SATCON2

Community Engagement Working Group Report

NOIR Lab

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SATCON2 Community Engagement Working Group

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1. Summary and Overview

This report is part of a collection of Working Group Reports from the SATCON2 Conference.

1.1. Charge

The SATCON2 Community Engagement Working Group aimed to engage a broad and diverse swath of stakeholders in dark skies and near-Earth space who are impacted by large mega-constellations of tens of thousands of low-Earth orbit (LEO) satellites, beyond professional astronomy alone. The working group consisted of 22 members across 23 time zones including professional and amateur astronomers, members of sovereign Indigenous/First Nations communities, dark-sky advocates, planetarium professionals, and environmental/ecological non-governmental organizations. We set out to work together towards a new and effective conceptual, ethical, legal, and regulatory framework for the protection and sustainability of space and the night sky as a global cultural, natural and scientific commons. Community Engagement Working Group members invested thousands of volunteer hours in working group meetings, listening sessions with impacted constituencies, numerous conversations, developing, conducting and analyzing surveys, and finalizing our results and recommendations.

1.2. Constituencies

For SATCON2, the Community Engagement Working Group focused on five specific constituencies that had not previously been explicitly included in SATCON1 or other policy discussions about satellite constellations, including some groups traditionally excluded from political and economic power**:**

1. Astrophotography and Astro-Tourism
2. Amateur Astronomy
3. Indigenous Communities and Perspectives
4. Planetariums
5. Environmental and Ecological Concerns

They shared their feedback, needs and recommendations during listening sessions and conversations before the workshop and during dedicated sessions at the workshop.

We acknowledge that there remain many constituencies and perspectives not included in the Community Engagement Working Group that may prove important players in future negotiation and policy-making, such as telecommunication companies, space contractors, economic development groups, ground-based internet equipment suppliers, and Internet service providers.

The largest group not included explicitly in the Community Engagement Working Group is the population of humans world-wide who admire, cherish, view, connect with, seek solace from, practice traditional religion and culture with, navigate by, are inspired by, and need the stars, the Milky Way, and unpolluted night skies. Our principles and recommendations include them implicitly, and we call for explicit consideration of the rights of humanity to see the stars in all future space activities including satellite constellations.

We emphasize that these reports represent the needs and perspectives of individuals, specific communities, and those who were able to offer feedback and participate. Our compiled report does not speak for all members of any constituency, or all examples of a group, e.g., all Native American tribal communities or all environmental groups.

Last, we honor all the voices and communities who offered their time and feedback for the months leading up to the SATCON2 workshop and this report. This included many who have been historically marginalized and are overloaded by disproportionate fallout from climate change and the pandemic. We are grateful for their uncompensated labor in a time of loss, crisis fatigue, and global pain, in which we are quickly approaching our and our planet's ability to cope — much like overcrowded low-Earth orbits.

1.3. Background and Context

In early 2020 much of work and life as we knew it ground to a halt with the arrival of the COVID-19 pandemic on the global stage. But one activity continued unceasingly at pre-pandemic levels: the relentless launch of satellite constellations by private operators, while the world was roiled by climate change, economic collapse, racial injustice and of course, the still ongoing pandemic.

The 18 months leading up to SATCON2 revealed widening inequalities among all these factors, including the dire need for affordable accessible broadband for all as education, work and much of daily life went online. Globally available cheap broadband is the main promise and potential from companies such as Starlink, OneWeb and others. It remains to be seen whether this promise is fulfilled, but in the process we stand to clutter LEO orbits with hazardous space debris, blind our ground-based telescopes to the cosmos, imperil life and well-being with falling rocket bodies and increasing greenhouse gas emissions — and lose dark skies for all of humanity and all flora and fauna over the next few years. The impacts will likely affect a broad swath of constituencies across humanity, beyond professional astronomy alone. By invoking the democratization of space, the commons of space itself — as enshrined in the Outer Space Treaty of 1967 (OST) — continues to be claimed piecemeal by corporations in a longstanding pattern of unchallenged, unregulated "progress" on our collective behalf. We are reminded of this through regular headlines on space billboards and space tourism; the SATCON2 workshop week in mid-July was itself bracketed by the brief space adventures of Richard Branson, Jeff Bezos and their crews. Some working

group members contrasted that billionaire space race with the two-week Red Road to DC[1], which began during the SATCON2 workshop week, and involved the journey of a 25-foot Native American totem pole through sacred Indigenous lands from Washington state to Washington DC, highlighting historical and continuing exclusion and erasure of marginalized communities and culture.

