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The Impact of Predictive Avoidance Restrictions on Astronomical Observatories

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About This Publication

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Executive Summary

Background

This report, produced by the Science and Technology Policy Institute at the request of the National Science Foundation (NSF), examines the impact of the Department of Defense (DOD) Laser Clearinghouse (LCH) predictive avoidance (PA) procedures on two astronomical facilities. These are the northern location of the Gemini Observatory (Gemini) and the W. M. Keck Observatory (Keck), both of which are located on Mauna Kea, Hawaii. The PA procedures are designed to protect satellites from lasers used by the observatories to produce an adaptive optics laser guide star (LGS) for increased imaging resolution. The NSF requires an observatory receiving its support to abide by these procedures.

Major Findings and Conclusions

- The Gemini North and Keck II lasers have the potential to damage certain components of satellites.
- The probability of the observatory lasers actually permanently affecting the operational capability of a satellite is minuscule.
- The requirement that Gemini and Keck follow DOD predictive avoidance procedures is a National Science Foundation policy directive and not a legislative or treaty necessity. Both Keck and Gemini have voluntarily complied with these procedures since they began laser propagation.
- No specific evidence was found that adhering to DOD predictive avoidance procedures has significantly affected the quantity or quality of the science performed at the observatories.
- Adhering to DOD predictive avoidance procedures has prevented the observation of particular targets at particular times.
- Considered over an observing semester of 6 months, the observing time lost by adhering to DOD predictive avoidance procedures is more than an order of magnitude less than the time lost due to other factors such as weather and equipment overhead.
- Considered over the entire observatory staff and operations, the cost in effort and dollars lost by adhering to DOD predictive avoidance procedures is more than an

order of magnitude less than that due to other factors such as weather and equipment overhead.

- The extra effort due to adhering to DOD predictive avoidance procedures is concentrated on a very small number of personnel who work under rigorous time constraints, and for these people the effect of adhering to the procedures is significant.
- A productive cooperation between DOD and the observatories has reduced the impact of DOD predictive avoidance procedures. However, any further significant reduction in impact with the possible exception of Gemini accepting rapid targets of opportunity and modestly further reducing its laser system exclusion cone angle will now be difficult.
- Both observatories place their highest priority on reducing the effect of planned laser closures produced by the submission of a laser request message to DOD several days before observations begin. This has the largest impact on routine operations. However, both observatories have said they can “live with” the current impact. There are no actions Keck can take at this time to reduce this impact. Gemini could expect some reduction in impact by reducing its laser system exclusion cone from 0.25 degrees to 0.1 degrees, which is the value DOD now uses for Keck. This is now under consideration but must be balanced against other priorities.
- For Gemini the next highest priority is being able to use LGS observations for rapid targets of opportunity (ToO). In the future, it may be possible for Gemini to respond to many rapid targets of opportunity in about 90 minutes. This may require some change in Gemini procedures and could not be guaranteed in all cases since it would be dependent on operational DOD priorities at the time of a request.
- For Keck the next highest priority is reducing the number and duration of what the observatories commonly call “blanket closures” or what DOD officially labels “space events,” which are when no use of the laser to observe any target is permitted. Keck has no additional direct way to reduce the effect of blanket closures caused by new satellite launches or maneuvers and whose length is determined by the amount of time it takes DOD to establish with sufficient accuracy new orbital parameters.
- The DOD predictive avoidance procedure tends to have a more severe impact on DOD laser use than on civilian observatory laser use. Certain proposed mitigation techniques to reduce the impact on DOD laser use would also reduce the impact on observatory laser use.

- Both Gemini North—the only Gemini facility using an LGS during the period of this study—and the Keck Observatory take seriously the restrictions imposed by National Science Foundation instructions, and they abide by the DOD LCH restrictions. The interactions between these observatories and the LCH have in general been cordial and productive.

Additional Details

No documented negative effect of the LCH restrictions on actual scientific productivity or quality was found. Gemini, however, felt that these restrictions prevented it from offering the same planned rapid target of opportunity (less than 24 hours) observing capability to its investigating astronomers using an LGS as it does for observations without one. No example was given where a Gemini astronomer could have potentially made an LGS short-lived transient observation while an astronomer at an observatory not limited by the LCH restrictions actually did. Keck felt that blanket closures, which prevent any LGS observing during a specified time, might in particular seriously affect the writing of a graduate thesis but could cite no specific examples of this affect actually occurring.

Although we cannot exclude the possibility that a negative impact on science productivity or quality has already occurred or may occur in the future, the impact of LCH restrictions is probably small compared with other factors, primarily because the laser closure times due to LCH restrictions are an order of magnitude below those caused by other effects such as weather and operational equipment overhead. LGS adaptive optics use require good weather conditions, which do not occur about 25% of the time at the observatories. However, there are increased workloads and costs associated with following the NSF policy. Taken over the entire observatory operations and staff these are small, but the additional workload tends to be concentrated in time and in the activities of only a few staff members.

Initially, the change in LCH predictive avoidance calculations to the Spiral 3 upgraded methodology implemented on the Space Deconfliction System workstations in November 2007 had a significant effect on observatory observations. It came as a surprise to the observatories and resulted in some significant effort over the years to work with the LCH to reduce its impact on their operations. A good part of this effort was related to reducing the uncertainty value used in the Spiral-3 calculations as to where the laser might be pointing if a major system malfunction occurred. This primarily involved documenting laser operations with the LCH, rather than making any actual changes in laser operations. Working with the LCH, each observatory could have a satellite Unique Protect List developed, which reduced the number of satellites of concern based on certain damage criteria. Currently, both observatories feel that the policy of sending in their observing schedules several days ahead of a set of LGS nights to the LCH and receiving a set of laser closures about 24 hours before each night's observations (called standard or classical PA) is working reasonably well. Using the same phrase, both said that they "can live" with the current procedure. However, they both would prefer that the impact of standard PA be further reduced since this is the primary workload associated with the LCH.

Keck now reports an average of about two classical PA closures a night, with each lasting on average about 20 seconds. This is about the lowest effect possible using current LCH guidelines. This compares with essentially no classical PA closures before the implementation of Spiral 3. A new, lower laser pointing value uncertainty for Gemini was instituted in July 2010 and should result in a reduction in standard PA impact there. The results will be similar to, but not quite as good as, those at Keck because Gemini uses a primary manual technique for shuttering the laser in case of a serious pointing error while Keck uses an automated one. This is not a safety issue, but due to how the LCH considers laser pointing uncertainties, it assigns a somewhat higher pointing uncertainty to Gemini than to Keck, which results in a somewhat higher PA impact. Gemini is considering moving to an automated system in the future.

At this time the major concern of Gemini is how LCH restrictions affect its response to transient targets of opportunity. Using the newly instituted protocols, it appears feasible to expect the LCH-restrictions-related portion of this response time to be approximately 90 minutes. This would allow many but not all rapid ToO to be addressed. Moving below this value while following LCH restrictions would probably be difficult. When not using an LGS, the minimum Gemini response time is about 10 minutes.

At this time the major concern of Keck is how it can respond to LCH instructions to prevent any propagation of the laser when the LCH or another DOD organization issues space events or blanket closures. These occur about 10 times a year and, while most are under about 40 minutes, 1 in the past 18 months in January 2010 lasted an entire night. In calendar year 2009, about 7 hours were lost due to blanket closures; in 2005, about 4 hours were lost. These closures occur because of uncertainties in satellite positions due to maneuvers or new launches. There is nothing the observatories can do on their own to reduce this impact. It is possible that a blanket closure could severely affect the productivity or quality of a particular science program of an individual observer. Keck could not cite a specific instance of this actually happening, however.

The lost time due to LCH restrictions only has an impact on science when all the equipment is operating properly and the weather allows LGS observations. Besides the weather, to which astronomers are long accustomed, it is the major factor outside the observatory's direct control that affects observations. Equipment overhead and failures are in principle preventable by actions the observatories could take. As such, the restrictions may trigger more frustration for the observers than other factors since they may be seen as the last step impeding observations. This may happen even though the absolute time lost to the LCH restrictions is only a few percent of the time lost to other factors such as weather, equipment problems, and system overhead.

Adaptive optics lasers of the type used by Gemini and Keck can, if conditions are right, cause permanent damage to some satellites. These would primarily be visible imaging satellites with large apertures that happened to be "looking" at the observatories as the same time the lasers were illuminating the satellite. Visible imaging satellites typically are not often used at night. The damage might be as small as destroying one pixel in an imaging array of thousands of pixels and might not have any significant effect on the operational capabilities of the satellite.

As LGS lasers are used now, the probability of a single LGS laser randomly illuminating a single satellite over the approximately 10-year satellite lifetime is very crudely estimated to be about 0.1%. Out of the over 1000 objects in the LCH database, about 200 satellites are of particular concern when considering damage that might be caused by an observatory laser. These are primarily low-orbit, Earth-observing satellites using optical sensors. As a rough approximation, a single laser will illuminate 1 out of this group of 200 satellites about every 50 years. As the number of observatories with LGS lasers grows and the use of multiple laser LGS systems becomes common, an observatory laser somewhere might strike a satellite about once a year. However, in most cases, simply striking a satellite will not damage it. Damage probabilities depend on satellite details, but a very rough estimate for one particularly susceptible kind of satellite, which is not now common, is a 1×10^{-4} probability of damage given that it is struck by a laser. Given these crude assumptions, the probability of a single LGS laser damaging a single satellite over its 10-year lifetime is about 0.00001%, or 1 in 10 million, which is very small. The possibility of actually significantly affecting satellite operations is even lower.

Information that would indicate that satellite damage due to LGS lasers was a serious concern of commercial satellite operators was not found. There are lasers that are not required to follow the LCH restrictions, and some lasers, such as those designed to determine satellite position, are used to deliberately illuminate satellites. No evidence was found that any satellite has been accidently damaged by a laser, although insurance companies have paid claims on loss of commercial satellite capability for other reasons. Eliminating the LCH restrictions on Keck and Gemini would not significantly affect current satellite operations. It was beyond the scope of this study to determine if there were any legal issues that differentiated the treatment of manned spacecraft from unmanned satellites.

In no special order, the alternatives to using the LCH include (1) place no observatory restrictions on LGS use, which is used by at least one foreign observatory; (2) place no observatory restrictions on LGS use but have observatories carry satellite operations liability insurance; (3) place observatory laser pointing schedules on an open

Web site and leave the satellite owners responsible for not "pointing" the satellite at the laser; (4) have the observatories do their own satellite avoidance calculations using publicly available satellite orbit information; (5) continue following the LCH guidelines; and (6) on a Web site controlled by a satellite owners note when satellites would be "pointing" at observatory locations. In the last case, the observatories would monitor the Web sites of those satellite owners who wanted to provide this information and construct their observing plans to avoid satellites pointing at the observatories.

The LCH uses extremely conservative "sure-safe" calculations in determining its laser closure periods. This is a deliberate DOD decision taken to best achieve its past and current goals. Military lasers are required by DOD policy to follow LCH instructions. The LCH restrictions have a greater impact on military LGS-equipped observatory facilities such as the Starfire Optical Range and the Maui Space Surveillance System than on the civilian observatories in terms of possible observing time lost. Consideration by the DOD of the use of a more risk-based approach to address some of the military observatory and other system concerns could eventually reduce the impact of LCH restrictions on the observatories.

At this time the LCH does not contemplate making any changes to its procedures, including any replacements to its Spiral 3 methodology that would adversely affect the observatories. It has said that it will in the future notify the observatories as much as possible ahead of time if any significant changes will take place. To the extent practical, interactions between the observatories and the DOD organizations such as the LCH that use or implement PA that enable the different parties to better understand each other's operations, purpose, and culture should be encouraged.

Contents

1. Introduction

This report describes the results of a study conducted by the Science and Technology Policy Institute for the National Science Foundation (NSF) Division of Astronomical Sciences. The purpose of this task was to determine how adherence to the use of certain laser guide star (LGS) restrictions determined by the Department of Defense (DOD) Laser Clearinghouse (LCH), collectively known as predictive avoidance (PA), affected two astronomical observatories that receive support from the NSF.

In the course of the study information was obtained from a number of individuals at many institutions. Without exception, everyone contacted was cordial and extremely cooperative. This study would not have been possible without the cooperation of the leadership and staff at the observatories and DOD organizations. Two people not directly connected with the study were particularly helpful. These were Dr. Robert Fugate, who was formerly a staff member at the U.S. Air Force Starfire Optical Range (SOR) and who is now a consultant to that organization, and Dr. Joseph Janni, who is a former director of the U.S. Air Force Office of Scientific Research and is now a consultant to the U.S. Air Force Maui Space Surveillance System (MSSS). However, the author is solely responsible for the information in this report.

Site visits were made to the Gemini North Observatory, W. M. Keck Observatory, MSSS, SOR, Metatech Corporation, U.S. Strategic Command (USSTRATCOM) LCH, and the U.S. Strategic Command Space Situational Awareness Operations (SSA Ops) Center. Detailed information was also obtained from the U.S. Air Force Satellite Assessment Center (SatAC). To help understand the qualitative as well as quantitative effects of PA, the visits to Gemini North and Keck included several days spent observing activities at their headquarters and several nights spent observing activities at the telescopes on the peak of Mauna Kea as astronomical observations were being made.

All the information contained in this report is unclassified without any Department of Defense or other organization dissemination restrictions. Some discussions with DOD organizations were held at the level of Top Secret/Sensitive Compartmented Information (TS/SCI). These were used primarily to provide clarification and more detail on certain topics. Because this report is for the NSF, terminology will tend to follow that used by the observatories, although equivalent DOD terminology will be indicated.

The names of organizations rather than individuals are used to designate the sources of information. Unless specifically noted, these should not necessarily be interpreted as official organizational policy. Also, Gemini North is usually shortened to just Gemini and

Keck usually denotes Keck II. During the period considered in this study, which covered up to the middle of July 2010, the Gemini South laser was not yet in operation and only Keck II was being used with a laser.

Although laser guide stars are used by about half a dozen civilian observatories, this study concentrated on their use by only two of them, Gemini North and Keck. There were several reasons for this selection. They both receive funding by the NSF sponsor of this report either through direct grants or equipment purchases. Both of them have relatively long experience in the use of laser guide stars under PA restrictions. Commissioning at Gemini was completed in 2006, and the first use by Keck for scientific observations was in 2004.[1] Since they are both located on Mauna Kea, Hawaii, the logistics of visiting them was simplified. Perhaps most significant, they also represent two different basic kinds of observation methodology, classical by Keck and queue by Gemini, which might be affected differently by PA. Keck and Gemini tend to use LGS viewing on nights near a full moon (about one quarter of a month) when observations not using adaptive optics are often not as useful.

Keck primarily uses the classical mode of observation for both non-LGS and LGS viewing. In this case, the principal investigator (PI) observing astronomer is assigned a particular time slot on a particular evening usually lasting a half or an entire night many months in advance. Typically, during an observing semester of 6 months, individual PIs have only one or a few nights during which their observations are scheduled. The PIs are present at the telescope control facility either physically or by remote access when their observations are being made.

In contrast, Gemini primarily uses a queue mode for LGS and non-LGS observations. At the beginning of an observing semester, each PI is assigned a certain amount of total time that will be devoted to his or her observations. Gemini decides how to allocate specific nights and times during the semester to each of the PIs. These observations defined by the PIs are carried out on their behalf by the Gemini scientific staff—the PIs have no role in the actual carrying out of the observations. Several factors combine to determine which observation is executed from the pool of possible observations at any particular time, but predominant are scientific ranking and the closeness of match of the required to the actual observing conditions. There are no maximum or minimum time limits for single observations, but long observations are likely to be split into smaller segments to be integrated into a nightly plan.[2] This means that observations for a particular PI might be spread over many nights, which might be

[1] "Overview of the Gemini AO Program," http://sciopsedit.gemini.edu/sciops/instruments/adaptive-optics?%20q=node/10742; M. C. Liu, "Astronomical Science with Laser Guide Star Adaptive Optics," in *Advances in Adaptive Optics II*, eds. B. L. Ellerbroek and D. B. Calia, *Proc. of SPIE* Vol. 6272, (2006) at http://www2.keck.hawaii.edu/optics/lgsao/docs/spie2006-6272-16.pdf.

[2] Gemini, "Queue Mode Observations," 19 April 2010, http://www.gemini.edu/?q=node/10996.

months apart. Usually, a PI will not know an observation has been made until after it has actually occurred.

2. The Predictive Avoidance Issue

Atmospheric turbulence can severely limit the effective resolution of ground-based astronomical observations. To overcome this limitation, a technique called adaptive optics using a laser guide star is now often used. This method propagates a visible laser very close in angular direction to the astronomical object being observed. The wavelength chosen excites sodium atoms that lie in a thin layer in the upper atmosphere at an altitude of about 90 km. These atoms fluoresce and produce what is known as a "laser guide star" (LGS). Light from the LGS passes through the turbulent atmosphere and is collected at the telescope. The nature of the light collected is influenced by the atmospheric turbulence and so by measuring how the light from the known LGS source is distorted, the nature of the turbulence can be determined. With this information, light from the actual object being observed can be corrected usually by using a deformable mirror to reduce the blurring caused by a turbulent atmosphere.[3]

For the purposes of this study, the main feature of interest in the use of an LGS is that it requires the propagation of a laser into the sky. Since the density of the sodium atoms is low, about 90% of the laser power entering the sodium layer continues into space.[4] It is thus possible that the LGS laser beam could accidently irradiate a satellite. (It could also strike an airplane—precautions are taken to prevent this from happening—but that is outside the scope of this study.)

There are several ways to address the issue of an LGS laser accidently hitting and damaging a satellite:

- Keep the laser intensity so low that no effect is produced on the satellite.
- Know where a satellite is either by orbit calculations or real-time observations and turn off the laser if there is a possibility the laser will strike the satellite.
- Build or operate satellites in a manner that minimizes laser effects.
- Determine that the probability of a laser hitting a satellite and affecting it is so small that this type of event can either be ignored or be addressed by purchasing satellite damage liability insurance if available.

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[3] G. Anderson, *The Telescope: Its History, Technology, and Future* (Princeton, NJ: Princeton University Press, 2007), 130.

[4] A. Quirrenbach, "Adaptive Optics with Laser Guide Stars" in *Laser Guide Star Adaptive Optics for Astronomy*, eds. N. Ageorges and C. Dainty, *NATO ASI Series*, vol. 551 (The Netherlands: Luwer Academic Publishers, 2000), 34.

Gemini has taken out insurance for the possibility of damaging aircraft even though aircraft flying near it are rare, and it has a system of human spotters to warn of any approaching aircraft.[5]

The possibility of real-time satellite observation at the observatories was briefly considered. The observatories currently use human spotters to determine if aircraft are in the vicinity of the laser. Systems using cameras are also under consideration. Humans using the naked eye typically can only observe satellites during the limited times when the satellites are illuminated by sunlight and the observer is in darkness. But since many LGS observations take place near a full moon, it is useful to consider what size telescope might enable a person to see a satellite under moonlight. The human pupil size is about 0.5 cm. The ratio of sunlight to moonlight is about 14 magnitudes, or about 400,000. Neglecting other issues such as sky background, the telescope would have to have a diameter of about 3 meters, which is not feasible. The telescope would also have to have a rather wide field of view. If 10 seconds warning was considered appropriate, this would require a total field of view of about 15 degrees.

Electronic detection was also considered. The solar constant is about 1400 W/m^2, so the equivalent value for the moon is about 0.003 W/m^2. Neglecting details such as illumination and observing phase angle and the actual shape of satellite, and assuming that all the light is uniformly reflected from an area of 1 m^2 and other factors, the intensity on Earth from a 600 km satellite at zenith would be about 1×10^{-15} W/m^2. A 1-meter diameter telescope would collect about 3,000 photons/s. If we assume that about three photons would have to strike a pixel on the focal plane array to give a usable signal, the pixel would have to be large enough to cover the motion of a satellite in 0.001 s, which means it needs a field of view of about 0.0005 degrees (2 arcseconds) since the satellite would travel about 0.007 km in this time. The photon number entering the telescope from the satellite would be about 1,000 photons/s (arcsecond)^2. The number of pixels required to have a 15 degree field of view is 30,000, which would mean a rather large 100 megapixel two-dimensional array. The measured broadband sky brightness at Mauna Kea would also produce about 1,000 photons/s (arcsecond)^2 at the entrance to the telescope.[6] If the pixels were square, increasing the size of the pixel would make the relative background contribution even larger since the satellite signal would increase as the linear dimension of the pixel while the background would increase as the area of the pixel. Then, the real-time sensing of satellites at the telescope location does not appear to be a practical alternative to PA.

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[5] F. Rigaut and C. d'Orgeville, "On Practical Aspects of Laser Guide Stars," *C. R. Physique* 6 (2005), 1097.

[6] Gemini, "Optical Sky Background," 26 April 2010, http://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/optical-sky-background.

