FINAL
03-2348

DEVELOPMENT OF A SAFE GROUND TO SPACE LASER PROPAGATION SYSTEM FOR THE OPTICAL COMMUNICATIONS TELESCOPE LABORATORY

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ABSTRACT

Furthering pursuits in high bandwidth communications to future NASA deep space and near-Earth probes, the Jet Propulsion Laboratory (JPL) is building the Optical Communications Telescope Laboratory (OCTL) atop Table Mountain in southern California. This R&D optical antenna will be used to develop optical communication strategies for future optical ground stations. Initial experiments to be conducted include propagating high-powered, Q-switched laser beams to retro-reflecting satellites. Yet laser beam propagation from the ground to space is under the cognizance of various government agencies, namely: the Occupational Safety and Health Administration (OSHA) that is responsible for protecting workforce personnel; the Federal Aviation Administration (FAA) responsible for protecting pilots and aircraft; and the Laser Clearinghouse of Space Command responsible for protecting space assets. To ensure that laser beam propagation from the OCTL and future autonomously operated ground stations comply with the guidelines of these organizations, JPL is developing a multi-tiered safety system that will meet the coordination, monitoring, and reporting functions required by the agencies. At *Tier 0*, laser operators will meet OSHA safety standards for protection and access to the high power laser area will be restricted and interlocked. *Tier 1*, the area defined from the telescope dome out to a range of 3.4–km, will utilize long wave infrared camera sensors to alert operators of at risk aircraft in the FAA controlled airspace. *Tier 2*, defined to extend from 3.4-km out to the aircraft service ceiling in FAA airspace, will detect at risk aircraft by radar. Lastly, beam propagation into space, defined as *Tier 3*, will require coordination with the Laser Clearinghouse. A detailed description of the four tiers is presented along with the design of the integrated monitoring and beam transmission control system.

1. INTRODUCTION

As National Aeronautics and Space Administration (NASA) space mission technology advances, so too must communications for future missions to downlink increasing amounts of data and uplink commands faster than by conventional means of communication. NASA's pursuit in high bandwidth communications has paved the way for the Jet Propulsion Laboratory (JPL) to build the Optical Communications Telescope Laboratory (OCTL) [1], to serve as a research and development optical antenna. Located at the JPL Table Mountain Facility in southern California, the OCTL houses a 1-meter aperture telescope built for both daytime and nighttime operations that is dedicated to optical communications. Not only will this ground station be utilized as a test bed for optical communication strategies, but will also serve as a model for future ground stations to ultimately create a network of remote autonomous stations. Among some of the early experiments planned, operations will include propagating high-powered, Q-switched laser beams to uplink commands to deep space probes and provide a pointing and tracking beacon for downlink communications. However, laser beam propagation from the ground to space must follow the requirements and guidelines established by various government agencies. One such agency is the Occupational Safety and Health Administration (OSHA), which is responsible for protecting workforce personnel. The second agency is the Federal Aviation Administration (FAA), which is responsible for protecting pilots and aircraft. And the third agency is the Laser Clearinghouse of Space Command, which is responsible for protecting space assets. This paper aims to describe the laser safety approach taken to address each agency and the design of an integrated monitoring and beam transmission control system to be implemented at the OCTL. The scope of this paper will be limited to discussion of providing protection external to the laboratory, where designing safety measures to support autonomous operations was the most challenging.

2. OCTL LASER PROPAGATION SAFETY APPROACH

The approach taken to free-space beam propagation safety at the site begins with dividing the space into internal and external areas. Safety within the internal area, designated *Tier 0*, is solely regulated by OSHA and enforced by the JPL safety office. Within the external area, safety is governed by the FAA and U.S. Space Command. In order to address each agency, the external area is further divided into three regions, designated *Tiers 1* through *3*. An illustration of the divided external safety zone is shown in Fig. 1. Although the safety approach is discussed at length in Wilson, et al [2], an overview of *Tiers 1* through *3* follows for the reader's benefit.