We view this report as the beginning, rather than the end, of a conversation that is long overdue. We urge active ongoing engagement among federal agencies, private and state actors in space, professional societies and especially organizations and communities representing the diversity of stakeholders in our shared skies, so we can co-create a new, ethical, sustainable approach to space exploration rather than the current regulatory maze of siloed concerns enabling business as usual.

1.4. Common Themes and Principles

We identified common themes that recurred and resonated across the Community Engagement Working Group's five subgroups. Collectively, the Community Engagement Working Group offers the following observations and principles:

1. The skies and space belong to everyone. Space is a global commons.
2. All people are impacted by changes in the sky. Nearly all consulted for SATCON2 had already noticed a dramatic rise in satellite constellation sightings in the past two years, and were worried.
3. Many communities see the unchecked actions of space actors as colonization expanded to a cosmic scale during a time of global crisis.
4. The sky must be considered part of the environment and the current National Environmental Policy Act (NEPA) exemption for the satellite constellation industry must end.
5. Ecosystems depend on the night sky and on each other.

1.5. Recommendations

The Community Engagement Working Group offers the following nine recommendations to decision-makers, regulators, the satellite industry, researchers, and all communities affected by satellite constellations.

1. Duty to consult

Satellite operators must first consult all impacted groups, including the sovereign American Indian / Alaska Native nations and global Indigenous communities, before launching satellites. Industry must fully consider the concerns of Indigenous nations, including sovereignty, transparency, written agreements, and jurisdiction of treaties in space. Space belongs to us all and we need to listen to all constituencies impacted by satellite constellations. The OST establishes space as a global commons, and the American Astronomical Society (AAS) mission statement emphasizes inclusivity, sustainability, and the importance of humanity's understanding of the Universe.

1 https://redroadtodc.org/

2. Need for more information and communication

Communities want more information and dialogue. Astronomers and other parties concerned about the impacts of LEO satellite constellations need to engage, listen, share, and act with affected constituencies, government agencies, and cultural, grassroots, and political leaders. Decision-makers and private satellite operators must intentionally invite the voices and groups that have historically been excluded from the power structure and decision-making regarding space activity. Involving youth is a key aspect to co-creating solutions together to protect the Earth and skies that they will inherit.

3. Engage with industry

Astronomers and other interested and affected groups need to continue to engage with the satellite industry to build relationships and find common ground. The Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference proposed by the International Astronomical Union (IAU) is one possible venue for such engagement.

4. Recognize and rebalance power structures

Decision-makers and advocates for the regulation of LEO satellites should recognize the economic, legal, and political structures that continually affect technology choices. The regulatory process must take those power structures into account to optimize societal and environmental benefit with equity — power over a global commons comes with responsibilities to the global good. The social systems of economic and technological opportunities that enable satellite constellations focus on technological solutions; but there is only so much back-correcting that software can do to remove satellite streaks in images, or that engaging affected communities in dialogue, reports, and conferences can do to make amends once irreparable damage is done to the sky and to communities — just as removing plastics from the ocean is proving an impossible task. We urge the broad inclusion of all affected communities in meaningful dialogue from the start.

At the same time, there has been an enormous amount of volunteer labor from mainstream astronomy, communities and institutions devoted to addressing the challenges posed by satellite constellations. Funding for training and FTEs from agencies and industry is needed for continued efforts in the future.

5. Learn from the past

History offers valuable lessons on many issues of concern with satellite constellations, including environmental concerns, loss of millenia-old practices, and the painful legacies of colonization. The past century in particular offers ample examples of disruptive technologies that have been developed first and regulated only later, with varying degrees of cost, benefit, risk, and impact, e.g., telephones, trains/planes/cars, fossil fuels, and the Internet itself. Examples of global challenges requiring international collaboration include damage to the ozone layer, for which corrective action has been largely successful, and climate change, for which a global course of corrective action has remained elusive. We must learn from those examples as we grapple with the satellite constellation challenge.

