Workshop on Mitigating the impact of Satellite Constellations on Astronomical Laser Propagation

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Summary

A workshop was held at Vandeberg Space Force Base on 12 and 13 April 2023 to bring together interested members of the US community to address the problem of the propagation of lasers by the US astronomical community to generate laser guide stars (LGS) for adaptive optics (AO) observing. This problem is caused by both the increasing number of low Earth orbit (LEO) communication satellite constellations (SATCONs), which now account for over 50% of the active satellites in orbit, and the fact that US astronomical observatories are required by the National Science Foundation to follow the Department of Defense (DoD) Laser Deconfliction policy which exists to protect satellites from inadvertent illumination and subsequent ‘damage’.

This workshop brought together representation from: the astronomical laser propagation community; US Space Command, in the form of the Laser Clearinghouse (LCH) and the Air Force Research Laboratory’s Satellite Assessment Center (SatAC); representatives from both the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA); and representation from the SATCON industry.

While several options for mitigation were discussed, by the close of the meeting, it was concluded that the best approach would likely be to have the astronomical lasers reclassified from the existing worst possible case, Category III, to either Category I whereby the lasers do not present any threat to the satellites or to Category II where the laser launch coordinates and laser parameters are circulated to the satellite community to enable them to avoid the lasers. In order to change the classification, a Probabilistic Risk Assessment (PRA) will need to be conducted of the astronomical lasers which will then be provided to the LCH to facilitate coordination. An analysis, for example by SatAC, will take a few months, depending on which LGS systems they are looking at and will likely require external funding. The latter is being looked into by Program Officers at the Division of Astronomical Sciences (AST) at the NSF.

1. Introduction — Laser Guide Stars

The astronomical community propagates lasers in order to create an artificial reference beacon, also known as a laser guide star (LGS) for adaptive optics (AO) observing. The observation of this LGS serves to measure the instantaneous atmospheric turbulence for which the AO system compensates.

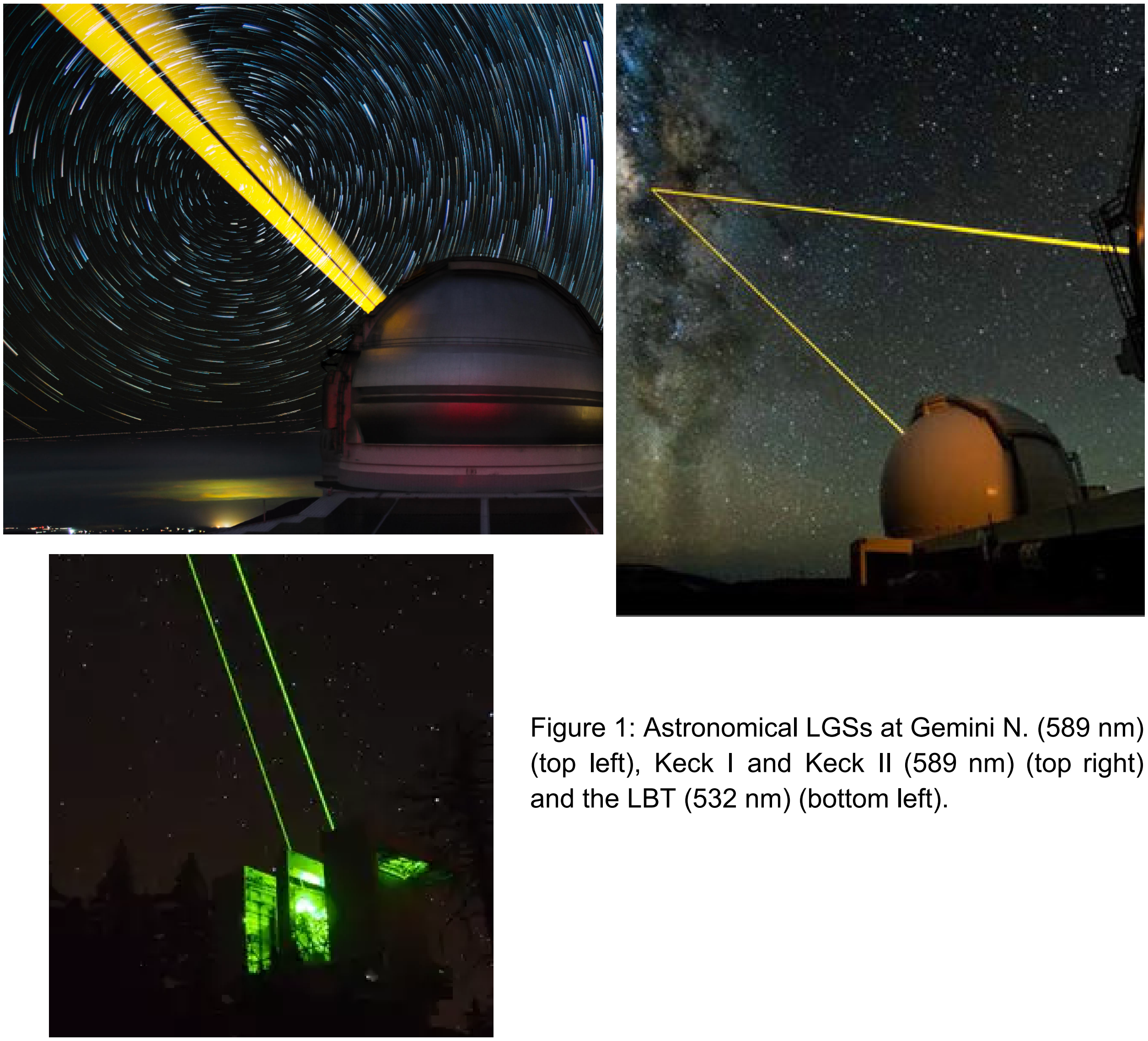

Figure 1: Astronomical LGSs at Gemini N. (589 nm) (top left), Keck I and Keck II (589 nm) (top right) and the LBT (532 nm) (bottom left).

By the late 1990s LGSs were being developed for astronomical AO systems, the first being demonstrated at the Shane 3-m telescope at Lick Observatory on Mt. Hamilton, CA. The field has matured considerably in the last couple of decades, with LGSs on both Keck 10-m telescopes, on the Gemini N. & Gemini S. 8-m telescopes, on both sides of the Large Binocular Telescope (LBT) and on a number of smaller-aperture telescopes (see figure 1.) The full list of US LGS systems is shown in Table 1. Note that it also includes the two US Extremely Large Telescope (ELT) projects which have yet to be completed.

