

A Multi-Tiered Safety System for Free-Space Laser Transmission from the Optical Communications Telescope Laboratory

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The Jet Propulsion Laboratory (JPL) has built the Optical Communications Telescope Laboratory (OCTL) atop Table Mountain in Southern California to serve as a research and development antenna, where communication strategies for future optical ground stations will be developed. Initial experiments to be conducted include propagating high-powered, Q-switched laser beams to retro-reflecting satellites. Laser beam propagation to space from the U.S. is under the cognizance of various government agencies, namely, the Federal Aviation Administration (FAA), responsible for protecting pilots and aircraft, and the Laser Clearinghouse of the U.S. Strategic Command (STRATCOM), responsible for protecting space assets. To ensure that laser beam propagation from the OCTL complies with the guidelines of these organizations, JPL has developed a multi-tiered safety system that will meet the coordination, monitoring, and reporting functions required by the agencies. Descriptions of each tier are presented, along with the design of the integrated monitoring and beam transmission control system.

I. Introduction

Pursuit of high-bandwidth communications for future missions by the National Aeronautics and Space Administration (NASA) has led the Jet Propulsion Laboratory (JPL) to build the Optical Communications Telescope Laboratory (OCTL) [1]. Located at the JPL Table Mountain Facility in Southern California, the OCTL houses a 1-meter telescope built for both daytime and nighttime operations to serve as a research and development optical antenna. Experiments to be performed at the OCTL will demonstrate a number of optical communication strategies, which will involve propagating high-powered laser beams through space. However, within the U.S., laser beam propagation to space must follow the requirements and guidelines set forth by the Federal Aviation Administration (FAA) and the Laser Clearinghouse of the U.S. Strategic Command (STRATCOM).

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The approach taken to address the concerns of each agency divides the space external to the building into three regions, designated Tiers 1 through 3 [2]. An illustration of the divided external safety zone is given in Fig. 1. The Tier-1 region was defined as extending from where the beam exits the building at the telescope dome out to a radius of 3.4 km, where small, low-flying aircraft predominate. Such aircraft, flying close to the mountainous terrain, would be lost in the background clutter of a radar return, so an optical system will be deployed to survey the Tier-1 region. Tier 2 was defined as the ellipsoidal region extending to 20 km at zenith and 58 km at a 20-deg elevation around the building. Within Tier 2, a radar system will be used to monitor the region dominated by commercial aircraft. The last region of the defined external zone was designated Tier 3. Beyond the FAA-controlled airspace, STRATCOM requires laser transmission coordination to protect space assets. Based on the detection/coordination information from each tier, safety external to the laboratory is accomplished by interrupting laser transmission with a shutter. This article presents the design of an integrated monitoring and beam transmission control system for the OCTL: Section II outlines the design requirements for integrating each tier, and Section III describes the integrated safety system.

II. Multi-Tier Integration Design

Since the chosen approach will implement an independent system for each tier, the shutter control command can be triggered by object detection or cleared by any one of the three tiers at any time. Therefore, detection 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 information, due to either power failure or system malfunction. Then, equipment status also must be retrieved and coordinated prior to commanding the shutter. Integrating each tier into a unified safety system then requires, at least, (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 outputs from each tier and to command the laser shutter.

A. Tier-1 Integration Requirements

The Tier-1 safety sensor is a custom-built packaged system developed by Image Labs International (ILI). Since optical communications is not limited to nighttime conditions, the system utilizes a pair of long-wave infrared (LWIR) cameras to permit aircraft detection during both daytime and nighttime



Fig. 1. The three JPL-defined safety tiers for ground-to-space laser beam propagation from the OCTL. Reprinted from [2].

