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Performance Criteria for Laser Control Measures Used for Aviation Safety

RATIONALE

Operators of lasers outdoors must show that the laser hazard control measures used to prevent aircraft illuminations are adequate in order to ensure aviation safety and receive a letter of non-objection from the FAA. Historically, control measures have included the use of safety observers to monitor for aircraft and, in many applications, the use of safety observers is an effective control measure. In other situations, the use of alternate control measures may provide additional safety and may be more cost effective.

For example, the use of safety observers can be expensive and, in remote and environmentally challenging locations, it can be difficult to find and retain enough qualified people willing to do this type of work. The cost for safety observers to support 140 full nights of laser operations per year at W. M. Keck Observatory on Mauna Kea, Hawaii is about $300,000, and the site is several miles away from cities and towns. With the addition of 3 other facilities on Mauna Kea that will routinely use lasers in their operations, the total cost for safety observers may be over $1,000,000/year and the number of safety observers needed may exceed the supply in the local population.

In addition to cost considerations, the effectiveness of safety observers in spotting aircraft is limited relative to the hazard distances of some lasers. To address the provision of safety at these distances, additional means to detect aircraft are needed to supplement or to replace the safety observer.

INTRODUCTION

The SAE G-10T was tasked to develop criteria for acceptable control measures for such outdoor laser operations. The criteria will include performance requirements for control measures. The customer for this project is the FAA and the laser industry. Clear and specific performance criteria will facilitate the research and development of improved control measures and their implementation. Without specific criteria for laser control measures, safety may be negatively affected by reducing the development of potentially more effective or reliable means of mitigating risk. It should be noted that regulations prohibit interference with crewmembers of an aircraft; therefore, laser beams shall not be used to track aircraft in flight, except for systems specifically designed for this purpose or when sufficient control measures are used to ensure aviation safety.

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1. SCOPE

This document provides guidance for laser operators and aviation authorities to determine the performance criteria that laser hazard control measures shall meet for the operation of an outdoor laser system in navigable airspace. The document does not cover systems intended to deliberately aim and or track lasers at aircraft except for FAA approved purposes, such as visual warning systems, search and rescue, etc.

Aircraft operations to be protected include all types that can be reasonably expected to operate in the affected area, which are traveling at speeds and altitudes defined in the Performance/Functional Requirements section. This document does not address all possible aircraft operations, (e.g. the operation of stealth, high-speed (> Mach 1), unmanned aircraft systems, aircraft above 60 000 feet MSL, etc.), including aircraft operating under a waiver from FAA regulations. Depending on the laser system's location and operational characteristics, the proponent may be required to coordinate with local military facilities and with the USAF Space Command. The military may request additional requirements (such as limitations on lasing hours or locations), or they may take actions to avoid the laser location.

1.1 Purpose

The purpose of this document is to specify performance criteria standards for control measures to ensure the safe incorporation of lasers propagated into the navigable airspace.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS4970 Human Factors Considerations for Outdoor Laser Operations in the Navigable Airspace

ARP5535 Observers for Laser Safety in the Navigable Airspace

ARP5572 Control Measures for Laser Safety in the Navigable Airspace

ARP5293 Safety Considerations for Lasers Projected in the Navigable Airspace

ARP5674 Safety Considerations for Aircraft-Mounted Lasers Projected into the Navigable Airspace

ARP5560 Safety Considerations for High-Intensity Lights (HIL) Directed into the Navigable Airspace.

2.1.2 ANSI Publications

Available from American National Standards Institute, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ANSI Z136.1 American National Standard for Safe Use of Lasers

ANSI Z136.6 American National Standard for Safe Use of Lasers Outdoors

2.1.3 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

Title 14 CFR §91.11 Prohibition on interference with crewmembers

2.2 Applicable References

Kosinski, Robert J. A Literature Review on Reaction Time, updated September 2008. Available at URL: http://biae.clemson.edu/bpc/bp/Lab/110/reaction.htm . (Accessed: 5 Feb, 2009).

2.3 Definitions

ATTENUATION: The decrease in the radiant power as a laser beam passes through a medium, such as an optical filter or air, typically through absorption or scattering.

ESSENTIAL FUNCTION: A function whose loss would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions. For an aircraft protection system, essential functions consist of those required to prevent laser illumination of aircraft.

FAIL-SAFE: A design feature that either ensures that the system remains safe or, in the event of a failure, causes the system to revert to a state which will not cause a mishap.

FLIGHT HAZARD ZONES: Locations within the navigable airspace for which the FAA has established levels of effective irradiance and effective radiant exposure that are less than the maximum permissible exposure (MPE), due to the possibility of visual interference. These include:

LASER-FREE ZONE (LFZ): Extends immediately around and above runways. It extends horizontally 2 nautical miles from the centerline of all runways, with an additional 3 nautical miles extension at each end of the runway. The LFZ extends to 2000 feet AGL. The laser irradiance within the zone must not exceed 50 nanowatts per square centimeter.

CRITICAL FLIGHT ZONE (CFZ): Covers 10 nautical miles around the airport reference point, and extends vertically to 10 000 feet AGL. The laser irradiance within this zone must not exceed 5 microwatts per square centimeter.

SENSITIVE FLIGHT ZONE (SFZ): An optional zone, designated by FAA, military or other authorities. An example would be designation of a SFZ around a busy flight path or where military operations are taking place. The laser irradiance within this zone must not exceed 100 microwatts per square centimeter.

NORMAL FLIGHT ZONE (NFZ): Includes all navigable airspace outside the other hazard zones and is limited to radiant exposure below the MPE limit for a particular laser (2.6 mW/cm2 for continuous-wave visible lasers).

LASER AFFECTED AIRSPACE: The airspace in which the laser beam may be propagated during the protection system response time and the lesser of:

a. The airspace from the edge of the laser beam outward to 1000 feet (perpendicular from the axis of the beam) or

b. The airspace from the edge of the laser beam outward (perpendicular from the axis of the beam) to a distance transited by an aircraft during a time period equal to two times the protection system response time.

The projected airspace extends along the laser beam to the end of the NOHD and, for visible laser beams which penetrate flight hazard zones (Sensitive, Critical and Laser-Free Zones), extends to the end of the appropriate visual protection distance. Laser affected airspace above 60 000 feet MSL is outside the scope of the performance criteria contained herein.

MAXIMUM PERMISSIBLE EXPOSURE (MPE): The level of laser radiation to which an unprotected person may be exposed without adverse biological changes in the eye or skin.

NOMINAL OCULAR HAZARD DISTANCE (NOHD): The distance from the laser source, beyond which the laser beam's irradiance does not exceed the MPE for that laser.

PROTECTION SYSTEM: A system of engineering and/or administrative control measures that prevent the interference with flight crew operations from a laser illumination.

REACTION TIME: When implementing a laser hazard protection system, the reaction time is the maximum time from when a protected event occurs (e.g., an aircraft entering a protected zone) until the hazard mitigation (e.g., beam shuttered or laser deactivated) becomes fully effective. This includes all time needed to detect the aircraft, process the information, decide on mitigation, and fully implement any needed control measures.

SAFETY OBSERVER: A person tasked with observing airspace into which a laser beam is being propagated so as to ensure that the beam does not illuminate unintended objects; thus avoiding adverse effects. The observer is trained and has the ability to immediately attenuate the laser beam.

SINGLE-POINT FAILURE: The failure of a critical component that causes the system to cease to provide required functionality. Single-point failures can be mitigated by providing redundancy or an alternate operational mode.

SHUTTER: To stop a laser beam from propagating beyond a specific point by blocking or covering the beam at that location. In the context of this document, shuttering stops the laser beam from entering airspace.

VISIBLE LASER: A laser operating in the wavelength range of 380 to 780 nm. Such laser beams can be seen by human beings.

VISUAL INTERFERENCE LEVEL: the minimum effective irradiance or radiant exposure which can produce a visual response that interferes with the safe performance of sensitive or critical tasks by aircrew or other personnel. Visual interference level is a generic term for critical level, sensitive level, or laser-free level. The visual interference level is generally a sub-injury threshold (i.e., less than the MPE).

2.4 ABBREVIATIONS AND ACRONYMS

AGL	Above ground level
ANSI	American National Standards Institute
CCD	Charge-coupled device
FAA	Federal Aviation Administration
IR	Infrared
Laser	Light amplification by stimulated emission of radiation
LIDAR	Light detection and ranging
LSO	Laser safety officer
MPE	Maximum permissible exposure
MSL	Mean sea level
NOHD	Nominal ocular hazard distance
NOTAM	Notice to airmen
NVG	Night vision goggles
RF	Radio frequency
USAF	United States Air Force

3. BACKGROUND

Historically, safety observers have been used as the preferred or primary control measure to provide safety by detecting the presence of aircraft that may be adversely affected by an outdoor laser operation and immediately terminating the beam. Information related to the attributes and training of a safety observer, and procedures that shall be followed are detailed in ARP5535 (Observers for Laser Safety in the Navigable Airspace). Although safety observers have a proven record of effectiveness, an unaided observer is generally considered effective for detecting aircraft at distances up to three miles. Furthermore, environmental factors, such as working at high altitudes or in cold locations, may impact the efficacy of the observers.

When the Nominal Hazard Zone or the applicable flight hazard zones (Laser-Free, Critical, Sensitive, and Normal Flight Zones) exceed the effectiveness of a safety observer, another control measure is needed to ensure aviation safety. Such measures may include optical aids (binoculars), or automated aircraft detection/safety systems utilizing bore-sighted radar, infrared cameras, CCD camera, etc., or some combination of these control measures.

