PEACEFUL USE OF LASERS IN SPACE

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COMMENTARY ON THE RESPONSIBLE USE OF LASERS IN SPACE IN REACTION TO THE UNGA RESOLUTION 75/36

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On 7 December, 2020, the United Nations adopted UNGA resolution 75/36, Reducing Space Threats Through Norms, Rules and Principles of Responsible Behaviours. This Resolution calls on States to submit their views on existing challenges to space security. Specifically, in operative paragraph 5, it:

"Encourages Member States to study ***existing and potential threats and security risks to space systems****, including those arising from* ***actions, activities or systems*** *in outer space or on Earth****, characterize actions and activities*** *that could be considered* ***responsible, irresponsible or threatening*** *and their potential impact on international security, and share their ideas on the further development and implementation of* ***norms, rules and principles of responsible behaviours*** *and on the* ***reduction*** *of the* ***risks*** *of misunderstanding and miscalculations with respect to outer space;"*

In this context, the Peaceful Use of Lasers in Space initiative, seeks to offer the following commentary on the benefits of lasers for space applications and how this technology might be used responsibly in outer space. This commentary is offered only as input for consideration by UN Member States and is not intended to be a part of the formal record.

The Peaceful Use of Lasers in Space (PULS) is a scientist-led international initiative to ensure peaceful and globally beneficial development and use of lasers in space.
You can find more on www.lasers4space.com or contact us at info@lasers4space.com

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INTRODUCTION

With growing dependency not only of modern societies on space technology but also the overall flourishing and survival of human civilization, it is increasingly critical to encourage and engage in open global discussions about responsible use of the space domain. In this regard, laser technology offers numerous potential benefits in space in areas from space traffic management and communications to space resource utilization, planetary defense, and interstellar travel. These benefits are matched by the number of safety and security risks arising from the absence of norms and rules of responsible use of lasers in space. This can include intentional and unintentional misuses of otherwise benign technology. This commentary aims to raise awareness of both the potential and dangers of laser use in space and encourage all actors, including member states, commercial entities, and non-governmental organizations, to engage in discussions about the responsible use of laser technology in space.

This commentary firstly describes some technical parameters of beneficial use of laser use in space, before characterizing their dual-use/multi-use nature and potential intentional and unintentional misuses. Further, the commentary points out existing practices, platforms, and new ideas to spur an inclusive discussion on how to address risks related to laser use in space.

BENEFITS OF LASER USE IN SPACE

LASER SYSTEMS FOR SPACE TRAFFIC MANAGEMENT (STM)

In 2018, humanity crossed the number of 2,000 operating satellites on Earth's orbit, some predictions suggest that within eight years we will cross the number of 100,000 operating satellites.[1] This will create considerable orbital congestion and will necessitate some form of Space Traffic Management (STM). The use of laser systems for STM carries considerable value mainly from two points of view.

Firstly, satellite laser ranging (SLR) provides precise and up-to-date data, addressing the otherwise lack of accurate data on orbital objects that represents an important limitation to global STM capabilities. Despite Earth's orbits being spacious even for 100,000 satellites, what limits the use of Earth's orbits is not necessarily the spatial dimension of the domain but our capacities to ensure the safety, reliability, and long-term sustainability of space traffic management. The existing STM capacities, however, are already stretched and their capability to deal with the exponential growth is uncertain. Additionally, the rise of mega-constellations and new methods for low-propulsion maneuvering of satellites (such as differential drag) also makes some techniques for the modeling of the space environment less accurate, increasing the need for more up-to-date data on objects' trajectories. The limits of STM capabilities are partially defined by the number of collision warnings that satellite operators must check and act on, with the majority of them being false due to imprecise data on the tens of thousands of operational and non-operational orbital objects.[2] The Space Coalition model estimated that by the year 2029 there might be up to 2,5 million collision warnings with an average of 40 orbital collisions a year.[3] More sensors and more precise data will be critical to lowering the number of false collision warnings, improve overall modeling of the space environment and ensure its sustainability as the number of objects on Earth's orbit continue to exponentially rise. As the use of ground-based SLR stations has been widely used for decades, a new generation of space-based lasers for satellite tracking is being developed.