experiments. The cameras operate simultaneously, and each camera provides a different field of view—a wide field of view to detect fast and relatively close aircraft and a narrow field of view to detect aircraft out to a range of 3.4 km. Both detectors are housed together in a single unit (see Fig. 2), which when mounted and bore-sighted to the telescope will enable local aircraft detection over a 58-deg maximum field of view (full angle) centered on the direction of laser beam transmission. The ILI system also includes its own driver electronics and dedicated computer with control and object-detection software. Images are acquired by the cameras at a rate of 30 Hz and are processed within the control system to identify possible moving objects [2]. These objects then are tracked by the software and deemed to be at-risk when the behavior of the movement satisfies a threshold test within the internal motion model, which is illustrated in Fig. 3. However, objects in the acquired images may appear to move either faster or slower than their actual speeds since the cameras will be moving with the telescope. To nullify this apparent motion, the ILI algorithms were designed to receive and utilize the velocity of the telescope when computing an object's motion.

Following the integration requirements outlined above, images acquired by the cameras are processed within the ILI system to identify at-risk objects, although the system requires telescope velocity input to enable the 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 allows the telescope motion parameters to be passed in the ILI-specified format to the object-detection software at a rate of 30 Hz. As regards the integration requirements for detection and equipment status outputs, the ILI electronics provide one electrical output to signal laser interruption. The output provides a continuous +5 VDC signal until either an object is detected, the control software is non-responsive, or power is cut from system electronics, in which case a voltage drop occurs so that a continuous +0 VDC signal is output. To fulfill the requirements, the system electronics have been modified so that object detection can be distinguished from a system failure. The modification provides an additional electrical output, which generates a continuous +5 VDC signal when the equipment electronics are 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.

B. Tier-2 Integration Requirements

Surveillance of the Tier-2 region during early experiments will use a commercial weather radar system that was employed in past optical communication demonstrations at Table Mountain. The Honeywell Primus-40 system, as shown in Fig. 4, consists of a transmitter/receiver unit, antenna, and display/control



Fig. 2. Image Labs International LWIR detection system for Tier-1 aircraft avoidance. Reprinted from [2].