A need exists for a certification process or standard for determining the efficacy of these systems as control measures. Also, control measures need to be designed, selected and evaluated based on site and laser use characteristics, since outdoor laser applications can vary widely. (See Appendix A for a table showing the uniquely different characteristics of two typical outdoor laser uses.)

To assist in developing effective control measures for a given site and laser use, the SAE G-10T, Laser Safety Hazards Subcommittee recommends the following performance criteria for specific control measures. These performance criteria may be specified by the FAA as conditions in a Letter of No Objection.

NOTE: For descriptions of control measures and information on typical applications, pros, cons, and limitations see ARP5535 (Observers for Laser Safety in the Navigable Airspace) and ARP5572 (Control Measures for Laser Safety in the Navigable Airspace). Additional information on related laser safety issues can be found in ARP5293 (Safety Considerations for Lasers Projected in the Navigable Airspace) and AS4970 (Human Factors Considerations for Outdoor Laser Operations in the Navigable Airspace).

4. PERFORMANCE/FUNCTIONAL REQUIREMENTS

The laser proponent’s protection system, which can include one or more control measures, shall meet the following criteria:

A protection system is required when aircraft can be illuminated by laser energy in excess of the MPE or applicable visual interference levels. Protective means shall be employed to ensure that aircraft occupants are not exposed to laser levels above the MPE and, for visible lasers, that pilots are not exposed above any applicable visual interference levels. The protection system shall detect all types of aircraft that may be reasonably expected (fixed wing, rotorcraft, dirigibles, balloons, gliders, etc.). The protection system shall detect these aircraft at all locations and distances where aircraft can be reasonably expected and shutter, or attenuate, the beam to safe levels before the aircraft enters the laser affected airspace. The laser affected airspace shall include the laser beam and a buffer zone extending from the edge of the beam to twice the reaction time of the protection system or 1000 feet from the edge of the beam. To adequately protect this airspace, at both near distance/low altitude and at far distance/high altitude, two or more control measure systems or techniques may be needed. Information and examples of reaction time determination for a protection system can be found in Appendix B.

Figure 1 illustrates the affected airspace that extends from the laser beam. Figure 2 illustrates the affected airspace that extends from a laser beam that is being scanned across the sky, which will result in a much larger zone of airspace to be protected.

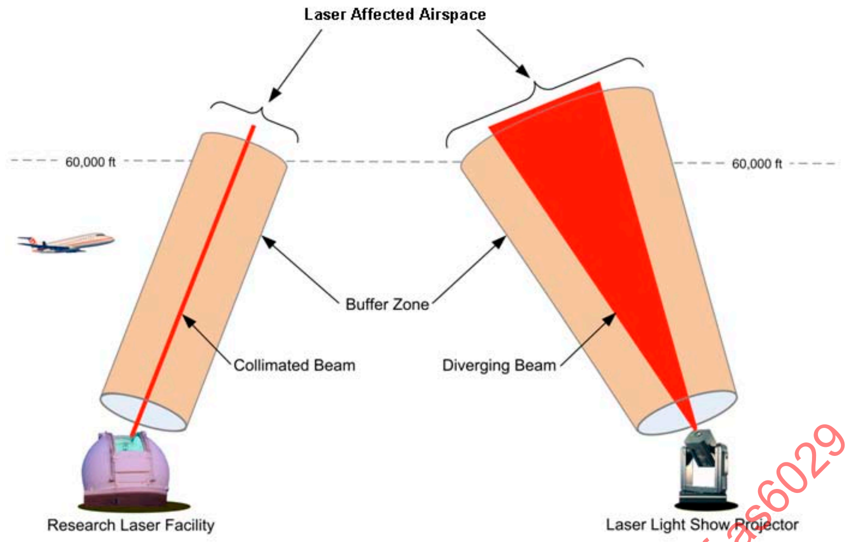

FIGURE 1 – ILLUSTRATES THE LASER AFFECTED AIRSPACE THAT EXTENDS FROM THE LASER BEAM

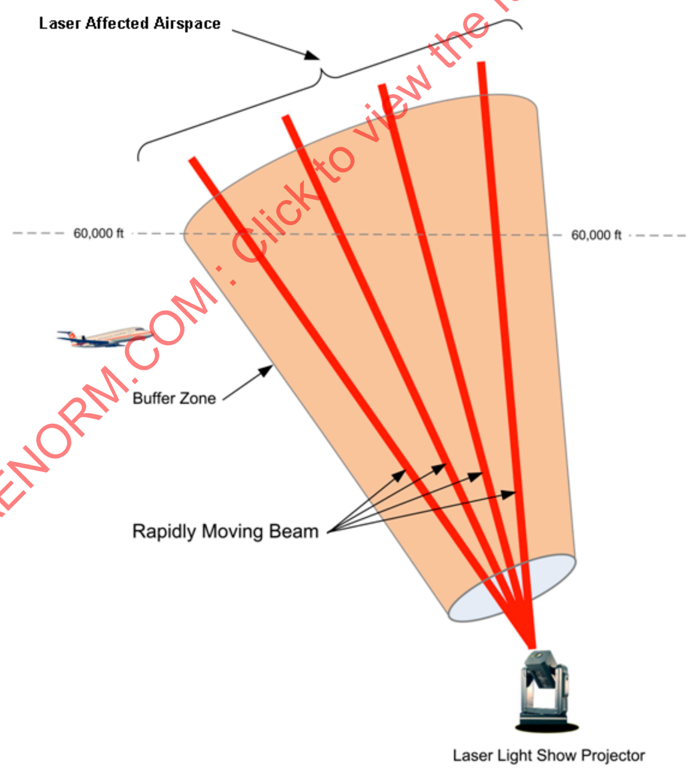

FIGURE 2 – THE LASER AFFECTED AIRSPACE AROUND A RAPIDLY MOVING LASER BEAM

The proponent shall determine what altitudes and speeds are to be reasonably expected at the laser facility location. The following operational characteristics shall be taken into account for aircraft reasonably expected to operate in the area:

- Maximum aircraft altitude: 60 000 ft MSL
- Minimum aircraft distance: 100 feet (It is reasonable to expect aircraft not to operate within 100 feet from the laser source.)
- Maximum civilian aircraft speed: 250 knots (287 mph) below 10 000 feet MSL.
- Typical military aircraft speed: 540 knots (621 mph) below 10 000 feet MSL, unless otherwise determined.

NOTE: The civilian aircraft airspeed of 250 knots is based on 14 CFR §91.117(a). The military aircraft airspeed of 540 knots is based on 0.9 Mach, which is typical for low-level training routes. The ceiling of 60 000 feet MSL is based on FAA having control of air traffic up to flight level 600.

For aircraft at any speed and distance that can be reasonably expected in the area, the proponent shall show either that 1) the laser can be terminated before the aircraft enters the protected airspace, or 2) the aircraft's speed and distance reduces any possible exposure below the MPE and any applicable visual interference level.

In summary, the protection system shall:

Detect all types of aircraft flying at all speeds and altitudes that may be reasonably expected to operate within the protected airspace.

Shutter or attenuate the beam when detected before the aircraft is projected to enter protected airspace.

Safeguard all lasers to the NOHD and, for visible laser beams that penetrate the corresponding flight hazard zones (Sensitive, Critical, and Laser-Free Zones), to the appropriate visual protection distances.

5. SYSTEM DESIGN REQUIREMENTS

The following list includes required features for protection systems.

5.1 Operator Interface

Provide feedback to users about the status of the system (faulted/on/off, etc.) so that they can take appropriate action. Systems, controls, and associated monitoring and warning means shall be designed to minimize operator errors that could create additional hazards.

5.2 E-Stop or Manual Over-ride

Include an emergency switch that terminates laser beam propagation. This system may drop power to the laser or include a separate shutter device completely separate from the normally-used protection system.

5.3 No Single-Point Failures

There shall be no identified failure mechanisms that prevent aircraft detection or laser shutoff and for which no redundancy or alternative operational procedure exists. It is preferred that essential equipment failures are detected via automatic means (i.e., continuous monitoring function) with automatic system transition to a safe state. Alternatively, such failures may be detected via regular operational checkout procedures. The frequency of checkout shall be specified to achieve equipment effectiveness goals (e.g., shift, day, month).

5.4 Fail-Safe

For any identified failure conditions that could otherwise allow laser illumination of aircraft, the aircraft protection system shall incorporate fail-safe provisions that cause the system to revert to a safe state. The goal of a fail-safe design is to ensure that inadvertent aircraft illumination is prevented. The fail-safe design concept may include provisions for failure warning or indication to provide detection and allow operator action (e.g., to address the condition or implement alternative measures).

NOTE: Proponents wishing to develop a protection system that will meet the criteria contained in this document may benefit from the description of the protection system development procedures contained in Appendix C.

6. ADDITIONAL SYSTEM FEATURES

The following list includes suggested features for system designers to consider in development of protection systems.

6.1 Event Logging

Log aircraft detections with date/time/location and responses (shutter, attenuate) to detected aircraft for later incident analysis, hazard analysis, etc.

6.2 Controls

Labels, watchdog timers, dead-man switches, and other engineering design features should be considered.

