the analysis does not just give us the maximum temperature at one point, but the distribution across the entire system. This better helps us understand and cope with the heat effects across the bar.

After importing the solid model into ANSYS, we created a detailed mesh. For this case, the mesh had 105,204 nodes and 51,027 elements. This gave us a very detailed temperature distribution. Figure 11 depicts the mesh for the light bulbs.
To solve the heat transfer problem and see the spread of heat across the light bar we used the program ANSYS version 12.0.1. This program was able to display both the steady state and transient heat transfer effects. For each case, the threshold temperature at the top of the light bar was 100° Celsius. Figure 12 depicts all the lighting heat effects on the light bar.
Figure 13 shows the steady state effects or the highest temperatures that can occur on the top of the light bar. This was the area of our primary concern.

![Figure 13. Steady State Temperature on Top of Light Bar](image)

The temperature on the top of the bar with a steady state analysis is approximately 166° Celsius. This was above our temperature threshold; therefore we decided to run the ANSYS models using transient effects.

The transient settings in ANSYS are similar to those of steady state, except that the time change was set to sixty seconds with time increments of one second. We chose this because we expect the modules to rotate at approximately one rpm. Figure 14 and Figure 15 show the transient effects.
From the analysis, with a time change of sixty seconds, the temperature on the top of the bar is within one degree of the ambient air temperature. The amount of time needed for the filament temperatures to transfer heat to the top of the light bar to reach the temperatures of the
steady state analysis would take a much longer, possibly hours. With the lights only being  
turned on for approximately sixty seconds, the heat transfer to the top of the bar is negligible. As  
a second safety check, the time change is increased to twenty minutes. Figure 16 shows the  
effects after twenty minutes.

Figure 16. Transient Heat Transfer Analysis @ 20 Minutes

Figure 17. Transient Heat Transfer @ 20 Minutes
Even though the simulation predicts the temperature after twenty minutes (approximately 17 minutes longer than the actual operating time) the temperature is 127° Celsius, we suggest the operators where some sort of glove when handling the light bar.

2.2 Heat Effects on Optic Bar

The purpose of this analysis is to ensure that the lights will not damage the optics, and that the bar will not be exposed to too much heat flux. This analysis is performed at steady state. Our reasoning for this is that the operators do not handle the optic bar immediately after the lights were on (not used to adjust the light bar) and therefore a steady state analysis, which will provide the maximum temperature, is sufficient. Our heat threshold for the optic bar is approximately 100° Celsius. Figure 18 depicts the mesh used for the optic bar heat effects.

![Figure 18. Optic Bar Heat Effects Mesh](image-url)
The temperature distributions for the optic bar are shown in Figure 19 and Figure 20.

![Figure 19. Heat Effects on Optic Bar](image1)

![Figure 20. Heat Effects on Collection Optics](image2)

The simulations predict that the maximum temperature on the collection optics is approximately room temperature. This is well below threshold because the optics have a low level of...
absorptivity, therefore the heat will not cause any distorting effects or be absorbed by the lenses. For the optic bar, the temperature is approximately room temperature because the system has been created that the lights will shine only on the lenses, not the optic bar.

2.3 Heat Effects on OSM

The final heat transfer analysis considers the effects of the irradiance on the optical sensor modules. The main purpose of the analysis is to determine the OSM skin temperature and the temperature at the sensors holes, and therefore provide to operators guidelines when handling the OSM. The analysis is performed at steady state, which predicts the maximum temperatures since the transient analysis on the light bar predicts that temperatures are much smaller after the sixty second operating time. For the OSMs, we performed two analysis, the effects on the sensors and the effects on the skin. Figure 21 depicts the temperatures on the OSM’s optics.

Figure 21. Steady State Heat Transfer on Sensors Holes

Figure 22 depicts the temperature on the OSM skin.
Although the temperature found by this analysis is very high for the skin, 285° Celsius, the system is built to withstand irradiance levels that are orders of magnitude greater than the surface of mercury. Although the temperatures on the sensors are low, 25° Celsius, which is because the sensors have a highly reflective gold plating, the irradiance levels are still high enough to excite the HEL sensors.

2.4 Summary

From the heat transfer analysis we can make three distinct conclusions. First, the steady state analysis gives us the maximum temperature on the object. We use steady state as a quick analysis to get an understanding for the temperatures we will be dealing with, and then if needed we look into transient cases. Second, the transient cases for this project conclude that the temperatures will be much less than the steady state cases. The change in time is only sixty seconds, and the filament’s heat transfer to the system in that short time period is negligible. Finally, although many of our temperatures were very high, that is a positive indicator for our system. Higher temperatures relate to high irradiance. From this analysis we can conclude that our lighting and optic choices can excite the sensors on both the LP and HP modules to the required levels.
Chapter 3 Optoelectronic Analysis

The optoelectronics required for designing this test apparatus include light sources and collection optics. We determined criteria for the lights and collection optics, researched possible options, and then chose the best option for our criteria. Both involved some heat transfer analysis detailed in the following sections.