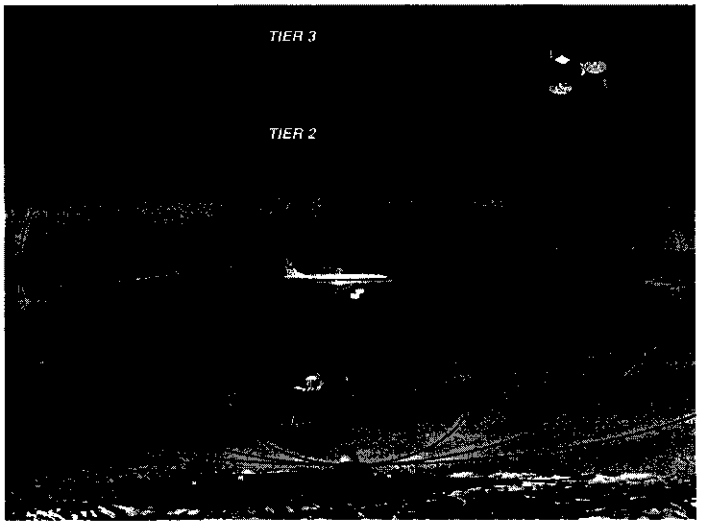

Fig. 1. The three JPL defined safety tiers for ground to space laser beam propagation from the OCTL.

Implementing safety measures external to the laboratory is a challenging task, since within FAA controlled airspace, the types of measures are highly dependent upon the constraints of the laser propagation site and the nature of the project. Such factors include the amount of traffic and type of aircraft predominant in the vicinity, the duration and frequency of the exercise, beam path direction and movement, etc. To support an autonomous site, the airspace is separated into two regions where a different detection system will be employed to surveillance each area. The *Tier 1* region was defined as the space where the beam exits the building at the telescope dome out to a range of 3.4 km. Where human spotters were endorsed by the FAA in the past for similar experiments conducted at Table Mountain, an optical imaging system will be adopted to identify aircraft that may be flying close to the mountainous terrain and lost in the background clutter of a radar return. *Tier 2* was designated as the ellipsoidal region spanning to 20 km at zenith and 58 km at 20° elevation around the building. Aircraft detection within *Tier 2* will use a method based on the radar display interface (RDI) system [3] that was developed for the Air Force Maui Optical and Supercomputing (AMOS) facility. The AMOS RDI system displays aircraft positions, supplied by a feed from the local traffic control center (TRACON), superimposed on a topographic map of the Hawaiian Islands. For implementation at the OCTL, the San Diego TRACON will supply a unidirectional feed based on data from the Boron and Long Beach FAA radar systems. However, development of an RDI type system designed for the OCTL awaits completion of a joint NASA and FAA Memorandum of Agreement (MOA) that will address the necessary *Tier 2* requirements identified by the FAA. As an interim measure, *Tier 2* aircraft detection will use a weather radar system that was utilized in past optical communication demonstrations conducted at Table Mountain. The last region of the defined external zone was designated *Tier 3*. Beyond the FAA controlled airspace, the Laser Clearinghouse imposes the use of predictive avoidance to protect space assets ranging from near-Earth to geo-stationary orbits. Based on the detection information from each tier, safety external to the laboratory is implemented by programming a shutter to interrupt laser transmission.

3. MULTI-TIER INTEGRATION DESIGN

Since the chosen safety approach implements an independent monitoring system for each tier, the shutter control command can be generated at different times and triggered or cleared by object detection from any or all of the three

tiers. Therefore, monitoring information from each tier must be assembled and coordinated prior to commanding the shutter. In addition, steps must be taken to avoid commanding the shutter based on invalid monitoring information, due to either power failure or system malfunction. In the case of remote or autonomous stations where an operator will not be available to check the equipment, equipment status information must also be retrieved and coordinated prior to commanding the shutter. Integrating each tier into a unified external safety system then requires: (1) information processing for each tier to identify at-risk objects; (2) an electrical output from each tier signaling object detection; (3) an electrical output from each tier signaling equipment status, that is whether equipment is powered and functional or not; and (4) electronics to assemble and coordinate information from each tier, and command the laser shutter.