Secondly, laser technology represents an effective solution for the active removal of small debris, which is otherwise challenging to achieve. With the growing orbital population, it will become increasingly critical to remove the 900 000 objects between 1 cm a 10 cm, and 128 million objects below 1 cm in size that according to the European Space Agency estimates orbit the Earth at the average speed of 28 000 kph.[4] Concepts for the application of ground-based laser technology are investigated and developed for maneuvering orbital debris using photon pressure[5] as well as removing debris using laser ablation[6], while space-based laser instruments for objects' ablation are being developed by private and public institutions.[7] Moreover, momentum transfer from high power lasers would enable a new option for collision avoidance which would not only protect satellites, but even collisions between two different debris objects could be avoided, thus, eliminating a main driver of the current increase in the number of space debris objects.[8,9,10]

LASER SYSTEMS FOR SPACE RESORUCE UTILIZATION

Lasers can provide valuable solutions in the area of space resource utilization (SRU). The utilization of various chemical elements and mineral resources available in space, especially on the Moon, Mars, and near-earth asteroids, is a critical step for sustainable human expansion into space. SRU is an enabler for the development of the space economy and new cosmic activities and by some estimates it represents an untapped market of up to 170 billion USD.[11] Yet, the development of the SRU is challenged by legal and technological barriers. The absence of a clear regulatory and legal framework for the utilization of space resources generates uncertainty and additional risks for investors.[12] From the technical side, the lack of sufficiently robust and precise knowledge of Celestial bodies only slows down the development of systems for the extraction, beneficiation, and use of space resources and its entire supply chain. Surveys of near-Earth asteroids (NEAs) with ground instruments do not provide detailed information about their internal structure or subsurface chemical composition and thus the whole resource potential. Landing missions to prospect individual NEAs are expensive and technically challenging. Meanwhile, probes on Mars and the Moon have provided a better understanding of the prevalence of different minerals and valuable resources, they still do not provide sufficient knowledge for complete development of SRU systems, as many measurements of potential resources widely vary.[13]

Laser illumination is to be used for surface spectrometry by the Lunar Flashlight 6U CubeSat mission in the permanently shaded regions of the Moon.[14] Instruments using the close-distance laser-induced breakdown spectroscopy (LIBS) are frequently used for prospecting and were deployed on various rovers on Mars.[15] They are used only for short distances of single units of meters at maximum. The prospect of upgrading this method for more distant use has been explored by many researchers.[16] The benefit of such capabilities would allow for more precise and accurate sub-surface prospecting than those surveys of the lunar surface affected by micrometeors, solar wind, and radiation, whether in terms of a flyby, rendezvous NEA mission, or prospecting probes with global coverage on other planets.

LASER SYSTEMS FOR SPACE EXPLORATION AND PLANETARY DEFENSE

Laser technology, however, carries even more ambitious potential. One such area concerns the defense of planet Earth against dangerous asteroids and comets which has attracted a growing scientific and policy community. As of 2020, over 23,000 near-earth asteroids and 110 near-earth comets are on record and being monitored, with planet defenders tirelessly looking for other potentially hazardous objects that could impact Earth.[17] From a technical point of view, lasers have the potential to become critical elements of planetary defense, for they may be used to deflect asteroids[18] and comets[19] by recoil from surface vaporization (ablation) under continuous laser irradiation at high intensities. They can also be used to explore asteroids' internal composition through laser-induced ablation, thus facilitating other possible methods of deflection.[20]

Closely related to planetary defense considerations are visions of space exploration and space resource utilization. While space exploration used to be the domain of astronomers or robotic probes, nowadays it includes private actors with the resources, capabilities, effectiveness, and will greater than those of nation-states to venture into the realm of space colonization, interstellar travel, and search for extraterrestrial life. For example, the non-profit philanthropic organization *Breakthrough Initiatives* funds comprehensive research and development of such technology.[21] The most futuristic uses, including large-scale laser arrays or interstellar travel,[22] have robust scientific background, to the effect that the main obstacles to their implementation are practical (financial, political, etc.).

ONGOING DUAL-USE OF LASERS

Despite the clear peaceful benefits, such technology can also be easily subject to irresponsible behavior given the absence of norms, rules, and principles for laser use in space.