3.1 Light Sources

To determine the light source needed, the irradiance level needed to excite each sensor is calculated for the optical sensor evaluation system shown in Figure 23. The irradiance is derived from a digital count versus irradiance graphs shown in Figure 23 and Figure 24.

![Figure 23. Low Power Module Sensors Digital Counts - Irradiance Relations](image-url)
As can be seen in the above figures, the irradiance needed to excite the HP sensors is many orders of magnitude higher than that needed to excite the LP sensors.

Using the irradiance levels, the filament temperature needed to excite the sensors is determined. The heat of the filament relates to the irradiance values through the Stefan-Boltzmann Law that states that ideally the irradiance \( I \) equals the Stefan-Boltzmann constant \( \sigma \) multiplied by the temperature to the fourth power \( T^4 \), as shown in Equation (8).

\[
I = \sigma T^4 \quad (8)
\]

This equation however, presents an ideal situation. Equation (9) accounts for emissivity of the radiation source and room temperature.

\[
I = \varepsilon \sigma T^4 - \varepsilon \sigma T_{\text{room}}^4 \quad (9)
\]

The emissivity \( \varepsilon \) value depends on the filament material; the temperature \( T_{\text{room}} \) is a known value (290 Kelvin) and the filament temperature \( T \) is the variable. Thus Equation (9) allows the evaluation of the filament temperatures needed to reach specific irradiance levels; a relation that narrows down the optoelectronics. Results for this analysis are shown in Figure 25 and Figure 26, which illustrate the Irradiance – Temperature relationship.
3.1.1 Light Source Options

Several light source options were considered including LED’s, incandescent, and electroluminescence. A comparison concluded that tungsten halogen lights provided the optimal design, irradiance, and electrical current for the light bar. The selected bulb needs to have the allowable wattage and voltage. Tungsten halogen MR16 bulbs, as shown in Figure 27, provide the optimal design since they have nearly collimated beams and small surface area. Cylindrical bulbs were also analyzed, but since they were not selected due to the fact that they do not have
the capability to focus the light nearly as much as MR 16 bulbs can. Table 4 shows the specifications of the top four light selections.

### Table 4. Final Light Selections

<table>
<thead>
<tr>
<th>Company</th>
<th>T10</th>
<th>MR16</th>
<th>MR16</th>
<th>MR16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watts</td>
<td>250W</td>
<td>100W</td>
<td>300W</td>
<td>150W</td>
</tr>
<tr>
<td>Volts</td>
<td>130V</td>
<td>120V</td>
<td>120V</td>
<td>120V</td>
</tr>
<tr>
<td>Current per 16</td>
<td>30.8A</td>
<td>13.3A</td>
<td>40A</td>
<td>20A</td>
</tr>
<tr>
<td>Base Type</td>
<td>E26</td>
<td>E26</td>
<td>GY5.3Bipin</td>
<td>GY5.3Bipin</td>
</tr>
<tr>
<td>Diameter</td>
<td>1.25&quot;</td>
<td>2&quot;</td>
<td>Length is Approx 2&quot;</td>
<td>2&quot;</td>
</tr>
<tr>
<td>Price</td>
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<td>$5.32</td>
<td>$9.90</td>
<td>$22.84</td>
</tr>
<tr>
<td>Irradiance</td>
<td>116695.46</td>
<td>44441.61</td>
<td>140968.25</td>
<td>68380.48</td>
</tr>
<tr>
<td>Counts</td>
<td>1876.64</td>
<td>1689.32</td>
<td>1939.57</td>
<td>1751.38</td>
</tr>
</tbody>
</table>

#### 3.1.2 Electrical Current Limitations

In order to finalize our light source selection for the pre-flight optical sensor system, it was important to analyze the electrical-current values outputted, given specific power and resistance numbers. This was an important consideration because once the current limitation is exceeded, it is highly probable that the circuit will trip and cause malfunction, thus making it very difficult for sensor testing.

Using Equation (10) and the arbitrary power and voltage values shown in Table 5, we determined the resistance values for various light scenarios. For example, Figure 27 displays a light with 100 watts and 120 volts.

$$ R = \frac{V^2}{P} \quad (10) $$

![Figure 27. EiKo Tungsten Halogen 100 Watt 120 Volt MR16 (eLightBulbs, 2009)](image)
If the light source is ideal for testing on the high-power MARTI then the corresponding resistivity and current values can be found by using Equation (11) and Table 5. A light source with 100 watts and 120 volts gives us a resistance value of 144 Ohms. Using this value of 144 ohms and 120 volts, it can be determined that an individual EiKo tungsten halogen 100 watt 120 volt outputs 0.83 amperes of current. The current values in Table 6 were calculated by using Equation (11). Since each of the OSM’s has sixteen rows of sensors, we needed to determine the current output for sixteen bulbs. Table 7 shows the current values for a system containing sixteen bulbs. By simply multiplying the 0.83 ampere value by sixteen, an EiKo 10 watt 120 volt’s maximum electrical current that it could withstand is 13.3 amperes, which is below maximum allowable current of 20 amperes.