6. "Science vs. Internet" is a false choice

Affordable broadband is crucial to almost all aspects of 21st century work and life, and some communities welcome satellite broadband. However, we must not assume that LEO satellite constellations are the only option, or that sacrificing the night sky is an acceptable trade-off. Industry and government agencies must develop a meaningful assessment of viable alternatives to satellite broadband, including ground-based fiber, from the aspects of cost, infrastructure and environmental impact. Satellite operator business models may not accurately assess the profitability of satellite constellation broadband Internet and its affordability for low-income users; in Mexico, Starlink currently charges roughly four times more than ground-based broadband, and one recent study found only a small overlap between global populations that need broadband and those that can afford to pay market rates for it. Costs of satellite constellations that are put on society — such as coping with space debris after satellite collisions or bankruptcies and environmental costs from launches, operations, and deorbiting — should be fully considered in the true cost of satellite constellations, rather than left as externalities.

7. Better international regulation and globally coordinated oversight/enforcement

We need coordinated international regulation of the satellite constellation industry with oversight and enforcement, in contrast to the current regulatory maze of siloed issues enabling business as usual. Most of the constituencies polled by the Community Engagement Working Group want industry to slow down until meaningful solutions can be developed in consensus, involving youth and communities. The fallout from unregulated unchecked satellite constellation launches includes dramatic predicted increases in all of the following: space debris, radio frequency interference, orbital traffic and collisions, environmental fallout in the upper atmosphere or oceans after satellite decommissioning, and global sky brightness (not just individual satellite streaks) washing out fainter stars or meteors, and undermining dedicated dark sky parks and preserves.

8. Slow or stop satellite constellation launches until problems are resolved

We strongly urge that the pace of launches be slowed or stopped until the issues can be much more fully understood and meaningful solutions to proven and likely problems can be developed in consensus. All the constituencies we polled and consulted are already noticing a dramatic rise in the number of satellites seen, when the number of satellites in orbit is currently only 5–10% of what is planned to be launched in the next decade. We need to plan for and mitigate both the known impacts of satellite constellations and a broad array of unintended consequences from them for many human endeavors.

9. Continued active engagement and conversation

The Community Engagement Working Group views the SATCON2 workshop as the beginning, rather than the end, of a long overdue conversation that was prompted by satellite constellations, but that extends

to far broader issues of preserving space and the night sky as a scientific, environmental and cultural commons for humanity. The Community Engagement Working Group urges active engagement and long-term relationship-building among industry, leadership, all space actors and communities representing the diversity of stakeholders in our shared skies so we can co-create an inclusive, ethical, and sustainable approach to space.

1.6. Subgroup reports

The reports from our five constituencies follow this overview. We emphasize that these reports represent the needs and perspectives of individuals, specific communities, and those who were able to offer feedback and participate. Our compiled report does not speak for all members of any constituency, or all examples of a group, e.g., all Native American tribal communities or all environmental groups. We acknowledge that we ran out of time and resources to include many perspectives at the workshop and in this report and that they still need to be honored, including the role of aesthetics, culture, heritage, art, storytelling, and humanity in our connection to the skies. There are other issues that we could do only peripheral justice to, including rural economic development, an assessment of alternatives to satellite broadband, the digital divide etc. Rather than being a comprehensive or conclusive document, this report shares early findings as we begin a long-term process of building relationships and listening to communities' needs and perspectives on the impact of LEO satellite mega-constellations, co-creating new ways for how we collectively approach space in the coming years.

2. Astrophotography, Astrotourism and Broader Implications of a Global Rise in Night Sky Brightness

The primary authors of this section and subgroup members are:

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Ruskin Hartley (International Dark-Sky Association)
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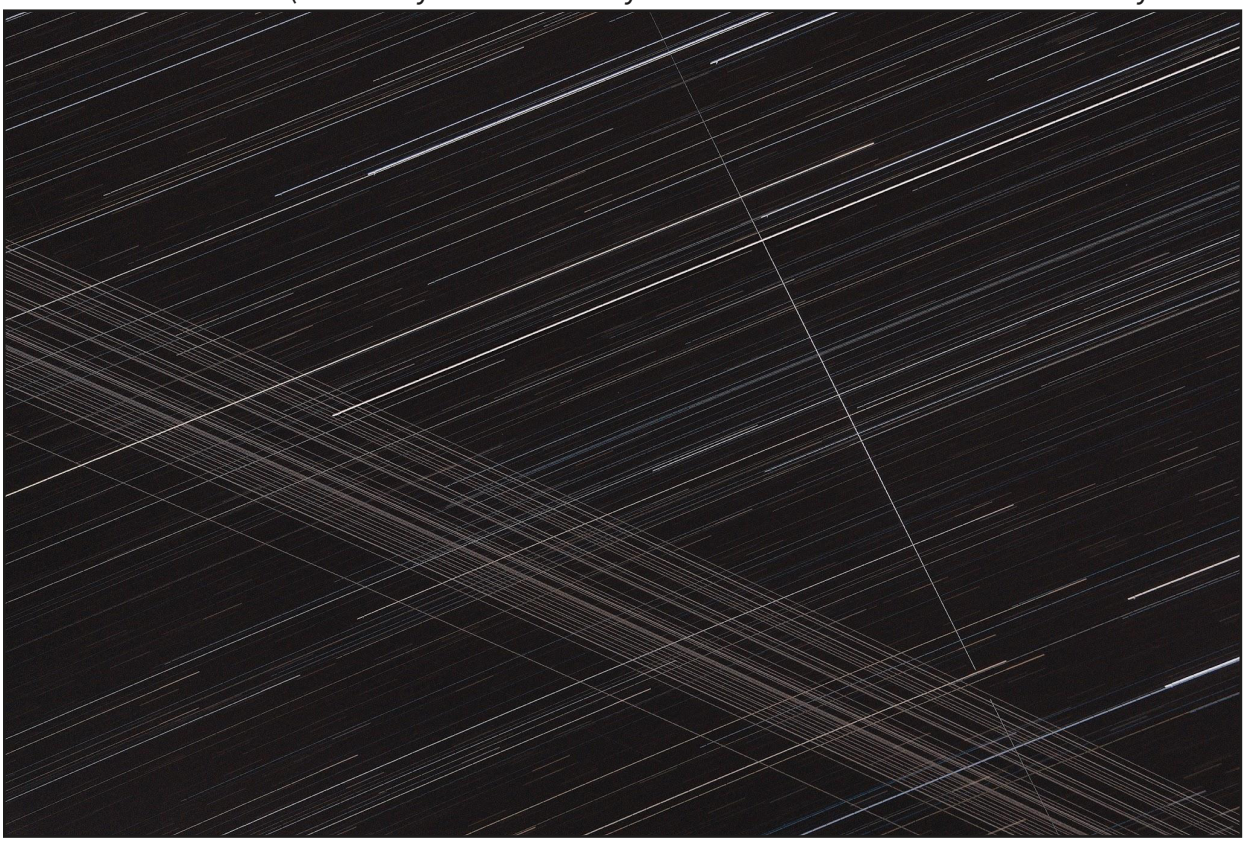

Figure 1. 39 Starlink satellites from Flight 10 appear as trails (upper left to lower right) across this 87-second photograph of the night sky made on 11 August 2020. The more vertical line at right is a trail from a Chinese Long March 2C rocket body. Image by Martin Bernardi, licensed under CC BY-SA 4.0.

2.1. Astrophotographers

Members of the astrophotography community were on the front line when the subject of satellite mega-constellations first entered the global public consciousness after the initial SpaceX Starlink launch in May 2019. Before the first group of 60 Starlink objects was raised to its final, 550-km station and the satellites were still flying in close proximity, their tendency to leave multiple parallel streaks in astrophotos (e.g. Fig. 1) was exploited by world media to suggest that Starlink represented a serious or even existential threat to ground-based astronomy.[2] Later it was revealed that not even space-based astrophotography was immune to the threat, as it was found that the Hubble Space Telescope, orbiting below on-station Starlink objects, experienced the same satellite trails in its images.[3]

In SATCON1, we explored the potential for large satellite constellations to yield negative impacts on astronomical images ranging from wide-field "nightscapes" to deep imaging through telescopes to casual astrophotography employing the cameras built into mobile devices.[4] Using the best information available at the time in terms of the expected number and brightness of objects planned for launch in the 2020s, we rated their impacts to various modes of astrophotography from "negligible" to "fatal". In the latter case, the expected victim was nightscape photography, which we expected to "*suffer the same problem as high-AΩ telescopes, albeit with considerably smaller apertures*." Assuming the fully built SpaceX Starlink and OneWeb constellations, simulations suggested an average of two satellite trails per square degree would appear in every 60-second exposure taken near the horizon. From this we concluded that "*we do not see how wide-field astrophotography can be performed to current standards with the projected density and brightness of the steady-state configurations of the Starlink2 and OneWeb constellations*."