The NSF Division of Astronomical Sciences requires any LGS observatory using its funds to abide by the DOD restrictions on laser propagation, which are designed to protect satellites. This requirement is an internal NSF policy decision and is not based on any specific statutory language.[7]

The DOD laser restriction policy is directed by a Chairman of the Joint Chiefs of Staff Instruction (CJCSI), "Illumination of Objects in Space by Lasers."[8] This satellite protection procedure is achieved through coordination between the observatory and the USSTRATCOM Laser Clearinghouse. This interaction will be described in more detail later in this report, but in brief, it basically requires the observatory to register its laser with the LCH and normally, with an exception made for transient objects, to submit its targets to be observed to the LCH several days before the observations are to be made. Based on the laser parameters, satellite characteristics, and required safety factors, the LCH, supported by information from the Satellite Assessment Center (SatAC), determines which satellites might be impacted if a laser irradiated them. The LCH then calculates the positions, with an appropriate margin of error, of these satellites during the time the observatory intends to propagate its laser skyward. Where there is a possibility that the laser may unintentionally irradiate the satellite, the LCH will issue a closure period during which laser propagation may not occur. This closure period information is typically sent to the observatories about 24 hours before the observations are begun for the night, although there have been exceptions to this timetable.

The LCH may also, with short notice, require that LGS laser propagation cease in any direction during the night. These events, which can be caused by satellites whose positions may be temporarily unknown to the LCH such as soon after launch or after maneuvers, are commonly called "blanket closures" by the observatory community, although the official and preferred terminology used by DOD is "space events."[9] This report will primarily use "blanket closure" because it is the nomenclature most familiar to the observatory community, although the term "space event" more clearly indicates the specific cause. A space event produces a notice from the LCH to cease all laser propagation until the Space Surveillance Network obtains a sufficiently accurate observation of the new orbit that the notice can to be lifted. Blanket closures do not arbitrarily occur. They are a response to an actual space event.

In the case of unpredictable transient events such as gamma-ray bursts, the observatory may request permission from DOD during an LGS night to observe these

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7 Telephone conversation with NSF Assistant General Counsel, 24 November 2009.

8 S. Goldfein, "Illumination of Objects in Space by Lasers," CJCSI 3225.01, 1 August 2008, http://www.dtic.mil/cjcs_directives/cdata/unlimit/3225_01.pdf.

9 A. Riter, "Laser Clearinghouse Reports Handbook," Change 2, 14 November 2008, 8, http://www.oir.caltech.edu/twiki_oir/pub/Palomar/PalmLGS/Eng_090806/LCH_Reports_Handbook_Change_2_(Rev_A4)_11-14-08_signed.pdf.

events using an LGS laser. This is done by submitting a completely new target list for the night that includes the transient event. The laser and satellite deconfliction calculations will then be done, usually by the Space Situation Awareness Operations Cell (SSA Ops Cell) for transient events, and a new laser window closure list including the transient event will be sent back to the observatory.

A fundamental effect of abiding by LCH restrictions is that the observatory may not be permitted to observe with an LGS a particular desired object at a particular desired time. This could affect the ability to collect important scientific data. Complying with these restrictions also places an additional workload and cost burden on the observatories. The Directors of Keck and Gemini discussed this issue at a meeting with NSF in Washington, D.C., on 5 January 2010. STPI attended this meeting as part of this study. Although not on the formal advance agenda, the issue of LCH restrictions was also discussed by some participants at the November 2009 Center for Adaptive Optics Fall Retreat and its associated 5th Laser Technology and Systems for Astronomy Workshop.

Observatories not funded by NSF and in particular foreign observatories not supported by NSF are not required to follow the NSF instructions to coordinate with the LCH. This has led to a concern among scientists within the domestic astronomical observatory community that United States observatories may be at a significant scientific disadvantage compared with foreign observatories.[10] The European Southern Observatory (ESO) located in Chile appears to be of particular concern because it does not coordinate observations with the LCH.[11]

The ESO first propagated a laser in 2006.[12] In 2007 laser guide star observations occurred on about 30 nights at the Yepun Unit Telescope 4, and although ESO had laser system reliability problems, the plan by 2008 was to schedule approximately 25% of the total scientific observing time, or 42 nights per 6-month semester, at the Yepun telescope for observations using a laser guide star.[13]

PA first became a major issue for the observatories when in November 2007, shortly after the LCH moved from Colorado to its present location at Vandenberg Air Force Base, California, the LCH changed its PA system to one that uses the Spiral 3 upgrade of

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[10] M. Lucibella, "Air Force Restrictions Impact Adaptive Optics," *APS News* 18, no. 9 (October 2009), http://www.aps.org/publications/apsnews/200910/optics.cfm; Association of Universities for Research in Astronomy, (AURA), "AURA's Assessment of Adaptive Optics: Present State and Future Prospects," AURA, September 2008, 63–64.

[11] AURA, op. cit., p. 64.

[12] ESO, "First Light for the VLT Laser Guide Star Facility," *The Messenger* 123 (March 2006), 16, http://www.eso.org/sci/publications/messenger/archive/no.123-mar06/messenger-no123-16-16.pdf.

[13] ESO, "Annual Report 2007," 2008, 25, http://www.eso.org/public/outreach/products/ann-report/ann-report2007_72dpi.pdf; ESO, "Annual Report 2008," 2009, 33, http://www.eso.org/public/outreach/products/ann-report/ann-report2008.pdf .

the Space Deconfliction System workstation. The change significantly increased the number and impact of laser closure windows at observatories like Keck and Gemini.[14] Both observatories said that laser closures were very rare and were not a significant concern before the implementation of Spiral 3.

Since there are no statutory or treaty requirements for civilian observatories to coordinate through the LCH, there have been proposals in the astronomical community for U.S. observatories not to clear laser use with the LCH. The issue of not coordinating has been assessed by these advocates, and they determined that "the risk is extremely small, the liability is high, and the cost is high [if a laser were to cause damage]."[15] It has also been suggested that the observatories could notify satellite owners through Web page information about laser pointing locations.[16]

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[14] R. Campbell and D. Le Mignant, "Space Command Changes Impact Keck Lasing," in *Keck Observers' Newsletter*, Summer 2008, 8–11, http://www2.keck.hawaii.edu/inst/newsletters/Vol5/newsletter.pdf.

[15] AURA, "Report of the AURA Oversight Council for Gemini," 9–10 September 2008, http://www.aura-astronomy.org/events/Aocg/AOCG-RPT-September%209-10,%202008.pdf.

[16] AURA, "Report of the AURA Oversight Council for Gemini," 12–13 March 2009, http://www.aura-astronomy.org/events/Aocg/AOCG-RPT-March%2012-13%202009.pdf.

3. Technical Background

A. Characteristics of Adaptive Optics Lasers

During the period covered by this report, the Gemini and Keck laser systems had similar although not identical properties. Table 1 gives the important properties of these lasers. These values are taken from the "Laser Clearinghouse Information Sheet" Keck and Gemini submitted in 2009 to the LCH as part of the process for registering their lasers.[17] The LCH uses this information to determine if an observatory laser should be considered in PA calculations.

Both lasers have approximately the same average power and divergence. The most significant difference is in their pulse structure—Gemini uses a mode-locked system and Keck utilizes a Q-switched system. The information sheet did not ask for the laser polarization. In some cases the two observatories used slightly different definitions. For example, one specification is for the maximum laser firing time. The numbers given are for the time the laser might continuously be propagating through the atmosphere. Keck gave a value of 4 hours since this would be the maximum time it would observe a target, and the laser was blocked from propagating, or "shuttered," when the telescope was slewed between targets. Gemini gave a value of "all night," which could be about 10 hours. In some cases such as the assumption of a perfectly transparent atmosphere, the observatories were trying to place an upper limit on the laser intensity that might irradiate a satellite. But as will be discussed later, due to the methodology used by the LCH, small differences in these laser parameter values do not significantly affect how PA influences observatory operations.

An important parameter in determining the interaction of an adaptive optics laser with a satellite is the laser beam diameter at the satellite, which depends on the laser beam divergence angle. Because the laser must propagate through the turbulent atmosphere, the divergence is larger than the divergence angle shown in Table 1, which does not include atmospheric effects. Table 1 is primarily used to calculate the laser intensity at a satellite, and using the smallest physically possible divergence is a conservative approach since it gives the maximum intensity.

[17] Keck, "Laser Clearinghouse Information Sheet," 30 January 2009; Gemini, "Laser Clearinghouse Information Sheet," December 2009.

Table 1. Comparison of Keck and Gemini adaptive optics laser parameters.

Parameter	Keck Laser	Gemini Laser	Units
Laser type	pulsed	pulsed	
Average power	20	14	watts
Atmospheric transmission	1	1	
Diffraction limited divergence half angle	2 (at 1/e point)	1.25 (at $1/e^2$ point)	μrad
Wavelength	.589	.589	μm
Beam quality	1.25	1.0	times diffraction limit
Strehl ratio	.65	1.0	
Maximum laser firing time	14,400	continuous during night	seconds
Laser telescope aperture diameter	47	45	cm
Minimum elevation angle	25	20	degrees from horizon
Maximum elevation angle	90	90	degrees from horizon
Pulse format	repeating pulse	mode locked pulses	
Energy per pulse	770	0.18	μJ/pulse
Pulse duration	130	0.8	ns
Pulse repetition frequency	26	76,000	kHz
Instantaneous pulse peak power	5,900	225	watts
Focus point	infinity	infinity	

Observatory sites like Mauna Kea are chosen for good seeing conditions as a result of low atmospheric turbulence. In astronomical terms, seeing is the blurring of the image caused by turbulence in the non-isothermal atmosphere of Earth. It is commonly described as an angular measurement, generally expressed in arcseconds corresponding to the full width at half maximum, of the image profile of an unresolved object such as a star other than the sun. The very good seeing conditions at observatories on Mauna Kea are often less than about 0.5 arcsec in the middle of the visible spectral region.[18]

Another measure of the optical condition of the atmosphere directly related to laser propagation is the Fried diameter, which describes over what aperture distance a wavefront is coherent. On Mauna Kea, the Fried diameter varies from about 17 to 32 cm, which is smaller than the laser propagation telescope aperture diameters and so the

[18] Gemini Technical Factsheet, 1999, http://gemini.physics.ox.ac.uk/observing/gems-specs.html.

divergence angle is dependent on it.[19] The measured divergence for the laser guide star for the Keck laser under median atmospheric conditions is a little more than 1 arc second at full width half maximum (FWHM).[20] This is equivalent to a full divergence angle of about 3 μrad. This varies somewhat, depending on how much atmosphere the laser beam passes through, which, in turn, depends on the elevation angle.

Some of the values in Table 1 suggest that the observatories were trying to be conservative in how much laser energy was propagated into space. For example, the atmospheric transmission is given as 1 although the actual transmission is about 0.8.[21] However, due to how the LCH evaluates the possibility of satellite damage, small differences such of this do not have any effect on PA.

In almost all cases the astronomical observatories are used to observe very distant objects such as stars. The adaptive optics laser must point close to the direction of the stellar object being observed and needs to be slowly moved across the sky to counteract the effect of Earth's rotation. The maximum object tracking rate is about 15 arcsec/second, or 70 μrad/second. Observing targets within the solar system, including Near Earth Objects such as certain asteroids, could require much higher tracking rates. (Slew rates for moving a telescope between objects to be observed are much higher than tracking rates, but the lasers are not used when slewing.) Government facilities such as the Starfire Optical Range and the Maui Space Surveillance System often use adaptive optics lasers to facilitate viewing of rapidly moving satellites close to Earth, and they require much larger object tracking rates—about 0.6 degrees/second or 0.01 rad/second.[22]

B. Characteristics of Satellites

Satellite orbits can roughly be divided into three classes: near Earth, about 500 to 2000 km in height above the surface of Earth; mid-altitude, about 20,000 km; and geosynchronous, about 36,000 km.[23] Orbits are generally rather circular, although highly elliptical orbits, called Molnya orbits, are also sometimes used. There are about 450

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[19] C. d'Orgeville, et al., "Gemini Mauna Kea Laser Guide Star System" in *Adaptive Optics Systems and Technology*, R. Tyson and R. Fugate, eds., *Proc. SPIE* 3762 (1999), 150.

[20] Keck, "LGSAO Basics and System Description" at http://www2.keck.hawaii.edu/optics/lgsao/lgsbasics.html.

[21] d'Orgeville, op. cit.

[22] R. W. Duffner, "Revolutionary Imaging: Air Force Contributions to Laser Guide Star Adaptive Optics," *ITEA Journal* 29 (2008), 341, http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA513924.

[23] J-C. Liou and N. L. Johnson, "Risks in Space from Orbiting Debris," *Science*, 20 January 2006, 340.

satellites in low-Earth orbits, 50 in mid-altitude, 50 in Molnya, and 350 in geosynchronous orbits, for a total of about 900 active satellites.[24]

At very low altitudes, satellite orbits can be significantly influenced by atmospheric drag, which is somewhat dependent on the solar cycle. The drag makes predictions of these satellite positions more uncertain than for satellites orbiting at higher altitudes, where drag affects are negligible. At 300 km the circular orbit lifetime, which has some dependence on satellite mass density, is only about a month, and it is about 4 months at 400 km.[25] A satellite in an elliptical orbit with a perigee of 300 km and an apogee of 1,500 km, such as the Korean STSAT-1, has a lifetime of about 2 years.[26] An altitude of about 700 km is typical for some recent low-altitude, Earth-viewing, high-resolution-imaging satellites.[27] At this altitude the orbital velocity is about 7.5 km/s. Many of these types of satellites are in sun-synchronous, near-polar orbits. By definition, geosynchronous satellites have an essentially fixed position above a point on a rotating Earth.

Besides the bands in satellites altitudes, there are also preferred inclinations. Geosynchronous satellites tend to be in equatorial orbits, and low-Earth-orbiting satellites tend to have inclinations above about 45 degrees. About 200, or almost half the low-Earth-orbit satellites, are in sun-synchronous orbits at inclinations of about 98 degrees. In total, approximately 200 of the low-Earth-orbiting satellites would appear to be most susceptible to an LGS laser in that they would have relatively large aperture optical systems used for observing Earth.[28]

Figure 1 shows satellite positions as small white dots. These data are taken from the NASA J-Track 3-D Web site for an arbitrarily chosen date and time projected on a view of Earth approximately centered on the Mauna Kea summit.[29] This database contains about 900 satellites. The outer ring shows the nominal effective horizon for 2,000 km altitude satellites assuming a minimum elevation angle of 20 degrees. The inner ring is

[24] Union of Concerned Scientists, "Satellite Data Base," April 2010, http://www.ucsusa.org/nuclear_weapons_and_global_security/space_weapons/technical_issues/ucs-satellite-database.html.

[25] J. Kennewell, "Satellite Orbital Decay Calculations," Australian Space Weather Agency, 1999, http://www.ips.gov.au/Category/Educational/Space%20Weather/Space%20Weather%20Effects/SatelliteOrbitalDecayCalculations.pdf.

[26] J. H. Lee, et al., "Korea's First Satellite for Satellite Ranging," *Acta Astronautica* 56 (2005), 547.

[27] WorldView-2, Satellite Imaging Corporation, http://www.satimagingcorp.com/satellite-sensors/worldview-2.html; GeoEye-1, GeoEye Corporation, http://www.geoeye.com/CorpSite/assets/docs/brochures/GeoEye-1_Fact_Sheet.pdf.

[28] Union of Concerned Scientists, op. cit.

[29] NASA, "J-Track 3-D" at http://science.nasa.gov/realtime/jtrack/3d/JTrack3D.html.

for 1,000 km altitude satellites. As indicated by the figure, only a very small number of satellites are in view of the peak at any one time.

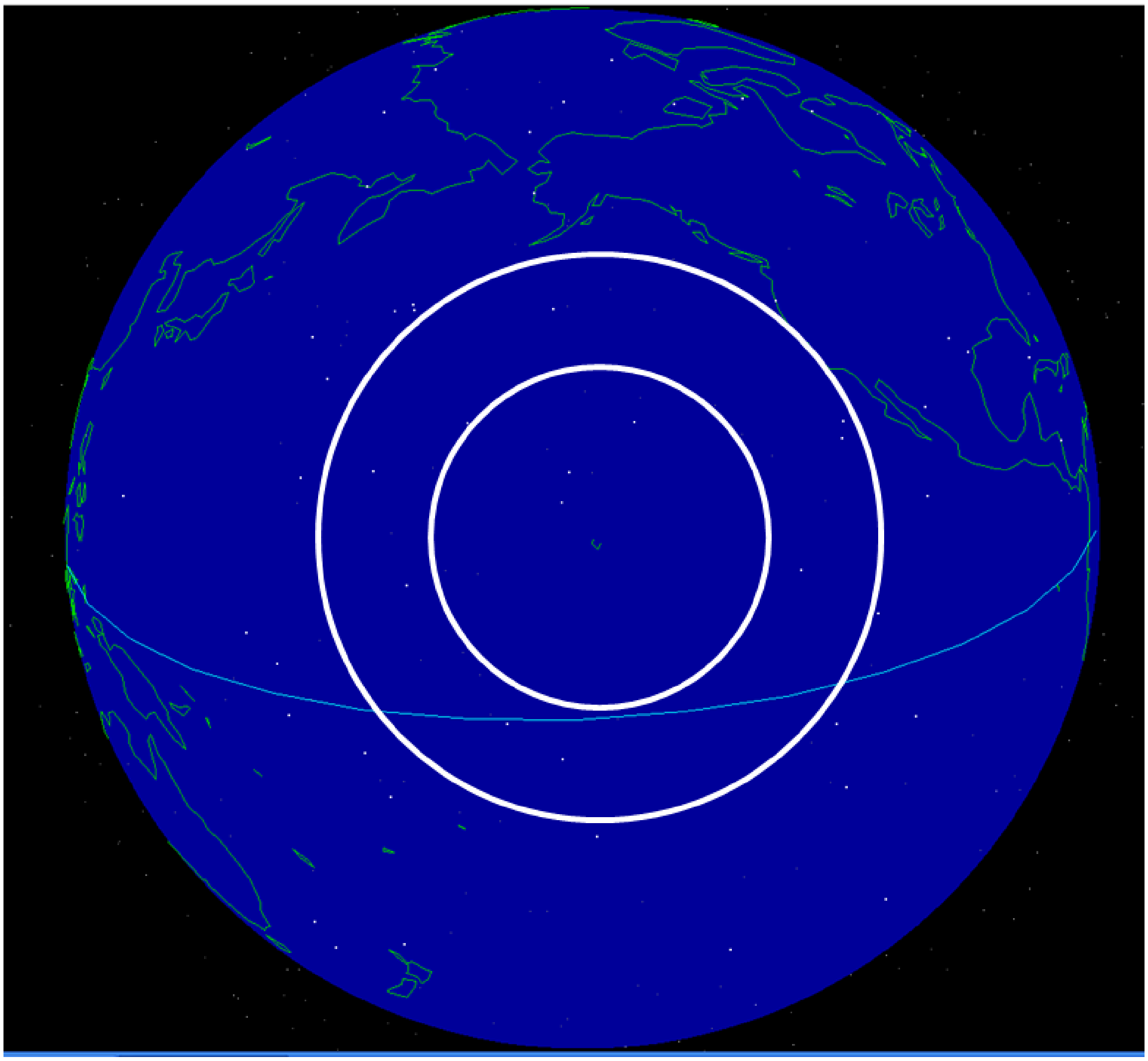

Figure 1. Satellites in view from the observatories at a particular instant.

Some satellites have well defined relationships to others. For example, geosynchronous communications satellites are spaced so as not to interfere with each other, and Global Positioning System satellites are positioned so the entire constellation gives suitable coverage. A few low-Earth-orbit satellites fly in formation. The A-train Earth observation constellation now consists of four sun-synchronous orbiting satellites that fly in the same orbit where the first, Aqua, and last, Aura, are separated by 7 minutes. The two middle satellites, CALIPSO and CloudSat, are separated by only 12 seconds.[30] This means there could in a few cases be some structure to PA laser closure periods.

[30] T. L'Ecuyer and J. Jiang, "Touring the Atmosphere Aboard the A-Train," *Physics Today*, July, 2010, 36, http://ptonline.aip.org/journals/doc/PHTOAD-ft/vol_63/iss_7/36_1.shtml.

Various components on the exterior of a satellite could be potentially exposed to a laser. These include structural and thermal-control materials such as metals, paints, and polymer-based multilayer insulation. Most satellites also have solar cells and optical devices such as star trackers or horizon sensors to help determine orientation. Depending on their design, these optical devices may or may not focus incoming light.[31] Finally, satellites such as the commercial Earth-imaging GeoEye and WorldView and the U.S. Government Landsat in low-Earth orbit, and weather satellites such as GEOS in geosynchronous orbit (among others) have imaging cameras, or, in a few cases, such as CALIPSO, have non-imaging optics with relatively large apertures, all of which focus incoming light and are normally pointed down toward Earth.