Table 1: US LGS Propagating Telescopes

Telescope	Location	Laser Wavelength (μm)	Laser Power RMS (W)	Laser Peak Pulse Power (W)
Gemini N. — Altair Gemini N. — GNAO*	Maunakea, HI, USA	0.589 0.589	25 44	-
Gemini South	Cerro Pachon, Chile	0.589	50	1.88E03
Keck I	Maunakea, HI, USA	0.589	25	-
Keck II	Maunakea, HI, USA	0.589	25	-
Large Binocular Telescope	Mt. Graham, AZ, USA	0.532	2 x 46.5	2 x 3.88E04
Shane (UCO/LICK)	Mt. Hamilton, CA, USA	0.589	15	7.7E03
UH88 (Robo-AO)	Maunakea, HI, USA	0.355	13	3.8E04
USNO (Robo-AO)	Flagstaff Station, AZ, USA	0.355	13	3.8E04
SOAR	Cerro Pachon, Chile	0.355	10	2.94E04
Subaru	Maunakea, HI, USA	0.589	20	-
TMT*	Maunakea, HI, USA	0.589	60 — 160	-
GMT*	Las Companas, Chile	0.589	120	-

* Systems designed but yet to be implemented.

There are two types of LGS currently in operation. The first of these are the Sodium Beacons which take advantage of the mesospheric sodium layer at an altitude of 85 km to 105 km where the sodium is deposited by incoming meteors. These operate at 589 nm (orange) with resonance scattering creating a laser spot for use as an LGS. The second type of LGS are known as Rayleigh beacons, which typically operate at a range of 8 km to 15 km using Rayleigh backscatter to create the guide star with range gated pulsed lasers. These two most common astronomical systems operate at 532 nm (green), such as the LBT in figure 1, and in the ultraviolet (UV) at 355 nm. The advantage of the UV lasers is predominantly operational as these are ‘invisible’ to aircraft cockpits, i.e. they do not transmit through the cockpit windows.

The advantage of the Sodium Beacons is that they sample more of the turbulent atmosphere than the Rayleigh Beacons, thereby suffering from less focal anisoplanatism, which is more important for larger apertures. A natural guide star (NGS), i.e. using an astronomical point source (star) as the AO reference, samples the column of atmosphere above the telescope, whereas an LGS samples the cone from the aperture to the distance of the LGS meaning that compared with the NGS, there is unsensed atmospheric turbulence. This is what is known as focal anisoplanatism (see figure 2).

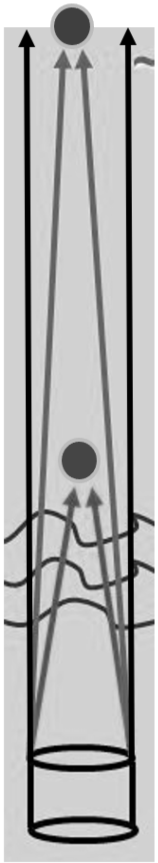

Figure 2: Focal anisoplanatism using LGSs. The solid black arrows indicate the atmospheric column as sampled with an NGS compared with the two LGS cases, the Rayleigh Beacon being the lower spot and the Sodium Beacon being the upper spot.

1.1. Restrictions on Laser Propagation

Propagating lasers requires laser safety protocols to be in place at the telescopes as these are not eye-safe lasers and the observatories have to follow OSHA standards. Additionally there are a number of operational protocols which have to be followed to be in compliance with Federal and other Government regulations as well as mutual laser operation on sites with multiple laser propagating telescopes. Those sites include Maunakea, which has four telescopes, Keck I, Keck II, Gemini N., and Subaru and with RoboAO coming on-line at the UH88.

1.1.1. Aircraft Safety

All laser propagating observatories are required by their local civilian aviation agencies, e.g., the FAA in the US, to prevent inadvertent illumination of aircraft cockpits for safety reasons. As noted above the UV lasers do not penetrate the cockpit windows and are safer to use but because they are Rayleigh beacons they do not provide the same level of correction as a Sodium Beacon especially for large aperture telescopes (> 4 m).

Initially human aircraft spotters were used but this added significantly to the expense of using LGSs, especially at sites where there is a lot of air traffic, such as Mt. Hamilton, CA, Mt. Graham, AZ, and Cerro Pachón, Chile. However, over the past decade, an aircraft transponder-based system has been developed and successfully implemented at various US observatory sites and it has been approved by the FAA. These are known as TBAD (Transponder-Based Aircraft Detection), originally developed at UCSD[1]. TBAD works by passive detection of omni-directional transponder signals at 1090 MHz from aircraft. These signals include altitude, identity, coordinates, velocity, etc. The location of the aircraft relative to the telescope/laser pointing is determined by the ratio of the signal from a phased array antenna to that of a single antenna element to within 15°.

1.1.2. Laser Traffic Control

Laser Traffic Control (LTC) systems have been developed and implemented at sites with multiple laser propagating telescopes and multiple telescopes with at least one being a laser propagator. This is to prevent contamination of astronomical data by pointing through the laser beam due to Rayleigh scattering in the lower atmosphere as well as LGS wavefront sensor contamination. It is also used to protect a ‘first-on-target’ protocol.

1.1.3. DoD Laser Deconfliction

For historical reference, LGS technology was originally developed by the US Air Force and the Air Force lasers were required to follow the standard Laser Deconfliction Protocol in order to protect satellites from inadvertent illumination and potential damage. This potential impact of ground-based lasers on satellites and other space objects, all classified by the Department of Defense (DoD) as Resident Space Objects (RSOs), is regulated by the DoD to prevent a laser from unintentionally illuminating and potentially causing damage to an RSO and/or its systems[2]. Note that this Laser Deconfliction protocol applies to all DoD lasers in space such as propagation from ground-to-space, space-to-ground, and space-to-space. With the advent of LGS technology for astronomical observations, the National Science Foundation (NSF) followed the DoD protocol whereby observatories are required to submit a number of forms to the Laser Clearinghouse, a branch of US Space Command, detailing (1) the laser specifications and (2) the pointing quality of the laser launch system. Prior to an LGS observing run, the observatories submit a target list to the LCH for clearance windows to propagate. RoboAO, which is an automated observing survey system, uses a different approach for determining closure windows. Instead of using a specific target list defined by the target

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[1] http://www.aircraft-avoid.com/tbad-overview.pdf

[2] https://www.jcs.mil/Portals/36/Documents/Library/Instructions/CJCSI%203225.01B.pdf

coordinates, e.g., Right Ascension and Declination, they break down the sky into ‘tiles’ and the LCH gives windows when a particular tile is not available.

The LCH uses a Predictive Avoidance (PA) algorithm which serves to protect the RSO from inadvertent illumination if they have been evaluated to have sensitivity to the power and wavelength of the laser. The clearance windows for a particular LGS depend upon whether there are any optical sensors which can be ‘blinded’ or ‘damaged’ by laser illumination and this depends upon: (1) the operational laser parameters, such as peak power, wavelength, beam quality etc., along with the satellite’s sensitivities to these parameters; (2) the pointing accuracy of the laser launch system; and (3) the response time needed to shutter the lasers if there were a problem with the laser launch system such as the telescope drive ceasing or running-away. From this a keep-out cone for each laser is determined. A closure window for laser propagation is determined when the satellite enters the keep-out cone which also takes into account uncertainties in the satellite’s orbital parameters. The keep-out cone half-angle sizes vary between 0.1° and 2.5°, depending upon the telescope / laser facility.