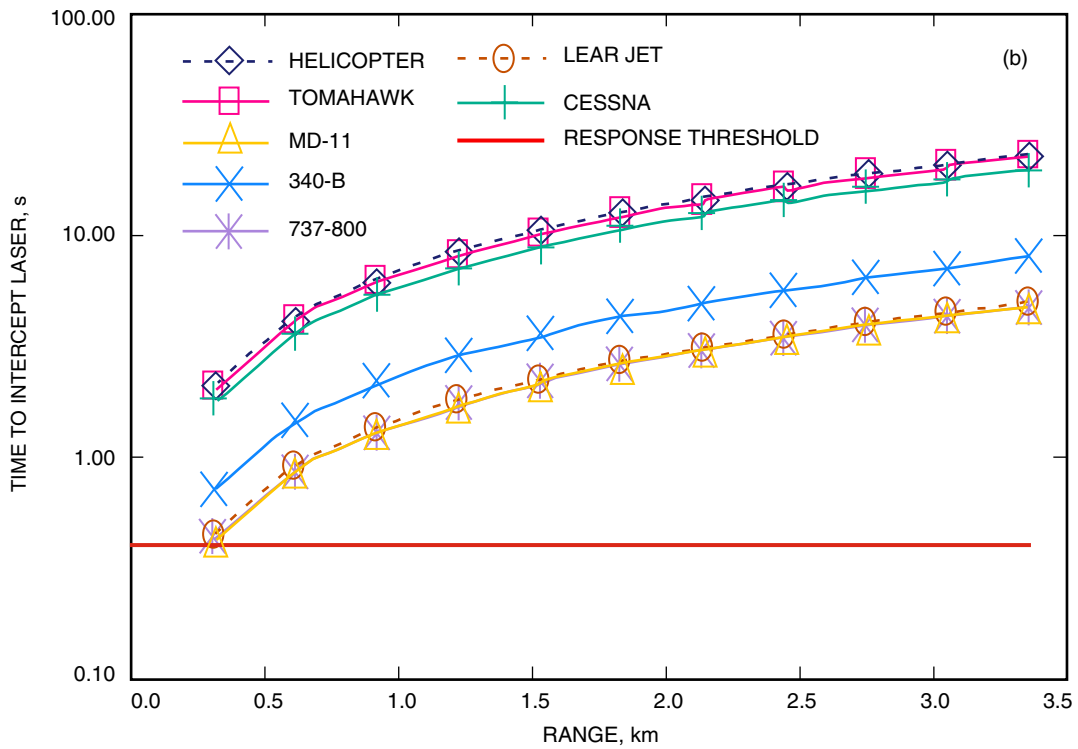
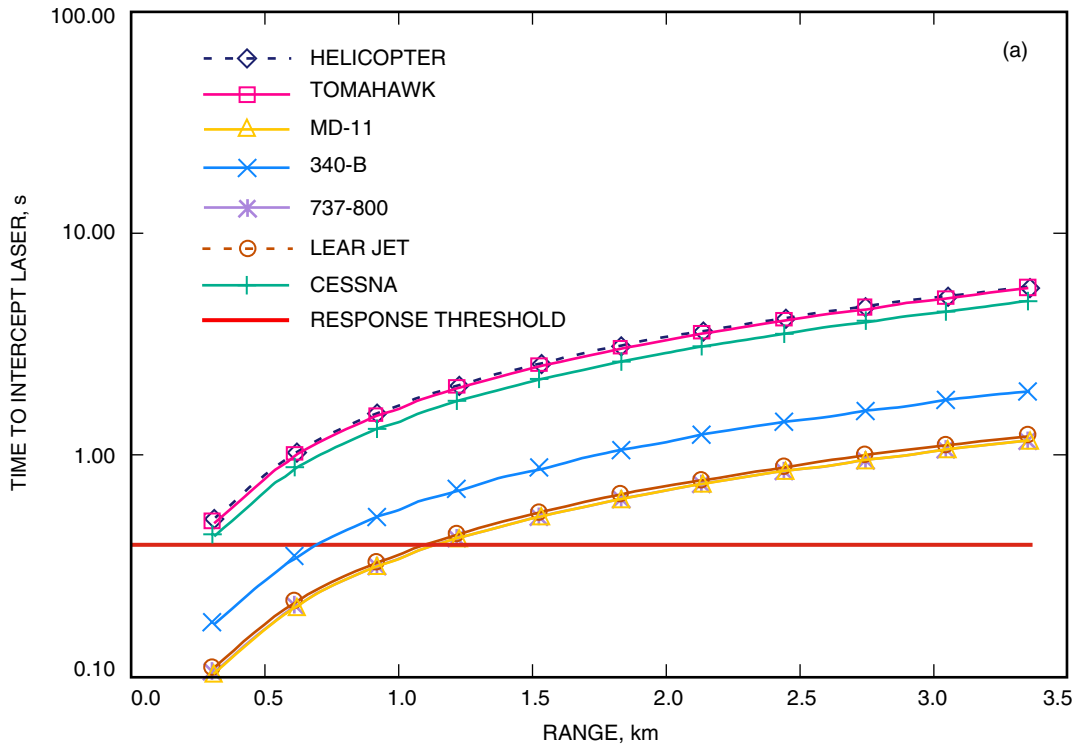


Fig. 3. Aircraft motion model for the (a) narrow field of view (NFOV) and (b) wide field of view (WFOV) based on an ILI scenario study that identified possible types of aircraft that can be encountered within the Tier-1 region. Simultaneous operation of both cameras permits total detection of aircraft within the Tier-1 region. Only objects exhibiting parameters below both the NFOV and WFOV threshold lines are deemed to be at risk.