3.1 *Tier 1* Integration

The *Tier 1* safety sensor is a custom built packaged system developed by Image Labs International (ILI), see Fig. 2. The system implements a pair of long-wave infrared (LWIR) cameras, offering a narrow and wide field of view, which when bore-sighted to the telescope will enable aircraft detection during both daytime and nighttime conditions. The ILI system also includes its own driver electronics and dedicated computer with object detection and control software that acquires images at a rate of 30 Hz. Since the cameras will be moving with the telescope, objects in the images may appear to move either faster or slower than its' actual speed. The ILI object detection algorithm has been designed to nullify the apparent motion caused by the moving cameras when given telescope pointing direction and velocity.

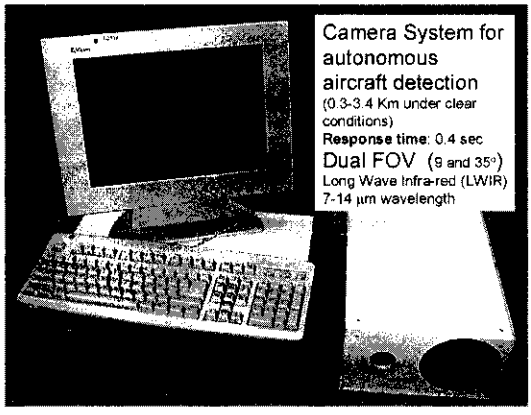

Fig. 2. Image Labs International LWIR detection system for *Tier 1* aircraft avoidance.

Following the integration requirements outlined above, images acquired by the cameras are processed within the control system to identify at-risk objects. However, the system requires a serial port connection from the telescope control system to enable the ILI object detection software to function effectively when the cameras are mounted onto the telescope. The telescope manufacturer has provided a serial output from the telescope control system that can be directly connected to the ILI dedicated computer. This connection allows the telescope motion parameters to be passed in the ILI specified format to the object detection software at a transfer rate of 30 Hz. Addressing the integration requirements for detection and equipment status outputs, the system electronics provide one electrical output to signal laser interruption for use with an external shutter control system. The output provides a continuous +5 VDC signal until either an object is detected, the control software is non responsive such as an operator changing the control software configuration settings during operations, or power is cut from system electronics, in which case a voltage drop occurs so that a continuous +0 VDC signal is output. Yet for remote or autonomous operation, it would be advantageous to debug the system remotely. The system electronics have been designed so that object detection can be distinguished from a system failure. The design provides an additional electrical output, which generates a continuous +5 VDC signal when the equipment electronics is powered and the control software is responding and a continuous +0 VDC signal otherwise. The original system signal output was left unmodified to serve as the object detection signal. Both the status and detection signals are updated at the system's sampling rate of 30 Hz.

3.2 *Tier 2* Integration

Until an OCTL RDI system is developed, the *Tier 2* monitoring system will use a JPL modified Honeywell Primus-40 weather radar. The radar system, shown in Fig. 3, consists of a transmitter/receiver unit that operates at a rate of 121 Hz, a display/control module, and an antenna that will be bore-sighted to the telescope. Additional electronics were developed to relay both sensor and object detection status from the original unit to outputs that can be read by an external shutter control system [4]. Similar to the modified ILI system, one of the outputs provides a continuous +5 VDC signal when the electronics are powered and a continuous +0 VDC otherwise. The additional electronics also provide a continuous +5 VDC signal when an object is detected and a continuous +0 VDC signal otherwise. Since the radar will be mounted onto the telescope, false detection could occur from the surrounding mountainous terrain when the telescope is pointing near the horizon. In addition to the integration requirements outlined, the unified system will be provided with a coordinate map of the terrain and a way to access the telescope pointing parameters. Not only will this requirement prevent false radar detection, but also prevent fires should the local terrain block laser transmission.

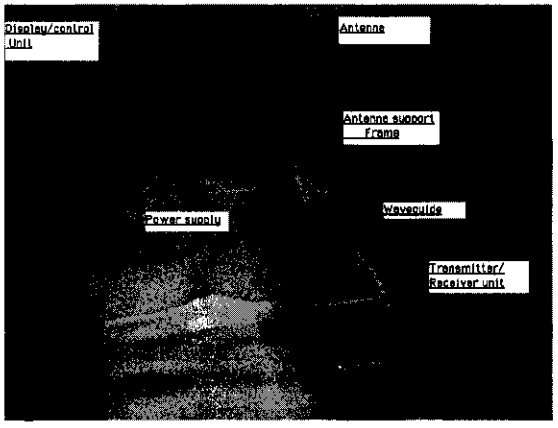

Figure 3: JPL modified Honeywell Primus-40 weather radar system for *Tier 2* aircraft avoidance.