For SATCON2, we contacted both amateur and professional astrophotographers to obtain information on their attitudes toward large satellite constellations. We took a cue from the online-survey approach of the Community Engagement Working Group's subgroup aimed at soliciting opinions from the amateur astronomy community. However, our survey[5] was marketed differently from the survey to broadly defined "amateur astronomers". While there certainly is some overlap between the groups, the astrophotography survey was aimed mainly at individuals who are less likely to identify as amateur astronomers and more as landscape photographers for whom the night sky is another backdrop. Consequently there were more responses from "nightscape" photographers than from those who engaged in planetary or deep-sky astrophotography, usually with the aid of telescopes.

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2 For examples of media stories illustrated by such images, see "***Astronomy group calls for urgent action on SpaceX Starlink satellites***", New Scientist, 3 June 2019 (https://www.newscientist.com/article/2205172-astronomy-group-calls-for-urgent-action-on-spacex-starlink-satellites/); ***Satellite constellations: Astronomers warn of threat to view of Universe***, BBC, 27 December 2019 (https://www.bbc.com/news/science-environment-50870117); and ***Latest Starlink Plans Unveiled By Elon Musk And SpaceX Could Create An Astronomical Emergency***, Forbes, 11 December 2019 (https://www.forbes.com/sites/startswithabang/2019/12/11/elon-musk-spacex-unveil-latest-starlink-plans-creating-an-astronomical-emergency/?sh=3e0755c1287e)

3 ***A proliferation of space junk is blocking our view of the cosmos, research shows***, Washington Post, 27 April 2021 (https://www.washingtonpost.com/business/2021/04/27/starlink-light-pollution/). The original Hubble image shown in the story can be found in the Space Telescope Archive at https://archive.stsci.edu/cgi-bin/mastpreview?mission=hst&dataid=IEDK12AOQ.

4 Barentine, J. (2020) ***Concerns of the non-professional astronomy community and adjacent night-sky stakeholders***, appendices to ***Impact of Satellite Constellations on Optical Astronomy and Recommendations Toward Mitigations***, NOIRLab Technical Document 004 (https://noirlab.edu/public/products/techdocs/techdoc004/), pp. 106-108.

5 Available on https://forms.gle/ZEMDNzHY3uoC1F2J9

The survey was distributed through our professional networks and social media. We received 21 responses. First we asked about geographic location. As expected, the respondents were overwhelmingly from North America (43%) and Europe (37%). The vast majority of respondents (81%) described their work as "amateur/hobbyist", which we take to mean they identified their work to be recreational in nature rather than professional/other work. Other roles mentioned included (semi-) professional photographer (33%) and “citizen scientist” (24%); we note that respondents could choose more than one option. About an equal number of participants said they took wide-field/landscape astrophotographs (76%) as compared to those who used long-focus lenses or telescopes to take deep-sky (71%) or planetary astrophotographs (57%). Far fewer engaged in speciality astrophotography, such as imaging asteroids (5%).

The overwhelming majority of survey participants (90%) rated the impacts of moving objects on their work as "moderate", "significant" or "severe". Less than 10% said the impacts were "zero" or "minimal". As expected, astrophotographers identified wide-field images of various targets as being most prone to the consequences of moving objects; over half cited subjects such as star trails, constellations and panoramas as examples. Of these, nightscapes featuring the Milky Way were mentioned most often, by three-quarters of participants.

It is not at all surprising — although perhaps the result of selection bias and a small sample size — that 100% of survey respondents described the impacts of satellites and other moving objects on their astrophotography as "more" than they were five years ago. It is reasonable to conclude that this is mainly the result of the launch of ~ 1800 SpaceX Starlink objects in the interim, which constitute nearly all of the larger, and brighter, objects launched into near-Earth space in the same period.

We asked those who said they felt the impact was more in recent years (i.e., 100% of respondents) to estimate the increase as a percentage over the baseline conditions of five years ago. We were surprised at the diversity of responses to this question, which was deliberately phrased as a free response rather than pre-established ranges of numbers. A small majority (61%) of respondents estimated the impact as +50% in the past five years, which turns out to be in rough proportion to the increase in the number of bright objects in near-Earth space in the same time period. With fewer responses each, other suggestions ranged from +5% to +200%.