7. SYSTEM VERIFICATION

The proponent shall verify compliance with Performance/Functional and System Design Requirements. Compliance may be shown by analysis and, as necessary, by appropriate operational tests. The analysis shall consider possible modes of failure, including malfunctions and adverse effects from the operational environment. The analysis shall consider multiple failures. If applicable, the analysis should assess the suitability of laser operator warning cues, corrective action required, and the laser operator's capability of identifying and reacting to alerts.

8. OPERATIONAL/PROCEDURAL CRITERIA

The administrative control requirements for operating the laser system are defined. These shall be addressed before operations of the laser systems can begin, including the protection system.

8.1 Characterization

The system performance shall be understood sufficiently so that system capabilities, including limitations and operational nuances based on both theoretical and experimental data, can be determined.

8.2 Operational Procedures

Procedures shall be in place to avoid using the system if environmental conditions are such that the system performance is compromised (e.g., protection system can not detect aircraft in cloudy skies).

8.3 Documentation

A laser safety data report shall be prepared that describes the design, performance, operation and limitations.

8.4 Training

The facility/operator shall have a training program on the safe use and operation of the laser system.

8.5 Roles and Responsibilities

The person(s) responsible for each aspect of operation and safety and their responsibilities need to be identified.

8.6 Initial Testing and Reassessment

Compliance with performance criteria, as described in this document, shall be assessed prior to operation and periodically thereafter.

9. CONSIDERATIONS FOR AIRCRAFT PROTECTION SYSTEMS

The following factors should be considered in the development of an aircraft protection system and are addressed in more detail in other reference documents. They are listed here to give a brief overview of important considerations in deploying a protection system:

9.1 Site Location Relative to Air Traffic

Site elevation in relation to and distance from airports, air traffic routes, and flight hazard zones (Laser-Free, Critical, and Sensitive zones).

9.2 Visual Environment

Atmospheric conditions and time of day/night (i.e., dusk to dawn).

9.3 Environmental Factors

Factors that may affect the protection system include high altitude, extreme cold, and limits on downrange tracks (angular limits on discharge, backstops to the beam).

9.4 Frequency of Operation

Regular or intermittent schedule that the laser system will operate (e.g., number of days per week or per year).

9.5 Laser Motion Characteristics

Movement of the beam (scanning, stationary).

9.6 Attended vs. Unattended Operations

9.7 Atmospheric Attenuation

Reduction of beam intensity due to the atmospheric effects based on actual test data and/or a published industry standard.

9.8 Type of Traffic

Aircraft with unique detection challenges can include:

a. High-speed military aircraft (especially if at low altitudes)

b. Low-flying aircraft, especially those that may suddenly appear from behind obstructions (mountains, buildings, etc.)

c. Gliders, balloons and dirigibles

9.9 Use of Proven Control Measures

Consider first control measures that have already been accepted by the FAA for operational effectiveness in a similar application/environment. Other considerations (cost, schedule, etc.) may also influence the control measure(s) selected.

9.10 Simultaneous Use of Multiple Control Measures

Some laser operations may require two independent control measures which together provide the required protection. These may use different technologies, and may have different operating ranges or characteristics. For example, one system may be more appropriate for use below 5000 feet while another may be required above this level. This is not a redundant system, as any given aircraft is only being detected by one system or the other.

9.11 Redundant Control Measure Systems

Some proponents may wish to have redundant, independent detection systems such that even if one system fails, the other is capable of protecting the laser affected airspace. Redundant systems are not required if the single detection system meets the Performance/Functional and System Design Requirements.

9.12 Faults/Interlock Systems

A manual action may be needed when a fault is detected or interlock is activated.

9.13 Modes of Operations

After a change in operational mode (e.g., calibration, service, maintenance, normal operation), the protection system shall default to a safe state.

APPENDIX A – COMPARISON OF ASTRONOMY LASER USES AND LASER SHOWS

Outdoor laser uses can vary widely. Accordingly, the control measures needed to ensure aircraft safety should be tailored to the application. The table below illustrates two well-known outdoor applications, 1) laser guidestar systems used in astronomy, and 2) laser shows. In many ways, these uses are mirror images of each other:

TABLE A1 – ASTRONOMY LASERS VS. LASER SHOWS

	Astronomy Lasers - Laser Guidestars for Adaptive Optics	**Laser Shows - Outdoor Laser Displays for Special Events and Theme Parks**
Site characteristics		
Fixed or variable	Fixed site. Laser location is known.	Site normally varies with event location. A few fixed locations such as EPCOT “Illuminations”.
Local population	Used in a lightly populated area	Performed in or near a populated area
Visibility	Very dark and clear sky	Light pollution from populated area
Air traffic	Far from major airports; low air traffic density	Crowded skies around cities; may be close to an airport
Altitude	Usually at high altitude	Usually at low altitude
Weather limits	Laser not used when clouds are present	Show usually continues despite clouds or even rain
Laser characteristics		
Beam power	Ranges from 3 to 20 watts per beam. Some systems may have multiple beams. May be pulsed lasers with high peak power	Ranges from 5 to 80 watts per beam; 20 watts is typical
Beam angle	Pointing upwards – 20° to 90° above horizon	Low, close to the ground – from horizontal to 20°
Beam movement	Normally slow sidereal (tracking a celestial object in the sky) motion. Laser does not propagate when moving from one object to another	Usually fast slewing movement or quick on-off of multiple beams in time to music. Some effects may be relatively slow and steady. Occasionally used as a “laser spotlight” where the beam pattern may move like a traditional searchlight. Occasionally used to create a stationary “light sculpture”.
Laser use characteristics		
Frequency	Very regular – most clear nights	Usually only 1-2 nights at any one location. (There are only a handful of regular, nightly outdoor shows such as EPCOT “Illuminations”)
Duration	Long duration; most of the night (10-12 hours)	Short duration; 30-60 minutes per night, usually early evening
Termination (stopping the beam)	Beam continues into free space. Note that the beam may be so powerful as to be a potential hazard to orbiting satellite sensors. In such a case, the use should be coordinated with the US Strategic Command’s (formally US Space Command) Laser Clearinghouse.	Many beams may be terminated on mirrors or nearby structures. These beams would pose a hazard only 1) if laser is misaimed or termination point (mirror) moves, or 2) in case of helicopter traffic between the laser source and termination point.
Other visual distractions	None	Lasers may be used along with fireworks
Control measures		
Practical & efficient safety methods	Automated detection and shutoff systems which can run all night	Safety observers which are used only during the short duration of the show.

APPENDIX B – PROTECTION SYSTEM REACTION TIME DETERMINATION

B.1 GENERAL

The purpose of having a laser hazard protection system is to ensure that people (particularly in aircraft) are not exposed to laser levels above the MPE or any applicable visual interference levels. To achieve this, the protection system shall detect all types of aircraft that may be reasonably expected to operate in the beams potential path and shutter or attenuate the beam to safe levels before the aircraft enters the protected airspace.

This standard requires a minimum safety buffer of twice the total protection system reaction time. Therefore, to verify the suitability of a particular protection system, determination of its reaction time is necessary. The total reaction time of a protection system is determined by summing up the worst-case lag times for all serial elements considered in the system. Some items to consider when calculating reaction time include:

a. Integration/Exposure Time of Aircraft Detection Sensor: This is the time that an aircraft detection sensor needs to collect its data. For example, this would be the exposure time for a camera sensor.

b. Sample Rate of Aircraft Detection Sensor: This is the time between data samples due to electronic or physical design limitations of the detecting device. For example, this may be the amount of time it takes for a radar system to make a complete rotation.

c. Data Transfer Time: This is the time it takes for data to move between elements of a protection system. This also includes the latency delay that can occur due to the periodic lag time inherent in synchronous communication systems.

d. Detection/Processing Time: This is the time it takes for the system to recognize the existence of an aircraft. This may include the time to compare multiple samples or to perform other data processing.

e. Decision Time: This is the time it takes for the system to determine if the situation requires protective action (e.g. engaging shutter or turning off beam).

f. Control Measure Activation Time: This is the time it takes for a control measure to become effective once triggered. For example, this would be the time from when a beam shutter receives its trigger to when it adequately blocks the beam.

g. Human Detection and Reaction Time: This is the time necessary for a person to detect an aircraft and react to that detection. Human detection and reaction times vary considerably from scenario to scenario and from person to person. Using human safety observers has historically been preferred – not because of an actual superiority over other control measures, but because of the inherent culpability afforded by their inclusion. Reliably quantifying the detection and reaction time of a person as part of a laser hazard protection system is very subjective. Worst-case allowances may, therefore, be extremely conservative to real-world experience.

B.2 REACTION TIME CONSIDERATIONS FOR HUMAN BEINGS

Extensive studies have been done on human reaction time. According to Kosinski (2008), there are three reaction times of interest. These are:

a. Simple, with one stimulus and one response: For example, the stimulus could be "spot the dot" and the reaction is "press a key".

b. Recognition, with multiple stimuli and one response: The subject must distinguish between desired stimuli ("react to A, B or C") and undesired stimuli ("do not react to X, Y or Z"). There is one response such as "press a key".

c. Choice, with multiple stimuli and multiple responses: For example, "press a key A, B or C depending on what letter you see"

Aircraft detection by safety observers can be considered as either "simple" or "recognition". Considered as "simple", there is a static background of stars, and the observer must detect an aircraft against this background. Considered as "recognition", the observer must distinguish between moving objects (e.g., aircraft) and unmoving objects (e.g., stars). In both cases, there is one response.