<table>
<thead>
<tr>
<th>Power [Watts]</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
<th>175</th>
<th>200</th>
<th>250</th>
<th>300</th>
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<tbody>
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<td>Vol t a ge</td>
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<td>81</td>
<td>64.8</td>
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<td>46.29</td>
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<td></td>
<td>110</td>
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<td>69.14</td>
<td>60.5</td>
<td>48.4</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>288</td>
<td>192</td>
<td>144</td>
<td>115.2</td>
<td>96</td>
<td>82.29</td>
<td>72</td>
<td>57.6</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>338</td>
<td>225.33</td>
<td>169</td>
<td>135.2</td>
<td>112.67</td>
<td>96.57</td>
<td>84.5</td>
<td>67.6</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>392</td>
<td>261.33</td>
<td>196</td>
<td>156.8</td>
<td>130.67</td>
<td>112</td>
<td>98</td>
<td>78.4</td>
</tr>
</tbody>
</table>

\[ I = \frac{V}{R} \quad (11) \]

<table>
<thead>
<tr>
<th>Resistance [Ohms]</th>
<th>130.67</th>
<th>133.33</th>
<th>135.2</th>
<th>144</th>
<th>156.8</th>
<th>161.33</th>
<th>162</th>
<th>169</th>
</tr>
</thead>
<tbody>
<tr>
<td>V o l t a g e</td>
<td>90</td>
<td>0.69</td>
<td>0.68</td>
<td>0.67</td>
<td>0.63</td>
<td>0.57</td>
<td>0.56</td>
<td>0.56</td>
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<td></td>
<td>100</td>
<td>0.77</td>
<td>0.75</td>
<td>0.74</td>
<td>0.69</td>
<td>0.64</td>
<td>0.62</td>
<td>0.62</td>
</tr>
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<td>0.84</td>
<td>0.83</td>
<td>0.81</td>
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<td>0.70</td>
<td>0.68</td>
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<tr>
<td></td>
<td>120</td>
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<td>0.90</td>
<td>0.89</td>
<td>0.83</td>
<td>0.77</td>
<td>0.74</td>
<td>0.74</td>
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<tr>
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<td>0.98</td>
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<td>140</td>
<td>1.07</td>
<td>1.05</td>
<td>1.04</td>
<td>0.97</td>
<td>0.89</td>
<td>0.87</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1.15</td>
<td>1.13</td>
<td>1.11</td>
<td>1.04</td>
<td>0.96</td>
<td>0.93</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Current [Amperes]
3.2 Collection Optics

From the Irradiance – Temperature – Count relations described in Chapter 2, it was determined the light bulbs themselves were not enough to excite the sensors. The light emitted by the light bulbs is only semi-collimated and collection optics allowed us to better focus the light on a single point to excite the sensors. Four main factors considered: size, shape, magnification rates, and focal lengths. Size and shape were deciding factors in determining the amount of irradiance that will be magnified by the lens. The diameter of the optic also limited our design of the optic bar created to hold optics below the light source. If the lens diameter is smaller than the light source, some of the irradiance will not hit the lens. It also is very relevant to the design of the light bar. Collection optics with specific sizes have distinct focal points and magnification rates. To decide on size, we researched the magnification rates and focal lengths, and then chose a collection optic. Magnification rates were determined using Equation (12):

<table>
<thead>
<tr>
<th>Voltage [V]</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
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</thead>
<tbody>
<tr>
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<td>11.0</td>
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<td>13.5</td>
<td>14.7</td>
<td>15.9</td>
<td>17.1</td>
<td>18.4</td>
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<tr>
<td>133.33</td>
<td>10.8</td>
<td>12.0</td>
<td>13.2</td>
<td>14.4</td>
<td>15.6</td>
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<td>18.0</td>
</tr>
<tr>
<td>135.2</td>
<td>10.7</td>
<td>11.8</td>
<td>13.0</td>
<td>14.2</td>
<td>15.4</td>
<td>16.6</td>
<td>17.8</td>
</tr>
<tr>
<td>144</td>
<td>10.0</td>
<td>11.1</td>
<td>12.2</td>
<td>13.3</td>
<td>14.4</td>
<td>15.6</td>
<td>16.7</td>
</tr>
<tr>
<td>156.8</td>
<td>9.2</td>
<td>10.2</td>
<td>11.2</td>
<td>12.2</td>
<td>13.3</td>
<td>14.3</td>
<td>15.3</td>
</tr>
<tr>
<td>161.33</td>
<td>8.9</td>
<td>9.9</td>
<td>10.9</td>
<td>11.9</td>
<td>12.9</td>
<td>13.9</td>
<td>14.9</td>
</tr>
<tr>
<td>162</td>
<td>8.5</td>
<td>9.9</td>
<td>10.9</td>
<td>11.9</td>
<td>12.8</td>
<td>13.8</td>
<td>14.8</td>
</tr>
<tr>
<td>169</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Electrical Current Values for a System Containing Sixteen Lights
The variables in Equation (12) are visually explained in Figure 28.