Satellite optical systems that focus incoming light and whose bandpass includes the wavelength of the adaptive optics laser might be expected to be the components most susceptible to the LGS lasers.[32] An example of a modern Earth-imaging satellite is GeoEye-1, which was launched in 2008 to an altitude of 681 km.[33] It has a telescope with an aperture diameter of 1.1 meter and focal length of about 13 m. The highest resolution detector is a silicon charge-coupled sensor made up of about 35,000 pixels arranged in a linear array, where each pixel has a length of 8 μm. This detector is sensitive to light in the visible band of wavelengths. At nadir, the swath width is 15.2 km with a ground sample distance of 0.41 m. This optical system will focus a beam of light from a ground resolution element to an area about the size of a pixel. The optical gain of the system—the area of the entrance aperture to the pixel area assuming there are no transmission or reflection losses in the optical train and ignoring the effects of any wavelength filters—is about 10^{10}. It carries enough propellant for 15 years. Although its highest resolution imagery occurs when it is looking straight down at Earth at nadir, it can make observations up to 60 degrees from nadir.[34] The total capitalized cost of the GeoEye-1 satellite and its necessary ground systems was $478 million, and in 2009 on-orbit insurance was carried in an amount of $250 million, most of which would be payable if

[31] SM-MDE1300 Star Tracker, Space Micro, Inc, San Diego, CA, http://www.spacemicro.com/pdfs/star_tracker_v2_7.pdf; N. Clark, P. Furth and S. Horan, "Intelligent Star Tracker," 14th Annual U.S.U Conference on Small Satellites, Logan, Utah, August 2000, http://telemetry.nmsu.edu/ssc00III01.PDF.

[32] Lee, op. cit.

[33] GeoEye parameters, http://directory.eoportal.org/presentations/223/13708.html.

[34] "Imagery Sources," GeoEye Corporation, http://www.geoeye.com/CorpSite/products/imagery-sources/Default.aspx.

certain satellite capabilities became impaired.[35] Yearly premiums for on-orbit operations insurance for low-risk satellites represent about 1.3% of the insured cost.[36]

The GeoEye-1 satellite uses a push-broom imaging technique. In this method the linear detector array is oriented perpendicular to the flight direction of the satellite. As the satellite travels along its trajectory, different portions of Earth are imaged in succession. It is used primarily for daylight imaging since its detectors are not sensitive to thermal radiation. However, visible satellite detectors, some with image-intensifier capabilities, such as on the low-Earth-orbit satellites of the Defense Meteorological Satellite Program, have been used at night in certain circumstances to image fires and artificial lights.[37] This type of detector may be particularly sensitive to damage from laser radiation. Some satellites that have infrared sensors can routinely take imagery at night. The National Aeronautics and Space Administration's Aqua platform at an altitude of about 700 km has an 18 cm telescope and is sensitive out to about 14 μm.[38]

C. Interactions between Lasers and Satellites

1. Possible Causes of Damage

In this section, we address three questions about the interaction of an LGS laser and a satellite: How long would a laser typically interact with a satellite? Can the laser actually damage a satellite if it strikes it? What is the probability of an LGS laser irradiating a satellite. The calculations in this section are meant to provide guidance in determining approximate magnitudes to provide the reader with a rough quantitative appreciation of adaptive optics lasers and satellite interactions.

It has been stated that the full-angle divergence of the laser is about 6 μrads. This gives a beam diameter of about 4 meters at 700 km altitude, about 90 meters at 15,000 km altitude, and about 220 meters at 36,000 km altitude. These are rather small spots. The rotation of Earth and the telescope angular rate are slow effects for satellites at 700 km altitude, which travel at about 7.5 km/s. At the latitude of Mauna Kea, the telescopes are rotating with Earth at a velocity of about 0.5 km/s. A satellite in low-Earth orbit would pass through the laser beam in about 0.5 ms. At the geosynchronous orbit distance of about 36,000 km the satellite would remain in approximately the same

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[35] GeoEye, Inc, SEC Form 10-K, 12 March 2010, http://www.sec.gov/Archives/edgar/data/1040570/000095012310024178/w77651e10vk.htm.

[36] P. de Selding, "2009 Shaping Up as Profitable year for Insurers," *Space News*, 4 September 2009, http://www.spacenews.com/satellite_telecom/2009-shaping-profitable-year-for-insurers.html.

[37] See http://www.ngdc.noaa.gov/hazard/dmsp_banda_aceh.html.

[38] See http://modis.gsfc.nasa.gov/about/specifications.php.

position relative to rotating Earth. Relative to the center of Earth, it is traveling at about 3.1 km/s. This satellite would pass through the laser beam in about 0.1 seconds.

Since the observatory lasers have a power of about 20 watts, their average intensity in low-Earth orbit is about 2 W/m^2 which is about 1/700 that due to solar illumination, about 1400 W/m^2. The peak instantaneous power of the Keck laser is only a few times the solar intensity, and the corresponding Gemini value is much less than the solar intensity. As a result, any satellite exterior materials designed to be resistant to solar radiation should not be affected by the adaptive optics lasers.

Imaging sensors on satellites are designed typically for detecting low light levels and not lasers. The peak solar intensity at Earth's surface is about 1000 W/m^2. If Earth's surface were a black body, it would radiate a comparable amount, about 500 W/m^2. Assuming the brightness of the solar reflection and radiation are approximately uniformly distributed in angle as from a Lambertian surface, a satellite with a ground resolution of 1 m at a distance of 500 km would intercept an intensity of about 10^{-9} W/m^2. This is very much lower than the intensity produced by the laser, 2 W/m^2.

At low-Earth-orbit altitudes where the total interaction time between the laser and satellite is 0.5 ms the Keck laser will produce about 10 pulses and the Gemini laser about 40,000 pulses. If a satellite intersects one of these lasers, the pulse repetition rate is high enough that it will be irradiated. There can be temporary dazzling for the very short time the satellite is irradiated or permanent damage.[39] The cause of permanent laser damage in materials and devices such as photodetector arrays that are composed of more than one material can be complex. However, the threshold for the onset of permanent change in parameters in one type of silicon photosensor array has been found to be about 0.3 J/cm^2 for a 10 ns pulse at a wavelength of 1.06 μm.[40] This value was found for a longer wavelength than is of interest here (0.589 μm) but since the absorption in silicon is higher at the shorter wavelength, we would expect the damage threshold to be even less for shorter wavelengths.[41] Damage to a silicon PIN diode was found at about 2 J/cm^2 for 20 ns pulses at a wavelength of 0.6943 μm.[42]

[39] Y. Butt, "Effects of Chinese Laser Ranging on Imaging Satellites," *Science and Global Security* 17, (2009), 20; J. Walker, S. Lang, L. Bernstein, "Seize the High Ground: The Army in Space and Missile Defense," CMH Pub 70-88-1,(Washington, DC: U.S. Government Printing Office), 216, http://www.smdc.army.mil/2008/Historical/Book/Chap6.pdf.

[40] C- Z. Zhang, et al., "Laser-Induced Damage in Silicon Photosensor Arrays," in *Laser Induced Damage in Optical Materials: 1989*, NIST Special Publication 801 (1990), 115.

[41] J. Lu, et al., "Measurement of Thresholds of Damage to a Charge-Coupled Device Caused by a Q-Switched Laser," *Microwave and Optical Technology Letters* 11, no. 4 (1996), 194.

[42] M. Kruer, et al., "Laser Damage in Silicon Photodiodes," *Optical and Quantum Electronics* 8 (1976), 453.

The thermal diffusivity of silicon is about 0.8 cm^2/s at room temperature and decreases at higher temperatures.[43] In 10 ns, heat energy will diffuse a distance of about 2 μm, which is small compared with the pixel size of 8 μm in at least one satellite. As a result, if an adaptive optics laser deposits at least 0.3 J/cm^2 in less than 10 ns at the focal plane of a satellite sensor, it will be taken that the probability is high that at least one pixel will be permanently damaged.

In low-Earth orbit, the laser beam at zenith is about 10 m^2. At that altitude the energy from the Keck laser in 10 ns, about 10% of the length of a single pulse, is about 60 μj and gives a fluence of about 6×10^{-10} J/cm^2. The optical gain for a 1-meter class telescope system is about 10^{10} neglecting optical train losses, so the fluence on the focal plane is about 6 J/cm^2, significantly larger than the 0.3 J/cm^2 damage threshold. A single Keck laser pulse would probably damage at least one pixel on the satellite detector. And due to the linear detector array orientation in a typical push-broom satellite sensor, the multiple pulses from the Keck laser in a single pass would probably only damage the same pixel.

The energy from the Gemini laser in 10 ns due to a single pulse would deposit about 0.02 J/cm^2 on the focal plane. This is below the nominal single-pulse damage threshold, but there could be multiple pulse effects. One such effect is the buildup of thermal energy from successive pulses. In low-Earth orbit the laser will hit the 8 μm pixel for about 0.5 ms. During this time the heat energy on the directly irradiated pixel will diffuse. If we consider just thermal damage in a silicon PIN diode, for times below about 0.01 ms, damage thresholds at a wavelength of 0.69 μm are calculated to be about 1 J/cm^2.[44] Taking into account the difference in absorption between 0.69 μm and the LGS wavelength of 0.59 μm would give a damage threshold of about 0.4 J/cm^2.[45] There could be heating beyond 10 ns due to the continuous-pulse train, as well as incipient damage from the first pulses, which increases the likelihood of damage on succeeding pulses.

Near the telescope focal plane there can be additional elements besides the sensor itself. These could include filters used to provide spectral separation and microlenses used to focus light onto the active pixel element, which might have damage thresholds below that of the actual sensor.[46] Sensors, particularly for infrared applications, can also

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[43] H. R. Shanks et al., "Thermal Conductivity of Silicon from 300 to 1400 K," *Phys. Rev.* 130, no. 5 (1963), 1743.

[44] F. Bartoli et al., "Irreversible Laser Damage in IR Detector Materials," *Appl. Opts.* 16, no. 11 (Nov. 1977), 2934.

[45] Virginia Semiconductor Inc., "Optical Properties of Silicon," http://www.virginiasemi.com/pdf/Optical%20Properties%20of%20Silicon71502.pdf.

[46] M. C. Hutley, "Microlens Arrays," *Phys. Educ.* 29 (1994), 160.

be made of materials that could have damage thresholds below that of a silicon-based sensor.[47]

We can also consider the possibility of damage due to simple thermal effects of the average laser power. For a pulse length of 0.5 ms, which corresponds to the maximum laser exposure time in low-Earth orbit, the damage threshold for a silicon PIN photodiode at 0.69 μm was found to be about 30,000 W/cm^2.[48] In low-Earth orbit the laser intensities produced at the focal plane of the satellite detector over a pixel size are about 2×10^6 W/cm^2. But over 0.5 ms, this energy spreads laterally about 0.03 cm. So the effective laser intensity at the focal plane for this time scale is the actual intensity multiplied by the ratio of the pixel area to thermal spread area provided the sensor size is large compared with this thermal diffusion length. This factor is about 0.001, and so the effective laser power at the focal plane is about 2,000 W/cm^2, which is about a factor of 10 less than the damage threshold of 30,000 W/cm^2. If the thickness of the detector substrate is much less than 0.03 cm so thermal diffusion perpendicular to the surface is hindered, however, there may be long-term average damage effects. Further, there is the possibility of other components near the focal plane with lower damage thresholds.

Under certain conditions, the Gemini laser could be less likely to damage a 1 m class satellite in low-Earth orbit than the Keck laser. Nevertheless, the difference considering all the inherent uncertainties is small enough that this report considers it reasonable to conclude that LGS lasers from both observatories have the possibility of damaging imaging optics near the focal plane of these satellites if the laser directly strikes the optical component within its detector optical field of view.

The larger the satellite aperture, the more laser light it will collect, provided the laser beam diameter at the satellite is larger than the aperture. The Hubble Space Telescope, which is a form of very large aperture imaging satellite, has an aperture diameter of 2.4 m so it will collect about five times the laser energy as the GeoEye-1. At its altitude of 560 km it will not intercept the entire laser beam. Because Hubble has about four times the focal length of GeoEye-1, however, its diffraction spot is larger, and the LGS laser energy fluence on the detector arrays of the two satellites is about the same. The Hubble, of course, is not designed to observe Earth. For comparison, the aperture diameter of the planned astronomical James Webb Space Telescope is 6.6 meters.[49]

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[47] Bartoli, op. cit.

[48] Ibid.

[49] NASA, "NASA's Largest Space Telescope Mirror will See Deeper into Space," 7 February 2007, http://www.nasa.gov/vision/universe/starsgalaxies/mirror_size.html.

Some satellites use imaging optics with entrance apertures of a few centimeters.[50] These include CubeSat amateur satellites that observe the Earth. Other satellites use witness cameras sensitive to visible light to monitor satellite operations. CubeSats are cubes with 10 cm sides. Some of the CubeSat cameras can have apertures as small as 0.3 cm, but even with very short focal lengths of 0.6 cm, the LGS lasers should not damage these components.[51] One suggested witness camera has pixels with a dimension of 9.9 μm and an approximately 2 cm aperture.[52] The LGS energy fluence on the sensor array would be less than 1/1000 that than for GeoEye-1, and the LGS lasers would not be likely to damage it.

The LGS laser concern associated with permanently damaging satellites should primarily be directed at large-aperture Earth-imaging satellites. These are most often found in near-Earth orbits or at geosynchronous orbits. The laser intensity on the focal plane of a geosynchronous satellite is about 1/3000 that on the same satellite in low-Earth orbit, but it is irradiated about 200 times longer. The combined effect is that the fluence is about 15 times less. For the long irradiation time in geosynchronous orbit, the thermal diffusion distances are large compared with a pixel, so depending on the detector design, the energy deposited may be spread over a relatively large volume. As a result, geosynchronous satellites are probably not a concern based on permanent damage considerations.

Manned space vehicles and satellites probably should be considered separately. The International Space Station (ISS) orbits at an altitude of about 350 km. At this low altitude it needs to be regularly boosted into a higher orbit. The laser beam diameter at the ISS at zenith would be about 2 m, which gives an average power of about 0.0003 W/cm^2 that lasts for about 0.0003 seconds.

Several guidelines are used to determine maximum permissible laser exposure levels, which among other factors depend on laser wavelength, pulse length, and pulse energy.[53] The Occupational Safety and Health Administration uses the American National Standards Institute ANSI Z136 Standard is used as a guideline for the maximum permissible laser exposure that with high certainty does not result in permanent eye

[50] Basler Vision Technologies, “Austrian Aerospace Study Highlights Basler Cameras,” http://www.baslerweb.com/downloads/14096/Application_AAE.pdf.

[51] R. Funase, et al., “Technology Demonstration on University of Tokyo’s Pico-satellite XI-V,” *Acta Astronautica* 61 (October 2007), 707.

[52] Basler Vision Technologies, “Basler A600f User’s Manual,” DA00056106, 22 March 2004, http://www.graftek.com/pdf/Manuals/basler/A600fmanual.pdf.

[53] D. Sliney, “Ophthalmic Laser Safety,” in *Lasers in Ophthalmology*, eds. F. Fankhauser and S. Kwasniewska (The Hague: F Kugler Publications, 2003), 4.

damage.[54] Guidelines are also published by the international Commission on Non-Ionizing radiation Protection (ICNIRP).[55] Using these guidelines, the LGS laser at the ISS would not cause permanent eye damage to an observer who was looking directly at it without using an optical aid such as a telescope. The Federal Aviation Administration considers laser average power exposure levels above 0.0001 W/cm^2 (which the LGS lasers could produce at the ISS, although only for a very short time) sufficient to produce unwanted effects in sensitive aircraft flight zones.[56] NASA provides information on the location of the ISS. It was beyond the scope of this study to determine if legislation and regulations controlling research which could affect human subjects is applicable to the use of LGS lasers inadvertently irradiating manned spacecraft.[57]

2. Probability of Satellite Illumination and Damage

In this approximate calculation it will be assumed that the satellites are uniformly distributed in space, although some types of orbits such as geosynchronous and sun synchronous preferentially populate particular portions of space. Low-Earth orbiting satellites are of most concern for LGS lasers so they will be considered. As already shown, the main portion of the laser beam at low-Earth orbit heights is about 4 meters in diameter, and large optic apertures are on the order of a meter. Because (1) the location of the telescope may be offset from its center of mass; (2) the laser could be pointed away from zenith, where the longer slant range to the satellite would increase the beam diameter; and (3) this is only a rough calculation, assuming that the center of the laser beam and the center mass of the satellite must pass within 5 meters of each other seems reasonable. We assume the laser will intercept the satellite if it is pointed within 5 meters to either side of the actual orbital track. In 1 second this interaction area would cover 0.075 km^2. At a 600 km altitude, the total area of the sphere where a randomly chosen satellite could be is about 6×10^8 km^2. So in 1 second there is about a 1 in 10^{-10} chance that a single laser will irradiate a single satellite. Taking into account that an adaptive optics laser only operates at most about 10 hours a day and only about 100 days a year, there will be a satellite and laser interaction at a rate of about 4×10^{-4}/year or, in round numbers and taking into account weather and other factors that would reduce the laser

[54] U.S. Department of Labor, "OSHA Technical Manual," TED 01-00-015, 1999, http://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_6.html#app_iii:6_3.

[55] ICNIRP, "Revision of Guidelines on Limits of Exposure to Laser Radiation of Wavelengths between 400 nm and 1.4 μm," *Health Physics* 79 (October 2000), 431; "Guidelines on Limits of Exposure to Laser Radiation of Wavelengths Between 180 nm and 1,000 μm," *Health Physics* 71 (November 1996), 804.

[56] V. Nakagawara, et al., "The Effects of Laser Illumination on Operational and Visual Performance of Pilots Conducting Terminal Operations," DOT/FAA/AM-03/12, http://www.faa.gov/library/reports/medical/oamtechreports/2000s/media/0409.pdf.

[57] "Federal Policy for the Protection of Human Subjects," 45 CFR Part 690, http://www.nsf.gov/bfa/dias/policy/docs/45cfr690.pdf.

propagation time from the maximum amount, 1×10^{-4}/year. Using a nominal satellite lifetime of 10 years gives only about a 0.1% probability that any single low-Earth orbiting satellite will be inadvertently irradiated by a single laser over its lifetime. For the low orbit, Earth-observing satellites of highest possible concern, this probability translates to a single laser striking one of the satellites about every 50 years.

Some new laser guide star concepts envision using multiple adaptive optics lasers in a process called multiple conjugate adaptive optics (MCAO). These next-generation adaptive optics (NGAO) lasers would have approximately the same characteristics of the current lasers, but they would be pointed in slightly different directions separated by about 1 arcminute, which would increase the probability of an observatory irradiating a satellite. Concepts from Keck and Gemini range from 4 to 9 lasers.[58] Based on this very crude analysis, an observatory using MCAO would have an inadvertent illumination on an Earth-observing, low-orbit satellite about once a decade (this type of satellite is of most concern).

The previous calculations concern only the possibility of a laser striking a satellite. They do not take into consideration whether there will actually be any permanent damage if such an interaction occurs. No one I spoke to had ever heard of any unintentional laser damage to a satellite. During the study I contacted two commercial companies that have low-altitude satellites with high-resolution Earth-viewing visible sensors, but neither one would provide any information about whether they had any concerns about damage due to lasers. A listing of about 200 satellite failures did not include the possibility of laser damage for any of them.[59]

Some satellites are deliberately illuminated by lasers to, among other uses, give precise satellite positions for geodesy applications.[60] Although these satellites typically have a corner cube assembly to deliberately reflect the laser light, they may have other components—particularly certain optical sensors—that might be susceptible to laser damage. The International Laser Ranging Service (ILRS) coordinates the laser irradiation of about 30 active satellites, of which about 20 are in low-Earth orbit, as well as several corner reflector arrays on the moon.[61] There are about 50 international tracking stations,

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[58] C. Neyman, et al., "NGAO Laser Facility System Design," *Keck Adaptive Optics Note* 570, version 0.3, 31 March 2008; J. Chin, "NGAO/Laser Clearing House Preliminary Design Phase Planning," version 1.0, 10 April 2010; and Gemini, "MCAO for Gemini-South: Preliminary Design Report," REV-AO-G0172, 1 May 2001, http://www.gemini.edu/documentation/webdocs/rev/mcao_pdr/MCAO_PDR_report.pdf.

[59] *Satellite News Digest*, http://www.sat-index.co.uk/failures/.

[60] *Proceedings of the 16th International Workshop on Laser Ranging*, October 2008, http://cddis.gsfc.nasa.gov/lw16/index.html.

[61] M. Pearlman, et al., "The International Laser Ranging Service," *Advances in Space Research* 30, no. 2 (July 2002), 135, http://ilrs.gsfc.nasa.gov/docs/cospar_paper_warsaw_final.pdf; ILRS, "List of Satellites," http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_satellites/index.html.

with 9 in the United States.[62] One of these domestic laser ranging sites, the Naval Research Laboratory Optical Test Facility at Stafford, VA, is a military facility; a number are run by NASA; and two, University of Hawaii at the Haleakala, HI, site and the University of Texas McDonald Observatory, are associated with universities.[63]

Note that the lasers used for laser ranging are different from those used for LGS adaptive optics. Consider the two U.S. university lasers. These have wavelengths of 0.53 μm, which is very close to the wavelength of the astronomical observatory lasers. These two ranging lasers have average powers of .5 W and 15 W, comparable to the average power of the LGS lasers, but the instantaneous power in their 0.2 ns pulses (about 0.5×10^9 W and about 7.5×10^9 W) is about a million times higher than that of the adaptive optics lasers. This is because the satellite ranging lasers only fire about 10 pulses per second. The satellite ranging lasers are much more likely to damage satellite components, particularly those that do not have large diameter entrance optics, than the adaptive optics lasers are, even though the former might have somewhat higher divergences than the later.