Next we asked respondents to rate the significance of the impacts of satellites and moving objects in terms of the burden their presence in images imposed on astrophotographers needing to remove them from their images in post-processing. About 95% of respondents indicated that some burden or disadvantage is imposed on their work by satellites and other moving objects in the night sky. Of these, a clear majority (76%) labeled the burden "moderate" to "significant". Curiously, none rated the burden as "severe", a label we defined as a condition in which moving objects essentially made their astrophotography work impossible.

We also asked astrophotographers to speculate on the future. We did not presume that survey respondents had any detailed knowledge of satellites, and we gave them very little information so as to attempt to not bias the results. In order to ask them about the potential for changes in impacts in the future, we provided them with relative numbers of existing functional satellites before the first Starlink launch and a total for the number of Starlink objects launched to date. A significant majority (86%) of

respondents said that they felt there was an approaching threshold in terms of the number of bright objects orbiting the Earth at which their astrophotography would suffer irreparable harm. None of the respondents indicated they did not think such a threshold existed, but a few (14%) admitted that they did not know. For those who answered “yes” to the previous question, we asked them if they cared to venture a guess as to the size of the number. Responses to this question varied wildly, suggesting that the answers are no more than speculations. One respondent simply wrote that it was “very difficult to estimate”.

The last substantive question was free-response: “Please provide any comments/suggestions you have regarding large satellite constellations, including additional information you would like to receive, ideas for mitigating effects, etc.” We received six responses, reproduced here in their entirety:

> *Ban them !!!!!!!!!!!!!!!!!! Space could be for exploration and not for commercial use.*
> *They are unneeded. In the 90s the Iridium needed less than 100 satellites to cover the world. Now there are 10s of thousands needed? Looks like the technology in 30 years went backwards.*
> *The industry is unsustainable for many reasons.*
> *Governments should impose a moratorium on all mega-constellations and negotiate an international framework to better regulate low orbit. It's a shambles and shouldn't be allowed to happen.*
> *There has been an interesting discussion about aluminium oxide from burned satellites and their impact on the earth's albedo and thus global climate. We will be deploying tons of it in the atmosphere in the coming years. This should be a) regulated and b) part of the overall bill (counter /compensating measures). We also need a broader discussion in the general public about this side effect.*
> *Every satellite needs a deorbit system. Also more analysts on the benefit to risk of having them.*

From the survey responses, and in consideration of the small sample size and potential for selection bias, we conclude the following:

- Like amateur astronomers, astrophotographers report impacts to their work imposed by large satellite constellations, namely Starlink.
- Many astrophotographers see a future in which the number of relatively bright objects orbiting Earth will affect their work to the point that it simply cannot be done effectively anymore.
- They seem frustrated by the status quo, and several indicated clearly that they preferred a moratorium on launches or other steps to be taken to limit the number of objects in orbit.
- While we can’t say how representative these views are of all astrophotographers, the results largely mirror the privately expressed opinions of many astrophotographers related to us as anecdotes about impacts on their work.

2.2. Astrotourism professionals

Astrotourism, broadly defined, is a form of sustainable tourism that engages clients in activities related to stargazing and astronomy, including terrestrial night-sky phenomena such as aurora watching. Usually classified alongside other forms of "ecotourism" or "green tourism", astrotourism has as its object the resource of the night sky, and it is usually pursued in places with relatively little light pollution. It offers participants content outside the realm of more traditional, destination-based tourism and fuses elements of outdoor/adventure tourism with resort and amenity activities.

There is little to date in the tourism and hospitality literature studying astrotourism, but limited evidence suggests great growth and revenue potential.[6] It is hypothesized that astrotourism can drive rural economic development, especially in economically depressed regions where former industries have departed as a result of globalization, natural resource exhaustion and other influences. The astrotourism field itself remains nascent despite growing public interest; as an indicator, no professional organization of astrotourism operators has yet emerged. It is not known how many people in the world are employed in astrotourism, but anecdotally we understand this number to be far fewer than those who engage in amateur astronomy or astrophotography as avocations.