![Figure 28. Collection Optic Diagram (Ref. 2)](image)

The variable $f$ is the focal length, and $f_b$ is the distance from the front of the lens to the object. Those properties and the figure above were provided in the catalog of collection optics found at ThorLabs.com (Ref. 2). The magnification rate is the rate at which the power would be magnified at the focal point before losses. Each lens had two different losses, clear aperture, and reflectivity / absorptivity. This was determined using the following steps and Equations (13) through (17):

1. First, we determined the effective lens area. This took into account the percentage of the diameter that is effective.
   \[
   A_{\text{LensEffective}} = \pi \left( \frac{D_{\text{lens}} \times \text{ClearAperture}\%}{2} \right)^2 \quad (13)
   \]

2. We next determined area of the light emitted from the bulb. This is dependent on the distance of the bulb from the lens. Using the Equation (14), we derived the light area. Refer to Figure 29 for variable definitions.
Using the lens area to light area ratio, we determined the amount of irradiance that the lens would be exposed to.

\[ A_{Light} = \pi \left( \frac{D_{Bulb} + 2h \tan \theta}{2} \right)^2 \]  \hspace{1cm} (14)

To find the irradiance that will be felt by the sensor, we multiplied the irradiance value from step 3 by the magnification rate and the % of irradiance transmitted through the lens (1-loss %)

\[ Irradiance_{Sensor} = Irradiance_{Lens} \times M \times \%_{Transmitted} \]  \hspace{1cm} (15)

We used Equation (17) to determine the power (Watts) on the sensor pinhole

\[ Power_{Pinhole} = Irradiance_{Magnified} \times A_{Pinhole} \]  \hspace{1cm} (17)

Using the Watts on Pinhole versus Digital Counts Graph, we found the digital count output.
We then determined the associated counts if the lens was moved closer to the sensors, or further away (tolerances). To calculate this, we changed the $f_b$ value, distance from the lens to the sensor, and then completed all the previous steps with the new magnification rate. A positive addition to $f_b$ placed the focal point before the sensor, a negative addition to $f_b$ placed the focal point after the sensor.

The final consideration was the focal length and the distance from the lens to the object. These properties were the biggest trade-off areas. The design of the light bar, distance from module, angle of the bar was dependent on those two properties. See Chapter 4 for more information regarding the design.

After determining the lighting and the collection optics criteria, we chose lights and optics that met the qualifications set by our calculations.

### 3.2.1 Collection Optic Options

After analyzing the collection option requirements, we were able to narrow down the list of collection optics to nine options. Each of the optics had the required magnification rate that gave the amount of needed power. The associated digital counts for the collection optics are shown in Table 8. The green highlighted optic gave us the desired amount of counts when adding a tolerance of 0.5in and -0.5inches. This optic also met the size requirements and was readily available for delivery. This was the optic that we used for the testing of the optical sensors.
Table 8. Collection Optics

<table>
<thead>
<tr>
<th>Item#</th>
<th>Diameter (mm)</th>
<th>f (mm)</th>
<th>fb (mm)</th>
<th>Price</th>
<th>M (magnification)</th>
<th>W at pinhole</th>
<th>Associated Counts</th>
<th>∆fb</th>
<th>Count Tolerance (fb+0.5 inches)</th>
<th>Count Tolerance (fb-0.5 inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA1399</td>
<td>50.8</td>
<td>175</td>
<td>170.6</td>
<td>$25.30</td>
<td>40</td>
<td>0.98</td>
<td>4845.95</td>
<td>12.70</td>
<td>3119.55</td>
<td>4007.99</td>
</tr>
<tr>
<td>LA1979</td>
<td>50.8</td>
<td>200</td>
<td>195.9</td>
<td>$25.30</td>
<td>49</td>
<td>1.20</td>
<td>5583.51</td>
<td>12.70</td>
<td>3679.31</td>
<td>4608.74</td>
</tr>
<tr>
<td>LA1301</td>
<td>50.8</td>
<td>250</td>
<td>246.4</td>
<td>$25.15</td>
<td>69</td>
<td>1.71</td>
<td>7275.49</td>
<td>12.70</td>
<td>5026.02</td>
<td>6019.65</td>
</tr>
<tr>
<td>LA1353</td>
<td>75</td>
<td>200</td>
<td>193.4</td>
<td>$34.25</td>
<td>30</td>
<td>1.00</td>
<td>4928.60</td>
<td>12.70</td>
<td>1315.62</td>
<td>3786.68</td>
</tr>
</tbody>
</table>

Figure 31 shows the associated counts with respect to various collection optics focal lengths. The highest amount of counts was reached with a focal length of 250mm and 60x magnification.