As a result of the possibility of satellite damage, the ILRS has certain restrictions related to satellite ranging.[64] These include coordination between the ranging lasers users and the satellite owners. The standard procedure for irradiating a satellite carrying a fixed-nadir pointing sensor is to set up a forbidden zone that is symmetric around the laser location's zenith, with a maximum elevation that prevents the laser from being in the field of view of the sensor (including a safety margin).

Many of the satellites are completely passive in that they consist of only passive corner cube arrays. The only ILRS satellite with large-diameter optics is the NASA Ice, Cloud, and Land Elevation Satellite (ICESat), which ended its mission this year.[65] When operational, it flew at an altitude of about 600 km. This satellite had a laser and a 1-meter diameter receiving telescope that always pointed directly in the nadir direction to collect distance measurements. It did so by measuring return times of the laser pulses, which were produced at the rate of 40 per second, where each pulse illuminated a diameter of about 70 m on the ground. Since it was a laser-ranging system, it did not produce an image. The maximum pulse energy at a wavelength of 1.06 μm was about 80 mJ, and at

[62] ILRS, "ILRS Station Identification Table," http://ilrs.gsfc.nasa.gov/stations/sitelist/index.html.

[63] Information on sites and their lasers is available in file ha4t, for the University of Hawaii, and mdol, for the University of Texas, ftp://cddis.gsfc.nasa.gov/reports/slrlog.

[64] W. Gurtner, "Restricted Laser Tracking of Satellites," 13 March 2009 (updated), http://ilrs.gsfc.nasa.gov/satellite_missions/restricted.html.

[65] See http://icesat.gsfc.nasa.gov/icesat/.

0.532 μm it was about 30 mJ in a 5 ns pulse.[66] The return signals were rather weak, and sensitive silicon avalanche photodiodes were used as detectors.

The ICESat was designed to look directly down at Earth with an off-nadir pointing angle of less than 5 degrees. The International Laser Ranging Service had placed restrictions on lasing ICESat. In particular, the ranging laser could not fire at ICESat if its elevation was more than 70 degrees, which included a margin of safety.[67] Taking into account the curvature of Earth, this meant that the laser must be offset from the satellite nadir direction by about 18 degrees. Since there might have been other components on ICESat that could be damaged by the laser, there might have been restrictions on energy even below 70 degrees elevation.

To directly strike optical components near the focal point of the telescope such as an imaging array, the laser light must be within the field of view of the satellite telescope. The high-resolution Earth-imaging satellites usually do not look more than 60 degrees from nadir, and the LGS lasers do not normally fire below 20 degrees as measured from the horizon.[68] Looking up to 25 degrees from nadir has been considered a good compromise between image resolution, which degrades as the nadir angle increases, and revisit time, which is quicker if larger off-nadir angles are used.[69] As a result of Earth's curvature, the 60 degree from nadir satellite restriction is approximately equivalent to the 20 degree minimum elevation observatory restriction. So if there is a possibility of an LGS laser to be in the propagation path of a low-Earth-orbit satellite, there coincidently is a possibility that the satellite telescope might be pointed at the laser. At an altitude of 600 km a satellite camera that looks within 60 degrees of nadir has a total possible area coverage of about 5×10^6 km^2. The high-resolution, low-Earth-orbiting satellites have an instantaneous field of view of a strip about 1 m along the satellite path by about 20 km perpendicular to the satellite path, with a total area of about 0.02 km^2. If it is assumed this strip is placed randomly anywhere within 60 degrees of nadir, the chance that the laser will damage the satellite imagery array is about 1×10^8. Some satellites may in normal operation typically move off nadir only in a direction perpendicular to the direction of the velocity. But without any additional knowledge, all that might be confidently known is that they might point in any direction.

Some Earth-observing satellites used for Earth environmental measurements and other observations have a much larger instantaneous field of view than the high-

[66] NSIDC, "Distributed ICESat GLAS Laser Operations Periods," May 2010, http://nsidc.org/data/icesat/pdf/glas_laser_ops_attrib.pdf; J. Abshire, "Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: Pre-Launch and on-Orbit Measurement Performance," in *IEEE Proceedings of the 2003 Geoscience and Remote Sensing Symposium,* 1534.

[67] "ILRS Governing Board Meeting," 26 April 2005, http://ilrs.gsfc.nasa.gov/docs/ilrsgb_appa_0504.pdf.

[68] See http://www.geoeye.com/CorpSite/products/imagery-sources/Default.aspx#geoeye1.

[69] Eurimage, "Multimission Satellite Data," http://www.eurimage.com/faq/faq.html.

resolution imaging satellites. For example, Landsat-7, which orbits at an altitude of about 700 km, has a push-broom view of 185 km by 0.03 km, for a total area of about 6 km^2.[70] Making the same assumptions as in the previous paragraph with this larger area gives about a 1 in 1 million chance of damaging the Landsat-7 satellite if it was in view.

The Spot-4 satellite, at an altitude of 820 km, has a vegetation sensor sensitive to radiation in the visible and near-infrared bands, although in this case the LGS wavelength is at the far edge of one of the visible bands.[71] The Spot-5 satellite has a similar vegetation sensor, and both have a high-resolution-imaging sensor similar to those on other satellites. The vegetation sensors are designed to give almost complete coverage of the land area of Earth in about 1 day with a resolution of approximately 1 km and a swath width of 2250 km. This is a very wide 101 degree field of view, and the aperture for this system is much smaller than the telescope diameters of the high-resolution systems. It uses a push-broom technique with a silicon CCD array made up of 1728 13 μm square pixel elements.[72] The instantaneous field of view of this detector covers about 2250 km^2. This would give roughly about a 1×10^{-4} chance of striking the silicon array if the satellite was irradiated by an observatory laser.

If we use the International Laser Ranging Service keep-out angle for ICESat of about 18 degrees from the telescope axis, then assuming random pointing of a 600 km altitude satellite, we might conclude based on simplified calculations that the probability that a ground laser would damage an imaging satellite that could randomly look 60 degrees off nadir would be the ratio of the areas on the ground subtended by a 20 and 60 half angle degree cone with apex at the satellite, which is about a factor of 30. However, this apparently included a large safety margin, perhaps due to the high peak power of the ranging lasers since the receiving telescope field of view was only about 0.03 degrees and the maximum off-nadir angle was 5 degrees.[73] For this kind of simplified probability calculation, the most appropriate angle to take would seem to be the one that determines whether the laser is within the instantaneous field of view of the telescope or 0.03 degrees. In this case the probability of damaging the sensor, given that the satellite is in view of the ground laser and is randomly oriented (which it normally is not) within about 60 degrees of nadir, is about 1 in 10^7.

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[70] D. Meyer, et al., "Cross-Calibration of the Landsat-7 ETM+ and EO-1 ALI Sensors," at Workshop on Inter-comparison of Large Scale Optical and Infrared Sensors, 12–14 October 2004, http://Earth.esa.int/workshops/ivos05/pres/20_meyer.pdf.

[71] "Vegetation User Guide at http://www.spot-vegetation.com/vegetationprogramme/Pages/TheVegetationSystem/userguide/userguide.htm.

[72] J. Reulet, "Vegetation Programme: Detectors," http://www.spot-vegetation.com/vegetationprogramme/index.htm.

[73] ICESat parameters given at http://eospso.gsfc.nasa.gov/eos_homepage/mission_profiles/docs/ICESat.pdf.

Other scans besides a push broom could be used. For example, the Tropical Rainfall Measuring Mission Satellite, which has a nominal orbit altitude of 350 km, uses a whisk-broom technique in which the sensor is scanned continually through an arc of ±45 degrees perpendicular to the satellite track.[74] The instantaneous field of view at the maximum scan angle is about 10 km^2.

Some satellites collect imagery by using two-dimensional arrays. Although not designed to look at Earth, the sensor array on the Kepler satellite consists of almost 100 million pixels.[75]

An exhaustive search was beyond the scope of this study, but we can conclude that an upper limit of about 10^{-4} for the probability of damage to a satellite given that it is irradiated by an observatory laser does not seem unreasonable. The laser will have to randomly illuminate a satellite about 10,000 times to damage it, if the satellite has a sensing system comparable to SPOT-4. The nature of the damage has not been carefully examined, but in certain cases it may it may be the destruction of a single pixel, which may not significantly affect the operational utility of the satellite. It has already been estimated that a single laser will irradiate 1 satellite about once every 50 years. Therefore, if there are 200 potentially susceptible satellites in low-Earth orbit, a single laser would damage a satellite about once every 500,000 years. Even if there were 10 observatories with MCAO systems with 5 lasers each and about 200 satellites with SPOT-4 vegetation coverage, there would be a damaging irradiation only about once every 10,000 years.

Damaging a single pixel on a satellite that might have several thousand pixels might not seriously affect its operational performance. For example, the short-wavelength infrared array on the SPOT-4 satellite was launched with about 5 defective pixels. This InGaAs CCD detector is sensitive to radiation, and at the end of 2 years of operation in space about 60 pixels were defective, yet this sensor produced very useful imagery.[76]

The above calculations assume that there is a uniformly random probability that a satellite will point its imaging optics toward an LGS laser. However, unless there is a malfunction, satellites are not usually randomly pointing their sensors. The GeoEye Corporation has an online archive of its imagery for any designated spot on Earth.[77] From July 2000 to November 2009, the three visible imaging satellites in its inventory took 19 exposures that included the Mauna Kea observatories' location (about 2 per year). These

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[74] C. Kummerow and W. Barnes, "Tropical Rainfall Measuring Mission (TRMM) Sensor Package," *Journal of Atmospheric and Oceanic Technology* 15 (June 1988), 809.

[75] D. Koch, "Overview and Status of the Kepler Mission," in *Optical, Infrared, and Millimeter Space Telescopes,* SPIE 5484, 2004, http://www.cfa.harvard.edu/kepler/papers/2004/SPIE.Glasgow.Koch.pdf.

[76] E. Bartholome, "The VEGA 2000 data set description of data properties (draft)," November 2000, GLC 2000 Workshop, http://bioval.jrc.ec.europa.eu/products/glc2000/publications/workshop/legend/dataset%20description.pps.

[77] See http://geofuse.geoeye.com/maps/Map.aspx.

all took place during the day so they are not directly relevant, but they nevertheless give some idea of how often this kind of area might be directly imaged. With the exception of one image taken at satellite elevation of 50 degrees and two near 61 degrees, all the exposures took place between 8 and 22 degrees from nadir. A total of 16 images were taken before March 2007, when GeoEye had a total of 278 million images in its inventory.[78] So based on this raw image count, only about 10^{-7} of the imaging time of its satellites was devoted over 7 years to imaging the area around the peak of Mauna Kea, which contained the Keck and Gemini observatories.

Currently, it appears that the probability of randomly damaging a satellite is minuscule. The only caveat for the future would be if optical systems using square arrays approaching a million pixels, coupled with wide-field-of-view optics such as used in SPOT-4, were developed for use on low-orbit, Earth-observing satellites and were commonly deployed. Assuming that a system of this kind might instantaneously cover about 10% of the area in view of a satellite, we might expect a physically damaging—although perhaps not operationally damaging—satellite irradiation about every 500 years for every observatory laser. This assumes that there are about 200 satellites with this capability. For perspective, the Wide Field Camera 3 (WFC-3) on the Hubble Space Telescope has about 17 million pixels, although its angular field of view is about 1000 times smaller than the Spot-4 vegetation sensor.[79]

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[78] W. Schuster, "GeoEye Corporate Overview," JACIE Civil Commercial Imagery Evaluation Workshop, 20 March 2007, http://calval.cr.usgs.gov/JACIE_files/JACIE07/Files/110Schus.pdf.

[79] "Hubble's Instruments: WFC3–- Wide Field Camera 3," http://www.spacetelescope.org/about/general/instruments/wfc3/.

4. Relevant Department of Defense Organizations

A. Laser Clearinghouse

The observatories have direct interactions with two primary DOD organizations, the Laser Clearinghouse (LCH) and the Space Situational Awareness Operations (SSA Ops) Cell. Both these groups are located at Vandenberg Air Force Base, CA. Figure 2 shows the organizational relationship between the LCH and SSA Ops Cell. This figure only shows the DOD components directly related organizationally to the LCH and SSA Ops Cell; many others are not depicted. The DOD leadership establishes policy; USSTRATCOM implements policy; the Joint Functional Component Command for Space (JFCC/S) establishes plans; the LCH performs operational execution, including pre-mission analysis and troubleshooting; and the SSA Ops Cell is engaged in real-time operations.

During the period of this study, the LCH was responsible for about 220 lasers at 38 sites. The main civilian sodium LGS observatories working with the LCH were Keck, Gemini, Subaru, Lick, and Palomar.[80]

The Joint Space Operations Center is composed of approximately 300 people, and about 50 are always on duty. One of these continuously manned positions is a military officer who occupies the position the observatories call the Space Battle Manager (SBM) and DOD calls the Space Battle Duty Officer (SBDO). During nighttime observing, the observatories are in primary contact by unclassified telephone and e-mail with the SBM. Interacting with the observatories is only one part of the responsibilities assigned to the SBM. An unclassified picture of a small portion of the space operations room is shown in Figure 3. The SBM who monitors certain voice communications and several computer screens with multiple windows is stationed in the far back corner of the photograph.

The LCH is a small organization currently composed of four military officers. Since this is a joint organization, personnel can come from any of the Services. Although there is no specific requirement for a scientific or engineering background, during the period of this study two people had technical backgrounds. One had a bachelor's degree in math and physics and had done research on the undergraduate level on variable stars and Kuiper Belt objects. This included observations at a small college teaching observatory.

[80] A. Riter, "Laser Clearinghouse Overview: Introduction for New Laser Programs," 8 February 2010.

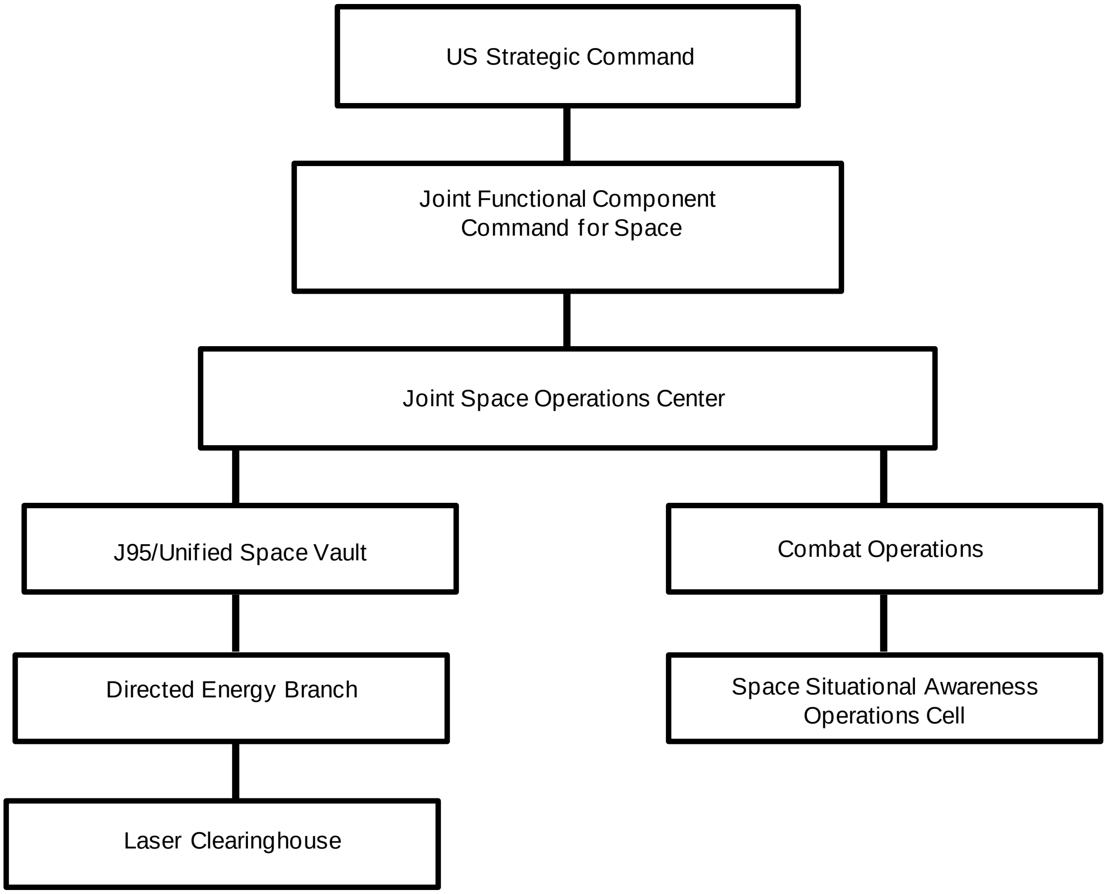

Figure 2. Major DOD Components interacting with the observatories.

DOD organizations using lasers are required by a DOD directive to use the LCH, but civilian observatories, since they are not DOD organizations, are not covered by this directive. Based on instructions from NSF, which provides them support, Gemini and Keck do abide by LCH restrictions. The LCH is permitted by DOD instructions to consider requests for PA information from non-DOD entities.[81] The interaction between an observatory and the LCH is controlled by a set of procedure and specification documents, the most important of which are the following:

- "Standard Centralized Predictive Avoidance and Capability Validation Plan," which describes the standard plan for the interaction between the LCH and a laser user.
- The "Laser Clearinghouse Reports Handbook," which provides voice and hardcopy report and message templates for information and data exchange between the LCH and a laser user.

[81] Goldfein, op. cit., p. 2.

- The "Laser Clearinghouse Information Sheet," in which the laser user describes the laser system parameters.
- The "Interface Control Document (ICD) between the Laser Clearinghouse and Observatories," which describes data-exchange message formats appropriate for lasers operating at fixed locations and observing fixed stellar targets.
- "Appendix A to Standard Centralized Predictive Avoidance Plan."[82]

Appendix A is specific to each user. The current Keck Appendix A is dated 3 November 2009 and that for Gemini is dated 22 June 2010; they are almost identical.[83] The term "centralized predictive avoidance" as used in the documentation refers to the case where all calculations related to satellite closure windows are calculated within the LCH framework, not by the laser user.[84]

Figure 3. View of a portion of the space operations control room.

[82] T. Coffin, U.S.STRATCOM JFCC-SPACE, "Standard Centralized Predictive Avoidance and Capability Validation Plan," Change 1, Revision A5, 12 November 2008; A. Riter, op. cit.

[83] R. Campbell and A. Riter, "W. M. Keck Observatory Appendix A to Standard Centralized Predictive Avoidance Plan," Revision B, 3 November 2009, http://www.oir.caltech.edu/twiki_oir/bin/viewfile/Keck/NGAO/LaserPDRPhase?rev=1;filename=Keck_Appendix_A_to_Standard_CPA_Plan_11-25-09.pdf; U.S.STRATCOM JFCC SPACE, "Interface Control Document (ICD) between the Laser Clearinghouse (LCH) and Observatories," Revision A2, 18 November 2009; B. Gregory and A. Riter, "Gemini North and South Laser Guide Star Facilities Appendix A to Standard Centralized Predictive Avoidance Plan," Revision C, 22 June 2010.

[84] A. Riter, "Laser Clearinghouse Overview: Introduction for New Laser Programs," 8 February 2010.

Once an observatory makes an initial request to the LCH for PA information, the LCH will determine if the laser parameters are such that there is essentially no possibility that the laser could damage any satellite. In some cases, waivers may be granted, but the observatory lasers were not eligible. Lasers that have received waivers had rather different properties. For example, the 1.06 and 0.532 μm laser beams used for laser altimetry on the ICESat satellite, which had an operational orbit altitude of about 600 km, did receive a waiver from the LCH.[85] This laser was designed to always point toward Earth, and there may have been concern that a lower altitude satellite could pass through the beam. The 0.532 μm beam had a maximum of 30 mJ in a 5 ns pulse, which repeated at a 40 Hz pulse rate. This gives an average power of about 1.2 W, which is comparable to although somewhat less than that of the observatory lasers. The peak power is 6 MW, which is much higher than the observatory lasers. However, the full angle divergence of the ICESat laser at about 110 μrad to the $1/e^2$ points is much larger than the approximately 3.0 μrad specified for the lasers in the LCH laser specification form.[86] Also the pulse-repetition rate of the ICESat laser is very much lower than that of the observatory lasers.

The initial ICESat laser waiver determination was made about a decade ago, and the satellite is no longer operational. Since the observatories told me that they needed all the laser guide star signal they could produce, I did not investigate in detail the possibility of changing the laser parameters to values where the lasers could be granted a waiver.

If as is currently the case, a laser waiver is not granted, the LCH and the observatory go through an interactive process to produce the site-specific "Appendix A to Standard Centralized Predictive Avoidance Plan." The recently completed updated Gemini plan required somewhat less than 1 person-month of observatory effort over about a 6-month period. However, Gemini has been interacting with the LCH for several years and is familiar with its procedures. The final step in this process is an end-to-end operational demonstration of the critical procedures described in the documentation.

There are several key features of the interaction that are described in the basic plan and the appendix. The plan described in the following is for Gemini, the most recent.[87] The one for Keck is very similar. Excerpts and comments follow.