The Satellite Assessment Center (SatAC), which is part of the Air Force Research Laboratory (AFRL), is one entity that performs analysis to determine the vulnerability of the satellites to ground-, and space-, based illumination, which the LCH uses to determine which laser systems are potential threats to which RSOs.

2. The Impact of DoD Laser Deconfliction

The impact of the LCH Predictive Avoidance Restrictions on LGS AO astronomy was considered in a report commissioned by the NSF by the Institute for Defense Analyses Science and Technology Policy Institute (IDA/STPI) in 2010[3]. This report considered only the Keck and Gemini LGS systems. Amongst the major findings and conclusions were the following:

- 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.
- The observing time lost by adhering to DoD predictive avoidance procedures is more than an order of magnitude less than the time lost to other factors such as weather and equipment overheads.

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[3] https://www.ida.org/research-and-publications/publications/all/t/th/the-impact-of-predictive-avoidance-restrictions-on-astronomical-observatories

- The DoD predictive avoidance procedure tends to have a more severe impact on DoD laser use than on civilian observatory laser use.

The report also noted that the RSOs mostly at risk from astronomical LGSs are primarily low-orbit, Earth-observing satellites using optical sensors and that 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. It was also noted that the LCH used extremely conservative 'sure-safe' calculations in determining its laser closure periods with the emphasis on RSO protection, i.e., Predictive Avoidance (PA). The IDA report also mentioned that the DoD could consider the use of a more risk-based approach (e.g., a probabilistic risk assessment) which could eventually reduce the impact of LCH restrictions on the observatories. They also encouraged interactions between the observatories and the relevant DoD organizations, such as the LCH, to enable the different parties to better understand each other's operations, purpose, and culture. However, because the impact of following DoD Laser Deconfliction did not demonstrably affect the quantity and quality of the science, it was recommended that there should be no change.

It is important to note that non-US observatories, in particular the European Southern Observatory (ESO), have been and still are propagating lasers for LGSs with no negative feedback from satellite owner / operators.

2.1. Satellite Constellations

On 23 May 2019 sixty Starlink low Earth orbit (LEO) communications satellites were launched, marking the start of a new phase in the industrialization of space. The planned deployment of tens of thousands of artificial satellites offers the possibility of low-cost broadband to even the most remote locations on the planet. However, their presence will impact ground-based astronomy at visible, infrared, and radio wavelengths. This impact has been addressed in a couple of community workshops (SATCON1[4] & SATCON2[5]). This is a significant concern of the astronomical community, such that the International Astronomical Union (IAU) has set up a *Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference*[6] (CPS) involving both the National Science Foundation's (NSF) National Optical-Infrared Astronomy Research Laboratory (NOIRLab)[7] and the Square Kilometre Array Observatory (SKAO)[8].

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[4] https://aas.org/satellite-constellations-1-workshop-report
[5] https://aas.org/satellite-constellations-2-workshop
[6] https://iau.org/news/announcements/detail/ann21039/
[7] https://noirlab.edu/public/
[8] https://www.skaobservatory.org/

According to the Union of Concerned Scientists (UCS) Satellite Database[9], there were ~ 5500 active satellites in orbit as of 30 April 2022. This is an increase of a factor of about three over the ~ 1400 satellites in 2015. Communications satellites comprised 66% of active satellites in 2022, with 21% for remote sensing. Of the total number of satellites in 2022, around 63 percent were operated by US-based entities, including government and commercial operators. Figure 3 shows the cumulative increase in the total number of active satellites from the launch of Sputnik in 1957 until 2021[10]. The increasing trend shows a near-exponential growth around 2019 with the launch of the first Starlink satellites. It is interesting to note that by May 2021 the Starlink satellites accounted for 50% of all satellites at LEO, a number which continues to increase.