3.3 Summary

The optoelectronic combination of the tungsten halogen 100 watt, 120 volt bulb and the optic with 250mm focal length provided enough irradiance to produce the amount of counts needed to excite the optical sensors. The light source selection was ideal given the shape and electrical properties; it had plenty of power to excite the high power sensors on the payload.
Chapter 4 Design and Mechanical Analysis

The initial designs of the system were analyzed, both thermally and structurally, and then re-designed to meet the desired specifications. This allowed for an optimal design and helped ensure that the theoretical thermal and structural analysis was accurate.

4.1 Design Parameters/Specifications

The parameters for the final product included system safety for the operators and the payloads, light bar adjustability so the lights can focused directly on the sensors, have the system fully autonomous, and lastly, the design needs to test two payloads, one on each side of the dolly.

4.2 Design Concepts

To reach the final design, several iterations were necessary. One original design was for the light bar would be positioned longitudinally along the center of the payload and the support bars move between payloads or slide along the dolly. Although this design was feasible and simple, it required a too much operation needs than others.

The final design consists of a single stationary bar with lights attached to it, radiating down onto the payload as the payload rotates on the support wheels. An optic bar is located between the lights and the payload, consisting of collection optics to focus the beam on a single sensor. The two bars are supported at each end of the payload.
Having the support bars fixed in-between the two payloads with the light bar attached, this alignment allows the light bar to rotate or tilt between payloads while the connected supports remain fixed. This final design met all of the specifications and parameters that were set in place.

4.3 Final Design

The final design is simple, making it easier to manufacture and build. The mechanical system requires little movement allowing a quicker and more practical transition between payloads. The following sections detail the parts for the system.

4.3.1 Dolly

The dolly is the platform used to transport and rotate the optical sensor modules and telemetry module. Each assembled payload weights nearly 1000lb, making the dolly critical for testing and analysis purposes. As shown in Figure 32, the dolly can support two payloads in an easily rotatable set-up. Many of the parts for the test system are attached to the dolly.
4.3.2 Support Bar and Lock

The support bar holds the light and optic bars and attaches the bars to the dolly. Each support bar attaches to an end of the dolly with four bolts through the wheel housing. An aluminum support block, places in the wheel housing space, evenly distributes the stress onto the housing. The support holds the light bar above the payload so the optic bar is exactly nine inches, the focal length of the collection optics, from the surface of the modules. There are two notches cut from the sides about half way up the bar to for payload clearance.
This bar supports the light bar with two pins, extruding from the bar, that sit in a top loaded cradle. The top loaded aspect removes any chance of the pins falling out of the cradle. The cradle is shaped to allow for the light bar to tilt facing either payload. A locking mechanism slides over the two pins and screws into the support to keep the bar in the correct position. When the bar is locked in place it will focus the light to be normal to the surface of the payload.

![Support Bar, Pins, and Locking Device](image)

**Figure 35. Support Bar, Pins, and Locking Device**

### 4.3.3 Extension Beam

The extension beam was added to both sides of the light bar after learning the telemetry module is attached to the payload during the test. The beam’s purpose is to extend the light bar length to cover the added telemetry module length. The material is a four-inch stock I-beam. By using an I-beam, the part will be lighter and will reduce bending. On each end modified clamps are bolted to the I-beam enabling the light bar and support pins to attach.
4.3.4 Light Bar

The light bar is just over three meters long, spanning the length of the three optical sensor modules. All forty-eight light sockets are screwed to the underside of the bar designed with the wires running along the underside. An aluminum plate is attached to each end of the light bar is designed so it can be bolted to the extension beam and for the attachment and adjustment of the optic bar. Utilizing a bolt and slot system, the optic bar has a vertical adjustment of a maximum of plus or minus a quarter of an inch. This accounts for any tolerances of the manufactured parts and the optics themselves.
A structural analysis was completed to ensure that this design wouldn’t have a significant amount of bending caused by stress (See Figure 38). The analysis showed a maximum deflection of just over 6mm, which is not significant enough to affect the results.