The accepted simple reaction time for individuals is less than 250 millisecond (0.25 second) for light stimuli. Recognition time is roughly 400 millisecond (0.40 second). Once an object has been recognized, the response time is consistent regardless of stimuli. As this assumes that the stimulus is directly in front of the subject who is expecting a stimulus, it should be noted, that when an aircraft appears outside the safety observer's direct field of view (FOV), additional reaction time would be expected (i.e., scanning and acquisition).

NOTE: Depending on the application, the observer may press a button to terminate laser emission or radio to an operator, who then terminates emission. Obviously, the added time to send the radio message, and respond to it, must be considered.

B.3 REACTION TIME DETERMINATIONS EXAMPLES

B.3.1 Protection System Utilizing a Boresighted Radar

This example protection system consists of a radar boresighted to a laser telescope that is used to track satellites. The radar is being used to detect aircraft before they could enter the path of the beam. It uses a shutter to block the laser beam emission when an aircraft is detected.

The boresighted radar is called the Laser Hazard Reduction System (LHRS). The LHRS is mounted on a gimbal assembly that is separate from the laser transceiver telescope. To ensure boresight retention, the gimbal is directed via position information it receives directly from the laser telescope assembly.

Once an aircraft has been detected by the LHRS, it sends a command signal to the laser interlock (LI) subsystem to activate the beam shutter. The mechanical shutter is then activated by the LI to block the transmitted laser energy.

To determine the overall reaction time of this system, the reaction times of each of the serial elements in the activation process are summed. For the purposes of this example, the activation is divided into two major parts – detection (LHRS) and response (LI).

The LHRS utilizes the transceiver from a marine radar system to detect aircraft. The radar operates at a rate of 750 Hertz – meaning that every 1.33 milliseconds, or 750 times a second, a burst of radar energy is transmitted along the path of the laser beam. The radar energy beam is significantly wider than the laser beam. If an aircraft is in the path of the radar energy, the radar energy reflected from it is detected by the radar transceiver. To discriminate aircraft from random noise, the radar logic algorithms compare three consecutive radar samples. As a result, the reaction time of the LHRS to detect an aircraft is $3 \times 1.33 \approx 4$ milliseconds. When the LHRS detects an aircraft, it sends a command signal to the LI via a synchronous communication link operating at 20 Hertz. Therefore, the lag from this could add up to 50 milliseconds to the time it takes for the LHRS to command the LI. So, it could take up to 54 milliseconds ($3 \times 1.33 + 50$) from the first radar reflection to command the LI to activate the shutter.

In addition to awaiting a command from the LHRS, the LI accepts input from other controls and sensors such as hand-held emergency switches, motion sensors, and pressure pads to ensure people and aircraft are not illuminated by the laser beam. The LI primarily uses discrete logic circuits to control its mechanical shutter. This means that since there are no clock signals or microprocessors used, the LI reacts to an input nearly instantaneously; activating the shutter circuit as soon as it receives an aircraft detect signal from the LHRS. Due to the finite capabilities of the discrete logic circuits, the delay to process the aircraft detect signal and activate the shutter circuit is taken to be 0.0005 milliseconds.

The shutter is a fail-safe, spring-assisted plunger that is closed unless provided a voltage to keep it open. When the LI activates the shutter circuit, it removes the voltage and the spring closes the shutter. It takes approximately 20 milliseconds for the spring to pull the shutter completely closed. The worst-case response time for the LI includes both the logic delay and the time to close the shutter. In this case, however, the logic delay is negligible, so the total response time for the LI is approximately 20 milliseconds.

The overall reaction time associated with detecting an aircraft, providing an inhibit signal, processing the inhibit signal, and shuttering the beam would be $54 + 20 = 74$ milliseconds.

B.3.2 Protection System Utilizing a Camera

The reaction time for a camera-based control system is composed of several distinct components. In general, it is the time required for the camera to capture an image of the sky (or in some cases multiple images), analyze the image(s) and react appropriately. This example is of a protection system that uses a digital camera and computer software to look for moving aircraft in the sky. It analyzes their location and speed and shutters the beam if they get too close to the laser beam. For this protection system, the reaction time is the sum of the times for camera exposure, data transfer, detection, decision, and shutter activation.

Exposure time at night for a digital camera can be rather lengthy. This camera needs an exposure time of almost 2 seconds in very dark conditions to integrate enough light to adequately discern aircraft in the sky. A high resolution camera is used to detect small items (or large items further away). The result of this is that it takes about 0.5 seconds to transfer an image frame to the computer processor. This software compares two consecutive images to find changes that suggest moving aircraft in the sky. This means that it takes about 5 seconds to create two exposures and transfer them both to the computer.

The detection algorithm for the computer takes no more than 0.3 seconds to find all aircraft and determine their angular speed. The computer then predicts the future location of all detected aircraft and verifies that they will not be entering the protection zone for the laser. Additionally, this algorithm accepts data from other discrete sources (i.e., emergency shut-off switches, etc.) to parse a final shutter/no shutter decision. As this can be a complex determination when tracking multiple aircraft at once, this decision process takes almost 2 seconds to complete.

Finally, if the decision algorithm produces a shutter command, the computer sends the control signal to the controller that controls the mechanical shutter. The maximum time from decision until full shutter activation is less than 0.1 second. Therefore, the total reaction time for this protection system is 7.4 seconds.

APPENDIX C – AIRCRAFT PROTECTION SYSTEM DEVELOPMENT CHECKLIST

This appendix summarizes the steps that a developer or proponent might undertake to develop an aircraft protection system. The following table lists the major activities involved in that development.

TABLE C1 – AIRCRAFT PROTECTION SYSTEM DEVELOPMENT CHECKLIST

1	Determine site specific considerations	□
2	Select appropriate control measures	□
3	Predict control measure performance	□
4	Implement control measures and infrastructure	□
5	Characterize actual performance	□
6	Develop operational procedures	□
7	Verify and document compliance with requirements	□
8	Prepare laser safety data report	□
9	Prepare submission to the FAA	□

C.1.1 Step #1: Determines Site Specific Considerations

Outdoor laser applications vary widely. Selecting, developing and verifying the performance of appropriate control measures should be done on a case by case basis for the specific site and laser use. Therefore, the first step in the development process is to investigate and document these site specific considerations and applicable requirements. These considerations may include the items shown in the following table.

TABLE C2 – SITE SPECIFIC CONSIDERATIONS CHECKLIST

1	Determine if control measures are required (based on MPE or applicable visual interference levels)	□
2	Determine site proximity to airports, flight zones, and flight operations areas.	□
3	Determine site proximity to and potential implications of military/special use airspace	□
4	Characterize the local air traffic expected during operation (volume, routes, direction, distance, minimum/maximum altitude and speed, etc.)	□
5	Determine the type of aircraft expected (fixed wing, rotorcraft, dirigibles, balloons, gliders, etc.)	□
6	Characterize the visual environment and its potential effect on control measures (day or night, air quality, light pollution, distance at which aircraft can be seen during operations, etc.)	□
7	Identify environmental factors that may affect control measures (elevation, temperature, weather, obstructions, etc.)	□
8	Identify constraints and issues for justification that may affect control measure development and operation (frequency of operation, development and operations budgets, risk, feasibility, etc.)	□
9	Characterize laser propagation direction and motion (fixed, scanning, propagation duration, etc.)	□
10	Identify personnel related issues (attended vs. unattended, required skill set for labor force, etc.)	□

C.1.2 Step #2: Select Appropriate Control Measures

The site specific considerations are taken into account in selecting appropriate control measures to meet applicable requirements. Additional information on control measures is available in SAE ARP5535 and ARP5572.

C.1.3 Step #3: Control Measure Performance Predictions

The purpose of the performance predictions is to mitigate risk to the development by ensuring that the final system will meet the applicable requirements before significant investment is committed.

C.1.4 Step #4: Implement Control Measures and Infrastructure

Implement the selected control measures and required infrastructure with due consideration to the following: fail safe design, no single point failures, event logging, appropriate controls and operator interface, e-stops and manual over-rides, documentation, training, clear roles and responsibility assignments, and plans for appropriate testing and periodic reassessment.

C.1.5 Step #5: Characterize Actual Performance

Characterize the actual control measure(s) performance, including operational testing of the system, identification of possible failure modes and responses, and evaluation of the system capabilities and limitations.

C.1.6 Step #6: Develop Operational Procedures

Develop and document appropriate operational procedures for safe use, including normal operating procedures, procedures for avoiding known system limitations, and any procedures required for detecting and responding to failure modes. Examples of limitations for which procedures may need to be adopted include: operating in less than optimal weather, such as through clouds; operating in the presence of problematic bright light, such as near the moon or during twilight; operating where the line of sight to possible aircraft is obscured; and, operating when a part of the system is not working properly.

C.1.7 Step #7: Verify and Document Compliance with Requirements

Evaluate compliance with the functional performance requirements. Compliance may be shown by analysis and, as necessary, by appropriate operational tests. Some combination of one or more control measures in the aircraft protection system are expected to meet the requirements shown in the following table.