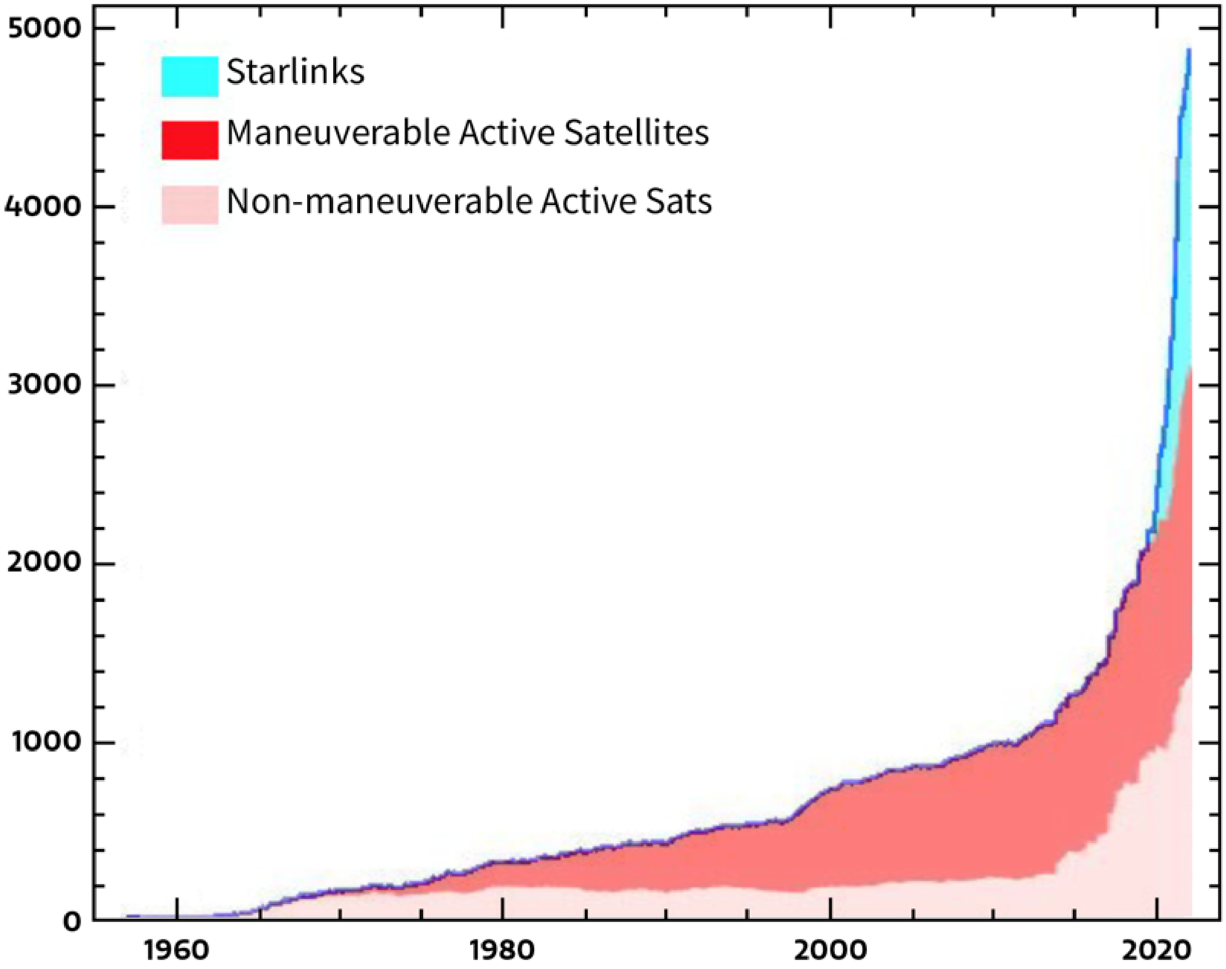

Figure 3: Cumulative increase in the number of active satellites between 1957 and 2021 (IAU CPS).

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[9] https://www.ucsusa.org/resources/satellite-database
[10] https://planet4589.org/space/stats/stats1.html

The impact of these satellites on astronomy in general at optical and radio wavelengths was considered in a JASON report[11] prepared on behalf of the National Science Foundation (NSF) and the Department of Energy (DoE). This also included a section on the impact on LGS propagation due to the DoD Laser deconfliction policy. Taking into account the 500,000 satellites proposed in regulatory filings in 2020, the JASON report to the NSF estimated that the number of closure windows could increase by up to two orders of magnitude. If this proved to be the case it would significantly impact LGS operations of current and future telescopes systems including both US ELT candidates, the Thirty Meter Telescope (TMT) and the Giant Magellan Telescope (GMT), which are planning to use LGS AO on a regular basis. They would find themselves at a competitive disadvantage compared to their European/ESO counterpart.

2.1.1. Starlink Satellite Constellations and Laser Deconfliction

Since the Starlink satellites were launched, the closure windows for astronomical LGSs increased by approximately a factor of two and the Starlink satellites accounted for between a quarter and a third of all astronomical LGS closures based on the target lists submitted by the major observatories, in particular Gemini and Keck, to the LCH.

Before discussion of the number of closure windows it is important to consider what happens in a closure window. Prior to the closure the science observation has to be paused and the AO loop has to be opened or paused and then the laser is shuttered. And after the closure event the laser shutter is opened, the laser return has to be verified on the LGS wavefront sensors and the AO loop is closed. The science observing then continues. The typical closure times do vary and are both observatory and AO system dependent. For satellite closure events, this can range between 30 seconds and 120 seconds per event.

Figure 4 shows the number of LCH closure events for four LGS propagating telescopes from 2012 until early 2023. All four use sodium-layer LGS systems operating at 589 nm and these numbers are based on the lists of routine engineering targets submitted to the LCH for each laser run, the number of which is invariant for each telescope. The same trend is obvious for all four telescopes, with the number of closure windows beginning to increase after May 2019, as shown by the red dotted vertical line, when the first Starlink satellites were launched, with a significant increase in closures in 2022 by factors of 2–5, followed by a fall-off after the blue dotted line which indicates the SpaceX Waiver used by LCH for the Starlink satellites as described below following the execution of a Coordination Agreement with NSF.

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[11] https://www.nsf.gov/news/special_reports/jasonreportconstellations/JSR-20-2H_The_Impacts_of_Large_Constellations_of_Satellites_508.pdf

During 2022 coordination discussions between the LGS propagating community, the NSF Electromagnetic Spectrum Management (ESM) Office, and SpaceX (the Starlink Owners), it was found that the SpaceX representatives were willing to opt-out or waive LCH protection based on an analysis of the potential impact of LGS laser systems on their satellite systems. It was confirmed that the SpaceX satellites had been automatically added to the Master Protect List. The LCH informed us that the satellite operator could submit a written request to the LCH to be removed from Laser Deconfliction. SpaceX, having both evaluated the LGS lasers and determined that there was an extremely small risk, submitted a request which was approved by the Commanding Officer and implemented at the beginning of December 2022. This corresponds to the blue vertical line in Figure 4. It is important to note that this waiver is included in the executed Coordination Agreement between the NSF and SpaceX[12]. This type of waiver is promising as an example of what can serve as the basis for Coordination Agreements between the NSF and other SATCON companies which will operate in the US.