![Figure 38. Structural Analysis of Light and Optic Bar](image)

4.3.5 Optic Bar

The optic bar also needs to be easily attached to the light bar, able to rotate, be adjusted, and to hold the optics in place. The optic bar has forty-eight counter bored holes the optics sit in. The counter bores are small enough to hold the optics while not obstructing the optics’ effective lens area. A thin aluminum support lays over the optic bar to hold the optics in place. The holes in the support are smaller than the diameter of the optical lenses, but it does not obstruct the effective lens area.
4.3.6 Thrust Stopper

Figure 40 shows a free body diagram of the payload when it is positioned on the dolly. Once the payload starts to rotate, a torque will cause the payload to be translated in the longitudinal direction, which is expressed by the green arrow.

This longitudinal displacement becomes a problem for the structural integrity of the telemetry module antenna. The dolly wheels on the telemetry module rotate around a thin strip of aluminum. If the wheels are displaced by more than 0.75 inches in either direction, then the wheels will be rotating on the antenna, which are not able to support the wheels. Figure 42 and Figure 43 depict the thrust stoppers that prevent longitudinal displacement of the payload. Once
the payload begins to rotate, the torque will cause it to press against the thrust stoppers, which have wheels attached to allow for rotating with the payload.

These thrust stoppers were designed with two primary objectives: withstand the torque emitted by the rotating payload to prevent longitudinal displacement; moveable along the longitudinal direction to ensure the wheel is tangential to the outer ring of the telemetry module. The straight slot located on the I-beam allows for the back and forth movement of the telemetry module thrust stopper, as shown in Figure 44. This is important in moving the wheel to align with the outer ring of the telemetry module.
The TM thrust stopper consists of a long beam extending across the dolly. ANSYS calculated the maximum force along the longitudinal axis of the payload to be 250N, see Figure 44 for a visual depiction.

We calculated its deflection of the thrust stoppers when a load of 250 Newtons is applied. The maximum deflection for the telemetry module and optical sensor module are 6.16e-5 mm and 6.7e-5 mm, respectively (See Figure 45 and Figure 46). We concluded the thrust stoppers are suitable to prevent the payload from moving in the longitudinal direction.
4.4 Dynamical Analysis on Payload

To analyze the external forces acting on the payload to ensure the design is feasible we analyzed each design objective:

1. **Determine the minimum force emitted by the proposed motor pulley system that would cause the payload to lift off of the dolly.**

The minimum force that would cause the payload to lift off of the dolly was calculated by analyzing the position of the current dolly supports. The total weight of the payload is 965lb. In
Figure 47, the length between the end of the OSM side of the payload and the closest support is 20.6”. This is 52.32% of the total length of one OSM. Assuming that the weight of the OSM’s is equally distributed, we took 52.32% of the 238lb OSM in order to calculate the total weight of the 20.6” portion of the OSM. We calculated it to be 124.5 lb. Taking this weight and subtracting it from the total weight of the payload; we were able to determine the minimum force needed for the pulley system to exert on the payload in order to move the payload in the direction of the green arrow displayed in Figure 47.

Payload weight – weight of 20.6” section = weight needed to move payload in the y-direction. = 965lb – 124.5lb = 845.43lb

Seeing that the pulley system would have to exert a force of at least 845.43lb to cause vertical movement of the payload, we determined that this would not be a major issue.

\[ \text{Figure 47. Dynamical Analysis on Payload} \]

2. **Determine the velocity of the payload when it is rotating at 1 rpm to see if it would rotate off of the dolly.**

   Below is the step-by-step analysis on how we calculated the payload velocity:

   **Given:**

   \[ \text{Circumference} = 1.756m, \text{rotating at 1RPM} \]
\[
\omega = \frac{d\theta}{dt} = \frac{2\pi \text{ rad}}{60 \text{ sec}} = \frac{.105 \text{ rad}}{\text{sec}} \quad (18)
\]

\[
v = \omega \cdot r = \frac{.105 \text{ rad}}{\text{sec}} \cdot 0.279 \text{ m} = \frac{.0293 \text{ m}}{\text{s}} \quad (19)
\]

After taking the velocity of the payload and the assumed coefficients of friction between the payload and the wheel supports, we determined that the payload would not rotate off of the dolly. The velocity of the payload will be \(0.0293 \text{ m/s (0.652 miles per hour)}\) about forty six times slower than the average walking speed of a human. With further discussion with our advisor, we determined that the payload would not have enough velocity to rotate off of the wheels supports.

### 4.5 Summary

The final design of the preflight optical evaluation system allows MIT Lincoln Laboratory to accurately test all sensors on the optical sensor modules. Each part was designed to meet the parameters and specifications that were needed. The thrust stoppers will prevent longitudinal movement of the payload, important to guarantee accurate data collection. After using ANSYS to analyze the structural effects of rotating the payload, we determined the system met all the set requirements.
Chapter 5 Realization

5.1 Prototype

Due to the limited time frame of the MQP and the amount of time it takes to machine parts, there was not enough time to build the entire system before leaving MIT Lincoln Laboratory. Instead a smaller edited version of the entire system was designed in order to test that and prove the concept works.