3.3 *Tier 3* Integration

Unlike the previous two tiers, *Tier 3* implements laser transmission coordination rather than a sensor package. Laser propagation into space requires that the laser and its' site be registered with the U.S. Space Command. Based on that information, Laser Clearinghouse determines whether coordination of laser activity is required. Should laser operation require such coordination, the operator must provide permissions from target owners prior to experiments. Once permissions are filed, the operator will provide a list of experiment times and pointing directions to the Laser Clearinghouse for approval at least 48 hours in advance of laser transmission. The Clearinghouse will then respond 24 hours prior to experiments with a list of times that laser transmission is precluded. Then additional requirements for the unified safety system include access to the list of precluded transmission times and maintaining accurate system time.

4. LASER SAFTEY MONITORING SYSTEM DESIGN

The Laser Safety Monitoring (LSM) system under development is an integrated system that will receive and process inputs from *Tiers 1* through *3* to command a beam-interrupt shutter system. The three tiers are unified through a PC with a Windows® based application program developed at JPL. The program provides coordination of the shutter command by collecting equipment status and object detection signals output from *Tiers 1* and *2* using a PCI-bus I/O card, and internally processing predictive avoidance information to determine the validity of the supplied information and whether predictive avoidance is in effect. The predictive avoidance data processing is achieved by comparing the list of precluded transmission times against the computer's system time. Although computers are notorious for clock drift, a PCI-based IRIG B time code reader card will be used to continuously synchronize the computer clock with that of the telescope control system for consistency. After evaluating the information provided from all the tiers, shutter commands are issued and delivered through the same I/O card to the shutter drivers to

block laser beam propagation. In addition, the program logs the activity of each tier and the corresponding system response to a file providing a record for future inspection, should the need arise, and offers a unified user display for the multi-tier safety system.

4.1 Beam-Interrupt Shutter

The LSM system will implement two beam-interrupt shutters, where the primary shutter will be located within the laser cavity to preclude lasing and a redundant shutter placed in front of the laser beam-lok in case the primary shutter should fail. Both shutters are spring loaded and controlled by driver electronics, which allow the shutters to be activated permitting beam propagation when an external +5 VDC voltage is applied and automatically close blocking the beam path when a voltage drop occurs. As a final validation that the laser is shuttered as commanded, a photodiode detector will be used to measure the intensity of the transmitted laser beam. As shown in Fig. 4, the detector will be placed behind a beam splitter located in the laser transmission optical train. The detector was also modified to provide two separate signal outputs to form a shutter loopback system. Similar to the required tier outputs, one output provides information on beam propagation with a continuous +5 VDC signal when the beam propagates through the transmission optical train and a continuous +0 VDC signal when transmission is blocked. The other output provides information on the detector status with a continuous +5 VDC signal when the detector is supplied with power and a continuous +0 VDC otherwise.