- The Appendix contains the sentence, "This is not a stand-alone document and approval of this appendix entails acceptance of the entire plan." According to the LCH, acceptance of the entire plan means that an observatory cannot choose to follow only certain restrictions. The observatory can only propagate the laser

[85] S. Schreiner, et al., "Environmental Assessment for Ice, Cloud, and Land Elevation Satellite (ICESat)," March 2002, http://icesat.gsfc.nasa.gov/icesat/publications/pubs/12538-r10.pdf.

[86] Abshire, op. cit.

[87] T. Coffin, op. cit.; B. Gregory and A. Riter, op. cit.

if it has specific authorization from the LCH. In addition to the LCH restrictions, there are other restrictions, such as the requirement related to avoiding the irradiation of aircraft.

- No earlier than 4 business days and no later than 3 business days before the start of a laser run the observatory will send a predictive avoidance request message (PRM) to the LCH. This is currently done by unclassified e-mail, and the SSA Ops Cell is the primary contact for PA processing. The PRM contains the position of each object to be observed on each night of laser observations. Each PRM can contain up to 150 objects; multiple PRMs can be sent if necessary.
- The SSA Ops Cell will compute the time periods when lasing will be allowed (open windows) for each object in the PRM using the Spiral 3 Deconfliction system. This information will be contained in a predictive avoidance approval message that will be sent to the observatory 24 hours before laser firing. As will be explained in more detail later in this report, the closer in time the open windows for a particular target are calculated relative to the laser firing, the more accurately satellite positions may be known and the longer the open windows will tend to be. But, as has happened occasionally, if the approval message is received relatively shortly before lasing for the night begins, there is an additional burden to quickly integrate the open windows into the observing plan.
- The plans allow for the possibility of the scientific need to observe unanticipated transient events, which the observatories call targets of opportunities (ToO). When such an event occurs, the procedure is for the observatory to resubmit by e-mail the entire PRM with the additional targets added. Sending the entire PRM rather than just the additional targets facilitates DOD tracking of the most current complete set request. Since the time difference between Hawaii and Vandenberg is only a few hours and observations are at night, the new PRM would typically be sent to the SBM, who has a variety of responsibilities besides monitoring observatory requests. As a result, an important part of this interaction is that the observatories also telephone the SBM to ensure that person is made aware that a new PRM has been issued. The SSA Ops Cell (or LCH) will process the updated PRM, subject to the priority of the transient event PRM against any other activities it is supporting at the time. The SSA Ops Cell will assess a transient event support activity as higher in priority than routine PRM processing. However, this cell is also responsible for other occasional space situational-awareness tasks that could take priority over this type of transient-event PRM monitoring. During periods when laser use is most active, approximately five organizations propagating lasers under LCH restrictions may be operating.

- The observatory is also responsible for several other communications besides the PRM: a laser test master schedule submitted to the LCH at the end of each quarter; a laser status report indicating the laser will be used, due 1 hour before observing begins for the night; a quick-look report within 15 minutes indicating that laser propagation has ceased for the night; and information about any inadvertent laser propagation. According to the observatories, inadvertent laser propagation has occurred only very rarely and only for a few seconds.

The LCH estimates that it can process an unanticipated transient response request in about 30 minutes if it has no other obligations. This time would be devoted to about 5 minutes of actual computer calculation time, about 10 minutes for entry checking, and about 10 minutes for declassification. The declassifying time is necessary since although the results are unclassified, the calculations need to be run on a classified computer.

Although the LCH did not write the Spiral 3 computer code, it can determine certain key parameters used in that code. In particular it decides the maximum appropriate laser pointing uncertainty and whether to use fixed or estimated satellite position uncertainties in the calculations.

B. Space Situational Awareness Operations Cell

Monitoring activities of the SSA Ops Cell take place in a large room with positions for up to about 50 people. It is continuously manned to provide potential awareness of all space events of interest to the U.S. Department of Defense. The SBM who is the primary contact between the observatories and the Cell monitors a number of computer screens and communications links. Only one SBM is on duty at any one time, although six are needed to provide continuous coverage. There is a relatively large turnover since an SBM has the position for only about a year. The SBM has many duties besides possibly communicating with the observatories during a standard 12-hour shift. Because the SBM has some discretion about the priority of these different activities, familiarity with the scientific needs and goals of the observatories could be helpful. The SSA OpsCell has the same capability as the LCH to perform Spiral 3 laser clearance window calculations.

C. Satellite Assessment Center

The LCH does not itself perform laser susceptibility analyses of satellites. It uses information provided by the SatAC located in Albuquerque, NM.[88] A component of the Air Force Research Laboratory (AFRL), SatAC collects information on the characteristics of all satellites. AFRL is an Air Force organization, and not part of

[88] "SatAC Support Contract," F29601-02-R-0006, 6 June 2002, https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=f5a133b685d4509c3734f21ed3d5a7b3&_cview=0.

USSTRATCOM. Every 3 months it holds a meeting attended by interested parties to determine satellite characteristics for satellites recently launched as well as certain planned future satellites. The current Air Force officer who leads these meetings has a bachelor's degree in astrophysics and has had some experience at a small teaching observatory.

Once the satellite characteristics are determined, the SatAC can decide, based on previous analysis and experimental results, whether a particular laser exceeds a "sure-safe" threshold in regard to a particular satellite.[89] This information can then used by the LCH to develop a Unique Protect List (UPL) for each laser under its jurisdiction.

The LCH maintains a Master Protect List of the approximately 1000 active satellites in Earth orbit. Not all these satellites may be reasonably expected to be damaged if illuminated by a particular laser. Using information on laser characteristics and satellite construction, it is possible to determine which satellites could not be harmed by the laser. The remaining satellites are then placed in a UPL. Both Gemini and Keck currently have UPLs of about 200 satellites. Using the UPL to determine laser closure windows reduces their number. Newly launched satellites are automatically included in the UPL unless their characteristics have already been determined.

The "sure-safe" philosophy as used by the LCH is a very conservative one in many respects. It assumes that the laser will strike a satellite component in a manner that will most likely cause permanent and instantaneous laser damage. For example, if a satellite has a large-aperture telescope, it is assumed that the satellite is oriented so that the laser is always aligned along the axis of the telescope. Once a minimum laser power for a defined pulse structure below which there is no evidence that permanent damage will occur is determined, a further additional safety factor is also incorporated into the final results.

D. Air Force Space Command/Space Analysis Division

The actual computer code known as Spiral 3 used by the LCH to determine laser closure windows was not developed or validated there. Defined menu items can be adjusted by the LCH, but it cannot change the actual code. Key parts of this code were developed at the Air Force Space Command/Space Analysis Division (AFSPC/A9) located at Peterson Air Force Base in Colorado. Most of this development took place about a decade ago, and the original people involved are no longer at AFSPC/A9. As a result, my attempt to understand certain specific details of the code to determine if they could be easily modified was not successful. I was also unable to determine how certain probability estimates of satellite positions were made. In any case, I was told that any

[89] Air Force, RDT&E Descriptive Summaries, February 2002, 419, http://www.dtic.mil/descriptivesum/Y2003/AirForce/0603500F.pdf.

change to the code would require a lengthy and expensive new verification, validation, and integrity procedure.

E. Starfire Optical Range and Maui Space Surveillance System

The Starfire Optical Range (SOR) in Albuquerque, NM, and the Maui Space Surveillance System (MSSS) on Maui, HI, are both Air Force Research Laboratory facilities that use adaptive optics lasers coupled to large telescopes to help track satellites.[90] As DOD entities they are required to utilize the LCH. A major difference between the observatories and these facilities affects their interaction with the LCH: observatories track, viewing from a fixed point on rotating Earth, slow-moving stars; the Air Force units tracks rapidly moving low-Earth-orbit satellites. As a result, the angular rotation rates of the Air Force telescopes can be about 100 times as fast as those of the observatories. Based on its sure-safe philosophy, the LCH considers the worst case pointing deviation of a telescope that depends on its maximum tracking rate while observing an object. This maximum deviation would be approximately the angular tracking rate of the telescope times the time it would take the laser propagation to be ended once the adaptive optics laser moved away from its desired position. This maximum deviation, which might be caused by a severe malfunction, is very much larger than any pointing deviations encountered during normal operations.

Around any direction the laser is pointing, the LCH defines a keep-out cone with the laser at its vertex. As a result, when considering any uncertainties in satellite position and the maximum deviation of the laser from its desired pointing orientation, there is essentially no possibility of the laser striking the satellite. The half angle of this cone is 2.5 degrees for the Air Force systems, 0.25 degrees for Gemini, and 0.1 degree for Keck. A major practical effect of this difference is that the laser closure windows for the SOR and MSSS telescopes prohibit operation about 30% of the time. As will be shown later, this is over an order of magnitude greater than the impact of the LCH closure windows on the observatories.

SOR and MSSC are becoming more proactive in trying to deal with the impact of predictive avoidance. In May 2010 a working group composed of members from SOR, MSSC, and SatAC, which are all components within the Directed Energy section of the Air Force Research Laboratory, met for the first time to discuss predictive avoidance. Among a growing number of DOD laser users, there is a desire for the DOD to move away from the "sure-safe" methodology to one that explicitly considers the level of risk

[90] Air Force Fact Sheet, "Starfire Optical Range at Kirtland Air Force Base, New Mexico," 2009, http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=15868; Air Force Fact Sheet, "Air Force Maui Optical and Supercomputing Site," 2009, http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=16930.

to a satellite from laser irradiation—Operational Risk Management (ORM).[91] The use of this concept is under very preliminary review by DOD, and nothing has been officially changed. If some form of ORM is implemented, however, it should only reduce the impact of predictive avoidance on observatory operations.

There is also a desire among some DOD laser users to move away from the centralized predictive avoidance methodology where all calculations are done by the LCH to a more distributed methodology called "decentralized predictive avoidance" or a hybrid methodology. With the former, all the calculations are done by the laser user; in the latter, the LCH and user both do PA on different sets of satellites to cover all of them.[92] This could also be applicable to the observatories. But even though a significant amount of satellite position data may be publicly available, there is no guarantee that the common databases include up-to-date and accurate information on all satellites.[93] In addition, it is not clear whether using a distributed PA procedure would actually be beneficial to the observatories. They would have to do the work on determining closure windows that the LCH now does. Also, determining if there is any satellite interference with a ToO is only one step that must be taken in regard to changing an observing plan to include an unanticipated transient target. Other steps could include slewing the laser to the new target and reestablishing the adaptive optics loop, adjusting a sensor, receiving permission to make a major change in the observing plan, and waiting for the object to move far enough above the local horizon. Laser open window determination may not be the limiting time constraint.

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91 "Operational Risk Management," Air Force Instruction 90-901, 1 April 2000, http://www.af.mil/shared/media/epubs/AFI90-901.pdf.

92 D. Vloedman, "Anti-Ballistic Missile Laser Predictive Avoidance of Satellites," AFIT/GSO/ENY/99M-09, March 1999, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA361667&Location=U2&doc=GetTRDoc.pdf; "Laser Predictive Avoidance for Air & Space Application," Solicitation10-RD-RFI(HEL-JTO), 19 November 2009, https://www.fbo.gov/index?s=opportunity&mode=form&id=092952e5404054d01c5b2abdfe403832&tab=core&_cview=1; and A. Riter, "Laser Clearinghouse Overview: Introduction for New Laser Programs," 8 February 2010.

93 Internet sources of satellite ephemerides include CelesTrak, http://celestrak.com/; Analytical Graphics, http://www.stk.com/resources/satdb/satdb1.cfm, which requires registration; and Space-Track, http://www.space-track.org/perl/login.pl, which is a U.S. government Web site that provides U.S.STRATCOM information to registered users.

5. Laser Clearinghouse Predictive Avoidance Calculations

Up until November 2007, the LCH used a PA code commonly called SPADOC after the acronym for the Space Defense Operations Center. Among other items, this code took into consideration uncertainties in laser pointing and satellite positions.[94] As a result of how this code was applied by the LCH and other factors, there were few laser PA closures, and the observatories felt that under SPADOC the impact of LCH restrictions on their operations was minimal. SPADOC had certain limitations, however. For example, the maximum number of targets that could be processed in a single batch run was very limited. As a result, with the number of targets normally requested by the observatories, multiple batches needed to be run by the LCH. It also required some manual entry. For these and other reasons, in mid-November 2007 the LCH transitioned to the Spiral 3 PA code. No advance notification was given to the observatories. The LCH now says its plan will be to give as much as possible notice to the observatories about any significant future changes in its methodology that would affect them, although none are planned at this time. According to the LCH, using Spiral 3 eliminated the need for manual entry, but a computer disk must be manually inserted to transfer information between unclassified and classified machines since Spiral 3 is run in a classified environment. Also, the number of targets that could be processed in a single run was increased to 150. This increase could result in shorter total processing times for Spiral 3 compared with those for SPADOC. In principle, this could result in reduced response times to ToO.

Keck immediately noticed a large and adverse effect when Spiral 3 was implemented.[95] Gemini also said that the use of Spiral 3 had a significant adverse effect on its operations. In the past 3 years the observatories and the LCH have worked together to reduce the impact of Spiral 3, but have not totally eliminated it. This has been primarily through the changing of two key parameters used in computing the PA laser closure windows, the Unique Protect List (UPL) and the laser system keep-out exclusion

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[94] S. Alfano, "Assessing the Instantaneous Risk of Direct Laser Impingement," *Journal of Spacecraft and Rockets* 40, no. 5 (September-October 2003), 678, http://www.centerforspace.com/downloads/files/pubs/JSR.V40.N05.pdf; S. Alfano, et al., "Predictive Avoidance for Ground-Based Laser Illumination," *Journal of Spacecraft and Rockets* 37, no. 1 (January-February 2000), 122, http://www.centerforspace.com/downloads/files/pubs/JSR.V37.N01.pdf.

[95] R. Campbell and D. Le Mignant, "Space Command Changes Impact Keck Lasing," in *Keck Observers' Newsletter*, Issue 5, Summer 2008, http://www2.keck.hawaii.edu/inst/newsletters/Vol5/index.html.

cone half angle. By default, when Spiral 3 was first introduced, both observatories did not have a UPL, and so approximately all 1000 active satellites were used in the PA calculations. New UPLs for both observatories reduced the number of satellites considered to about 200, which reduced the PA impact.

If the laser pointing angle and satellite position were known exactly, than they would only interact when the laser beam of a few meters diameter at low-Earth-orbit altitudes struck the satellite, which might be a few meters in size. However, there can be errors and uncertainties in both the laser pointing direction and in the satellite position.

Figure 4, adapted from a slide from the LCH, depicts how the uncertainties in laser pointing and satellite position are combined to define a keep-out exclusion cone half angle. All the laser-pointing uncertainties are incorporated into a fixed laser system keep-out cone half angle denoted as A. The standard default value for A is 2.5 degrees, but this can be changed based on individual laser system operating characteristics. This standard default value is huge compared with large telescope absolute pointing accuracies of about 1 arcsecond, and it is based on assumptions about possible instrumentation malfunctions rather than normal operation.[96] The satellite position uncertainty cone half angle B can be set at a fixed value of 1 degree, or it can be derived using an "autoconing" procedure to take into account that these uncertainties may change in time and be different for different satellites. Since the fall of 2008, the LCH Spiral 3 calculations for the observatories use "autoconing." If the satellite and laser pointing uncertainty cones touch, which occurs when their angular separation is less than or equal to C = A + B, Spiral 3 will declare a laser closure window for the time when this intersection occurs. The parameter C is called the keep-out cone half angle. Reducing either the laser pointing uncertainty cone half angle, the satellite position uncertainty cone angle, or both will reduce the number and length of the laser closure windows.

We can make some simple and rough estimates of the effect of the half-angle C on the number and duration of the laser closure windows. Since the fraction of the sky contained within the keep-out cone is proportional to C^2, we might expect the number of closure windows to be proportional to C^2. Since the distance a satellite will move in traversing the keep-out cone is proportional to C, we might expect the length in time of an individual laser closure window to be proportional to C. Finally, since the total closure time during a night is proportional to the number of closures multiplied by their length, we might expect the total closure time during a night to be proportional to C^3. We might also expect the number of closure windows to be linearly related to the number of satellites.

[96] P. Bely, ed., *The Design and Construction of Large Optical Telescopes* (New York: Springer-Verlag, 2003), 253.

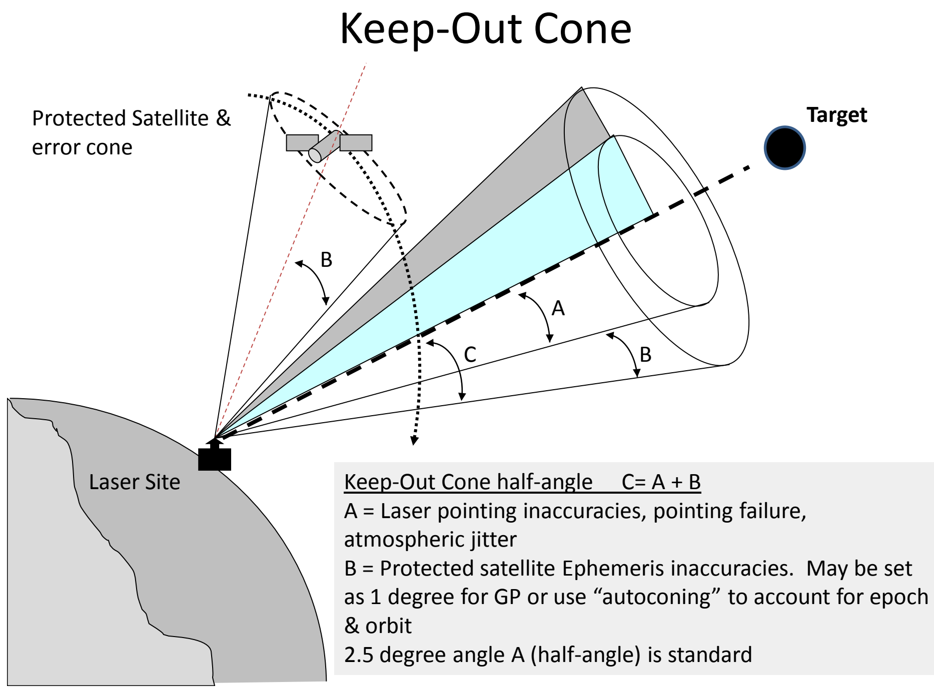

Figure 4. The keep-out cone.

Under normal operating conditions, the pointing direction of the laser mounted on the telescope is known very accurately. The observed stellar object and the adaptive optics laser have to be within about an isoplanatic angle or about 1.0 arc seconds, or 0.0003 degrees.[97] For Gemini, taking account of actual normal operational conditions where the laser may be dithered and the telescope may be offset for background measurements, the maximum normal operating deviation between the observed object and the telescope propagation direction is about 300 arc seconds, or 0.08 degrees.[98] Because the LCH uses a sure-safe philosophy, it assumes for the laser pointing uncertainty a worst case scenario. To counteract the rotation of Earth, the telescope has a maximum sidereal rate of 15 arc seconds per second. To monitor the laser, Gemini uses a human, who can react to an anomaly and shutter the laser within 24 seconds—in which case the laser will have moved 360 arc seconds. So taking into consideration that the anomaly could occur when the telescope is taking a background measurement and when the laser is at the limit of its 72 arc second projection optics field of view, a catastrophic failure would produce a maximum deviation of .21 degrees. As of July 2010, the LCH uses .25 degrees as the laser pointing uncertainty for Gemini.[99] Keck uses an automated

[97] J. Lawrence, et al., "Exceptional Astronomical Seeing Conditions above Dome C in Antarctica," *Nature* 431 (16 September 2004), 278.

[98] D. Coulson and C. d'Orgeville, "Gemini Observatory Laser Pointing Accuracy," 22 June 2010.

[99] Letter from J. Moss, "Centralized Predictive Avoidance Authorization for Gemini North and South," 21 July 2010.

laser shuttering system and a somewhat different system, and since the LGS observations in December 2009, the LCH has used 0.1 degrees as the laser-pointing uncertainty for Keck, which is also the minimum value the Spiral 3 input interface permits. Since proposed Multi-Conjugate Adaptive Optics systems have laser patterns about 1 arcminute in extent, the use of MCAO should not increase these values.[100] For comparison, the initial default angle used for PA when Spiral 3 was first implemented was 2.5 degrees.

The LCH uses what are known as Two Line Element (TLE) sets to establish satellite positions and position uncertainties. In conjunction with the Simplified General Perturbations simulation which models such things as the gravitational field of Earth, the TLE sets can be used to predict satellite positions.[101] DOD TLE data sets contain information for a particular time on satellite orbital parameters and position and are widely used.[102] Drag effects due to Earth's atmosphere can significantly affect the orbits of very low altitude satellites, and a term related to this factor, which is basically a normalized satellite ballistic coefficient, is also included in the TLE. The TLE sets do not explicitly contain position uncertainty information. Another methodology that incorporates uncertainty through a covariance matrix can be used, but because it is much more computationally intensive and can sometimes result in mathematical divergences, it is not used for observatory calculations.