In order to solicit opinions about the impacts of large satellite constellations on the work of astrotourism professionals, we contacted individuals in our professional networks with whom we have had previous communications about their work. For this report, we conducted interviews with five people, all of whom agreed to be identified by name and affiliation:

- Roy Alexander (AstroVentures CIC and Battlesteads Dark Sky Observatory, UK)
- Etta Danemann (Visit Dark Skies, Germany)
- Sabine Frank (Verein Sternenpark Rhön e.V., Germany)
- Catherine Johns (Kielder Observatory, UK)
- Samuel Singer (Wyoming Stargazing, US)

In their respective roles, their work ranges from those who provide nighttime star tours on a freelance basis to those who operate small private observatories open to the public. The respondents have work experience in astrotourism ranging from eight to 15 years. They work in astrotourism on a part-time or full-time basis, showing that while for some it has become their primary means of earning a living, others are working in this space in a way that supplements their income or engages their interests beyond their main paid jobs. While some own astrotourism businesses that employ other people, others are either sole proprietors or work essentially as freelancers. Business owners employ between two and 12 individuals on a full-time basis, and have help from others who are employed part-time, are self-employed, or serve in a volunteer capacity.

The respondents offer a wide array of astrotourism products and services to their clients. Most provide some kind of in-person "star tours," telescope viewing, or comparable kinds of programming. Some

6 For recent case studies, see, e.g., Mitchell, D., & Gallaway, T. (2019). ***Dark sky tourism: economic impacts on the Colorado Plateau Economy, USA***. Tourism Review, 74(4), 930–942. https://doi.org/10.1108/tr-10-2018-0146 and Rodrigues, A. L. O., Rodrigues, A. & Peroff, D. M. (2014). ***The Sky and Sustainable Tourism Development: A Case Study of a Dark Sky Reserve Implementation in Alqueva***. International Journal of Tourism Research, 17(3), 292. https://doi.org/10.1002/jtr.1987.

mentioned more specific activities like astrophotography, light pollution education and aurora watching. However, not all astrotourism follows this model. For instance, Danemann's company markets an "audio experience" to parks and similar places for self-guided stargazing adventures. Johns reports that Kielder Observatory is branching into this space as well, offering “immersive and digital” experiences in addition to its usual educational activities. The respondents reported a wide range of visitor/guest totals each year, ranging from 2500 to 25,000 before the COVID-19 pandemic began.

We asked whether the appearance of satellites in the night sky affects the respondents’ work in astrotourism, and if so, what the significance of the effect is now. The respondents mostly reported no effect at all, or a net-positive effect in terms of engaging the curiosity of guests. One (Singer) specifically noted that satellites “frequently interfere” with his company's astrophotography offerings.

Of the respondents who are field practitioners of astrotourism, all noted that the appearance of satellites in the night sky has increased in recent years; two rated the status quo as “much more” than in the past. Frank summarized the effect on visual observations of the night sky: “*It's simply the multitude of satellites moving across the sky at different speeds that change the view and also distract the participants, especially since the brightness is often as great as that of stars*.” Alexander compared the situation to the past, in which “*apart from the ISS, spotting satellites would need an app and you'd have to be sharp-eyed to spot them. Now they're all over the place*” (e.g., Fig. 2)

We then asked whether the respondents were aware of their guests’/clients’ attitudes toward satellites. All suggested that guests or users of their products are curious about satellite constellations like Starlink and some enjoy seeing them. “*Guests tend to be excited to see satellites*,” Alexander wrote. “*The ISS and Starlink in particular put on a good show, and on dark sky nights there's normally a couple of guests who end up informally competing to see who can count the most*.” Despite presenting a nuisance to the astrophotographers among his guests, Singer noted “*they are a welcomed added attraction to the stargazing programs. Guests are excited to see them*.”