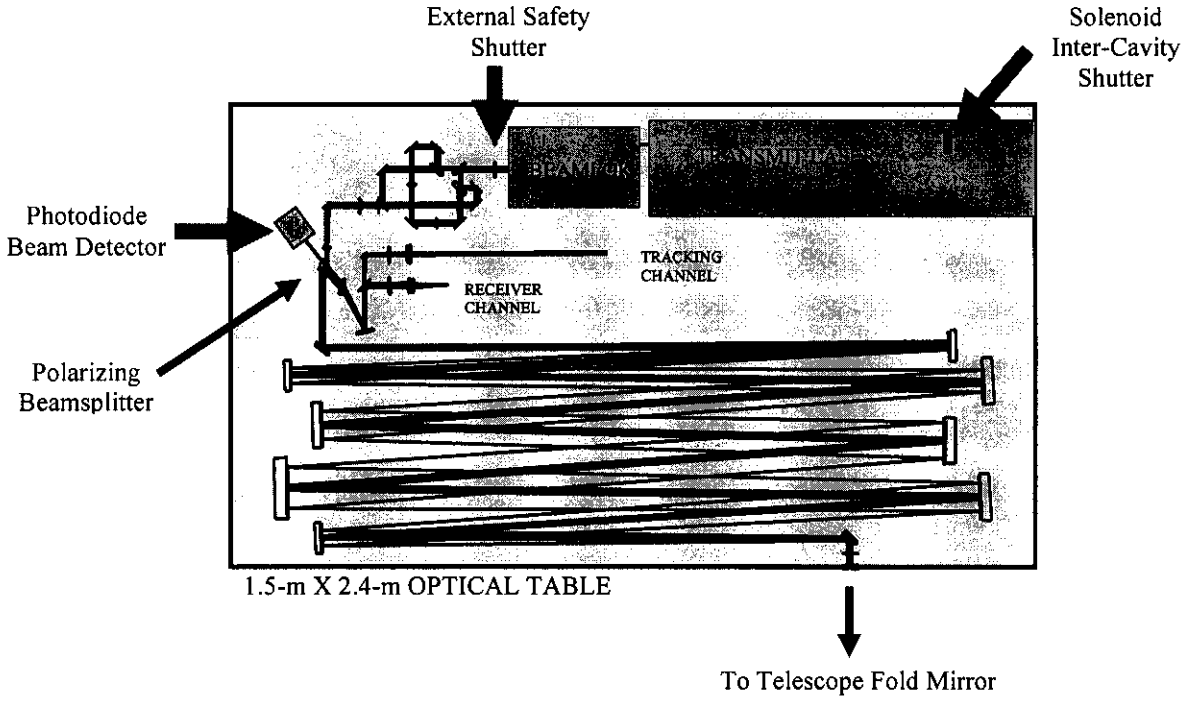

Fig. 4. LSM beam-interrupt shutter system hardware.

4.2 Tier Coordination and Shutter Control

At the onset of operation, the LSM application program prompts the user for the files containing the site terrain and predictive avoidance data. Before storing both sets of data into a lookup table, the format of the data are first checked to verify the validity of the files. The program then checks the site terrain data to make sure the terrain elevation is defined for the full azimuth range of the telescope, and the predictive avoidance data is compared to the computer system time to determine whether the times listed for unapproved laser propagation are expired or valid. If both sets of data prove to be acceptable, a continuous loop is initiated to process the predictive avoidance data and retrieve the output signals from *Tiers 1* and *2* through the I/O board at a rate of 18,150 Hz. This retrieval rate was determined by taking the least common multiple of the *Tiers 1* and *2* operating rates. Concurrently, the program initiates a separate continuous loop to intercept the motion parameters from the telescope control system serial

output and compare the pointing elevation to the site terrain lookup table before routing the information to the ILI control system. Once all the tier information has been collected, the program applies a logical OR to the signals to determine whether the shutters should be activated to block the laser beam path. If yes, the corresponding shutter command is issued through the I/O board to the shutter drivers. However, if either the telescope pointing is below the terrain elevation for the corresponding azimuth angle or the photodiode detector status signal shows the detector is not powered, the program will command the shutter to block the beam path. Only when all the safety conditions are met, namely, each tier is running properly, no at risk object is detected, telescope pointing is above the terrain elevation, and photodiode detector is powered, will the shutter open. Once the command is issued, the program will retrieve the laser intensity signal from the photodiode detector to verify the shutter response. All signals are time stamped and recorded to file at a rate matching that of the tier that was triggered, i.e. 30 Hz if *Tier 1* or the telescope pointing is below the terrain elevation, 121 Hz if *Tier 2*, and once every 30 seconds for *Tier 3*. However, if any of the tiers or the photodiode detector do not respond, the operator is alerted immediately and all time stamped signals are recorded at a rate limited by the continuous tier coordination loop. A flowchart representation of the tier coordination and shutter control is shown in Fig. 5.