The direct threat of satellite blinding by low-powered ground-based lasers rose to prominence after the testing of the US two-megawatt Mid-Infrared Advanced Chemical Laser in 1997 on a defunct US Air Force satellite, during which the main laser failed but another smaller 30-watt laser surprisingly demonstrated capabilities to temporarily blind electro-optical satellites.[23] The 2021 Secure World Foundation Global Counterspace Capability Report points out that lasers can be used for dazzling, damaging satellites imagining sensors, the satellites bus or its subsystems.[24] Low-power lasers ranging from as little as 10W are capable of dazzling and temporarily blinding satellite imaging sensors[25], while even a 40W laser star guide system can easily permanently damage silicon photosensor array or silicon diodes.[26] Note that the latter power level is appropriate for laser ranging to space debris.[27] Therefore, it is difficult to draw a line between what lasers can cause temporary dazzling and which can lead to temporary damage.

China, Russia, and the US can be considered the main actors in the testing and development of ASAT laser systems.[28] US officials in the past claimed that China has tested a ground-based laser to blind a US satellite, which could also be interpreted not necessarily as testing of a weapon but of a satellite tracking system.[29] US Defense Intelligence Agency has repeatedly described China's satellite laser ranging (SLR) stations as a threat to US satellites.[30] Mobile satellite laser ranging (MSLR) units offer another type of dual-use capability, which strips satellites of many ways to protect themselves against laser dazzling, blinding, or damage while passing over known permanent SLR bases.[31] Both France and Germany have developed or are currently developing MSLR units.[32] In 2020, Russia has made public detailed information about a new Russian mobile satellite dazzling laser system, Peresvet, which is believed to be deployable on a ground vehicle as well as on aircraft.[33] Further, France has unveiled plans to construct a laser-armed satellite constellation to destroy satellites posing threat to French space assets in an act of self-defense.[34] South Korea has announced plans to develop anti-satellite laser systems and space-based lasers for surveillance and tracking capabilities.[35] Furthermore, another 20-30 states, including Libya and Iran, have reported or been considered as possessing ASAT laser capabilities to interfere with satellites.[36] Even low-power lasers have the capability to temporarily blind, jam, and interfere with electro-optical satellites.

However, lasers can be utilized in a more complex way. When used for space debris maneuvering by photon pressure or ablation, lasers can be used for hardly attributable actions. Maneuvering of space debris can accommodate malicious intent if the debris is redirected as a kinetic weapon into another satellite or another piece of debris, making the maneuver appear as an error. While rather aiming for debris fragments than for (still) integer space debris[37], moving space debris by the ablation method can easily damage satellites[38]. Methods of space-based laser ablation are being developed to function on the typical materials satellites are made of (aluminum, composite materials, titanium alloy, hardened steel, etc.) since it is mostly pieces of satellites that make up space debris.[39] The threshold of laser fluence for ablation of such materials is estimated between 5-7 J/cm^2 at pulse lengths in the nanosecond range, which are typically proposed for ground-based laser-ablative debris removal.[40] Considering a fraction of 10-60% of this fluence that might enter the irradiated object in form of residual heat,[41] such surface energy density would be fatal if directed at payloads or the satellite bus, especially in the case of highly repetitive irradiation and/or targeting for example tanks with fuel or batteries. A similar thermal risk, depending on the debris absorptivity, applies for debris nudging by photon pressure, demanding for several tens of kW on a spot of a few square meters,[42] however, without the additional risk that arises from laser-induced shockwaves in the case of laser ablation. To be efficient in terms of possible energy losses from outshining the debris target, both methods require very precise focusing of the laser beam upon a very small area of a quickly moving and presumably rotating object on the orbit which demands for a thoughtful assessment of the potential risk in space, airspace and on ground arising from back-reflections of the high-intense laser beam from the debris object.[42]

Furthermore, since the source of debris in the majority of cases are unknown or at least difficult to determine, there is no way to establish the culprits for their emission and thus the responsible party for their removal. Also, if any benevolent actor wishes to act on their maneuvering, they become liable for any incidents resulting from their final trajectory. Such legal framework can complicate the use laser debris removing, given its high necessity of reliable prediction of laser-imparted momentum that, however, depends on a variety of parameters like beam pointing offset and jitter, tracking uncertainty, target orientation and outshining ratio, as far as albedo (in the case of photon pressure) and actually the specific debris material itself (for laser ablation).[10,43] As the origins of millions of small debris cannot be easily determined, leaving culprits unaccountable for their emission, then laser operators, even if the ultimate goal of moving the debris was its removal, would become accountable for those pieces if they caused an unexpected collision.