TABLE C3 – PERFORMANCE / FUNCTIONAL REQUIREMENTS CHECKLIST

1	Protect all types of aircraft expected	☐
2	Protect aircraft at all distances where both laser hazards and aircraft can occupy the same airspace	☐
3	Protect aircraft traveling in any direction	☐
4	Protect aircraft traveling at all speeds expected	☐
5	Protect aircraft traveling at all altitudes expected	☐
6	Detect aircraft at risk and attenuate the laser beam before the aircraft enters the laser affected airspace	☐

The analysis required to methodically evaluate compliance with the performance / functional requirements can be non-trivial. The parameters of aircraft speed, altitude, direction and distance can be combined in various ways that create different sorts of challenges for the control measures. As such, demonstrating that a control measure can protect aircraft throughout the range of each of these parameters is difficult. For example, a fast flying aircraft at great distance and altitude, flying directly toward the control measure (no apparent motion), versus the same fast flying aircraft, very low and directly overhead, present completely different challenges for the control measures. Therefore, compliance with the requirement that the control measure must protect aircraft traveling at all speeds cannot be evaluated without considering altitude, direction and distance.

C.1.8 Step #8: Prepare Laser Safety Data Report

A laser safety data report describes the design, performance, operation and limitations of the control measures and how the selected control measures meet the performance / functional requirements.

C.1.9 Step #9: Prepare Submission to the FAA

To receive a letter of no objection from the FAA, the proponent submits a notice of their intent to propagate the laser. The contents of this submission are described in FAA Advisory Circular AC 70-1. The submission will contain the conclusions from laser safety data report. Proponents may be requested to supply additional detail in support of the FAA's aeronautical study.

C.2 CASE STUDY

The following case study is offered as an example of application of the checklist described in this appendix. It is based on a fictitious astronomical observatory. The details presented are realistic, and illustrate just one way that proponents might work through the application of the steps presented in this appendix.

The proponent for this case study is a facility operating an astronomy laser application called a Laser Guide Star (LGS) system. This facility will be referred to in this case study as the Laser Guide Star Observatory (LGSO). LGSO is an astronomical research facility based on a 13 700 foot mountain top in rural Hawaii called Mauna Kea. This facility uses lasers in the night time sky as part of a LGS Adaptive Optics (AO) system. LGS-AO is a technology which provides a means for astronomers to gather data with far higher spatial resolution on more potential science objects than has ever before been possible from ground based telescopes. This approach uses a laser propagated into the night sky to create an artificial star called a “laser guide star.” This artificial star is then used by AO systems on the telescope to aid in sharpening scientific images in real time. The astronomy community has enthusiastically embraced the use of this technology and the associated potential for discovery. The LGS-AO systems, including lasers, at many observatories are scheduled for regular operations hundreds of nights per year.

C.2.1 Determine Site Specific Considerations

The discussion below addresses each of the suggested site specific considerations presented in Table C2 of this appendix.

- 1. Determine if control measures are required (based on MPE or applicable visual interference levels)

The table below shows the technical specifics of the laser in use. In general, the laser is very powerful and highly collimated to the extent that the MPE and NOHD indicate that appropriate control measures must be developed before LGSO can begin operations.

TABLE C4 – LASER SPECIFICS FOR THE CASE STUDY

Laser Type	Dye
Mode (Pulsed)	Pulsed
Power (Watts)	20
Pulse Energy (Joules)	0.00077
Pulse Width (s)	1.3 X 10^-7
Pulse Rep. Freq (Hz)	2600
Beam Diameter (cm)	47
Beam Divergence (mrad)	0.002
Wavelength (nm)	589
MPE (Watts / cm^2)	0.00145
NOHD (feet and NM)*	2 980 000 ft. 490.4 NM

*NOTE: Since the beam originates from a high altitude and propagates vertically, the NOHD calculation does not include any atmospheric attenuation consideration.

- 2. Determine site proximity to airports, flight zones, and flight operations areas.

LGSO has performed 3 dimensional geographic analysis of the location of the laser facility and all nearby airports. The conclusion is that there is no overlap between LGSO operational airspace and the flight hazard zones of any Federal Air Regulation (FAR) Class I, II or III airport, but one small overlap with the critical flight zone of a local intermittent use military airfield.

Figure C1 is a plan view of the Big Island of Hawaii showing the location of the LGSO on Mauna Kea (marked on the map with an “M”), and the locations of each of the five airports/airfields in the region. The five airports on the Island of Hawaii include two FAR 139 Class I airports (Kona and Hilo International airports), no Class II airports, one Class III airport (Waimea-Kohala Airport) and two airfields that do not have an FAR 139 classification (Upolu and Bradshaw Army Airfield). Each airport is shown on the drawing along with its name, location, elevation and three character airport abbreviation.

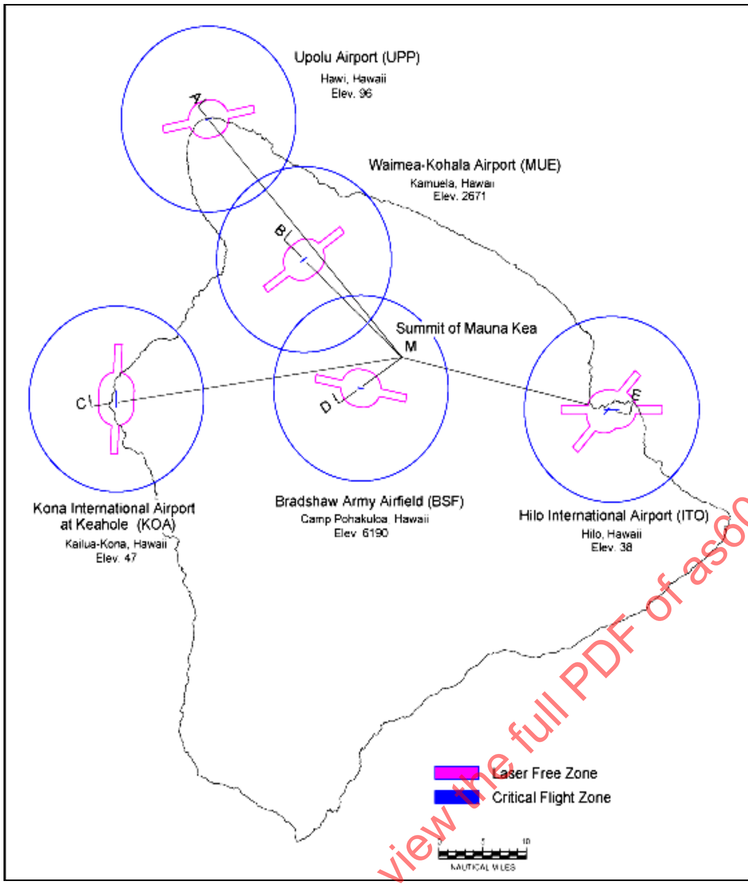

FIGURE C1 – PLAN VIEW OF PROXIMITY TO AIRPORT FLIGHT ZONES

Around each airport in this plan view, the laser free zone and critical flight zone are drawn to scale. The laser free zone is outlined in magenta, around the actual runway(s) location, length and orientation. Hilo is the only airport with more than one runway, and hence has a more complicated laser free zone. The critical flight zone around each airport is shown to scale by a dark blue circle of radius 10 nautical miles from the airport reference point. There are no sensitive flight zone dimensions established by local authorities for this area.

Figure C1 shows that the laser operations appear to be outside of the laser free zone around all nearby runways. It also shows that from a plan view, the operations appear to be outside of the critical flight zones for all airports except Bradshaw Army Airfield where there is an overlap. Making a definitive determination on this potential overlap requires analysis of the corresponding elevation view to draw conclusions about this 3-dimensional problem.

In Figure C1, there are a series of straight lines connecting Mauna Kea with the reference point for each airport. These cross section lines depict the location of a corresponding drawing of the elevation view along that line. Each end of the cross section lines is labeled. Each cross section has one end, labeled “M” on Mauna Kea, and the other end at one of the airports. Two of the elevation views are described below.

Elevation views for airport proximity evaluations for Kona International Airport (C-M) and Bradshaw Army Airfield (D-M) are shown in Figure C2 and Figure C3.

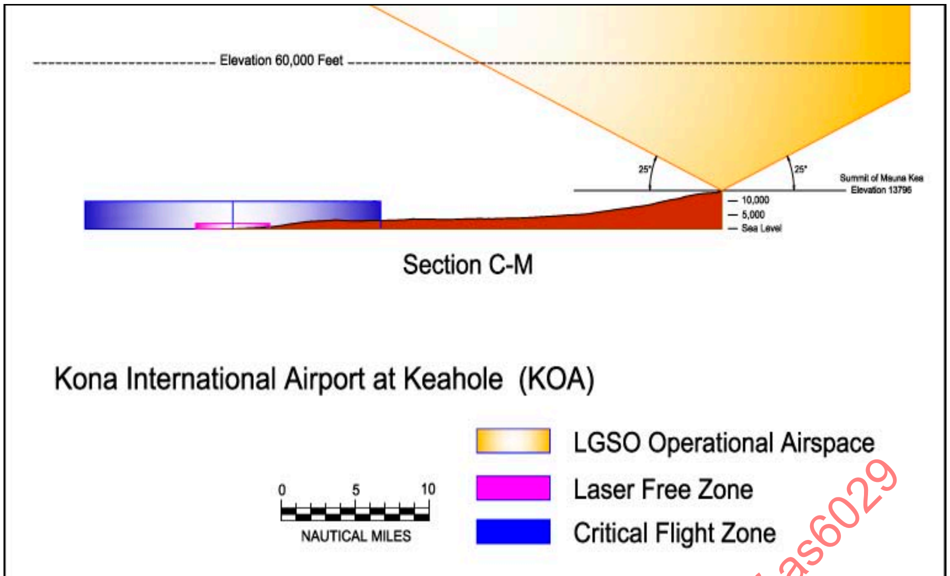

FIGURE C2 – ELEVATION VIEW OF THE GEOGRAPHIC RELATIONSHIP BETWEEN KOA AND THE LGSO ON MAUNA KEA

The elevation drawings shown in Figure C2 and C3 are drawn to scale and show the following: The location of LGSO on Mauna Kea on the Big Island of Hawaii; The 2-dimensional view of the conical volume of airspace through which the laser may be propagated shown in yellow (referred to as the LGSO operational airspace in this case study); The actual ground contours between the airport and the summit of Mauna Kea, shown in brownish red; the elevation view of the laser free zone around airport runways, shown in shaded magenta. (This zone appears fairly small at the scale of these drawings.); The elevation view of the critical flight zone around the airport (shown in shaded blue); A dotted reference line showing 60 000 feet MSL elevation corresponding to the top of the Class A airspace.