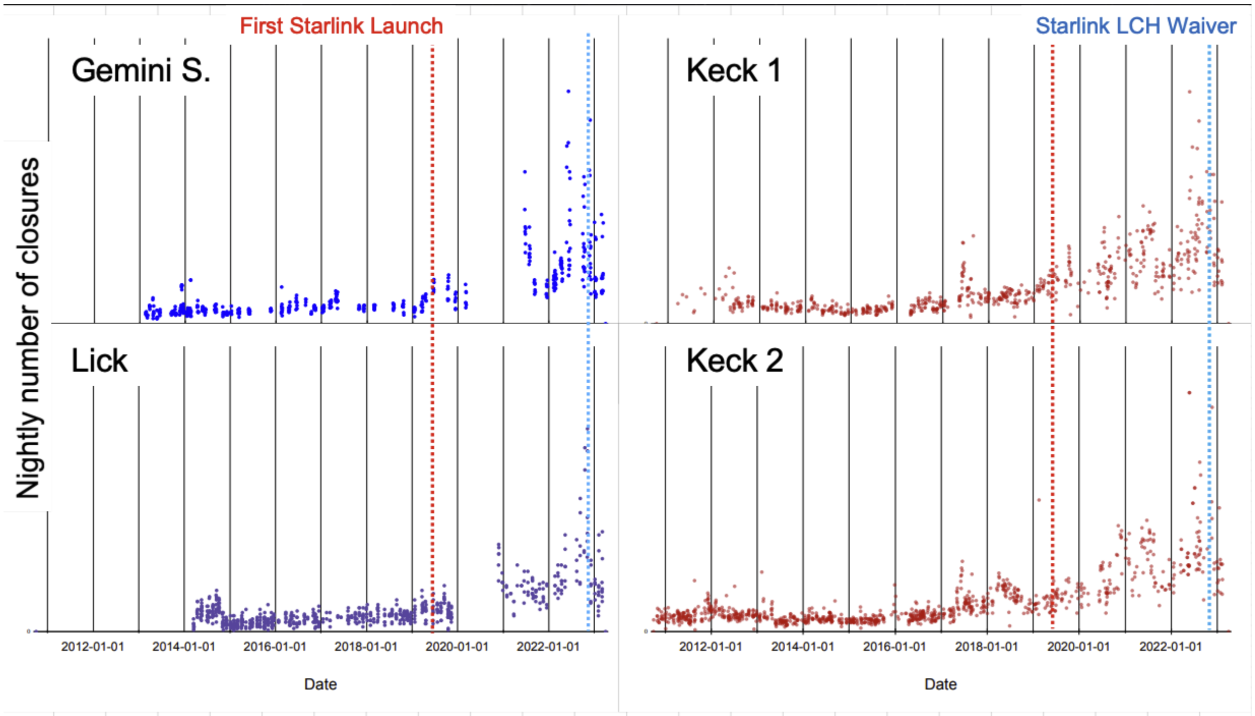

Figure 4: Historical number of engineering target closure windows for four different telescopes covering 2012 to early 2023. The number of closures per telescope depends upon a number of variables, such as the laser power, the telescope's location, the size of the keep-out cone etc.

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[12] https://new.nsf.gov/news/statement-nsf-astronomy-coordination-agreement

The vertical axes of these four panels have been normalized to illustrate the common trend. The number of closures per night for each of these four telescopes is given in Table 3 below.

2.2. Minimizing the Impact of Future Satellite Constellations

As noted above the NSF Coordination agreement with SpaceX included the implementation of a Waiver for Laser Deconfliction. NSF noted during the workshop they intend to use this approach in future Coordination agreements with other SATCON companies planning to do business within the US, and in fact, OneWeb has already committed to performing the calculation and considering requesting a waiver.

However, there are many companies that have plans to launch large numbers of SATCONs within the next decade which will not fall under the NSF Coordination Agreement. So a solution to minimize the impact of those SATCONs, i.e, the SpaceX Waiver used by the LCH, will not be applicable and a more long-term solution is required.

To this end a Workshop was held at Vandenberg SFB near Lompoc, CA on 12–13 April 2023. This was hosted by the LCH and sponsored and organized by NOIRlab in conjunction with the LCH. The goal of this workshop was to identify and prioritize strategies and options for mitigating the impact of the low Earth orbit (LEO) satellite constellations (SATCONs) on the propagation of astronomical lasers for US and US-based Observatories. This hybrid (in-person and virtual-Zoom) Workshop, Mitigating the impact of Satellite Constellations on Astronomical Laser Propagation, had attendees (see Appendix 2) representing the following communities:

1. US Astronomical LGS Propagators
    a. Including Keck, Gemini, Lick, TMT, GMT, Subaru, CalTech, …
2. US Astronomical Community
    a. NOIRLab, US-ELT, IAU/CPS
3. DoD Laser Deconfliction Representation
    a. US Space Command — Laser Clearinghouse
    b. Air Force Research Laboratory — Satellite Assessment Center
4. SATCON Community Representatives
    a. SpaceX
    b. Satellite Industry Associates
5. Relevant Federal Agencies
    a. NSF
    b. NASA
    c. Office of Space Commerce (Dept. of Commerce).

The Workshop featured presentations on the following topics:

1. General Impact of Satellites on Astronomy
2. Adaptive Optics and Astronomy
3. Laser Guide Stars and Adaptive Optics
4. Laser Deconfliction Policy
5. Impact of Laser Deconfliction on Astronomy
6. Commercial Satellite Company Overview
7. Roles of Government and other Agencies
8. Identification of follow-up activities

The presentations introduced the background information presented above and generated a number of discussions centering on general mitigation strategies for US LGS systems, for the increasing number of non-US SATCONs. The NSF only implements Coordination Agreements with certain SATCON operators operating within the US, so the Waiver approach will not more broadly apply to SATCON operators globally. An example of these would be the Chinese, who are proposing ~14,000 commercial communication satellites and 1354 optical remote-sensing satellites. There are also proposed constellations with thousands of satellites from Europe, South Korea, Rwanda, and Canada. Table 2 breaks down the number of proposed next-generation commercial satellites by country[13].

As can be seen, the majority of these satellites, ~ 100,000, are from Rwanda. Whether that will be the case remains to be seen for a number of reasons which include access to the launch vehicles, and access to financing. But if we take this to be the worst possible case, then it's likely that we will have ~ 120,000 satellites not covered by the NSF Coordination agreement. If the astronomical LGS telescopes have to cease laser propagation for these satellites, then there will be a significant impact. A simple calculation using the closure rates per satellite from the data in Figure 4 coupled with an average closure window length of one minute yields the total time lost as shown in Table 3[14]. This assumes a ten-hour observing night on average. As can be seen, this prediction implies that in the worst possible case LGS AO will become unsustainable without SATCON-LCH Mitigation. Even if we drop the US SATCONs from the list, assuming that they are covered under the NSF Coordination agreement, the large number of non-US satellites, dominated by the 100,000 from Rwanda, means that it does not make a significant difference. However, by considering only the Chinese satellites, then there is a significant drop to 10% or less of an average night being lost to

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[13] Therese Jones — Satellite Industry Associates.
[14] Warren Skidmore (TMT) — private communication

SATCONs. The general consensus is that the Chinese satellites have a higher launch potential. Note that these numbers do not take into account the shuttering due to non-SATCON satellites.

Table 2: Total number of proposed next generation satellites.

Company	Total # of satellites proposed for next gen	Total proposed	Type	Country	Type
E-Space	100000	327000	Comms	Rwanda	Commercial
SpaceX	19500	41998	Comms	USA	Commercial
Astra	40	13620	Comms	USA	Commercial
Guowang	12992	12992	Comms	China	Commercial
Kuiper	3236	7774	Comms	USA	Commercial
OneWeb	6372	6372	Comms	UK	Commercial
Boeing	5789	5789	Comms	USA	Commercial
Lynk	10	5000	Comms	USA	Commercial
Stellar	2484	2484	Comms	France	Commercial
Hanwha Systems	2000	2000	Comms	South Korea	Commercial
Hughes	1440	1440	Comms	USA	Commercial
Telesat	298	1373	Comms	Canada	Commercial
Spinlaunch	1190	1190	Comms	USA	Commercial
SatRev	50	1024	Optical	Poland	Commercial
Galaxy Space	1000	1000	Comms	China	Commercial
Total proposed satellites, constellations > 10 sats (80 constellations in total)	~162000	~437000			

Table 3: Closure windows impact with the future SATCONs (~ 2040) shown in Table 2.