Sub-surface prospecting of Celestial bodies for the space resource utilization by the LIBS method can also be a source of intentional or unintentional damage. Besides direct use on some objects, the ejected plumes of fine-grained regolith in the microgravity environment can significantly damage any instruments or infrastructure in the wider area.[44] And in case of a high-power laser array, diffractions of a powerful laser beam from an intentionally irradiated object could unintentionally blind sensors of other satellite. In more advanced concepts for the use of laser technology for planetary defense, the capability to change the trajectory of a near-earth object, even a small one, could be misused to direct it towards another actor's space assets.

WHAT IS IRRESPONSIBLE USE OF LASERS?

The absence of norms for laser use in space does not only increases the likelihood of their intentional misuse due to the absence of clear rules, but most importantly it increases a chance of unintentional incidents. Intentional use can be motivated by self-defense, for example, if ground-based lasers are used to blind optical payloads of reconnaissance satellites as they pass above sensitive infrastructure critical to national security or if space-based lasers are used as a protection against a non-cooperative satellite conducting a close-proximity operation. Similarly, the intent can be clearly offensive, if lasers are used to blind space-based sensors of an anti-ballistic missile system or damage payloads or satellites.

Three characteristics of laser use in space play an important role in the discussion about their responsible use in space. Firstly, laser systems can be used for both malicious and peaceful purposes by their original design, increasing the risks of disguising the original intent of use. If a debris maneuvering laser is used to maneuver a dangerous piece of debris onto the path of another satellite, it could be hard to distinguish whether this was an accident or by malicious intent. Secondly, the use of lasers in many cases can be very hard to detect and thus verifiable. Unless an imaging payload of a reconnaissance satellite malfunctions while over an area with a known ground-based laser station or during close proximity of a non-cooperative laser-armed satellite, it would be hard to attribute damage to lasers. Thirdly, while lasers can have only a temporary or permanent effect on a satellite's functions, the threshold between what can cause temporary or permanent damage is technically hard to establish. Would the intentions to temporarily laser blind a satellite sensor in self-defense be considered the same as permanent laser damage to a satellite with the same intent? This absence of norms in this area increases risks of unintentional escalation as the original intent, whether it is to temporarily or permanently blind a sensor for defensive or offensive reasons.

Many of these issues fall on the absence of general norms in outer space. What constitutes a right to self-defense by a spacecraft on orbit? What is the minimum distance for conducting non-cooperative rendezvous and proximity operations (RPO) or close-proximity operations (CPO) before it is considered a threat? And what mechanism can lead the international community to lower such risks? Verification and transparency and confidence-building measures (TCBMs) are considered the main tools of arms control. Among the best practices belong notifications, registration, and disclosure, consultation, and maintenance of direct lines of communication and information sharing on capabilities. Yet, these measures can differ for each technical area. Most importantly, they require a prior agreement on what information needs to be shared on what type of behavior to ensure equal distribution of compliance's benefits and costs.

The UNGA resolution 75/36 is an ideal opportunity to start the process for getting to know what member states' opinions on what constitutes responsible and irresponsible behavior in space. The potentially harmful use of lasers was ranked third in the most pressing space risks by a group of space security experts in the Project Plowshares.[45] Yet, an attempt to create an arms control for use of lasers in space has failed in the past.[46] Therefore, a dedicated, inclusive, and trusted process to identify and ensure normal uses of lasers in space is needed. This process should be organized to include not only views of individual member states, including non-allied countries, but also of non-government actors (research institutions, commercial subjects or philanthropic actors).

EXISTING COOPERATION AND PLATFORMS FOR CURRENT USE

On the national level, the United States Department of Defense has been operating the Laser Clearinghouse (LCH), which is tasked with clearing any use of lasers to, in, through, or from space or above the horizon. The LCH offers deconflicting products for US laser operators that ensure laser use is not causing any damage to any objects in space. Based on the requested parameters of the intended laser use (location of the laser, date, time, and sky location of its use) the LCH then evaluates its use, analyzes the best predictive avoidance approach, plans of predictive avoidance, and capability validation plan and finally authorizes the defined time window for the specific laser use. A study from the Institute for Defense Analyses suggests that the process of compliance with the LCH guidelines has not to lead to any significant loss of observational time or reduced the quality and quantity of results.[47]