Areas of overlap between the LGSO operational airspace and the flight hazard zones of the airport would show up as an overlap between the yellow shaded volume and either of the blue or magenta shaded hazard zones.

Figure C2 shows an elevation view of the cross section of the Big Island of Hawaii cut through KOA on the left, and the summit of Mauna Kea on the right along with propagation volume and hazard zones. As the figure shows, there is no overlap between the LGSO operational airspace and the hazard zones of KOA.

The LGSO laser operations are also entirely outside the laser free and critical flight zones for Hilo International, Waimea-Kohala and Upolu airports. The geographic proximity analysis has been performed for these other airports and is available to the FAA on request.

The plan view in Figure C1 shows a possible overlap of the critical flight zone and the operational airspace for the laser and Bradshaw Army Airfield (BSF). BSF is an intermittent use military facility, located six nautical miles horizontal distance from LGSO, and 1.25 nautical miles below LGSO in elevation. The corresponding elevation view is shown in Figure C3. Figure C3 shows an elevation view of the cross section of the Big Island of Hawaii cut through BSF on the left, and the summit of Mauna Kea on the right along with the LGSO operational airspace and hazard zones.

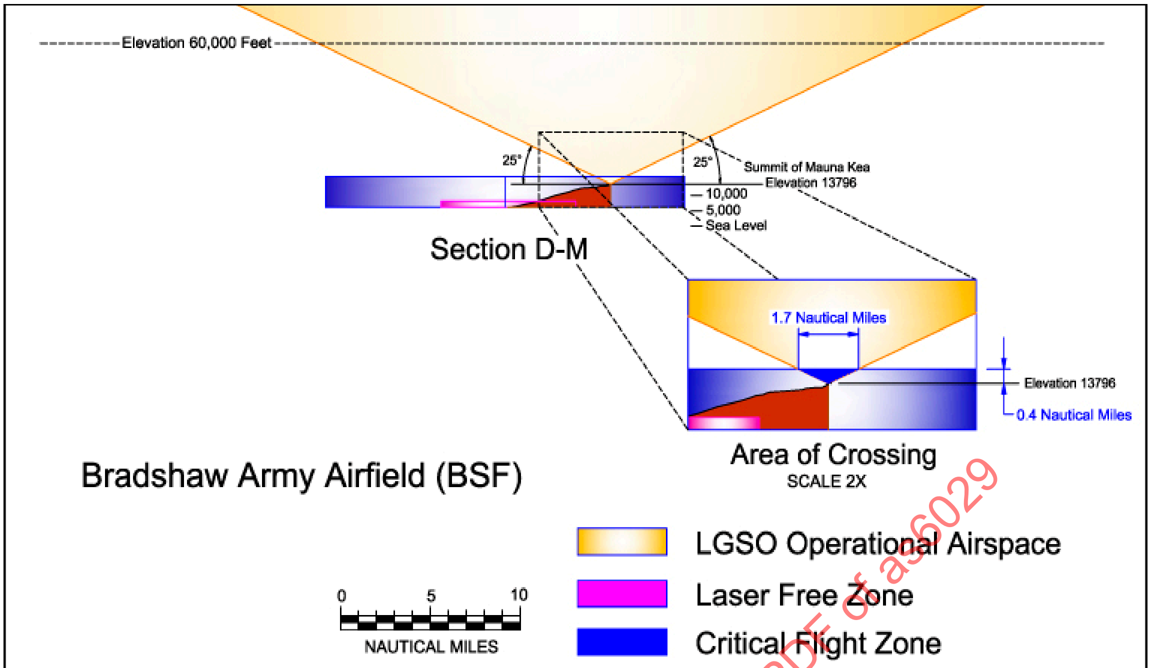

FIGURE C3 – ELEVATION VIEW OF THE GEOMETRIC RELATIONSHIP BETWEEN BSF AND THE LASER OPERATIONS ON MAUNA KEA.

As the figure shows, there is a small overlap or crossing between the operational airspace and the critical flight hazard zone of BSF. The overlap is a conical volume, 0.4 nautical miles high and 1.7 nautical miles diameter at its widest, located directly over the top of Mauna Kea and at the top edge of the BSF critical flight zone. The location of this small overlap with the critical flight zone, very low to the ground just over the summit of the mountain, is outside the airspace typically used by BSF aircraft and therefore the corresponding risk is quite low. Mitigation for this potential hazard includes control measures and also the administrative procedures for proactive coordination with the local military authorities in advance of each operational night.

- 3. Determine site proximity to and potential implications of military/special use airspace

There is a military facility near LGSO on the Big Island of Hawaii. It is called Pohakaloa Training Area (PTA), and includes BSF and also restricted airspace R-3103. Figure C4, below, shows the proximity of R-3103 to the LGSO on the summit of Mauna Kea. The horizontal distance from the summit of Mauna Kea to the closest edge of R-3103 is about 5.2 NM.

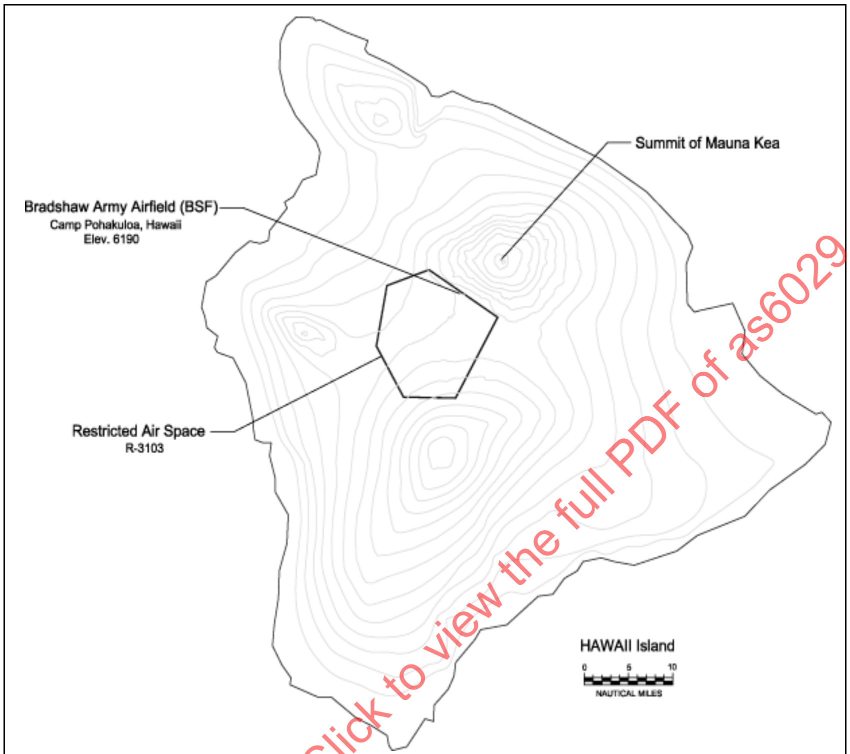

FIGURE C4 – MAP SHOWING THE PROXIMITY OF MAUNA KEA TO RESTRICTED AIRSPACE R-3103

The 3-dimensional proximity of LGSO operations to the military operations areas requires both plan view, as provided by the map in Figure C4, as well as an elevation view which appears in the Figure C5.

In Figure C5 the volume of airspace through which LGSO propagates the laser is a conical volume, labeled "LGSO Operational Airspace," with its bottom tip at the observatory on the summit of Mauna Kea up to the top of the FAA Class A airspace at 60 000 feet MSL. It is shaded yellow. The sides of this cone are at an angle of 25 degrees above horizon. The laser is restricted to propagate only within this cone. R-3103 is shown as an irregular extruded solid, based on the ground and extending upwards to 30 000 feet MSL. The figure shows a very small overlap between the laser cone and R-3103.

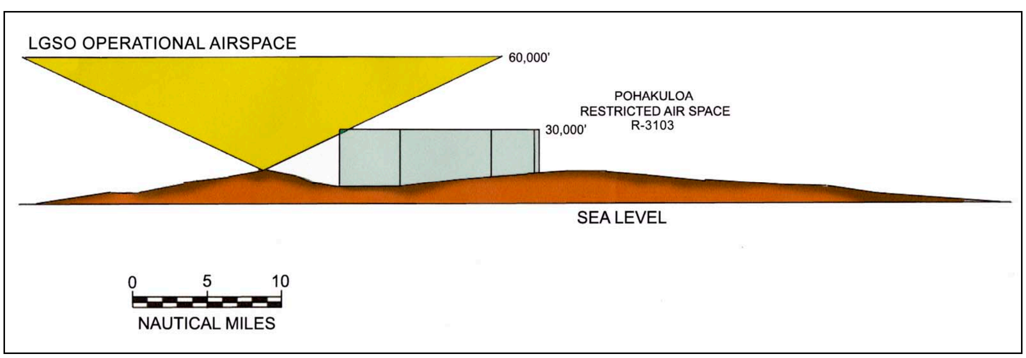

FIGURE C5 – ELEVATION VIEW OF THE BIG ISLAND, SHOWING THE LGSO OPERATIONAL AIRSPACE AND RESTRICTED AIRSPACE R-3103.