5.1.1 Redesign

Since it was primarily the light bar and optic bar that was slowing down the process, those two parts were edited to be much shorter for a test. In order to prove the concept of the system worked properly, we had to not only show that the optical sensors would get excited, but also that the alignment of the lights worked as well. The only other edit that had to be made to the system was that the bar end had two extra tapped holes in it for the support pins to be screwed into (see Figure 48). This would allow for the shortened light bar and optic bar to be used without having to add on the bar extension. This extension is not necessary because the test will be done with only the three OSM’s and not the telemetry module. Since the TM is not being used the payload does not have to be offset on the dolly when being tested, ridding the need of the extension beam. With the two extra tapped holes, the bar end could still be used for the full system in future tests; no extra bar ends would need to be made.

Figure 48. Bar end with added tapped holes (outlined in orange)
5.1.2 Test

The prototype was successfully built before the end of the project, but was unfortunately unable to be tested. There was other activity in the MARTI program such as testing, and preparing to ship to California for launch, that restricted the group from being able to complete a test on the payloads before the completion of the project. However, from visual inspection and computer tests, there was analytical success for the test prototype as well as the design and concept of the entire system.
Chapter 6 Conclusions and Recommendations

The optical sensor evaluation system will provide Lincoln Laboratory the last step to test all of the sensors on the Missile Alternative Range Target Instrument. It has provided an easy and automated method for completing the sensor testing. Many of the parts created for the system had to be iterated several times and we acknowledged that the initial design did not always work. Mechanical and thermal analyses were critical in ensuring that the design for each part was practical and feasible.

6.1 Importance of Design Iterations and Analysis

The design work for our project could not have been completed without the proper mechanical and thermal analysis. After completing analyses, we were able to alter and iterate our designs to ensure that they would work with the system. Without iterating our designs, the evaluation would simply not work. This helped our project team realize that this is an extremely important aspect of any major design project.

6.2 Value of the Sensor Evaluation System to Lincoln Laboratory

Each of the Missile Alternative Range Target Instruments are being created and tested on for the advancement of the Airborne Laser Program put on by the U.S. Department of Defense. A large amount of money was put into researching and creating the MARTI’s and if the sensors did not work properly prior to flight, then the entire prior work becomes meaningless. The sensors need to be functional in order to output data on the laser’s accuracy and irradiance levels. This optical evaluation system is extremely important to Lincoln Laboratory because it will let them know if the sensors are working or not prior to flight.

6.3 Recommendations for Future Development

In order for the optical sensor evaluation system to be valuable, we suggest that Lincoln Laboratory move forward with more analysis and design work. During our work on the project for nine weeks, we were not able to fully develop the system. The system needs to be fully machined and assembled for all of the optical sensors to be tested at once.
6.3.1 Method for Rotating the Payload

A motor with the correct horsepower and RPM capabilities will allow the payload to rotate freely and slow enough to accurately determine which sensors are working correctly. If the motor was not capable of running at a low RPM (i.e. 1-3RPM) then it would be more difficult to link each optical sensor with specific digital counts. One of the major problems when analyzing motors was how to create a design where it could be easily attached to the dolly and not prohibit the dolly from rotating. Figure 49 shows the design that we recommend to attach a motor to the system.

![Figure 49. Motor and Pulley System for Payload Rotation](image)

The design includes a pulley system that attaches to the payload and a motor that sits directly on the dolly. The motor will transmit horsepower through a series of gears that will be connected to the optical sensor module side of the payload. The slotted ring that is shown in Figure 49 connects directly to the end of the optical sensor module and allows the motor to easily rotate the payload.

We used the formula below to determine the maximum amount of horsepower that could be used with the system. Each bulb on the light bar has 120V and the series of sixteen lights puts out 6 amperes of electrical current. The efficiency of .78 can be seen in Table 9. With these considerations, we recommend that a motor be used with a maximum of .75HP and a minimum of .168HP, as shown from Equations (20) and (21).

\[
MaxHP = \frac{V * I * Eff}{746} = \frac{120V * 6Amps * .78}{746} = .75HP \quad (20)
\]
Using Example 5.5 in Hibbeler as a reference, we were able to calculate the required diameter of the motor’s shaft if it is being used with 0.5HP and at 2RPM. We first calculated the power and angular velocity of the shaft:

\[ P = \frac{550 \text{ft} \cdot \frac{\text{lb}}{\text{s}}}{1 \text{ hp}} = 275 \text{ ft} \cdot \frac{\text{lb}}{\text{s}} \]  
(22)

\[ \omega = \frac{2 \text{ rev}}{\text{min}} \cdot \frac{2\pi \text{ rad}}{1 \text{ rev}} \cdot \frac{1 \text{ min}}{60 \text{ sec}} = \frac{209.44 \text{ rad}}{\text{sec}} \]  
(23)

Since \( P = T\omega \),
\[ T = 1313.03 \text{ ft} \cdot \text{lb} \]  
(24)

\[ \frac{I}{c} = \frac{\pi}{2} \cdot \frac{c^2}{c} = \frac{T}{\tau} \]  
(25)

Solving for “c” in Equation (25) gives us .8845 inches, which represents the shaft’s radius. Thus, the required diameter of the shaft to rotate the payload would be 2c or 1.77 inches.