In 1998, the United States reportedly proposed the establishment of an international laser clearinghouse in reaction to Russia's criticism of US tests of anti-satellite laser systems. Yet, these efforts were criticized by US military officials due to the risks of indirectly sharing sensitive information about satellite positioning, and never materialized.[48] However, in 1998 the International Laser Ranging Service was established, to collect, merge, analyze, archive, and distribute laser ranging data for scientific, engineering, experimental, and engineering purposes.[49] Today, the ILRS coordinates a volunteer network of 40 SLR ground stations in 24 countries (including China, Russia, or the US) and provides information on their capabilities, plans, and future development. The ILRS's Central Bureau coordinates tracking missions and strategies, including safety measures to avoid damaging satellite instruments. This includes an authorization process to ensure that only specific stations in specific time periods track concrete satellites. Should a satellite operator require tracking, they can submit a Missions Support Request Forms including detailed information and approval to perform laser ranging on the satellite.[50] The ILRS also coordinates activities on laser tracking of space debris, but mainly aimed at deceased satellites to better understand the dynamics of their reentry.

Both the Laser Clearinghouse and the International Laser Ranging Service provide ideas and platforms for steps ahead in international coordination of laser use in space. Firstly, the LCH can be an example of a national authorization process to ensure safe laser use in space for other laser operating nations. Direct lines of communication between national laser clearinghouses or laser use contact points could provide an important deconflicting tool. Secondly, the ILRS provides a platform for building trust and transparency by sharing information about capabilities, plans, and intentions for laser use in space. In the case of ILRS, not all ground laser ranging stations are part of the network nor share their details. Other activities such as laser space debris maneuvering or the use of space-borne lasers are not covered by the service. Sharing information about tracking missions and programs outside of those carried out under the ILRS would be a valuable confidence building measure.

Raising awareness about the existing laser platforms and their importance of sharing information to increase transparency is a needed first step forward. Not only ILRS member states but also private actors should be encouraged to share information about their laser capabilities, tracking strategies or debris maneuvering plans. Additionally, consultations about similar information-sharing mechanisms should be initiated to include other uses of laser, including mobile satellite ranging systems and space-based systems for laser ablation.

CIVILIAN COOPERATION ON FUTURE LASER SYSTEMS

For systems under development, importance should be given to the environment in which they emerge as it defines their normative framework. Given the large potential of high-power laser systems to advance human flourishing, ensure its shared survival and extend its knowledge of outer space, including interstellar travel, a more global perspective of shared human destiny needs to be considered.

Early international cooperation in the development of new systems can imbed transparency and deconflicting measures into technology and preventing many issues down the road. Further, as large-scale high-power laser projects, such as Breakthrough Starshot for interstellar travel, will require a complex multi-stakeholder scientific cooperation, they will also require a complex multi-stakeholder type of governance. Cooperation on such large technical systems (LTS) is considered one of the ways to build trust between rivals through scientific cooperation, which creates a networked reality that transcends traditional notions of national security and creates a shared social environment and positions.[51] Among the main examples of large technical systems that lock member states in close cooperation are the International Space Station (ISS), European Organization for Nuclear Research (CERN), International Thermonuclear Experimental Reactor (ITER) or Internet Corporation for Assigned Names and Numbers (ICANN). They offer best practices in large scientific cooperation in terms of financing, knowledge sharing, division of labor, and shared governance. And despite the fact that the US-Russian cooperation on the ISS has not eliminated conflicts in other areas, it has withstood them through turbulent times while still preserving shared governance on the space station.

Novel powerful space technology will thus require novel governance models, to ensure the technology serves the flourishing of humankind rather than particular power interests. This can include a shared trigger control of the technology or system, or design features of the system to ensure it technically cannot be used for anything other than the original purposes. In a practical example, the Breakthrough Starshot system can be designed with a limited range of azimuths ensuring that the high-power laser can be only used in the targeted direction, specifically the Alpha Centauri system. Further, globally legitimate governing principles can be based on the specific security and technical complexities of the technology. For example, while legitimate deployment or use of a powerful laser system would require a globally inclusive consensus among all actors due to the risks of its misuse, the legitimate development of the system, which carries higher technical complexity and higher risk of misuse, would require rather scientific consensus of the qualified, invested and involved actors.

The ideas on technical design features, shared governance mechanism, and other ways to ensure the peaceful use of powerful technology require more study, international conferences, and globally inclusive discussions. To prevent dangerous scenarios of private or public actors being empowered into a hegemonic role by extremely powerful laser technology in the future, the questions of their governance should be addressed before they are developed, not after.