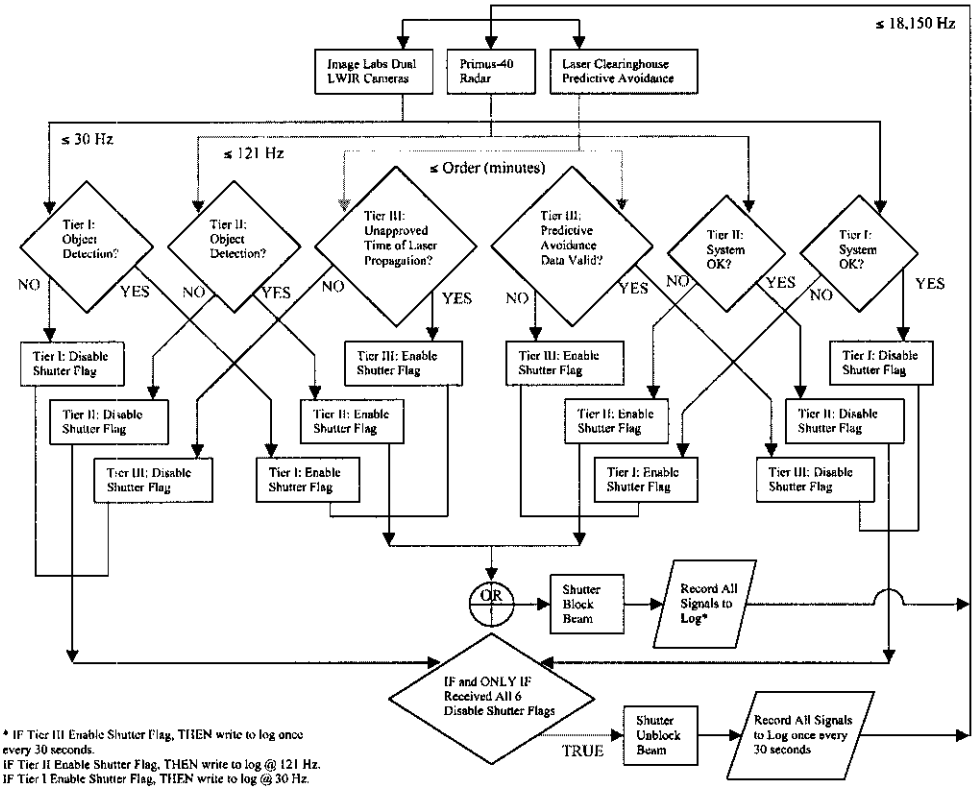

Fig. 5. LSM application software flowchart for shutter command coordination.

4.3 Response Time

Although the *Tiers 1* and *2* systems were specified to allow adequate time to respond to an at-risk object as a stand-alone system, the LSM response adds an estimated 0.165 seconds to the total response time from object detection to shutter activation. The specified response time for the ILI system is 0.4 seconds, making the total response approximately 0.565 seconds for an object detected in the *Tier 1* region. Considering a single engine plane traveling at 80 mph along the edge of the *Tier 1* region, the plane would have traveled 3.85° from the point of initial detection by the time the shutter is activated. Given that the wide and narrow fields of view have a pixel resolution of 0.14°/pixel and 0.04°/pixel respectively, the plane would have moved about 27 pixels in the wide field of view and 103 pixels in the narrow field of view on identical 320 by 240 pixel detectors. Since the square object exclusion zone surrounding the telescope bore-sight for each detector can be defined to a maximum of 240 by 240 pixels, the total response time for the *Tier 1* region allots enough time to block laser transmission. In the case of the radar system, the time from object detection to *Tier 2* signal output was estimated to be less than 0.001 seconds making

the total response at most 0.166 seconds. As a worst case scenario, considering a commercial airplane traveling at 500 mph along the outskirts of the maximum *Tier 1* range, the plane would have traveled less than 1° from the point of initial detection. Given that the half-angle field of view of the radar is ~5°, the total response time for the *Tier 2* region is more than sufficient to avoid illuminating the object.