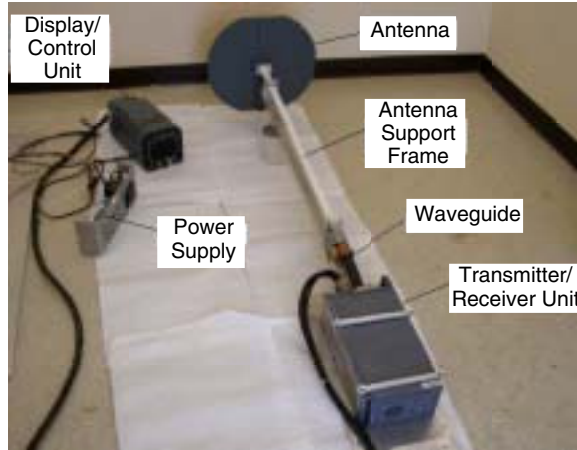


Fig. 4. JPL-modified Honeywell Primus-40 weather radar system for Tier-2 aircraft avoidance. Reprinted from [2].

module. The radar system transmits signals at a rate of 121 Hz, and objects are detected when a return signal is received. With the antenna and transmitter/receiver unit mounted and bore-sighted to the telescope, the system will enable aircraft detection out to a range of 58 km over an 11-deg field of view centered on the direction of laser beam transmission. However, false aircraft detections could occur due to signal returns from the surrounding mountainous terrain when the telescope is pointing near the horizon. In order to distinguish between aircraft and terrain detections, which also will prevent ocular hazards to the public, the integrated safety system will be provided with a coordinate map of the local terrain together with access to the telescope pointing parameters. In order to fulfill the remaining integration requirements, additional electronics have been developed to relay both equipment and object-detection status from the transmitter/receiver unit to outputs that can be read by an external shutter control system [2]. Similarly 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. Both output signals are driven by the radar transmission rate of 121 Hz.

C. Tier-3 Integration Requirements

Unlike the previous two tiers, in which object sensors are used, laser transmission is coordinated into space with the Laser Clearinghouse by satellite predictive avoidance. Based on laser location and characteristics, the Laser Clearinghouse determines whether coordination of laser activity is necessary. Should laser operation require such coordination, the operator must submit a list of experiment times and pointing directions for approval at least 48 hours prior to laser transmission. The Laser Clearinghouse then will respond 24 hours prior to experiments with a listing of times during which laser transmission is precluded. Then, additional requirements for the integrated safety system include access to this list of times and maintenance of an accurate system time. Fulfilling the originally outlined integration requirements is addressed in the next section.

III. Laser Safety Monitoring System

The Laser Safety Monitoring (LSM) system is the integrated system that will receive and process inputs from Tiers 1 through 3 to command the beam-interrupt shutter. The three tiers are unified through a personal computer (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 with a peripheral component interconnect (PCI)-bus input/output (I/O) card and by internally processing Tier-3 data from the Laser Clearinghouse to determine the validity of the

supplied information and whether predictive avoidance is in effect. The Tier-3 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 Inter-Range Instrumentation Group, Standard B (IRIG B) time code reader board 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, and presents a unified user display for the multi-tier safety system.

The LSM system will implement two beam-interrupt shutters, with the primary shutter 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 to permit beam propagation when an external +5 VDC voltage is applied and to automatically close to block the beam path when a voltage drop occurs. To verify the response of the shutters, a photodiode detector will be used to measure the intensity of the transmitting beam. As shown in Fig. 5, the detector will be placed behind a beam splitter located in the laser transmission optical train. The detector also was modified to provide two separate signal outputs to form a shutter loopback system. Similarly to the required tier outputs, one output provides a continuous +5 VDC signal when the beam is detected in the transmission optical train and a continuous +0 VDC signal otherwise. 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.