CONCLUSION

While the military origins and utility of laser technology cannot be omitted, it should not limit its potential to advance the shared interests of all humanity. An inspiring example that it is possible can be seen in the case of the servicing module of the Soviet megawatt space-based laser weapon Polyus, which has never reach full operational capacity, but whose servicing module ended up serving other than waring purposes, as it became a Russian contribution to one of the hallmarks of international cooperation in space, the International Space Station (ISS).

There are different sets of challenges for the current and future uses of lasers in space. Yet, everything starts with engaging in sharing of views on the topic. Moreover, focusing the wide discussion about norms of behavior in space on a particular technical area, such as responsible use of lasers in space can enable a more substantial and practical discussion with a higher chance for an agreement. In this regard, the Declaration on the Peaceful Use of Lasers in Space[52], endorsed by the Nobel laureate Gérard Mourou, aims to encourage the international scientific community to engage in an inclusive discussion about global governance of both the futuristic large lasers systems and existing laser technologies, and to participate in international conferences and expert workings groups on the Peaceful Use of Lasers in Space.

However, the agenda for igniting an exchange of views, sharing of information, starting global cooperation and developing norms of responsible behavior can be advanced only so much by non-governmental entities. Commercial entities with a particular interest in sustainable and safe use of laser technology in space should turn to their national governments to raise awareness of this issue and the need of their engagement. The issue ultimately rests on the UN member states and their willingness to utilize their diplomatic tools and mechanisms at international organizations to launch global discussions on the Peaceful Use of Lasers in Space.

ABOUT THE COMMENTARY

The report was authored by Petr Bohacek on behalf of the Peaceful Use of Lasers initiative with the help of important contributions, reviews and commentaries by:

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ABOUT THE PULS INITIATIVE

The Peaceful Use of Lasers in Space (PULS) is a scientist-led initiative started following the Prague Laser SpaceApps conference in 2019. Its aims are to create awareness about the laser potential to advance human flourishing and the equal risks of its misuse and mobilize global actors to engage in inclusive discussions about the peaceful development and use of lasers in space. To these ends, the initiative organizes international conferences, reports, studies, and scientific collaborations.

The initiative has also published the Declaration of the Peaceful Use of Lasers in Space endorsed by the Nobel prize laurate Gérard Mourou to garner the support of the scientific community and can be found online at www.lasers4space.com/declaration.

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NOTES

[1] The Space Safety Coalition model predicts 107,641 satellites and 68 mega-constellations by 2029. As described by Daniel L. Oltrogge of Space Safety Coalition during the "Safety of Spaceflight: Looking Back at the Past Decade, Looking Ahead at the Next Five Year" conference.
[2] Secure World Foundation, "Safety of Spaceflight: Looking Back at the Past Decade, Looking Ahead at the Next Five Year," July 29, 2020, https://swfound.org/media/207058/sda-event-transcript-final.pdf
[3] These numbers are part of the above mentioned Space Safety Coalition model.
[4] Data according to European Space Agency Space Debris Office. Available at https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers.
[5] Recently, the company Electro Optical Systems (EOS) announced completion of their ground-based laser system for maneuvering space debris (see Kearsley, 2021).
[6] B. Esmiller et al. 2013; Phipps et al., 2013.
[7] Next to substantial research activities of such technology (Vetrisano, Thiry, and Vasile 2015; Schmitz, Fasoulas, and Utzmann 2015), a Japanese public-private consortium plans to develop a space-based laser satellite to remove space debris (See Nipon, 2020).
[8] F. Yang Yang et al., 2016.
[9] H. Krag et al., 2018.
[10] S. Scharring et al., 2021.
[11] Such estimated is given by a comprehensive study of the space resources utilization economic potential for the Luxembourg Space Agency by the PriceWaterhouseCoopers. See Scatteia et al., 2018.
[12] Svec, Bohacek and Schmidt, 2020.
[13] NASA's Lunar CRater Observation and Sensing Satellite (LCROSS) estimated water content in the Cabeus crater on the Moon's south pole between 2.9 – 55.6%, ISRO's Chandrayaan probe estimated the water content to be 30%.
[14] The Lunar Flashlight is part of the Artemis 1 flight of the Space Launch System scheduled at the time of publishing for November 2021.
[15] Weins et al., 2020.
[16] Choi & Yoh, 2012; Ferus et al., 2019; Knight et al., 2000.
[17] Data according to European Space Agency Planetary Defense Office NEO Coordination Centre. Available at http://neo.ssa.esa.int/
[18] Lubin et al. 2016.
[19] Zhang, Lubin, and Hughes, 2019; Zhang et al., 2016.
[20] The Space Mission Planning Advisory Group (SMPAG) recommended the development of technologies for compositional analysis as well as push deflection methods of asteroids in September 2019 and February 2020, respectively.
[21] Parkin 2018.
[22] Kulkarni, Lubin, and Zhang 2018; Phipps et al. 2018.
[23] Koplow, 2010.
[24] The 2021 Global Counterspace Capabilities Report can be found at https://swfound.org/media/207162/swf_global_counterspace_capabilities_2021.pdf
[25] Kramer, 2010.
[26] Kruer, et al. 1976, p. 453.
[27] P. Lejba et al., 2018.
[28] Fears of Russian and Chinese anti-satellite laser weapons were used to justify the budget for US ASAT lasers during the 1970s and 2000s, respectively.
[29] See Vago Muradian, "China Attempted to Blind U.S. Satellites with Lasers," Defense News, September 25, 2006; Warren Fester and Colin Clark, "NRO Confirms Chinese Laser Test Illuminated U.S. Spacecraft," Space News, October 2, 2006; and Elaine Grossman, "Top Commander:Chinese Interference with U.S. Satellites Uncertain," Inside the Pentagon, October 12, 2006.
[30] Defense Intelligence Agency, 2019.
[31] Brian Chow and Henry Sokolski, "U.S. satellites increasingly vulnerable to China's ground-based lasers," SpaceNews, July 10 2020, https://spacenews.com/op-ed-u-s-satellites-increasingly-vulnerable-to-chinas-ground-based-lasers/
[32] Nicolas et al., 2000. & Wagner et al., 2019.