The final design of attaching the motor to the dolly was not reached until we analyzed several other options. The original idea for freely rotating the payload was to attach a bar across the payload diameter and use this bar as the driving force for rotation. The main problems of this design were how structurally stable the design would be with the torque requirements and whether or not it would be able to be designed without getting in the way of the thrust stopper.
Several other design ideas for rotating the payload were drafted, but were dismissed with some analysis. Both ideas involved using the existing wheels attached to the dolly as a means for payload rotation. The problem was the low coefficient of friction between the wheels and the payload. Since the wheels were originally designed to prevent friction on the payload, they would not be a great source for rotating the payload. In order to use the wheels to rotate the payload, enough friction would have to be produced to prevent slippage.

6.3.2 Configuring Wiring for the System

Since we were not able to configure the wiring for the optical sensor evaluation system, we recommend that the wiring be done in a way that will not get in the way of the rotating beams and that will allow the system to test both the HP and LP MARTI. The current design of the system does not have holes or slots for wiring purposes; these would have to added if Lincoln Laboratory decides it is the best way to attach the wires. Clamps that could easily attach to the light bar would be the best alternative to drilling holes.

6.3.3 Testing High Power and Low Power MARTI

In order to ensure that the system is able to test both the HP and LP MARTI, a variac would be useful to alter the amount of irradiance. If the existing lights were used on the LP that are used for the HP then the sensors would be ruined. The variac would be needed to reduce the amount of power emitted onto the optical sensors. However the wires are configured, Lincoln Laboratory needs to remember that only sixteen lights can be used at any given time when testing the HP MARTI. This is due to the electrical current limitation of twenty amperes.
6.3.4 Additional Support to Prevent Beam Deflection

From our calculations, the maximum deflection of the light bar will be less than 6mm. If this amount of deflection poses a problem to the system, we recommend that bolts be added between the optics to hold the optic bar tighter to the light bar.

6.3.5 Create Operating Manual for System

There are specific reminders that anyone using this equipment to test the sensors should be aware of and know. It would certainly be useful for the operators to fully understand all of the parts associated with the system and any problems that may arise. We recommend that Lincoln Laboratory create an operating procedure for the system to ensure that all future operators know how to use the system. Here are some of our suggestions for operating the system:

- Use the crane to lift the system to prevent injury
- Use gloves or some type of heat resistant material to touch the light bar or optic bar is something needs to be changed.
- Only operate sixteen lights at any one given time to prevent shorting the circuit.

6.4 Summary

This project has great significance to Lincoln Laboratory’s overall progress on the Missile Alternative Target Instrument project. All of the parts have been completely designed and a large part of the relevant analysis has been completed, but all of the parts need to be machined in order to bring this project to fruition. It has provided LL a practical method for testing the sensors and hopefully it can be used as guidance for testing other payload sensors.
Work Cited


Boast, W., B. (2009). Light panel. AccessScience@McGraw-Hill,


Ref. 1 "Convex Lens." Available 30 September 2009
http://passmyexams.co.uk/GCSE/physics/images/convex_lens.jpg

Ref. 2 "BK7 Plano-Convex Lenses (Uncoated)." Thor Labs 2009; Available 3 September 2009

## Appendices

### Appendix A Final Light Selection

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T10 eLightBulbs (Courtesy of eLightBulbs)

MR16 eLightBulbs (Courtesy of eLightBulbs)
MR16 Superior Lighting (Courtesy of Superior Lighting)

MR16 Bulbtronics (Courtesy of Bulbtronics)
## Appendix B Optics Choices

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Appendix C Drawings

Housing Block
Support Bar
Pin Brace
Extension Beam
Extension Plate
Light Bar
Optic Bar
Optic Support
Test Light Bar

#10-32 Tapped Hole
THRU x 4

#10-32 Tapped Hole x 4
Test Optic Bar
Optical Sensor Module Thrust Stopper
Telemetry Module Thrust Stopper

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Chris Jeznach

Telemetry Module Support Bar

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MANUFACTURING TOLERANCE NOTE:

NOMINAL TOLERANCE [

MATERIAL:

AI 6661

FINISH:

NICKEL

APPLICATION:

DO NOT SCALE DRAWING

REV

SCALE: 1:12 WEIGHT:

SHEET 1 OF 1

DRAWN: C.J. 9/29

CHECKED

SIGNED:

APPROVED

SIGNED:

SIGNED

COMMENTS:

5  4  3  2  1