Information for producing the TLE sets comes from the United States Space Surveillance Network (SSN), which is a worldwide collection of radar and electro-optic sensors.[103] As a result of the limited number of sensors, their geographical distribution, their capability, and their availability, the SSN does not track objects continuously. This means that the TLE set for a particular set is only updated when sufficient new information becomes available. Because a TLE set is generated at a particular time, the projected orbital position of a satellite will have increasing errors associated with it as the time between the TLE generation time and the projected time increases. This causes the keep-out cone half angle to increase with time until an updated TLE is available. One of the reasons for the LCH to send predictive avoidance approval messages within 24 hours of their use is an attempt to reduce the latency time of the TLEs used in the PA calculations. However, the observatory needs to receive this information in sufficient time to enable it to efficiently incorporate any restrictions into its observing plan.

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[100] Rigaut, op. cit., p. 1091.

[101] D. Vallado, et al., "Revisiting Spacetrack Report #3."

[102] See footnote 77 as well as sources of satellite position information such as http://science.nasa.gov/realtime/jtrack/3d/JTrack3D.html and http://www.n2yo.com/.

[103] NASA, "Handbook for Limiting Orbital Debris," NASA-Handbook 8719.14, 30 July 2008, http://www.hq.nasa.gov/office/codeq/doctree/NHBK871914.pdf.

A major source of the growth of satellite position error with time is the drag on the satellite due to the residual atmosphere at its orbit altitude. About 80% of low-Earth-orbit satellites are above about 600 km.[104] In 2004 the Landsat-7 Earth observation satellite, which orbits at an altitude of about 700 km, had TLE updates about every 6 hours.[105] If the LCH sends its laser window closure list 1 day before it is to be used and the Landsat-7 TLE update rate is typical, it will be using TLEs only about 6 hours old to predict positions about 24 hours in advance. At 600 km the LCH autoconing satellite position keep-out cone half angle using a 1-day-old TLE is about .7 degrees, and it increases by about .4 degrees a day for the first few days after the TLE is generated. At 1000 km the corresponding half-cone angle is about 0.3 degrees, and the growth rate is about 0.1 degrees per day. Once the laser pointing uncertainty cone becomes comparable to the satellite position uncertainty cone, improvements in the laser system keep-out cone produce diminishing returns. Since the LCH satellite position uncertainty keep out cone half angle for a 6-hour-old TLE for a 1000 km altitude satellite is about 0.2 degrees, observatory efforts to reduce the laser pointing keep-out cone half angle to about this value would be useful in reducing the impact of LCH restrictions. Gemini now uses 0.25 degrees and Keck 0.1 degrees. So long as the TLEs used are less than a day old as seems probable based on the 2004 TLE history for Landsat-7, uncertainties based on these autoconing calculations should reduce the impact of PA compared to using a fixed 1 degree cone half angle.

There has been significant interest in understanding the accuracy of satellite positions for upper atmospheric research and geodesy research, and also to calculate the probability of collisions between objects in orbit. Some of this work has compared predictions based on TLE sets with known positions determined with techniques such as laser rangers and on-board Global Position Systems.[106] The three components of position error are along the satellite track; along the radial distance from the center of Earth; and cross track, which is perpendicular to these other two directions. For low-Earth orbit satellites where atmospheric drag effects can be important, the position error along the satellite track is usually much larger than the error in the other two directions. Taking ICESat at an altitude of 600 km as a typical low-Earth orbit satellite, it has been found

[104] Union of Concerned Scientists, op. cit.

[105] Data from http://celestrak.com/NORAD/archives/. The year 2004 is used since certain distribution restrictions were put on DOD TLEs after that year.

[106] T. Kelso, "Validation of SPG4 and IS-GPS-200D Against GPS Precision Ephemerides" in 17th AAS/AIAA Space Flight Mechanics Conference, 2007, AAS07-127, http://www.centerforspace.com/downloads/files/pubs/AAS-07-127.pdf; P. Legendre, et al., "Improvement of the Two Line Element Accuracy Assessment Based On a Mixture of Gaussian Laws" in AIAA/AAS Astrodynamics Specialist Conference, 2008, AAS07-390, http://debris-spatiaux.cnes.fr/articles/AAS07-390.pdf; V. Osweiler, "Covariance Estimation and Autocorrelation of NORAD Two-Line Element Sets," Air Force Institute of Technology, AFIT/GSS/ENY/06-M09, 2006 at http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA446817&Location=U2&doc=GetTRDoc.pdf.

that for 1-day-old TLE sets the in-track error is several times that of the other errors. For this case, the autoconing half angle was consistent with a half angle based on in-track errors produced by the use of TLEs.[107] The autoconing algorithm uses a circular keep-out cone rather than the perhaps more realistic elliptical cone, which has its long axis oriented along the satellite velocity direction—expected if in-track errors dominate. I was told this was because the autoconing methodology chooses the largest position error calculated to determine the cone half angle. There was agreement that this could substantially overestimate the number and duration of the laser closure windows, but changing this would require a substantial rewriting and revalidation of the code, and resources are not available for this activity.

The LCH has considered one much simpler modification (as yet unfunded) to the way the Spiral 3 algorithm is used that would relax the assumption that the satellite telescope is always pointing toward the observatory laser. This would allow a limit to be placed on the off-nadir viewing angle by the satellite. But (1) since the high-resolution imagery satellites often specify 60 degrees as their off-nadir viewing angle limit, although they normally prefer much smaller angles, and (2) since the observatories do not use LGS lasers at less than 20 degrees from the horizon and prefer operation at much higher angles, this change would probably have only a very limited effect on PA impact to the observatories.[108]

[107] Ibid, p. 50.

[108] Digital Globe, "The Digital Globe Constellation," 2009, http://worldview2.digitalglobe.com/docs/Constellation_Brochure.pdf, and GeoEye, "GeoEye Constellation," 2010, http://www.geoeye.com/CorpSite/assets/docs/brochures/GeoEye_Constellation.pdf.

6. Effects of Predictive Avoidance Restrictions on Observatory Operations and Science

A. Types of Predictive Avoidance Restrictions

The observatories stated that they are concerned about three basic types of PA restrictions: classical PA, blanket closures (which the DOD calls space events), and ToO.

1. Classical PA

In classical PA, the observatories submit target lists several days before a monthly LGS observing session, and the LCH provides the laser closure window information about 1 day before the observing night begins. Certain designated targets are given specified laser closure windows for the night. Classical PA affects observatory observations essentially every LGS observing night. The typical cause is the possibility that the laser may illuminate a known orbiting satellite whose position is calculated using its TLE.

Although the initial impact of Spiral 3 in November 2007 on the observatories was large, both have said that the implementation of UPLs and reduced laser system exclusion cone angles have significantly lessened the problem. During the period when this report was written, both Keck and Gemini indicated that although they would like to see the impact of the LCH restrictions even further reduced, they could "live with" the current situation. Nevertheless, both observatories said that the further reduction of classical PA was their highest priority, since even at the current level, it still affected their operations almost every night LGS was used.

Classical PA had different effects on the observatories because of the differences in their observing methods. Currently, the overall effect on science is small. Gemini is usually able over the course of a semester to schedule around classical PA closures. The effect on a particular PI at Keck could potentially be significant, but no instances were given to me where this had actually occurred, particularly during the currently existing conditions where there are only a few short-duration, classical PA laser closures per night.

2. Blanket Closures

Either shortly before or during an observing night, the SSA Ops Cell will notify the observatories that all LGS observations must cease. These periods where the laser cannot be used range from about 10 minutes to an entire night. Occasionally, a few hours' notice is given before the laser must be shuttered. These occur about a dozen times a year. The typical cause is that there is a newly launched satellite or a satellite has maneuvered and a new TLE set has not yet been generated.

This type of closure had very different effects on the observatories. Over the course of a year, the relatively limited number of hours affected meant that the overall effect on observatory productivity was minor. Gemini using its queue system experienced a small effect, since observations could be scheduled around a blanket closure. The effect on an individual investigating astronomer would be minimal. In contrast, if a significant blanket closure fell on the one or two nights an investigating astronomer was observing at Keck, it could have a major effect on that person's ability to complete the planned observations. Such severely affected individuals could be expected to be rather vocal in their criticism of the NSF policy to adhere to LCH procedures. As a result, Keck considered the reduction in blanket closure effects to be second in priority to only classical PA, but Gemini considered it to be only a third priority after classical PA and rapid ToO.

3. Targets of Opportunity

The first of the several kinds of ToO are targets like variable stars that undergo known, relatively short-time-scale periodic variations. Since they have a known temporal scale and recur relatively often, LCH closures are usually not much of an issue because these objects can reliably be observed at another time. The exception to this might be a situation where a Keck investigating astronomer had only a limited time in which to observe.

Another type, called standard ToO, consists of targets that appear unexpectedly but last through several nights, so the observations can be executed more than 24 hours after the observatory is notified.[109] These include such things as novas and Titan weather effects. Gemini observed ToO at the rate of about 1 or 2 events for every 7 to 10 adaptive optics lasing nights, but the rate for Keck was less. This discrepancy was likely because the Gemini queue system could respond more facilely to these requests, the general nature of which was ranked at the beginning of a semester. For Keck, its classical observing scheme required investigating astronomer approval that might only be granted for an object of very high scientific value. Since these standard ToO last a relatively long time, the additional delay due to the LCH procedure was not thought to be a major issue, although there may be some effect if a large number needed to be processed in a single night. At Gemini, astronomers were concerned that they did not know how many standard ToO the LCH could process for a night, and if there were several, they might not be able to observe them all. This has not yet been a limitation, however. Since the

[109] Gemini, "Target of Opportunity Activation," 26 February 2010, http://www.gemini.edu/sciops/observing-with-gemini/phase-ii-and-s/w-tools/too-activation.

turnaround time from the LCH could be about 30 minutes if the SBM does not have other priorities, more than a dozen independent standard ToO should be possible in a night, considering just the LCH response. Note that this would place a high burden on the SBM and does not take into account the required efforts by the observatory to interact with the SBM.

A third class is unique, short-lived events that will be known to occur many months in advance. These include spacecraft impacts on the moon or asteroids and the 1994 Shoemaker-Levy comet impact on Jupiter. Perhaps because such events are rare, this was not a major concern, although it was mentioned. Gemini said it was able to successfully use laser adaptive optics to observe the 9 October 2009 impact of the LCROSS spacecraft on the moon.

There was particular concern by both observatories about what were called rapid ToO. Rapid ToO are objects like gamma ray bursts (GRBs) that are unpredictable and last only a short time. Ideally, they would like to observe these objects within minutes after notification (Gemini uses a formal definition of objects that need to be observed within 24 hours). Although I was told by Gemini that GRB notifications are issued about once a day, only 27 of them were considered important enough to be observed during the 6-month 2009B semester during non-adaptive optics laser nights. Extrapolating from this number, there would have been about 9 during laser adaptive optics observing nights. I was told by Gemini that the actual number of requests was much smaller because of their inability to guarantee observations within 24 hours due to LCH restrictions. Gemini and Keck were not able to give me a specific example of a journal or meeting paper on a GRB or other object observed by a non-LCH observatory that was denied to Gemini by the LCH restrictions. It was stressed that in the future with the addition of a number of new alerting sensors, the number of rapid ToO requests would increase significantly.

When I asked them to list their priority issues, Gemini considered the ability to respond to rapid ToO to be much more important than the blanket closures. For Keck, the effect of blanket closures was considered much more significant than those produced by rapid ToO. This was apparently due to their different observing procedures. Since the intrinsic LCH and SSA Ops Cell response time is about 30 minutes, and with the new July 2010 standardized procedures initiated between Gemini and the LCH, Gemini may now be better able to observe rapid ToO . Of particular importance would be the response time of Gemini itself to rapid ToO requests, which would include time to prepare the PA request message and process the PA request message, which I was told might be about an hour. Telescope operations, such as moving to a new target and perhaps waiting for weather and Earth’s rotation to allow good viewing, could also affect how quickly a rapid ToO could be observed. Based on what I was told and my observations, it takes about 5–10 minutes to move the telescope to a new object and establish the new LGS adaptive optics loop. At Keck, the observing astronomer would probably not be the one requesting the ToO. Since the observing astronomer’s time would be interrupted by a ToO request—

and so permission of the observing astronomer would be required—the ToO issue did not have as high a priority at Keck as at Gemini because it has been rarely requested.

B. Predictive Avoidance Impacts before the Implementation of Spiral 3

Both observatories agree that before the introduction of Spiral 3 in November 2007, the impact of PA was minimal. There were essentially no classical PA effects and very few blanket closures, and they did not mention any concern with ToO. The impact on staff time was said to be minimal and not an issue.

The first propagation of laser light from Gemini occurred in March 2005. Gemini began offering LGS observations to the science community in the second semester of 2006, 2006B, although the actual observations were not made until the first semester (February–July) of 2007, 2007A.[110] As a result, Gemini had less than a year of scientific observing experience before the implementation of Spiral 3.

In the 12 months preceding October 2005, Keck reported that "only a handful of targets have been restricted" due to LCH laser closure windows.[111] Scientific observing began at Keck in November 2004. During this time target lists and laser closure windows were sent by fax. Weather effects such as clouds being too close to the laser beam for the human spotters to observe aircraft and laser interference with other observatory fields of view dominated the restrictions on laser operations. During this period the LGS observatory shuttered its laser whenever there was the possibility of interference with another observatory on Mauna Kea. Since the adaptive optics system requires certain good seeing conditions greater than what might be required by other observations and has aircraft-spotting cloud restrictions not required if LGS lasers are not used, weather and seeing conditions have a somewhat larger affect on LGS operations than on observations not using an LGS. In 2007 Keck estimated that the average time lost to bad weather at Keck was about 21%, the average time that the LGS lost to bad weather was about 25%.[112]

Figure 5 and Figure 6 show the LGS performance metrics for the period from November 2004 to June 2006.[113] The first figure includes weather losses; the second does

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[110] M. Boccas, et al., "Laser Guide Star Upgrade of Altair at Gemini North" in *Advances in Adaptive Optics, Proc of SPIE* 6272 (2006), eds. B. Ellerbroek and D. Calia; Gemini 2006B queue schedule at http://www.gemini.edu/sciops/schedules/schedQueue2006B.html.

[111] D. Le Mignant and A. Bouchez, "Summary of Laser Propagation Restrictions and Procedures," *Keck Adaptive Optics Note (KAON)* 269 (2005), http://www2.keck.hawaii.edu/optics/lgsao/docs/kaon269.pdf.

[112] D. Le Mignant, "Lessons Learned for Keck LGS Operations: Weather impact, Efficiency and Science Operations Model," *KAON* 463 (2007), http://www.oir.caltech.edu/twiki_oir/pub/Keck/NGAO/ObservingEfficiency/KAON463.pdf.

[113] D. Le Mignant, et al., "LGS AO Operations at the W. M. Keck Observatory," *SPIE* 6270, http://www2.keck.hawaii.edu/optics/lgsao/docs/spie2006-6270-12.pdf.

not. The sector labeled “Space Cmd” is the fraction of the time due to LCH restrictions. Even when the effects of weather are removed, these restrictions prevented LGS observations only about 1% of the time, which is about half the time lost to laser traffic control to avoid interfering with other observatories and much less than the 43% of the time required for various required overhead activities that allow observing to take place. Difficulties with operating the laser resulted in 12% downtime, which completely dominated any downtime due to LCH rules. Excluding weather, LGS AO observations could occur about 33% of the time. Figure 5 includes weather and indicates that following LCH instructions resulted in an average of about 2.4 minutes a night of PA-prevented LGS observing time for Keck. This average time includes several blanket closures, which I was told accounted for much of this time, so there were many nights when there was no closure at all.

Based on readings of contemporary documents already referenced and discussions with staff from the two observatories who were present before Spiral 3, the LCH restrictions at that time seem to have had little effect on operations and were of minor concern. One major report on adaptive optics published in early 2008 did not even mention the LCH restrictions (this document was primarily focused on technical issues, but it did discuss competition with foreign observatories).[114] It also appears that LCH restrictions had little effect on both observatories in terms of the entire interaction with the LCH, including the staff time and effort spent in preparing the PA request message as well as incorporating any laser closure windows into the observing plan. Since there were virtually no PA laser closure windows, the amount of time observatory staff (and in the case of Keck also PIs) had to spend on rearranging observing schedules to account for closures was minimal. The preparation of the PA request message for the LCH, which could be done days ahead of time of the monthly LGS observation period, was not considered a significant burden.

By late November 2005 Gemini reported that it had never received any closures on the target lists it had submitted and that it had received same-day LCH approval for special requests such as adding new targets or changing targets. Its major issue was a desire to move from faxing the target list to LCH to using e-mail or a Web interface. Keck’s experience was similar, except that it mentioned that up to that point in 2005 it had lost about 4 hours of LGS observing time to space events. Keck also desired a change from faxing target and approval lists to using e-mail. At this time, Keck felt that significant coordination with the LCH was required. This took about 5 hours for each observing period, which was made up of several LGS nights.[115]

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[114] NOAO, “A Roadmap for the Development of United States Astronomical Adaptive Optics,” 18 April 2008, http://www.noao.edu/system/aodp/AO_Roadmap2008_Final.pdf.

[115] Mauna Kea Laser Guide Star Technical Working Group, “Working Group Meeting,” 22 November 2005, http://www2.keck.hawaii.edu/optics/aodocs/KAON384.pdf.

About 0.4% of a typical 10-hour LGS night is lost to LCH restrictions. This amounts to about 2.4 minutes, as shown in Figure 5, which could serve as a benchmark for what could be considered a minimal effect of LCH restrictions on observatory operations. However, the 4-hour total closure period over the approximately 100 nights of LGS operation was primarily due to blanket closures and not to classical PA.

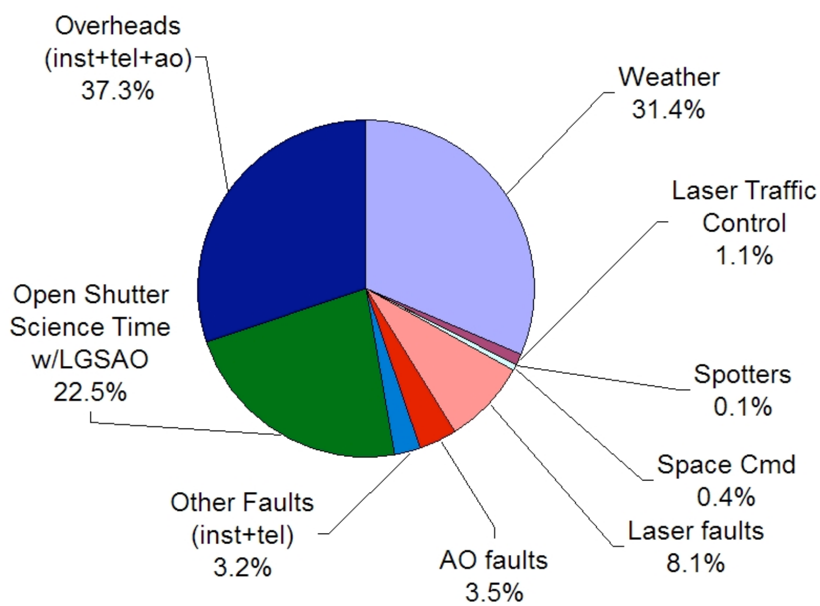

Figure 5. Keck time allocation before Spiral 3.

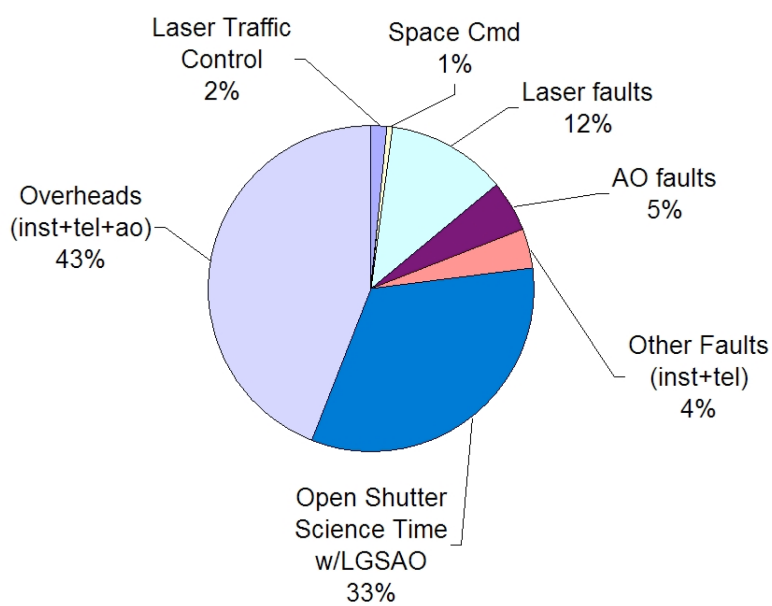

Figure 6. Weather-removed Keck time allocation before Spiral 3.