[33] An authoritative analysis on Russian laser capabilities and the new Perservet system has been published by Bart Hendrickx, "Peresvet: a Russian mobile laser system to dazzle enemy satellites," The Space Review, June 15, 2020, https://www.thespacereview.com/article/3967/1.
[34] Theresa Hitchens, "Space Lasers for Satellite Defense Top New French Space Strategy," Breaking Defense, July 26, 2019, https://breakingdefense.com/2019/07/france-envisions-on-orbit-lasers-for-satellite-defense/
[35] South Korean Defense Acquisition Program Administration unveiled plans for antisatellite laser weapons in 2019 (See DefenseWorld, 2019) and in 2021 unveiled a $41 million project to develop a space-based laser surveillance system by 2025 (see Yonhap, 2021).
[36] The estimate of 20 to 30 countries has been given in 1999 by Robert Bell as the United States National Security Council arms control specialist (See Gertz, 1999), while Libya and Iran have already used lasers against US satellites (See Everett, 2007).
[37] Lorbeer et al., 2018.
[38] Loktionov, Phipps, Sharaborova, 2021.
[39] Numbers of catalogued debris as of end of 2019 are: 12033 payloads (including payload fragments, debris and payload-mission related objects) and 8742 rocket bodies (including rocket fragments, debris and rocket-mission related objects), according to ESA's Annual Space Environment Report.
[40] Such numbers are presented by Eckle et al., 2016 as well as Soulard et al., 2014.
[41] S. Scharring et al., 2018.
[42] S. Scharring et al., 2021.
[43] S. Scharring et al., 2018.
[44] One of the examples of such risks is the observation of the impact of Apollo 12 lunar landing on the 155 meter distant Surveyor III probe. While the Surveyor was only affected indirectly, the plume ejected by the landing has sand-blasted its coating. See Immer et al., 2011.
[45] Jessica West and Gilles Doucet, "From Safety to Security: Extending Norms in Outer Space. Global Workshop Series," Project Ploughshares, January 2021.
[46] Bill Gertz, "U.S. weighs sharing satellite laser test data," Washington Times, January 2, 1998, https://fas.org/spp/military/program/asat/wt_980102.htm
[47] Kramer, 2010.
[48] Bill Gertz, "U.S. weighs sharing satellite laser test data," Washington Times, January 2, 1998, https://fas.org/spp/military/program/asat/wt_980102.htm
[49] Pearlman et al., 2002.
[50] Pavlis et al., 2011.
[51] Mayer & Acuto, 2015.
[52] The Declaration is available at https://lasers4space.com/declaration/