At the onset of operation, the LSM application program prompts the user for the files containing the site terrain and Tier-3 data. Before storing both sets of data into a lookup table, the format of the data first is 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 Tier-3 data

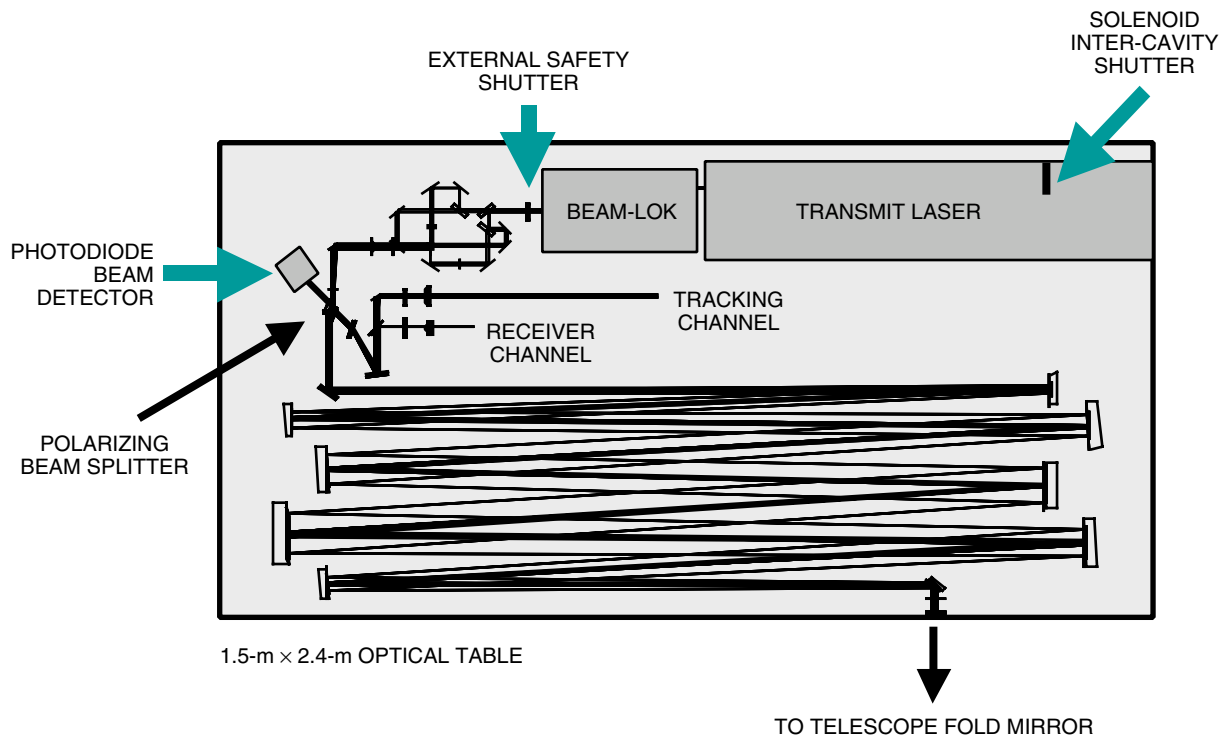


Fig. 5. LSM beam-interrupt shutter system hardware.

are 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 Tier-3 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 Tier-1 and Tier-2 operating rates and the highest laser pulse repetition rate of 50 Hz. Concurrently, the program initiates a separate continuous loop to intercept the motion parameters from the telescope control system serial output and to compare the pointing elevation with 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, in which case the corresponding command is issued through the I/O board to the shutter drivers. But, 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 a voltage drop for 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 the 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.

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 5-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. However, 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 detector indicates the transmission is blocked. In the same column of labels, located near the top of the display, a label is dedicated to