C. Immediate Effects of the Implementation of Spiral 3

The use of Spiral 3 was introduced in November 2007 without any advanced warning to the observatories. This resulted in a very significant increase in PA closure times, mostly due to an increase in classical PA because it was instituted under its default conditions of 2.5 degrees laser keep-out angle, 1 degree satellite keep-out half angle, and no unique protect list. These initial conditions resulted in a very large total exclusion cone half angle of 3.5 degrees, which gives an exclusion area centered on the laser about 200 times the area of the full moon. Under these conditions, for the nights of 3–4 December 2007, the average number of closures per object observed by Keck was 10.2, with the average length of closure 3.3 minutes, for a total closure time per night of 34.1 minutes. This compares with the total average closure time of 2.4 minutes per night before Spiral 3. The fraction of total time lost to PA restrictions increased from about 0.4% to almost 6%, while the number of closures per night went from being a rare event to an average of about 10. Although I was not able to obtain firm figures, I was told by both observatories that this had a significant impact on operations—from the large increase in the amount of effort the staff (and for Keck, the PIs) had to devote to schedule planning, to initially interacting with the LCH to understand what had happened, and to provide information to the LCH necessary to reduce the laser system half-cone angle and establish a UPL.

Within about 1 month of the start of the use of Spiral 3, cooperation between Keck and the LCH led to an understanding about what had occurred and what could be done to quickly mitigate the effects. The first steps taken for Keck were to establish a UPL and reduce the laser system cone half angle to 1.5 degrees. This reduced the average closures per night to 6.5, the average duration per closure to 2.0 minutes, and the total time lost to PA per night to 13.3 minutes. This reduction is about what might be expected using the simple scaling relationship given in Chapter 5 and suggests that the UPL established at that time did not eliminate many satellites. These times include the time required to start and stop the laser with enough buffer time to prevent inadvertent lasing in the laser closure windows. The UPL and change in laser system cone angle helped but did not reduce the impact to anything close to that experienced before the Spiral 3 implementation. In addition, there was quite a bit of variability, which made planning difficult. For Keck, which uses the classical observing mode, a significant part of this increase in observational planning was borne by the investigating astronomer, although the individuals involved in controlling the laser propagation also had an increased workload. Figure 7 shows the Keck results for the period from January to May 2008, which totaled 34 LGS nights for the number of times a single target would be closed per night, and indicates a rather large amount of variability.[116] The total number of closures

[116] R. Campbell and D. Le Mignant, "Space Command Changes Impact Keck Lasing," in *Keck Observers' Newsletter*, Summer 2008, http://www2.keck.hawaii.edu/inst/newsletters/Vol5/index.html.

in this period is based on the 2,452 astronomical targets submitted to the LCH, about 72 targets per night. There apparently was some concern as to what targets would be permitted each night, so the investigating astronomers submitted many possible targets.

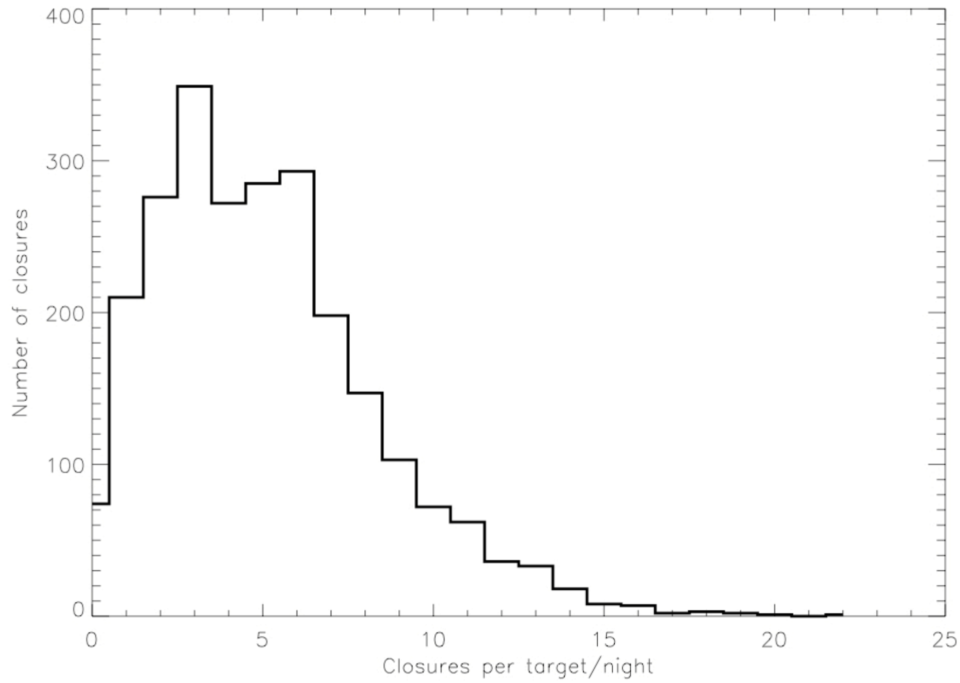

Figure 7. Histogram of Keck closures per target per night.

It was not possible to translate these raw closure numbers into the actual effect on science since there is a possibility that the PI could adopt an observing schedule to mitigate some if not all of the effects of the laser closure windows. The total closure time on a target averaged only about 2% of the total time per night, and other effects such as weather were much larger. However, this might have been important for a particular observing astronomer looking at a particular target on a particular night. Some instruments integrate over a period of time, and depending on the circumstances, even a relatively short laser closure window might render a much longer exposure useless.

The majority of these closures (65%) lasted between about 3 and 20 seconds. This is about the time a low-Earth orbit satellite would pass through the full exclusion cone angle. The half-cone angle includes 1 degree due to satellite position uncertainty and 1.5 degrees for the laser system, for a total cone angle of 5.0 degrees. At 600 km altitude this exclusion cone would have a diameter of about 50 km, and it would take a satellite about 7 seconds to cross it. However, about one-third of the closures are for times longer than 20 seconds, and about 16% are longer than 5 minutes, with about 1.0% longer than 15 minutes. The UPL used at this time seems to have included a number of satellites with altitudes above low-Earth orbit.

Since Gemini uses a queue system, the major effect was not the actual increase in particular closure windows and their duration during an observation night (if a target had at least some clearance windows, this system allows significant flexibility in scheduling of observations). Instead, the most significant impact was on the queue coordinator, who must do the queue planning in a much more complicated context than in the era before Spiral 3, and the people at the summit, who must control the propagation of the laser and the fraction of an LGS night that can be actually used for LGS observations. Starting in January 2008, Gemini noticed a significant impact due to the implementation of Spiral 3. This impact included a 2-hour increase per LGS night for queue planning, a situation where only 60% of science targets had suitable clearance windows on a given night and a 25% reduction in the fraction of an LGS night that could be devoted to LGS observations.[117]

The observatories said that at the time of its first use the major impact of Spiral 3 was on classical PA. As indicated by the effects discussed in contemporary documents and in later discussions with me, they did not appear to have major concerns with increases in blanket closures and ToO. Since blanket closures are associated with objects whose positions are unknown, one would not expect major changes in them when Spiral 3 was implemented.

D. Current Impact of Spiral 3 PA on Gemini

1. Impact on Science

Potentially, the most important impact of PA could be on the ability to produce scientific results. This is somewhat difficult to determine since it can involve what did not occur as a result of PA. For example, determining if requests for LGS observing time were not made due to past experience with PA restrictions was not practical. Gemini and Keck did not have a specific example of a journal or meeting paper written by an observatory not following LCH restrictions that described observations denied to Gemini by the LCH restrictions.

A major Gemini concern is the use of LGS for ToO and that astronomers have been discouraged from using this due to potentially long PA delays. ToO programs make up about 20% of those in the two highest priority observing program bands, and Gemini expects this to increase in the future as instrumentation that can provide triggering events improves and increases in number. Gemini currently accepts LGS observations only for standard ToO, which it defines as those that can have useful observations for response times longer than 24 hours. In semester 2010A, Band 1 had no requested LGS standard

[117] AURA, "Report of the AURA Oversight Council for Gemini," 9–10 September 2008, http://www.aura-astronomy.org/events/Aocg/AOCG-RPT-September%209-10,%202008.pdf.

ToO in about 84 observing hours of LGS requests but had about 60 hours of standard ToO out of about a total of 263 non-LGS hours, excluding hours devoted to rapid ToO. So all other things being equal, we might have expected about 19 hours of LGS standard ToO observations instead of the 0 actually in the queue. Although there is no direct evidence, this could be the result of PI choices or band prioritization mechanisms giving a lower preference to LGS standard ToO in Band 1 due to a perception concerning uncertain or lengthy response times. Some indirect evidence for this explanation might be found in the observation that in Band 2, 17% of the LGS queue programs are for standard ToO and a roughly comparable 12% of non-LGS queue programs are for standard ToO.[118]

One important metric used by Gemini is the percentage of observing time allocated to a PI astronomer in a semester that is actually used for scientific observations.[119] Before the start of a semester, Gemini divides the individual scientific programs into three priority bands, 1, 2, and 3, with Band 1 having the highest priority. The lowest priority, Band 3, does not have any laser guide star programs in it by design. The requirement is that over the course of its assigned semester and the following rollover semester, 90% of Band 1 programs will have been completed, with an ultimate goal of 100% completion. For Band 2, the completion rate requirement for the assigned semester is 75%, with a goal of 90%. There is no rollover for Band 2. Gemini feels that a program that has been able to use 75% of its observing time has collected sufficient information to produce significant scientific results, usually resulting in at least one paper.

Table 2 gives scientific program completion rates for the 2009A semester programs at Gemini North including rollover to the 2009B semester. Table 3 gives Gemini North completion rates for all programs in the 2010A semester, which includes rollover programs from the previous semester.[120] Semester 2010A is the latest completed semester. Of the approximately 400 hours of scheduled observing time in each of Semester 2010A Bands 1 and 2, approximately 22% of Band 1 and 31% of Band 2 was devoted to LGS observing. In terms of scheduled science completed, it does not appear that the LCH restrictions had a significant effect since the scientific program completion rates for these semesters are similar whether or not an LGS was used. The queue methodology apparently gives sufficient flexibility that the effects on scientific program completion rates of standard PA and blanket closures can efficiently be overcome during the course of a semester.

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118 Gemini, "Queue Summary: Semester 2010A Gemini North and Gemini South," 14 August 2010, http://www.gemini.edu/sciops/schedules/schedQueue2010A.html.

119 Gemini, "Science Operations Statistics," 11 August 2010, http://www.gemini.edu/sciops/statistics.

120 Gemini, "Queue Summary: Semester 2010A Gemini North and Gemini South," 14 August 2010, http://www.gemini.edu/sciops/schedules/schedQueue2010A.html.

Table 2. Scientific program completion rates for 2009A semester.

Priority Band	2009A Completion	Completion by 2009B	Observing Use
1	75%	90%	No LGS
1	75%	90%	LGS only
2	70%	—	No LGS
2	70%	—	LGS only

Table 3. Scientific program completion rates for 2010A semester.

Priority Band	Programs Completed	Program Hours Completed	Observing Use
1	85%	92%	No LGS
1	80%	96%	LGS only
2	72%	81%	No LGS
2	75%	92%	LGS only

Gemini does not accept rapid ToO for LGS use since it feels it cannot reliably support its stated 24-hour response time for these objects due to PA requirements. According to Gemini, the majority of the non-LGS rapid ToO requests require responses within the same night and many of them ask for immediate interruption of the planned observing schedule. The time from request to actual observing is on the order of 10 minutes for requests that require immediate servicing. There were about 10 rapid ToO requests in the first half of 2010. The observatory felt that there is an unsatisfied demand for LGS rapid ToO use, but thought it was not feasible to gauge its possible extent.

With the adaption of the new agreement in late July 2010 with the LCH, it may be possible for Gemini to reliably accept LGS rapid ToO. The time to slew to a new target and establish a new adaptive optics loop can be about 10 minutes, the LCH response time is about 30 minutes, and the time to prepare the PA request message and incorporate the new PA target information when it is received is about 1 hour.[121] So in the future it might be possible for Gemini to respond reliably to a rapid ToO using the LGS in about 90 minutes, provided the SBM can give the request immediate attention. I could not determine how often the SBM could give immediate attention to rapid ToO requests. However, the SBM has some discretion on how to handle different situations, although important DOD operational requirements would take precedence over observatory requests. The potential LGS response time of about 90 minutes compares with a minimum response time of about 20 minutes for rapid ToO without an LGS.[122] Some of

[121] Gemini, "Observing Overheads," 27 February 2009, http://www.gemini.edu/?q=node/10037.

[122] Gemini, "Target of Opportunity Activation," 26 February 2010, http://www.gemini.edu/?q=node/11014.

this time might be done in parallel with other activities, such as waiting for the target to come into view (although LGS use at Gemini South could reduce this time) or any required instrumentation-related activities (although these can often be completed during slewing). It is possible in some cases that these other activities may be the actual limitation on response time.[123] Gemini North collected useful scientific information without an LGS on GRB 100513A about 4.1 hours after the event was first detected.[124] In the first half of 2010 there were two Gemini LGS standard ToO. Although one of these in March was processed in about 48 hours, the request in June was processed in about 5 hours, which at least shows the possibility of LGS observations within the 24-hour requirement of a Gemini rapid ToO. Those events that exhibit significant signal changes between 20 and 90 minutes would appear to be the ones potentially most affected by PA restrictions. Gemini predicts increased use and importance of ToO in the future.

2. Impact on Operations

As discussed in more detail in the next section, the primary PA impact on observatory operations is the additional workload it places on Gemini staff. The additional workload over a year to incorporate PA represents about 15% of a person-year. While small compared to the total staffing of over 100 person-years, it is concentrated on just a few staff members who work under sometimes severe time restraints. In particular, the queue coordinator spends about 4 hours to prepare the queue on nights when there is no LGS and 6 hours to prepare the queue on nights when an LGS is used. Although the PA permission message typically is received from the LCH about 24 hours before observing begins, sometimes it has been received just before observing was scheduled to begin, which meant the queue had to be adjusted in a short time. About 25% of the nights in semester 2009A required significant queue revisions; the corresponding number for 2009B was 10%.

Laser registration, demonstrations to reduce the laser exclusion cone angle, and preparing procedural documentation for the LCH took about 15 staff days (about 7% of a person-year) over a period of about 6 months in 2010. Although this does not have to be done every year, it did require the attention of personnel who were also busy with other important activities such as installing the laser system at Gemini South.

From January 2009 to January 2010 there were three blanket closures (space events) that lasted the entire night. Since Keck and Gemini chose somewhat different LGS observing nights, they can be affected differently by blanket closures. About 3% of the total nights in that period were planned to be devoted to LGS observations. In addition,

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[123] Gemini, “Multi-Instrument Nights at Gemini North and South” http://www.gemini.edu/node/160; Gemini, “Gemini Focus,” December 2009, http://www.gemini.edu/images/pio/newsletters/pdf/gf_1209.pdf.

[124] GCN Circular 10752, http://gcn.gsfc.nasa.gov/gcn3/10752.gcn3.

there were about 6 other blanket closures, with the longest lasting a few hours. During these shuttered periods, observations were typically made on alternate targets using just natural guide stars. Table 4 gives Gemini blanket closure information from 1 January to 15 June 2010. Sometimes advance notice of a blanket closure of up to a few hours was given, sometimes no notice was given, and sometimes advance blanket closure notice was given about a closure that was canceled before it was to occur. These all require extra work and affect operations. Even the canceled blanket closures may affect operations since the queue may have been rearranged in anticipation of the closure. On average, the time lost to blanket closures (approximately 3%) is small compared with the time lost to poor LGS adaptive optics observing conditions (75%). Only about 25% of the time are observing conditions sufficient for the use of LGS observations. This forces Gemini to schedule 3.5 to 4 times as many LGS nights in the queue as actual approved queue science time.[125]

Table 4. Blanket closure durations at Gemini.

Date (UT)	Duration (Hours:Minutes)
January 27, 2010	10:00
March 31, 2010	0:11
April 1, 2010	1:36
April 2, 2010	0:10
April 3, 2010	0:15
April 4, 2010	1:19
May 20, 2010	0:28

In about the first half of 2010, the typical classical PA closure lasted less than about 30 s, although there were two nights where waiting through multiple longer LCH closures took a total of about 30 minutes. There were seven extended LCH closure windows nights where waiting through multiple longer LCH closures resulted in a loss of about 18 to 30 minutes for each night. These extended closure periods totaled about 2.7 hours, or about 0.5% of the LGS observing time in the first half of 2010. During a night there would be about three closures if no adjustments were made to the original queue. As a safety margin, the laser was typically shuttered for about 30 seconds to accommodate a 10 second PA closure. By rearranging the queue, the number of actual closures could be reduced. This could mean that even if there were PA closures, there was enough flexibility in the queue to eliminate all closures by picking targets and times that were not affected by PA restrictions. Depending on conditions, such as length of closure, this is

[125] AURA, "Report of the AURA Oversight Council for Gemini," 28–19 October 2009, http://www.aura-astronomy.org/events/Aocg/AOCG-RPT-October%2027-28,2009.pdf.

not always done, however. For example, a sensor often used for LGS observing is the Near-Infrared Integral Field Spectrometer (NIFS).[126] The longest exposure time with this instrument is usually 10 minutes. Even if as is often the case the desired exposure time on a target is approximately 1 hour, this time is broken up into 10-minute segments. If there is a single LCH closure window, it usually only "contaminates" the data for a single 10-minute data block. I was told the data usually were still collected and the PI astronomer would be notified of the amount of time the laser was turned off. That individual could then decide how to use the data. As a result of the way the data software is written, it is not possible to stop taking data during the actual time the adaptive optics laser is off. I was told it would be a major effort to change this software.

Both Gemini and Keck reported that occasionally they would receive what they considered unusual responses from the LCH, which sometimes affected operations or caused extra work to resolve them. Since these were often one-of-a-kind events, I was usually not able to verify them or to understand the actual cause of most of them. These included what the observatories called "typographical errors" on the part of the LCH (although there should have been no manual typing of data at the LCH) that appeared to affect closure windows, a laser clearance list which included only a zenith position for the laser, a target that was closed to LGS use for all of 4 consecutive nights, and closure windows on targets when they were below the horizon.

3. Impact on Personnel

I did not speak to any of the PI astronomers—they usually are not present during actual observations because Gemini uses the queue format. As such they are insulated from the direct operational conditions imposed by PA. Their choice of program requests for Gemini may be influenced by their perception of PA limitations, however.

The Queue Coordinator is typically a Ph.D.-level assistant astronomer at Gemini. This person puts together the detailed queue schedule. For the approximately 7–10 nights a month where laser adaptive optics are used, the planned target list for all the nights in a monthly block is transmitted to the LCH about 7 days in advance. The LCH sends back the required closure windows nominally about 24 hours before each night. There can be considerable variation in this timing, however. For 53 LGS nights from 1 January to 15 June 2010, there were four instances where the closure windows from the LCH were received with less than 4 hours in the workday remaining, four instances where revised closure windows were received after the queue coordinator had finished planning the night and one instance where the initial closure windows were received after planning for the night had begun. Revising the queue after the initial queue is planned typically takes

[126] NOAO, "Final Report of the Committee on Access to Large Telescopes for Astronomical Instruction and Research," 9 March 2009, http://www.noao.edu/system/altair/files/ALTAIR_Report_Final.pdf.

about 0.5–1.0 hour of additional Queue Coordinator time right before the start of observing for the night. For 15 nights, multiple clearance lists (in one case as many as four) were received by Gemini, although in some cases these lists were received before the first queue was constructed, so no additional work was required.

Since different scientific programs require different observing conditions (which cannot be predicted and have different priorities), the detailed queue schedule produced by the queue coordinator after receiving the LCH closure list includes several alternative sequences. For this reason and because weather is a major uncertainty and equipment problems can occur, the queue schedule includes plans that total several times the actual number of possible observing hours. Although only approximately 10 targets might be actually observed if all the night hours could be used, the queue coordinator plans include about 30 targets that together currently have on the order of 100 LCH closures over an entire night. The additional workload imposed on the queue coordinator by the closure restrictions is approximately 250 hours per year, or about 2 hours per laser-adaptive-optics observing night. When the laser is not used, the queue coordinator spends about 4 hours per observing night constructing the queue. Note that this additional 2 hours must take place within the limited time period between the receipt of the LCH closures and the beginning of observations that night. I was told this was sometimes stressful for the queue coordinator because much of the final scheduling process was not automated—it required the professional judgment of the queue coordinator, who is also an astronomer. So about 12% of a person-year is devoted to LCH-specific work that is done by the queue coordinator. The daily Gemini afternoon planning meeting I attended had approximately 20 people, and the total Gemini staff is over 100 people, so the additional effort and cost to Gemini of the queue coordinator to incorporate the LCH restrictions is small. However, a major impact of the LCH restrictions falls on the queue coordinator.

The Telescope Astronomer position is typically held by a Gemini Science Fellow or other Gemini staff member who is a Ph.D.-level astronomer. This work takes place at the Mauna Kea summit and lasts all night, so it is rather physically and mentally demanding shift work. It is stressful even without LCH restrictions, since the person must make real-time decisions about what objects to observe even given the observing scenarios prepared by the queue coordinator because seeing, weather conditions, and other factors such as equipment availability can change significantly in an unpredictable manner during a night. The additional restrictions imposed by the LCH closures only increase this workload. About 15% of the LGS nights in the first half of 2010 had blanket closures. Some of these had no warning time and some had several hours. The telescope astronomer manually monitors the closure periods. This person also must make real-time decisions that can help minimize the effects of LCH predictive-avoidance closure windows. For example, an observing sequence might require looking at an “empty” area of sky without using the laser to subtract out certain background effects. The timing of these periods can be chosen so that they occur during LCH laser closure periods, which would have no impact on actual observing time. While the LCH restrictions do not increase the work time for the telescope astronomer since this is fixed by the length of the night, they do substantially increase the work load on the individual even if there is no effect on the science that is actually accomplished.