Telescope	**Averaged closures / night / satellite**	**Closures / night**	**Hours lost / night**	**Closures / night**	**Hours lost / night**	**Closures / night**	**Hours lost / nights**
		All Satellites		**Non-US Satellites**		**Chinese Satellites**	
Gemini S.	0.0044	709	11.8 (total loss)	524	8.7 (87%)	61	1.0 (~10%)
Lick/Shane	0.0036	589	9.8 (~98%)	436	7.3 (~73%))	51	0.8 (~8%)
Keck I	0.0019	304	5.07 (~50%)	225	3.8 (~38%)	26	0.4 (~4%)
Keck II	0.0018	291	4.86 (~50%)	215	3.6 (~36%)	25	0.4 (~4%)

2.2.1. Mitigation Strategies

So what mitigation techniques are possible? The following mitigation strategies were discussed:

1. Company Waiver
   As mentioned above, this can be applied to those SATCON companies doing business within the US but the NSF has no leverage over non-US companies. There is no guarantee that any foreign company or Government agency would voluntarily waive LCH protection, even assuming that they knew about it in the first place. This is the primary reason why we need to look for an alternative long-term solution. It is possible that we could work with some countries who have a large astronomical community which currently use or plan to use LGS via the IAU CPS but this is still not guaranteed.

2. An ‘Opt-In’ Protocol
   According to the Laser Deconfliction office this is not possible, given the process for automatically including satellites on the Protect List.

3. Satellite Hardware Design Modifications
   A relatively simple solution in theory would be to have the SATCON companies install protection for their optics from the typical lasers being used. This would involve the installation of notch filters for 355 nm, 532 nm, and 589 nm. However, this would involve some fundamental redesigns of the optical paths in the satellite systems with some cost involved and as for item 1 would require voluntary participation from the SATCON companies. Thus it is not realistic.

4. Laser Deconfliction Reclassification

   One approach which was discussed at length during the workshop was the Laser Deconflicture procedure itself. It has been mentioned above that a Predictive Avoidance (PA) algorithm currently used to determine which satellites are at risk from which lasers is designed to prioritize the protection of satellites from inadvertent illumination. The 2010 IDA Report mentioned that the DoD could consider the use of a more risk-based approach to inadvertent illumination of satellites, taking into account both the probability of inadvertently illuminating a satellite and the probability of any damage (transient or permanent) which could be caused by that illumination. If such a scheme were implemented, the IDA analysis suggested that it could reduce the impact of LCH restrictions on the observatories.

   a. Probabilistic Risk Assessment

      The 2023 revision, CJCSI 3225.01B, Procedures for Management of Illumination of Objects in Space by Lasers instructs that a Probabilistic Risk Assessment (PRA) be implemented for Laser Deconfliction and defines the PRA as follows:

      An analysis to estimate risk by computing real numbers to determine what could go wrong, how likely is it that something will go wrong, and what the consequences would be if something did go wrong. Specific to this issuance, PRA is a quantitative analysis of the potential illumination of, and effect on, RSOs (e.g. satellite) by specific laser systems or activities. The analysis shall utilize reasonable expectation standards and a probabilistic approach. Laser categorization and subsequent risk reduction measures shall be based on this assessment.

      At the workshop, the AFRL representatives from the Satellite Assessment Center explained that this risk assessment analysis comes under their purview and that they are in the process of transitioning the geometric-only PA towards a full PRA.

      In order to do this, their analysis uses the laser, atmospheric and satellite information as inputs to a Monte-Carlo simulation which looks at a number of possible scenarios to calculate the probability of damage. This damage can be to (1) optical sensors, (2) non-optical sensors, and (3) eye safety for manned missions. The different scenarios include (1) when the satellite is looking at a laser, (2) when the satellite is inadvertently illuminated, (3) the atmospheric effects, and (4) when the irradiance exceeds a damage threshold. An estimate of the risk of damage is obtained by taking the collective number of laser operations over a period and the probability of damage events to create a Poisson distribution.

In order for them to perform the PRA for any of the astronomical lasers, the community is required to submit the laser information as laid out on their custom form as well as the location of the laser launch system in order to evaluate the atmospheric effects (see Appendix 2).

The output from their analysis typically consists of a 50–60 page report which comprises the following information:

1. Executive Summary
2. Introduction
    a. Overview – how we do the study
    b. Background – (history of PRA)
    c. Methodology (Overview) – explains probabilistic factors used to determine probability of illumination and/or damage
    d. Caveats – any known assumptions with the current methodology
3. System Characterizations & Models Used
    a. System – laser system(s)
    b. Atmosphere – location of laser system(s)
    c. Beam Specifications – various inputs from form
    d. Satellite Population – optical and non-optical payloads – detailed information for satellites on orbit/payloads of each satellite used for PRA simulation
4. Results
    a. Simulation Scenarios/raw results
    b. Astronaut Eye Safety – manned missions – provided by the American National Standards Institute (ANSI); provided by report requestee
    c. Total Risk – results (2 years) posed by laser system using the atmosphere for each location
5. Conclusions
6. References

Appendix
Acronyms
Completed Laser Information Form

Figures
Tables

This report can then be submitted to the LCH for a re-evaluation of the classification of the lasers. The current categories are:

- **Category I:** This is the lowest risk category and applies to lasers which pose no risk to satellites and therefore no requirement to follow Laser Deconfliction.
- **Category II:** This is a medium risk category where the risk of inadvertent illumination is no greater than other nominal flight risks. In this case the LCH notifies Satellite Owners of a Potential Hazard.
- **Category III:** This is the highest risk category and laser operators are required to follow Laser Deconfliction. The current astronomical LGS lasers fall into this category, hence the requirement to follow LCH protocol. However, it should be noted that USSPACECOM may allow for Risk Acceptance under special circumstances.

It is expected that a PRA of the astronomical LGS lasers would reclassify the systems into Category I or Category II. This would depend upon the laser systems being used as well as the atmospheric parameters at that site. It should be noted that the DoD LGS systems at MSSS in Maui and SOR in NM have been reclassified as Category II and they are using lasers that are similar, if not identical, to those being used for astronomy, i.e. the 589 nm Sodium Beacons.

b. Special Use Space Range

The 2020 revision of CJCSI 3225.01A Procedures for Management of Illumination of Objects in Space by Lasers also mentions the Special Use Space Range (SUSR) designation which can be applied to various DoD laser propagation sites. An SUSR is defined as:

A specified three dimensional region defined in earth coordinates during a specified time period in which DoD-owned,-operated or -leased laser operations will occur. Notification of satellite owners and operators of these parameters will allow operational tactics to minimize risk.

Unfortunately this is not written for non-DoD, i.e. civilian, laser systems, and is therefore not directly applicable to astronomical lasers. In order to designate astronomical sites as SUSR, a rewrite of the scope would be needed to include them. Note that Laser Deconfliction strictly applies to DoD lasers and that the US astronomical community follows it because of an NSF requirement. It is interesting to note that one of the DoD LGS systems (SOR), which uses similar lasers to the astronomical ones and is also currently classified as Category III, has been designated as an SUSR. A civilian equivalent to the DoD SUSR was discussed as another approach worth investigating.