The airspace through which the laser propagates is a cone, so the intersection of that cone and the flat edge of R-3103 shown as the small green triangle whose volume at its maximum is 0.27 NM high, 0.5 NM wide and extends about 4.5 NM along the edge of R-3103.

Astronomers prefer observing at high elevations when possible, so the probability that the LGS-AO science program would require propagation into the small overlap area with R-3103 is extremely low. Restricted airspace R-3103 and Bradshaw Army Airfield are used only intermittently and night time operations are only a small percentage that. Given that LGSO operations are exclusively at night, simultaneous operations are very infrequent and when they do happen, may only last for a few hours.

Mitigating the risk associated with the overlapping airspace used by LGSO and R-3103 is accomplished by proactive coordination between the LGSO and the local military. This is a routine part of LGSO standard operating procedure. There is also a cautionary note on the FAA navigation chart about laser light activity, which also serves to mitigate risk by raising awareness. Both military pilots as well as civilian pilots can be expected to reference these charts. The local military authorities are also supplied with general information on LGSO operations as well as LGSO laser propagation schedules to help educate the pilots preparing for operations at PTA on the nights when a laser will be propagating.

- 4. Characterize the local air traffic expected during operation (volume, routes, direction, distance, minimum/maximum altitude and speed, etc.)

In order to better understand the air traffic in and around the airspace in which the laser is operated, the LGSO acquired six months worth of Aircraft Situation Display to Industry (ASDI) data. LGSO purchased this publicly available FAA data from a commercial source and had them filter the data set to include only aircraft that actually passed through LGSO operational airspace. Specifically, these are aircraft that pass within 28 NM of the observatory at altitudes above 13 700 ft. MSL at night. The data analyzed are from July–December 2007.

The results of this analysis show that during that 6 month period, only 14 aircraft passed through the LGSO operational airspace at night. Those 14 aircraft were all commercial fixed wing aircraft (Boeing 747 or 767). Their speed ranged from 420 to 560 knots. Their altitude ranged from 31 000 to 37 000 feet MSL. All 14 of these aircraft were flights that neither originated in Hawaii nor had Hawaii as their destination. They were over-flights of aircraft flying between California and the south Pacific (Australia, Fiji and Samoa). None of these aircraft changed altitude during their time within the LGSO operational airspace. They were effectively in horizontal flight.

Military operations are filtered out of the ASDI data and VFR data is also not included. LGSO accounts for this in two ways. First, it is reasonable not to expect VFR traffic at altitudes over 13 700 feet at night over the mountain top so LGSO asserts that the absence of VFR data from the data set does not change the conclusions in any way. Second, LGSO routinely takes proactive steps to coordinate with the local military airspace operations and scheduling officers to raise awareness and mitigate risk to military operations. This cooperative coordination between the observatory and the local military has been tested and has worked well.

The conclusions taken from this research are that, in the LGSO nighttime environment above the summit of Mauna Kea, it is reasonable to expect only fixed wing aircraft (no helicopters, gliders, hot air balloons, etc.). The range of speed and altitudes for the flights in the ASDI data sample represent a realistic range at which to expect future air traffic. The data show that a very low expected volume of air traffic of about one aircraft every two weeks on average will pass through the LGSO operational airspace at night. Based on this data, LGSO will optimize, but not limit, control measure performance and procedures accordingly. It should be noted that the control measures are capable of protecting aircraft well beyond the expected air traffic flow.

- 5. Determine the type of aircraft expected (fixed wing, rotorcraft, dirigibles, balloons, gliders, etc.)

Both LGSO experience and historical FAA data from second half of 2007 support the assertion that only fixed wing aircraft are reasonably expected over the top of Mauna Kea at night. There is no record of helicopters, gliders, hot air balloons, etc. over the mountain at night in either the ASDI data, or in records kept during the last several years of observations near this site.

- 6. Characterize the visual environment and its potential effect on control measures (day or night, air quality, light pollution, distance at which aircraft can be seen during operations, etc.)

The observatory site was originally selected in part because the night time sky is extremely dark and transparent; characteristics that are ideal for both astronomy and aircraft detection. The laser operations occur only at night. The environment has excellent air quality and extremely low light pollution.

In this remote, high altitude site, it is typical for people to be able to see aircraft lights as they approach, take off or land at KOA, which is over 38 NM away.

- 7. Identify environmental factors that may affect control measures (elevation, temperature, weather, obstructions, etc.)

LGSO is at a high altitude and can be very cold and windy. This environment is particularly difficult for people but poses less of a problem to automated control measures.

There could be some obstructions within the FOV of control measures depending on design and implementation details of the aircraft protection system. The local hillsides do not rise high enough to obstruct most feasible control measures. The observatory building and dome as well as the buildings and domes of the other facilities that share the mountain top could obstruct some control measure selections depending on where they are installed.

- 8. Identify constraints and issues for justification that may affect control measure development and operation (frequency of operation, development and operations budgets, risk, feasibility, etc.)

Operational plans for the foreseeable future include hundreds of nights per year of laser operations, with an average night lasting 12 hours in duration. As such, investing in automated control measure development is justified. Additionally, in the harsh environment of Mauna Kea, automated control measures are expected to prove to be more reliable and effective. Automated control measures also alleviate the problems with staffing, transporting and training large numbers of people for safety observer positions, which historically have suffered from high turnover rates. LGSO has significant technical expertise and has determined that there are feasible alternatives with acceptable levels of technical and budget risk.

- 9. Characterize laser propagation direction and motion (fixed, scanning, propagation duration, etc.)

LGSO operates the lasers at all azimuths, at elevations from 25 degrees to 90 degrees above the horizon. The operations are regularly scheduled, from sunset to sunrise (typically 10 to 14 hours in duration).

The beams are basically stationary, although in reality they move very slowly across the sky as they point to astronomical objects tracking across the night time sky. The laser propagates only when the telescope is tracking on an astronomical object. It does not propagate when the telescope slews from one astronomical object to another.

- 10. Identify personnel related issues (attended vs. unattended, required skill set for labor force, etc.)

The operation will be attended at all times by a qualified laser safety lead. This person along with the system operators will require training and must have a moderate level of technical expertise. Safety observers will be available in case there is a partial system failure with the automated control measures. Safety observers will need appropriate qualifications and training, but no significant technical expertise will be required.

C.2.2 Select Appropriate Control Measures

Three control measures have been selected that will be used in a flexibly configured multi-tier system. The control measures include:

- InfraRed Boresight Camera (IRB): A narrow field, boresighted infrared wavelength (3 μm – 5 μm) camera. This is a very fast system that is particularly well suited for use at closer distances where faster reaction time might be required. The reaction time is 0.2 seconds. The IRB has a FOV that forms a concentric circle with a radius of 10 degrees around the laser beam that tracks the beam's path as it moves. There are no obstructions in the FOV of the IRB at any time.

- Wide Field Visible wavelength camera (WFV): This camera has a slower reaction time than the IRB but has significantly better sensitivity, ideally suited to detecting aircraft at farther distances. The camera is permanently mounted pointing straight up with an extremely wide angle lens that allows image capture of nearly the entire sky. The reaction time is 10 seconds. From the place that the WFV is installed, the FOV is generally unobstructed above 10 degrees elevation from the horizon, but there is one local obstruction between azimuths 20 degrees and 35 degrees (North-NorthEast) that extends up to 20 degrees. Procedural mitigation steps have been adopted to avoid depending on WFV when the laser is within 8 degrees of the obstruction in the FOV unless the IRB or safety observers are also being used.

- Safety Observers: Reaction time is estimated at two seconds. Observers have a very wide and dynamic FOV given their ability to scan using the motion of their eyes, neck and body. Depending on where they stand, their FOV could be partially obscured by the telescope dome, but geometric analysis and testing has shown that this can be mitigated by standing at least 75 feet away from the 100 foot high dome. If the safety observer stands at that position, on the side of the dome toward which the laser is propagating, he/she can see the entire affected airspace including over 11 seconds of flight for a 600 NM/hr aircraft at 25 000 feet MSL approaching the beam from any direction, including coming from the behind. This allows the observers sufficient time to react and effectively mitigate the problems of obscuration from the dome.

The system will be operated primarily in one of two configurations; (1) fully automated which will use both the IRB and WFV without safety observers, and (2) safety observer based configuration where observers are the primary and sufficient control measure. The IRB or WFV may also be used in parallel with observers while in the safety observer based configuration. The aircraft protection system can be configured in either of these two modes of operation through software. Appropriate interlock and control system changes take place automatically and the operators interface shows clearly which configuration the system is in. There are also a few procedural differences between safety observer based and fully automated configurations.

C.2.3 Predict Control Measure Performance

Aircraft flying at night have lights that meet FAA specified brightness requirements. The movement of these lights in the night time sky can be detected by safety observers and WFV.

The light from any source will appear dimmer to an observer as the distance to the source increases. LGSO has modeled this effect for aircraft lights. With the camera sensitivity specifications and testing, LGSO predicts that the WFV will be able to detect aircraft lights over Mauna Kea at distances well exceeding 21 NM, the maximum distance to aircraft in LGSO operational airspace.