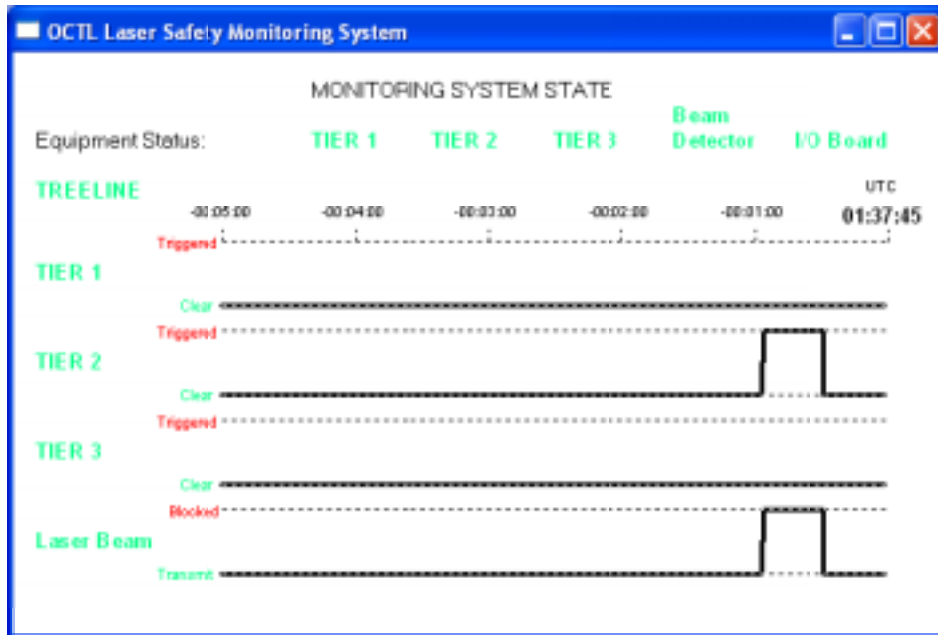


Fig. 6. LSM application program user display.

the status of the telescope pointing with respect to the site terrain elevation. The “treeline” label is highlighted in green when the telescope pointing is above the site terrain elevation or red otherwise. 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 Tier-3 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 as the program communicates with the board. The Tier-3 lookup table label is highlighted in red if either the data are expired 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. The computer system time was added to the 5-minute history plot time label to provide a running clock as evidence to the operator that the program is executing.

Although the Tier-1 and Tier-2 systems were designed to allow adequate time to respond to an at-risk object as a stand-alone system, the LSM response adds at most 0.165 second to the total response time from object detection to shutter activation. The maximum response time for the ILI system is 0.4 second, making the total response approximately 0.565 second for an object detected in the Tier-1 region. Since the ILI system utilizes two cameras, and since the type of aircraft that possibly can be encountered in this region is so broad, two cases are examined. First, as a worst-case scenario, consider a commercial aircraft descending for landing at a range of 0.3 km, moving as fast as 483 km/h. In this case, the plane would be detected with the wide-field-of-view camera and would have traveled about 14.5 deg from the point of initial detection by the time the shutter was activated. Given that the wide field of view is 46 deg by 35 deg, the 0.565-second response time is reasonable in order to block laser transmission. On the other hand, a more typical scenario would be a single-engine plane traveling at 193 km/h along the edge of the Tier-1 region, where the plane would have traveled 0.5 deg from the point of initial detection. In this situation, the plane would be detected with the narrow-field-of-view ILI camera. Given that the narrow field of view is 12 deg by 9 deg, the total response time in this example also would be reasonable in order to block laser transmission. In the case of the radar system, the time from object detection to Tier-2 signal output was at most 0.001 second, making the total response approximately 0.166 second. As a worst-case scenario, consider a commercial airplane traveling at 735 km/h along the Tier-1 and Tier-2 border; the plane would have traveled less than 1 deg from the point of initial detection. Given that the total field of view of the radar is 11 deg, the total response time for the Tier-2 region would be more than sufficient to avoid illuminating the object.

IV. Summary

Because of the increasing interest in high-bandwidth communications, the OCTL was constructed to serve as a test bed for optical communication strategies. However, such strategies generally entail propagating high-powered laser beams to space. This article has described a system for safe laser beam propagation at the OCTL that would protect the flying public and space assets. The LSM system provides integration of multiple independent tiers with a beam-interrupt shutter and offers a unified user display allowing an operator to monitor each tier. Such a system can be used as a baseline for developing a system capable of supporting autonomous ground stations. The system in its current configuration is scheduled for deployment at the OCTL in the fiscal year of 2004.

Acknowledgments

The author would like to thank Keith Wilson for his guidance and Vachik Garkanian for his technical assistance and suggestions.

References

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