5. Drop the NSF LCH Requirement
   The NSF requirement to follow DoD Laser Deconfliction goes back to the early days of astronomical LGS laser propagation using the same safety protocols in place for the DoD LGS systems. Given that this requirement has been in place for over two decades, it is not expected that the NSF Office of the General Counsel (OGC) would drop this requirement without any supporting evidence as to why it is not necessary. The best way to show that laser deconfliction is no longer required would be to have an independent agency evaluate the potential damage which could be caused by the LGS lasers to RSOs. Hence the SatAC PRA analysis, assuming a positive outcome, could be used not only to request reclassification by the LCH but also to inform the NSF OGC of the actual potential risks to RSOs associated with the propagation of LGS lasers and permit them to revisit the requirement.

3. Summary & Follow-up Activities

It is expected that over the next decades there will be a significant increase in the use of LGSs for astronomical AO, not only on the existing telescopes but also on the US ELT projects when they come online. Future AO systems will be making more use of LGSs because they make available increased sky coverage for the newer AO systems such as Laser Tomography Adaptive Optics (LTAO) and Ground-Layer Adaptive Optics (GLAO). As an example, Gemini N. is currently developing an LTAO system which is expected to be used for 25% of telescope time and is studying a GLAO system which will use the same LGSs. GLAO systems do not produce diffraction-limited correction but enhanced-seeing correction which essentially improves the image quality to ~ 0.3 arcseconds FWHM over fields of view of several arcminutes. This serves to increase the scientific productivity of the telescope in seeing-limited operation.

Along with the increased operational use of LGSs, there is also a corresponding increase in the number of LEO SATCONs which will increase the number of LCH closure windows, discussed above, thereby affecting telescope productivity. It is expected that there will also be a significantly increased use of follow-up with astronomical AO systems of transient events, such as those identified by Vera C. Rubin Observatory and the Laser Interferometer Gravitational-Wave Observatory. If rapid follow-up LGS-assisted AO observations are required, then these previously unknown targets of opportunity (ToO) will have to be cleared with the LCH as quickly as possible, adding an extra burden to the LCH office.

With an increased number of laser operations there will be increased overheads at the observatories, especially those operating in queue mode to prepare observations taking into account the higher number of closure windows. Additionally, it will add an increased burden to the LCH. Feedback from the LCH noted that the open-shutter turnaround time calculations were taking significantly longer, around three to five times, when the Starlink satellites were taken into account.

With this in mind, the general consensus from the Workshop was that the best approach to mitigating the impact of LCH closure windows would be to re-evaluate the classification of the astronomical lasers. This will require the submission of the astronomical laser systems parameters and atmospheric locations to the AFRL SatAC for a Probabilistic Risk Assessment analysis. Discussions during the meeting indicated that such an analysis can take up to three months, depending on the number of systems being studied, and that SatAC would expect to be contracted for this analysis. It was initially suggested that the Spectrum and Wireless Innovation enabled by Future Technologies–Satellite-Terrestrial Coexistence (SWIFT-SAT) program[15] would be the best to apply for funding for this analysis. While the SWIFT-SAT solicitation encourages synergistic collaborations or partnerships with industry or government, it does state that no NSF funds will be provided to these organizations. Feedback from the SatAC personnel indicated that the cost for an initial analysis would be ~ $70k. The NSF representatives, in particular Ashley VanderLey, are following up about the availability of NSF resources for these charges and how best to transfer the funds between the government agencies. It seems that an MOA already exists between the NSF and the AFRL. As of the time of the writing of this document, the AFRL SatAC contact is Courtney Smith.

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[15] https://www.nsf.gov/pubs/2023/nsf23567/nsf23567.htm

Table 4: Maunakea LGS-Propagating Telescopes

Telescope	Location	Laser Wavelength (μm)	Laser Power RMS (W)	Laser Peak Pulse Power (W)
Gemini N. — Altair Gemini N. — GNAO*	Maunakea, HI, USA	0.589 0.589	25 44	-
Keck I	Maunakea, HI, USA	0.589	25	-
Keck II	Maunakea, HI, USA	0.589	25	-
UH88 (Robo-AO)	Maunakea, HI, USA	0.355	13	3.8E04
Subaru	Maunakea, HI, USA	0.589	20	-
TMT*	Maunakea, HI, USA	0.589	60–160	-

* Systems designed but yet to be implemented.

Feedback from SatAC said that costs could be reduced by looking at a single atmosphere case. This would suggest that we consider Maunakea where we have five laser-propagating telescopes and the possibility that it may be the site for TMT. These telescopes are Keck I, Keck II, Gemini N., Subaru and the UH88. The laser parameters are outlined in Table 4. As can be seen, the majority of LGS systems are Sodium Layer systems using CW Toptica systems which are basically the industry standard, but there is also a UV laser for the RoboAO system on the UH88. Similar laser systems are used at SOAR at Cerro Pachón in Chile and one is currently being implemented at the USNO in Flagstaff, AZ. Thus two ‘standard’ LGS laser systems, a continuous wave sodium laser and a pulsed UV laser, would be considered and which we deem to be a representative sample of the astronomical LGSs. We would have to decide whether there is a substantial difference in the sodium lasers to justify submitting multiple analyses from AFRL/SatAC. We can collect the information for the different systems via the Laser Information Form and use that to determine the level of redundancy.

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Patricia Cooper (Constellation Adv.)

Robert Q. Fugate (AFRL — Ret.)
David Goldstein (SpaceX)
Richard Green (U. Arizona)
Michael Hart (HartSci)
Mark Kilijanski (AFRL — Ret)
Erik Kolb (AFRL)
Pat McCarthy (NOIRLab)
Maj. C. McLemore (LCH)
Maj. E. Ramirez (LCH)
Richard Rast (HartSci)
Ashley VanderLey (NSF)

Appendix 1 — Attendee List for Vandenberg SFB Workshop

In Person Attendees

Ericka Begody (AFRL)
Julian Christou (NOIRLab) — Chair
Scott Dahm (Gemini Obs.)
Olivia Garton (AFRL)
Elinor Gates (Lick Obs.)
Richard Green (U. Arizona/IAU CPS)
David Goldstein (SpaceX)
Therese Jones (SIA)
Jim Lyke (Keck Obs.)
Pat McCarthy (NOIRLab)
Cher Ron McLemore (LCH)
Edward Ramirez (LCH)
Courtney Smith (AFRL)
Martin Still (NSF)
Gelys Trancho (TIO)
Ashley VenderLey (NSF)
Connie Walker (NOIRLab/IAU CPS)

Virtual Attendees (via Zoom)