From the facility, observers routinely see aircraft lights during approach, take off and landing at KOA, 38 miles away. The observer’s capability to see aircraft at such great distances is well beyond typical expectations due to the very dark and transparent sky in this remote, high elevation environment.

Commercial fixed wing aircraft of the type expected in the LGSO environment have a significant IR signature. This IR signature can be detected by the IRB in the 3 μm - 5 μm wavelength range. The IRB might have difficulty with other types of aircraft (military, stealth, gliders, etc.) but, as supported by the air traffic characterization effort described earlier, these types of aircraft are not reasonably expected over the remote mountain top at night.

The combination of IRB and WFV into a single, multi-tier system will provide overlapping aircraft protection capability in most situations and complementary capability in situations where extreme sensitivity or reaction time is required.

C.2.4 Implement Control Measures and Infrastructure

The implementation and testing of the two automated tiers has taken place over a period of years. During this development period, observers have been used as the primary control measure with testing of the automated systems going on in parallel.

The final design meets the LGSO standard for failsafe design. All possible single-point failures that have been identified have been mitigated. Features designed into the LGSO aircraft protection system include automatic data logging, clear and operationally-tested computer user interfaces, separate E-stop system, hardware interlocks and over-rides.

User documentation has been developed and training of the personnel conducted. Operational procedures and defined roles and responsibilities have been established. A schedule for periodic reassessment has been adopted with test procedures documented. Some system elements are checked nightly while others are tested less frequently, but all are reassessed at least once every two years. The specifics of this maintenance schedule are available to the FAA on request.

C.2.5 Characterize Actual Performance

Performance characterization is composed of operational testing, failure mode and response identification, system capabilities, system limitations and mitigation. These are discussed in more detail below.

- Operational testing:

  The operational testing of the automated control measures was performed while operating in the safety observer based configuration. The time stamped data logs of aircraft detected by the IRB and WFV were compared against ASDI time stamped aircraft positional data. The ASDI data give time, latitude, longitude, aircraft type, speed and altitude. With this ASDI data as the reference, LGSO confirmed that both of the automated control measures correctly detected all commercial jetliners. These aircraft were at distances between 4 NM and 40 NM and at speeds from 320 to 560 knots. Tests were performed on 100 nights over a period of six months.

  In that period of time, WFV correctly detected 14 aircraft, one of which was near the propagating laser. The laser was successfully shuttered for that one aircraft. There were no instances of aircraft in the ASDI data that were not also detected by WFV.

  The WFV incorrectly identified four different satellites as aircraft and shuttered the laser. This was expected and since it is not an additional risk to aircraft, the loss of efficiency of LGSO operations is accepted.

  During that same period of time, there were no aircraft detected by the IRB. The one aircraft in the ASDI data that did come near the beam, did not pass within 10 degrees and was therefore never within the IRB FOV. The extremely low air traffic density over Mauna Kea makes testing challenging. In order to increase the number of test aircraft within the IRB FOV, it was removed from the boresight fixture on the telescope and placed in a separate mount that could be redirected toward incoming aircraft quickly anywhere in the sky. This allowed LGSO to gather data on six aircraft over the next five months. The IRB detected commercial jetliners as far away as 30 NM. There were no aircraft within the FOV that were not properly detected. There were two events where the IRB incorrectly detected an aircraft that was not actually there. These events were caused by scattered moonlight. In actual operations, the system would not be pointed close to the moon per our standard operating procedures.

- Failure modes and responses

  LGSO identified five failure modes that would cause the aircraft protection system to fail to perform as designed.

  - Infrastructure failures such as loss of power would cause wider disruptions than just the aircraft protection systems. Power disruption would also affect the ability to propagate the laser and perform normal astronomical research. Therefore this failure mode would not cause increased risk to aircraft and requires no planned response related specifically to our aircraft protection systems.

  - There are several critical components that must be functional before the laser can be propagated. These include the computers and programmable logic controllers used in the safety and control systems. These components are required regardless of how the system is configured or what control measures are being used. Automated monitors are in place to detect failures of these components and prevent the laser from being propagated.

- There are monitors on the dedicated computers for each of the individual control measures. If these computers indicate via telemetry that there is a problem with a control measure in use, or if the computer is unresponsive, the safety system will automatically shutter the laser.

- The mechanical shutter used to block the beam in the event an aircraft is detected is equipped with a pair of redundant sensors that report the physical devices true position. If these sensors do not agree, or indicate that the shutter is not in the correct position, the laser is automatically attenuated by the safety system computer controlling backup/redundant shutters.

- The possibility of multiple simultaneous failures is mitigated by virtue of the design of the overall automated safety system. All known failure modes can be detected by either dedicated sensors or system telemetry. Each failure mode is monitored for occurrence in parallel; any combination of failures, single or multiple, will result in the laser being put in a safe state.

- System capabilities

Performance predictions were confirmed with the operational testing. Both the IRB and the WFV are capable of detecting the fixed wing aircraft seen above Mauna Kea at night.

- System limitations and mitigation

System limitations have been identified and include environmental conditions that keep a properly functioning control measure from performing at optimum levels. Mitigation steps for each of these system limitations are also discussed.

- Bright Light Interference: The performance of WFV sensitivity to signal degrades near sources of bright light interference. Sources of bright light interference in the LGSO environment are the moon and the brightening sky during morning or evening twilight and day time. The scientific instrumentation used with the LGS-AO system is adversely impacted by bright sky light more than the aircraft safety control measures. Therefore, propagation of the laser is allowed so long as the LGS-AO system can handle the background light. This mitigation assures that safety observers and WFV effectiveness is not compromised.

- Clouds: Clouds also cause a degradation of WFV performance relative to sensitivity to signal. To mitigate this, LGSO compares the brightness of the stars being observed with the astronomical instruments to their expected brightness, and if specific cataloged stars appear significantly dimmer than expected, LGSO shutters the laser. Additionally there is a separate camera on Mauna Kea that is used to monitor cloud cover. This camera display is made available to operators on LGS observing nights so that they can react to changes in cloud cover as necessary.

- Wind: Wind can compromise the effectiveness of control measures if it is strong enough to pick up dust and debris which can reduce atmospheric clarity. Wind can also pose problems for safety observers outside, especially if it is combined with cold temperatures. This airborne debris is also bad for the astronomical instruments and there is a procedure that requires that operations cease when the winds exceed certain thresholds. This procedure is sufficient to also mitigate the risk of high wind impacting the aircraft protection system.

- Aircraft traveling directly toward the observer: The WFV ability to detect motion can degrade in cases where the aircraft is traveling for an extended period of time directly toward the control measure, resulting in an apparently stationary light source. This scenario is not reasonably expected in our environment. All of the historical air traffic data show only level flight for all aircraft passing though LGSO operational airspace. Potentially stationary aircraft, such as helicopters and balloons, are not expected in our environment.

- Unrealistically close aircraft: The reaction time of WFV is slow enough that there are limitations to its ability to detect and respond to fast moving aircraft at extremely close ranges. This risk is mitigated in two ways. First the FOV of WFV is large enough that the aircraft will be detected well before it can reach a position directly overhead. The second mitigation is the pairing of the slower WFV with the much faster IRB in our multi-tier automated operational configuration.

- Satellite confusion: Satellites traversing the night time sky can be mistakenly identified by the WFV as aircraft. In these cases, a false aircraft detection causes the laser to be shuttered. This failure mode does not pose a risk to aircraft but only results in reduced operational time with the laser in the sky. Given the extremely low frequency of this occurrence, LGSO accepts the loss in efficiency without further mitigation at this time.

- Precipitation: Precipitation or high humidity can adversely affect the IRB by increasing the background radiation in the 3 µm to 5 µm range caused by the moisture in the air. Standard operating procedures prohibit propagating the laser under these conditions.

- Condensation: Condensation on WFV or IRB lenses can degrade image quality and compromise aircraft detection. A similar risk exists with other lenses and mirrors used throughout the telescope and astronomical instrumentation, many of which are even more sensitive than the aircraft detection systems. The procedures defined to monitor this risk for all observatory systems is sufficient to ensure aircraft protection is not compromised.

C.2.6 Develop Operational Procedures

LGSO has developed a set of procedures that clearly defines for the operations staff when conditions are such that the system is and is not capable of meeting the performance criteria. Use of these procedures will eliminate any ambiguity or inconsistent use of the safety systems in various conditions or by different operational team members. The procedure set includes the following: normal operating procedures, procedures related to weather, bright light interference, obscurations and partial system failures.

- Normal Operating Procedures

    - Pre-Propagation

      In the three day period immediately prior to LGS operations, the following steps must be taken.

      - Honolulu FAA and Air Traffic Control notified.
      - Notify local military contacts and ask about possible military operations
      - Laser Safety Officer approval of schedule
      - Notify other observatories on Mauna Kea
      - Send observing object list to US Space Command

    - Start-up

      In the afternoon before each and every night of LGS operation the following steps are required:

      - Nightly meeting to inform and coordinate the on-site staff
      - Verify that the staff are all aware of established operational procedures and have access to related documentation
      - Remind staff of emergency contact information and procedures
      - Roles and responsibilities clearly assigned
      - Control measure readiness checks
      - Interlocks and intercom verified
      - Final operational system checks and verifications
      - Verify that automated data logging is working for all control measures in use that night