The System Support Associate (SSA) position is held typically by a Gemini staff member with a bachelor's degree usually in astronomy or a related field. This work takes place at the Mauna Kea summit and lasts all night, so it is rather physically and mentally demanding. In regard to LCH restrictions, the SSA follows instructions from the telescope astronomer as to when to shutter the laser so there is a small additional work load due to the restrictions.

4. Conclusions Concerning Current Gemini Conditions

Gemini said that the classical PA restrictions and blanket closures before Spiral 3 were not a problem. During the beginning of 2010, it felt that conditions had improved sufficiently that classical PA was no longer a significant issue; the impact of classical PA restrictions should only decrease now that a 0.25 degrees laser system exclusion cone half angle was approved in July 2010. Downtime due to space events is much less than that due to weather and other effects, so the flexibility allowed by the queue procedure means that this is not considered a significant issue.

The main concern of Gemini is ToO. Objects with significant changes in times less than about 90 minutes from a trigger are very difficult or impossible to observe under the current PA procedures. Changes in objects that occur in less than about 10 minutes from a trigger cannot be seen even if LCH restrictions were ignored. By shortening the time it takes for Gemini to prepare and receive LCH messages, the total response time due to Gemini activities might be reduced to about 1 hour, but making it much shorter is probably not possible. Servicing standard ToO under current PA procedures should not be an issue, and if the new July 2010 procedures yield their expected results. rapid ToO using LGSs with response times of about 90 minutes should be possible when the SBM can give an immediate response.

In general, the scheduled science produced by Gemini does not appear to be affected. But there is some indirect evidence that high-priority ToO programs are not being considered because of perceptions concerning PA. The new July 2010 procedures agreed to with the LCH should enable Gemini to accept rapid ToO requests and guarantee responses within 24 hours. The new procedures could allow, although not necessarily guarantee, rapid ToO LGS response times as quick as about 90 minutes.

Taken as a whole, the additional staff time and cost to Gemini due to PA is very small. However, the additional effort due to PA is concentrated on only a few members of the observatory staff, primarily the Queue Coordinator, Telescope Astronomer, and System Support Associate. This additional work often occurs when these individuals have other responsibilities. Reducing this workload should be possible by increased automation of Gemini procedures, perhaps by utilizing concepts similar to those used at Keck, to reduce the laser system exclusion cone half angle to 0.1 degrees. This is a possibility already being considered by Gemini.

Under certain conditions, the Gemini laser could produce permanent damage to certain satellite components, particularly large-aperture visible imagers, although it is not evident that there would be a significant effect on the operational capability of the satellite even if laser-induced damage occurred. Under present conditions, the probability of the Gemini laser actually causing damage to current satellites is extremely small. With current satellite numbers, the Gemini North laser will illuminate a possibly susceptible satellite about once every 50 years. The probability of actually damaging a satellite given that it is illuminated is no more than about 1×10^{-4} and probably significantly lower.

E. Current Impact of Spiral 3 PA on Keck

1. Impact on Science

The Keck observatory uses the classical observing mode. Based on information supplied by Keck, PA restrictions did not appear to have a significant effect on the overall quality or quantity of science done over a semester. Keck did not have specific examples of science that was not done or not attempted due to PA restrictions. Likewise, Keck did not have a specific example of a journal or meeting paper written by an observatory not following LCH restrictions that described observations that were denied to a Keck PI by the LCH restrictions.

A PI at Keck typically has from 0.5 to 3 nights of LGS observing time per semester.[127] Since a particular PI might have only a single observing night in a year, a laser closure window of only a few hours that can occur during a blanket closure could significantly affect that scientist's observing program. Of course, this program could also be affected by other causes such as weather or equipment difficulties. For its entire program, Keck has about 150 PIs per year for each telescope and is oversubscribed by about a factor of 5. In past years its LGS program was oversubscribed by a factor of 2.[128] The PIs can be upset if a blanket closure occurs during their observing period and often make their displeasure known to Keck management. It is possible that individual PIs

[127] Keck, "Telescope Schedule," http://www2.keck.hawaii.edu/observing/sched/Keck2historic/index.html.

[128] NOAO, "A Roadmap for the Development of United States Astronomical Adaptive Optics," 18 April 2008, 5, http://www.noao.edu/system/aodp/AO_Roadmap2008_Final.pdf.

could be seriously affected by a lengthy laser closure window, but Keck could provide no specific examples.

There have been four blanket closure events from January 2009 to June 2010 that lasted more than 40 minutes, approximately 7% of the available observing time during a night. The longest was for the entire night of 27 January 2010, which occurred on the third night of a 3-night observing program for a particular PI. This PI lost about one-third of total observing time due to PA. The next longest occurred on 1 March 2010 and lasted 4 hours and 20 minutes when I happened to be at Keck. This was the second night of a 2-night campaign in support of graduate thesis work, so the blanket closure represented about a 20% loss in observing time in these two nights. The graduate student had also observed several nights the previous semester and estimated that about 30% of observing time had been lost to weather. Other data from Keck indicates that about 20% of LGS nights have more than 8 hours of time lost to weather.[129] The student and her advisor both told me that the blanket closure event was very frustrating and reduced the opportunity for data collection. However, the advisor also said that observational astronomy depended on a number of factors outside his control, and so his planning for thesis work took this into account. The completion of the thesis in a timely manner would not be prevented by the blanket closure. The longest time lost to blanket closures in 2009 in one night was on 9 December 2009, when the laser shuttered time was 2 hours and 41 minutes. This occurred on the last night of a 3-night campaign and so represented about 10% of the allocated observing time. These aggregate numbers could hide specific details—such as the blanket closure occurring at the only time a particularly important object could be observed, perhaps due to weather effects or Earth's rotation placing it in view.

Since there was the one instance where a blanket closure lasted an entire night and some PIs only observe on one night a year, it is possible for PA restrictions to completely prevent a PI from observing for an entire year. However, the reasons for not observing could also be caused by weather or equipment difficulties. On average these occur more than 10 times as often as PA restrictions of all types.

2. Impact on Operations

Since approximately mid-January 2010, the LCH has been using a 0.1 degree laser exclusion cone half angle for Keck. Table 5 shows the significant reduction in standard PA closures that occurred following the start of Spiral 3 calculations when UPLs were introduced and the laser system exclusion cone half angle was reduced over time in several steps from the initial default value of 2.5 degrees to the final value of 0.1 degrees. The table is based on PA closures for a consistent set of 21 calibrations stars used by

[129] R. Campbell et al., "AO Operations at the W. M. Keck Observatory," *SPIE* 7016, 2008.

Keck, which considers them a good representation of PA closure statistics. At an average of about 1.8 closures per night, with each lasting on average about 20 seconds for a total laser closure time of about 0.5 minutes (0.01 hours/night), Keck does not now consider standard PA to be a significant issue.

Table 5. Reduction in the impact of standard PA closures over time.

Date	Average Number of Closures per Night	Average Minutes for Each Closure	Average Total Minutes of Closure per Night
Early December 2007	10	3.4	34
Late December 2007	6.6	2.0	13.2
Late December 2009	4.1	1.6	6.6
Late January 2010	1.8	0.3	0.5

There are apparently very few requests for ToO at Keck, and it handles them on an individual basis. This topic was mentioned by Keck only after I brought it up. Between November 2009 and May 2010 Keck had only one request for a ToO using an LGS, and that occurred in early May for a relatively slowly decaying target. For this event the time between the initial request to Keck and the sending of the PRM to the Space Battle Manager was about 14 hours. In the classical observing scheme the observing PIs generally have to give permission for the use of their preplanned observing period, and a portion of this time was devoted to this activity. Keck estimates that preparing the PRM took 1–2 hours and the Space Battle Manager responded in about 2 hours. A telephone call by Keck to alert the SBM to the presence of the PRM was not made, which might have delayed the response. There was about 15 hours of time between the receipt of the laser closure windows, which permitted observations of the object, and the beginning of actual observations. In this instance, adherence to the PA restrictions did not affect the scientific results. Keck feels that a 30-minute turnaround time by the LCH would satisfy their needs—even 1 to 2 hours would satisfy many of their requirements.

At this time the primary concerns of Keck are blanket closure events since these can potentially have a severe impact on specific individual PIs. Because Keck uses a classical observing methodology where the PI decides on the observing schedule for a given night, a significant portion of the actual operational impact of blanket closures is on the PI rather than on the Keck staff. The impact on Keck staff is the necessity to shutter the laser and perhaps make plans to run the laser when in the end it is not used.

Table 6 shows all blanket closure events for Keck from January 2009 to June 2010. In 2009 there were 10 events on 6 nights for a total of 7.4 hours. With 113 LGS observing nights with about 1130 total LGS observing hours, this gives in 2009 about 4 minutes (0.07 hours) per night or about 0.7% of the total observing time lost due to blanket closures. This compares with about 0.5 minutes per night lost to classical PA. In 2009 Keck lost about 0.8% of LGS observing hours to blanket closure and classical PA compared with 0.4% before the implementation of Spiral 3.

Table 6. Blanket closure durations at Keck.

Date (UT)	Duration (Hours:Minutes)
January 23, 2009	2:28
June 9, 2009	0:32
September 23, 2009	0:16
September 23, 2009	0:08
September 29, 2009	0:10
September 29, 2009	0:12
December 9, 2009	2:27
December 9, 2009	0:14
December 15, 2009	0:15
December 15, 2009	0:40
January 27, 2010	10:00
March 2, 2010	4:20
May 21, 2010	0:02

From January 2010 to June 2010 there were three events on three separate nights for a total of 14.4 hours, and they caused some concern at Keck. The first two occurred during the first 60 days of the year. One lasted the entire night (about 10 hours), and one lasted over 4 hours, and both were much longer than any time during the previous year. There were 61 LGS observing nights with about 610 observing hours in the first half of 2010. The average time lost per night in this time period due to blanket closures was about 14 minutes (0.23 hours), or about 2.4% of the total possible observing time. The number and duration of these blanket closures can be compared to weather effects. From 2004–2006, 18 entire LGS nights, an average of 6 entire LGS nights a year, were lost to weather.[130]

The instructions to close for the entire night came only about 10 minutes before observations were scheduled to start, which considerably disrupted the planning and observing process. Although on average blanket closures have only a small effect on overall operations, this one had a major operational effect on that night for that particular PI whose planned LGS observing was completely prevented. Observations with a natural guide star or without adaptive optics were still possible. In some cases the observatory

[130] D. Le Mignant, "Lessons Learned for Keck LGS Operations Weather Impact, Efficiency &Science Operations Model," *KAON* 463 (February 2007).

has been warned by the SBM to expect a blanket closure several hours before it was to occur. This type of information is useful to the PI and a warning as far in advance as possible could be very helpful.

Table 7 compares the yearly average Keck observing time in hours per LGS night lost to various factors. The last column is the total yearly average number of hours per night that could have been used for observing. Spiral 3 began in November 2007, a month after FY2008 began. The change to 0.1 degrees laser exclusion angle occurred during FY2010, which was still ongoing when this report was written. While the time lost to LCH restrictions is always very small when compared with the total due to all other effects, there is a noticeable increase in FY2008 following the implementation of Spiral 3. Before Spiral 3, the effect on operations due to LCH averaged about 0.06 hours (3.6 minutes) per night. These were caused by blanket closures and not classical predictive avoidance. For the first half of 2010, the average time lost per night was 0.01 hours due to standard PA and 0.23 hours due to blanket closures. This is about 2.4% of the total observing time and about four times the average value before the change to Spiral 3. This is still very small compared with the total observing time lost to all factors in FY2009 (about 62%), which is dominated by the 25% lost to weather and 25% lost to routine overhead.

In Table 7 LGS Science (also known as open shutter time) includes some science target acquisition overhead (centering the object on the science array, checking saturation, etc.), any calibration data recorded during the night, as well as any LGS science data taken under marginal conditions. Data acquired on natural guide star backup targets is not included in this time. Routine overhead includes time spent in setting up the systems. Faults occur when systems are not operable.[131]

Laser traffic control refers to time lost due to an adaptive optics laser interfering with the observations of another observatory. Initially, the non-laser observatory had priority, but there has been movement to giving the first observatory on target priority irrespective of laser use.

[131] D. Le Mignant, "Lessons Learned for Keck LGS Operations: Weather Impact, Efficiency & Science Operations Model," *KAON* 463 (February 2007).

Table 7. Keck observing time loses in hours per night.

Year	Weather	Laser Traffic Control	Aircraft	LCH Restrictions	Laser Faults	Adaptive Optics (AO) Faults	Other Faults (Instruments and telescope)	LGS Science	Routine Overhead (instruments, telescope, AO)	Total
FY2005	1.89	0.14	0.02	0.09	1.33	0.29	0.33	2.26	3.73	10.07
FY2006	2.56	0.11	0.00	0.00	0.62	0.63	0.19	2.84	2.99	9.94
FY2007	2.29	0.07	0.01	0.08	0.14	0.89	0.12	3.18	3.24	10.01
FY2008	3.10	0.08	0.01	0.17	0.04	0.37	0.27	3.31	2.67	10.02
FY2009	2.51	0.06	0.00	0.10	0.26	0.30	0.18	3.71	2.69	9.82

Keck considers the two long blanket closures in early 2010, which together gave a closure time of about 14 hours, to be unusual. For this reason there was considerable concern when they first occurred that they might have been caused by some change in LCH procedures that would produce many more events like them. LCH procedures were not changed, however. It is not possible to predict with certainty the future likelihood of such events, but only one event (about 2 minutes) has occurred in the 5 months since the last long one on 2 March 2010 (about 4 hours). In 2005, all the time lost by Keck was due to blanket closures, which totaled about 4 hours.[132]

Keck estimates that about 0.15 staff year is devoted to adhering to the LCH PA restrictions. This is very small compared with the over 100 staff-year effort at Keck.[133] It is also small when compared with the approximately 8 staff-years allocated to just adaptive optics operations.[134]

The OSIRIS instrument is the main sensor used for laser guide star observations, and it is used approximately 80% of the time on laser guide star nights. Data is taken in a maximum of 15-minute blocks. If the laser is shuttered during one of these blocks, the investigating astronomer can decide if and how to use the data. As a result even a brief laser shutdown of a few seconds could in principle “contaminate” a maximum of 15 minutes of data.

As already noted in Section 6.D.2, both Gemini and Keck reported that occasionally they would receive what they considered unusual responses from the LCH, which sometimes affected operations or caused extra work to resolve them. Since these were often one-of-a-kind events, I was usually not able to verify them or to understand the actual cause of most of them. These included what the observatories called “typographical errors” on the part of the LCH (although there should have been no manual typing of data at the LCH) that appeared to affect closure windows, a laser clearance list that included only a zenith position for the laser, a target that was closed to LGS use for all of 4 consecutive nights, and closure windows on targets when they were below the horizon.

3. Impact on Personnel

Keck uses the classical observing system. A significant impact of the LCH restrictions can be on the PI. In preparing for LGS observing sessions, Keck personnel send the PRM and receive the laser closure information from the LCH and SBMs. They

132 Mauna Kea Laser Guide Star Technical Working Group, “Working Group Meeting,” 22 November 2005, http://www2.keck.hawaii.edu/optics/aodocs/KAON384.pdf.

133 “W. M. Keck Observatory Annual Report 2009,” http://keckobservatory.org/images/files/Keck2009_annual_report.pdf.

134 R. Campbell et al., “AO Operations at the W. M. Keck Observatory,” *SPIE* 7016 (2008).

also interact with the LCH in regard to registering lasers and developing procedures for coordinating activities.

The principal investigator is typically either a visiting Ph.D.-level astronomer or a Ph.D. student who is doing scientific observations with a Keck telescope. If a PhD student, the thesis advisor would often have some involvement. The actual observing is done remotely at night in a low-altitude office environment. Once given time on the telescope, the investigating astronomer controls the viewing schedule. This person would normally receive the LCH predictive avoidance clearance windows the day before the observing night. As a result of sleep schedules to accommodate the night observation timetable, Keck estimated that incorporation of the clearance windows needed to be done during an approximately 12-hour period, when final preparations were being made for observations. Keck roughly estimated that this additional work due to LCH restrictions might take as much as an hour during a time when the PI is involved with final observing planning and preparations. Any decisions on how to deal with unanticipated blanket closures or targets of opportunity that may arise during the observing period are made by the investigating astronomer. I spoke with an experienced PI from the University of Hawaii who was familiar with observing procedures at Keck, and this person said decisions related to the LCH were no more stressful than those related to weather, which can also somewhat unpredictably affect observations. A less experienced PI such as a graduate student might find this activity more stressful.

The Keck observing assistant works at the telescope and basically follows instructions from Keck headquarters. This work takes place at the Mauna Kea summit and lasts all night, so it is physically and mentally demanding. The additional workload and stress due to LCH restrictions is rather small, however, and is primarily related to making sure that the laser is shuttered when required.

The Keck support astronomer is a Ph.D.-level astronomer who works in office-type conditions at the low-altitude Keck headquarters building during an observing run. This astronomer is physically near the PI astronomer. The additional workload and stress due to LCH restrictions is relatively small, primarily related to ensuring that the laser is shuttered when required and making any changes in the telescope observing plan as requested by the investigating astronomer.

Keck estimates that in total approximately one-eighth of a staff person's time over a year is devoted to LCH activities. Since there are about 100 people supporting the two Keck telescopes (although only one is currently used for laser guide star observations) and about 8 directly involved with adaptive optics, this is a very small additional effort. Most of this effort is done in a standard office environment. It involves formatting the planned observing targets from the PI for transmittal to the LCH for predictive avoidance calculations and putting the closure information after possible schedule changes by the PI into the automated laser propagation system. This work does not require any significant decision-making in regard to integrating the LCH closure windows into the PI's observing scheme. The observing information is supplied to the LCH about a week before the monthly laser guide star period begins, and the LCH returns the closure information about 24 hours before each observing night.

4. Conclusions Concerning Current Keck Conditions

Keck stated that the classical PA restrictions and blanket closures before Spiral 3 were not a problem. From the beginning of 2010, when the 0.1-degree laser system exclusion cone half angle went into effect, Keck has felt that conditions have improved enough that limitations due to classical PA were no longer a significant issue. ToO are not a major concern at Keck. Although not yet tested, total PA-related response times of about 90 minutes, including preparing a PRM, LCH turnaround time and incorporating any laser closure windows, may be expected. This time may not be the limiting factor since other considerations, such as receiving permission from the scheduled PI, may be important.

The main concern of Gemini is blanket closures. Since they occur on about 5% of LGS nights and usually last less than about 40 minutes, they have a small effect on average over a year. The downtime due to blanket closures is more than an order of magnitude smaller than that due to weather and other causes. However, since a typical PI might observe only on a few nights a year, blanket closures could have a significant effect on the observing plan for a particular astronomer on a particular night. Although it has never happened, Keck was particularly concerned about the effect of a significant blanket closure on a graduate student working on a thesis who had limited access to the telescope. This same type of concern would also appear to be applicable to unexpected equipment failures or weather, which may be considered in planning thesis work or observation requirements. Keck did not know of any examples where LCH restrictions resulted in the inability to publish a paper or significantly affected the content or quality of a paper.

There does not appear to be anything Keck can do to efficiently reduce the effect of blanket closures. As evidenced by their small number compared with the total number of satellite launches and maneuvers, the LCH is already providing significant screening of these kinds of events.[135] Any changes in space event number or duration would have to come from changes in internal DOD procedures and policies.

Taken as a whole, the additional staff time and cost to Keck due to PA is rather small. However, the additional effort due to PA is concentrated on only a few members of the observatory staff who primarily interact with the LCH and SBMs, as well as on the PIs. This additional work, particularly for the PIs, often occurs under significant time

[135] See http://spaceflightnow.com/tracking/launchlog.html.

constraints when these individuals have other responsibilities. Keck PA procedures are already efficient, and there are not obvious ways for Keck to further reduce the impact of PA while following current LCH procedures.

Under certain conditions, the Keck laser could produce permanent damage to certain satellite components, particularly large-aperture visible imagers, although it is not evident that there would be a significant effect on the operational capability of the satellite even if laser-induced damage occurred. Under present conditions, the probability of the Keck laser actually causing damage to current satellites is extremely small. With current satellite numbers, the Keck II laser will illuminate a possibly susceptible satellite about once every 50 years. The probability of actually damaging a satellite given that it is illuminated is no more than about 1×10^{-4} and probably significantly lower.

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14. ABSTRACT
This document examines the impact of the Department of Defense Laser Clearinghouse predictive avoidance procedures on the science, operations, and personnel of two civilian astronomical observatories, Gemini North and Keck II. These procedures, which are mandated by the National Science Foundation for observatories it supports, are designed to protect satellites from lasers used by the observatories to produce an adaptive optics laser guide star for increased imaging resolution. The two observatories were chosen since they receive support from the National Science Foundation and they represent two different observing paradigms. Gemini primarily uses a queue observing mode, while Keck uses the classical observing model.

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