Corinne Boyer (TIO)
Patricia Cooper (Constellation Adv.)
Celine D’Orgeville (GMT/ANU)
Chris Davis (NSF)
Markus Duelli (Amazon/Kuiper)
Susana Deustra (DoC)
Marissa Herron (NASA)
Paul Hertz (NASA)
Robert Lafon (NASA)
Paul Lynam (Lick Obs.)
Noelia Martinez Rey (GMT/ANU)
Yosuke Minoway (NAOJ)
Mark Mulholland (DoC)
John O’Meara (Keck)
Dianne Poster (DoC)
Tae-Soo Pyo (NAOJ)
Reed Riddle (CalTech)
Gaetano Sivo (Gemini Obs.)
Warren Skidmore (TIO)
Jonathan Williams (NSF)

Appendix 2 — AFRL / SatAC Laser Information Form

Table 1. General information

Name of laser system	
Number of laser beams and their names/functions	
Country or governing agency of ownership	
System developer company/organization	
Operating institution	
Point of contact with phone and email	
Timeframe of planned laser activities/deployment (start to end dates; typically, a year in duration)	
Name(s) of operating platform(s)	
Name(s) of operating site(s)	
Site Location(s)	Latitude: ____ (deg North) Longitude: ____ (deg East) Altitude: ____ (m) (above WGS84 ellipsoid)
All Security Classification Guides (SCG's) for this project (if applicable):	
Notes (multiple sites, moving laser platform, special POC notes, etc):	

Table 2. Beam parameters

Variable	Mean Value	Min Value	Max Value	Uncertainty
Wavelength (nm)				
Beam quality (M^2 – ratio of linear divergence to diffraction limited ideal value)				
Wave Mode: Continuous wave (CW) or pulsed				
CW equivalent power at the exit aperture (W)				
Pulse length (sec; if pulsed)				
Pulse repetition frequency (Hz; if pulsed)				
Energy per pulse at the exit aperture (J; if pulsed)				
Beam Shape (circular, square, rectangular, etc.)				
Beam profile (Tophat, Gaussian, Truncated Gaussian, etc.)				
Is the beam collimated, focused or intentionally diverged? (if focused or intentionally diverged, specify if could operate collimated)				
Divergence — 1/e half angle (rad) (for collimated beams, the diffraction-limited beam divergence; for focused beams, the diffraction-limited beam divergence as if the beam				

Variable	**Mean Value**	**Min Value**	**Max Value**	**Uncertainty**
were operated in a collimated mode; for intentionally diverged beams, the larger of the diffraction-limited divergence or the controlled divergence angle)				
Pointing system exit aperture diameter or x & y dimensions if rectangular (m)				
Pointing system exit aperture obscuration diameter or x & y dimensions if rectangular (m)				
Beam $1/e^2$ radius (if Gaussian) or half-width in x & y (if rectangular) at exit aperture (m)				
Beam waist radius (m; if focused or intentionally diverged)				
Waist distance from aperture (m; if focused or intentionally diverged; negative if before the aperture for intentionally diverged)				
Focus range (m; specify if true focus or wave front radius of curvature at aperture)				
Adaptive Optics (AO) used? (Y/N)				
Notes (multiple wavelengths, multiple operational modes, uncommon laser characteristics, AO details, details on complex pulse/pulse train shapes (e.g., micro/macro pulse trains), etc.):				

Table 3. Operating parameters

Variable	**Mean Value**	**Min Value**	**Max Value**	**Uncertainty**
`The following parameters in this table only refer to above-the-horizon operations.`				
Azimuth angles (degrees clockwise from local true north)				
Elevation angles relative to the local horizon (deg)				
Portion of total operations* spent with fixed pointing (i.e., no slewing: 0deg/s) versus slewing (%) (e.g., a specified value of 20% indicates 20% of the time spent in fixed pointing operations and, subsequently, 80% of the time spent in slewing operations)				
Slew rate when slewing (deg/sec)				
Laser “on” duration per operation** (sec)				
Operations* per day of activity (#/day)				
Active calendar days per year (days/year)				

Number of operations* per year (#/year)				
Summary of how, when and under what conditions the system is used or not used; values specified that refer to system capabilities/limitations vs. those expected during operations*, etc.:				

* A single "operation" refers to each instance where laser energy is propagated beyond the exit aperture (i.e., laser "on" to laser "off" or shutter open to shutter closed). The "total operations" refers to the expected total number of single operations within the planned laser activities/deployment timeframe.

Table 4. Target parameters

Variable		**Mean Value**	**Min Value**	**Max Value**	**Uncertainty**
`The following parameters in this table only refer to above-the-horizon operations.`					
Target Type(s) (mortar, missile, UAV, etc.)					
Target size (m)	Length				
	Width (or Diameter)				
	Height				
Laser spot size (diameter) at target (m)					
Percent of the beam spillover at the target? (%; including any jitter contributions)					
RMS pointing stability and tracking jitter (urad)					
Time to laser off after target destroyed, track lost, runaway slew, or other problem (s)					
Number of targets engaged per engagement					
Notes (target description, uncommon spillover contributions, status of laser while slewing between multiple targets, etc.):					

Important: Please attach details about the target trajectory or flight path if known.

Table 5. Atmosphere considerations

Question	**Response**

Distribution of lasing activities through the year	`January: ___% February: ___% March: ___%`
	`April: ___% May: ___% June: ___%`
	`July: ___% August: ___% September: ___%`
	`October: ___% November: ___% December: ___%`
	`Check if uniform through year: ___`

Distribution of lasing activities through the day	`6am-10am: ___% 10am-2pm: ___% 2pm-6pm: ___%`
	`6pm-10pm: ___% 10pm-2am: ___% 2am-6am: ___%`
	`Dawn___% Dusk____%`
	`Specify if UTC or local time: _____`
	`Check if uniform through 24 hours: ____`

Are there weather-related restrictions or preferences that influence whether to operate (e.g., no lasing if wind > 15 mph)? If so, please specify.	

Appendix 3: List of Commonly Occurring Acronyms

- AFRL - Air Force Research Laboratory
- AO - Adaptive Optics
- DoD - Department of Defence
- DoE - Department of Energy
- ELT - Extremely Large Telescopes
- GMT - Giant Magellan Telescope
- IAU - International Astronomical Union
- IDA - Institute for Defense Analysis
- LCH - Laser Clearinghouse
- LEO - Low Earth Orbit
- LGS - Laser Guide Star
- NASA - National Aeronautics and Space Administration
- NGS - Natural Guide Star
- NOIRLab - National Optical-Infrared Astronomy Research Laboratory
- NSF - National Science Foundation
- PA - Predictive Avoidance
- PRA - Probabilistic Risk Assessment
- RSO - Resident Space Object
- SatAC - Satellite Assessment Center
- SATCON - Satellite Constellation
- SIA - Satellite Industry Associates
- TMT - Thirty Meter Telescope