4.4 User Display

The LSM application program user display, as shown in Fig. 6, is a Windows® styled window display for the operator to monitor each tier and the LSM system response. The display provides a five-minute time history plot of each tier's activity and the laser intensity signal from the photodiode detector. In addition, when the program has determined that it is safe for laser transmission, the label of each plot is highlighted in green. But when an object is detected, the label of the corresponding tier is highlighted in red. Likewise, the photodiode detector label is highlighted in red when the laser intensity shows the transmission is blocked. In the same column of labels, located near the top of the display, a label is dedicated to the status of the telescope pointing with respect to the site terrain elevation. The "treeline" label is highlighted in red when the telescope pointing is below the site terrain elevation. The display also provides updates to the status of the equipment/data using a row of highlighted labels located at the top of the window for the I/O board, photodiode detector, *Tier 1* sensor, *Tier 2* sensor, and predictive avoidance lookup table. Labels are highlighted in red when the input equipment status signals, read in through the I/O board, show the equipment is not responding. In the case of the I/O board, its' label is highlighted in red when errors are returned when the program communicates with the board. For the predictive avoidance lookup table, its' label is highlighted in red if either the data is expired as compared to the computer system time or the data file does not match the expected format. Since an encounter with an at-risk object is expected to be infrequent, the appearance of the display may remain the same for an extended period of time, which may also signal that the program has hung up. Since the display is updated at a rate of 4 Hz, the computer system time was added to the five-minute history plot time label to provide a running clock allowing the operator to verify that the program is executing.

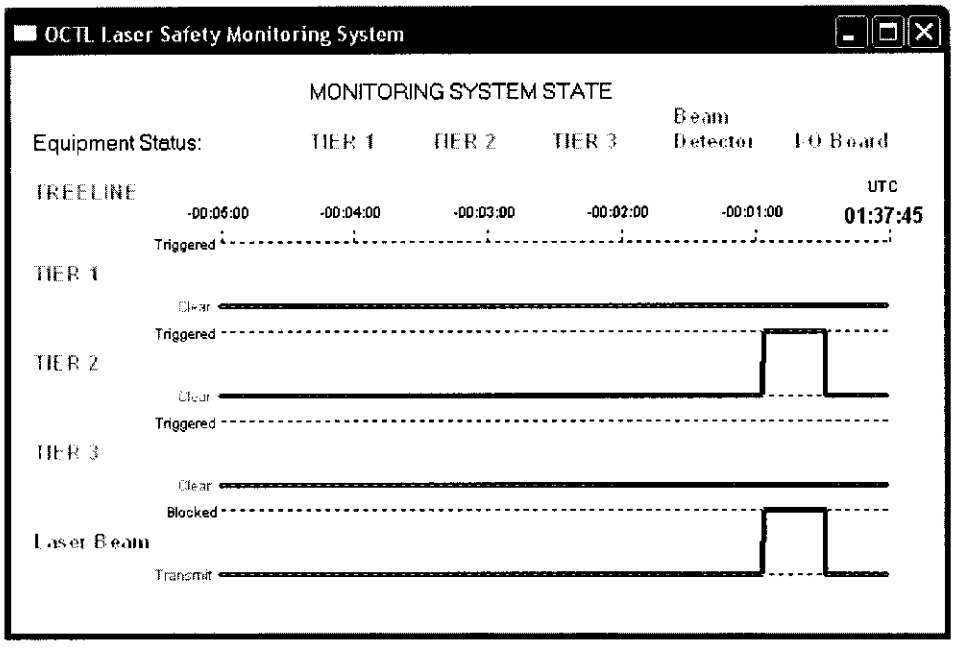

Fig. 6. LSM application program user display.

5. SUMMARY

This paper has described our approach for safe laser beam propagation from ground to space, and detailed the system design to implement the approach. The development of the LSM provides an integrated multi-tiered safety approach for high-powered laser transmission to space from the OCTL. The LSM not only provides a way to coordinate the multiple tier signals and command a beam-interrupt shutter response, but also offers a unified user

display that allows an operator to monitor each tier. Until an OCTL RDI system is developed, which awaits completion of a joint MOA between NASA and the FAA, the presented integrated system employs an interim approach for *Tier 2* aircraft detection. The system in its current configuration is scheduled for deployment at the OCTL in the fiscal year of 2004.

6. ACKNOWLEDGEMENTS

The author would like to thank Keith Wilson for his guidance, and Vachik Garkanian for his technical assistance and suggestions. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

7. REFERENCES

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