Often it seems that astrotourism experiences are when these people for the first time pause to consider the implications of such large numbers of objects orbiting Earth. This suggests that astrotourism may be a route to increasing the overall public awareness of the issue of the sustainable use of outer space. Alexander described engaging with guests on the topic of satellites: “*Everyone tends to feel that space is getting too cluttered, that there might come a time where the sky is just crawling with sat tracks and most people are unhappy with the way billionaires can just launch whatever they like with impunity*.” Frank described her guests as “*impressed and curious*” with the mega-constellation phenomenon. “*People want to know a lot of information. Especially the Starlink satellites are causing some anxiety and some participants are a bit afraid*.” Johns reported her guests at Kielder Observatory “*love seeing them and it's an interesting opener to a discussion around the sustainability of space. The Starlink trains are especially spectacular in this regard*.”[7]

We were curious as to whether, compared to the situation now, astrotourism operators envisioned a time in the future when the number of satellites might be sufficiently large as to disrupt or negatively impact their businesses. Responses to this question were mixed, with some suggesting relatively little

7 “Starlink trains” refers to the configuration of newly launched Starlink objects that are physically grouped together in their initial parking orbits. At ~ 300 km altitude, they are brighter than the same objects after reaching their 550-km station orbits approximately 90 days later.

impact to their business to those who say it may adversely affect specific activities like astrophotography. For Alexander, this time is "*not in the near future*", but he suspects that "*there will come a time where if the skies are allowed to become more busy, our type of visual and amateur-astrophotography evenings will be negatively impacted by too many visible satellites*." Singer wrote that while he didn't think that satellites will impact his visual stargazing programs, he expected that "*they will become more and more of a nuisance with imaging*." Danemann suggested that the potential of programs like Starlink to bring broadband internet into remote areas where astrotourism often takes place "*might even be positive*" for her business. And Johns raised the possibility of a link between casual attitudes among the public regarding the visual pollution of the night sky represented by satellites and a lack of concern for sources of terrestrial light pollution as they may affect the accessibility of the night sky. "*The clear and present danger is a lack of joined-up thinking around dark skies as an asset beyond astrotourism leading to ill-conceived lighting schemes*," wrote Johns. She further mentioned that Kielder Observatory is developing a "Dark Skies NE'' plan, referring to the northeast of England, to address this concern on a regional basis.

The attitudes of these astrotourism professionals largely mirror those of amateur astronomers, astrophotographers, and general supporters of dark-skies initiatives. They expressed concern for the future accessibility of the night sky, although none specifically cited potential negative effects on their businesses as a reason for concern. Some argued for new regulations, or strengthening of existing regulations, having to do with the use of near-Earth space. Singer wrote that "*more regulations are necessary to prevent abuses of the use of low-earth and mid-earth orbits for satellites*," while Alexander opined that "*billionaires shouldn't be able to just launch what the heck they like, when they like, in some kind of space one-upmanship. There needs to be more regulation*."

Frank pointed out that the increasing commercialization of near-Earth space "is *against the common good*" associated with the accessibility of the natural night sky. Danemann further suggested that the real harm of large numbers of satellites may be in simply redirecting the gaze of viewers from the natural to the artificial: "*A night sky full of satellites would direct visitor interest to the space close to Earth, thus harming the exposure to the vast Universe with its life-changing eternity aspect*."

Our limited survey of a few astrotourism professionals in the US and Europe points to something of a double-edged sword in how large satellite constellations affect the nature of their business: while the public is excited to see satellites swarming about overhead, that phenomenon can also detract from the experience of viewing the wonders of a dark night sky. It may motivate some customers while alienating others. Astrotourism professionals seem to be situated along the sidelines of the public debate about the issue of satellite constellations, cautiously observing developments that may influence their businesses for better or worse and whose full ramifications are not yet known.

What is the potential for loss of astrotourism revenue as night skies become brighter? There are no published data on astrotourism potential as a function of night sky conditions, although it seems anecdotally that pristine night skies are not a precondition for running a successful astrotourism enterprise. Accessibility of the resource is an important concern based on the premise that certain tourists are willing to travel across the world and spend significantly to see "pristine" night skies; others would be willing to stay closer to home and spend less on each visit but might choose to visit more often.

At present, we do not have anything even like a heuristic model of astrotourism spending that can suggest how the monetary value of nighttime darkness scales with metrics such as night sky quality. But we raise the alarm that a global rise in night sky brightness from satellites and space debris (collectively, "space objects") will be akin to a rising tide that lifts all boats. It seems reasonable to expect that such increasing worldwide night sky brightness will tend to diminish the value of *all* "dark-sky" sites, particularly those that are now thought of as pristine such as dedicated dark-sky parks and preserves. This will impact millenia-old human observations of the Milky Way, meteor showers and more, which we elaborate on and attempt to quantify below. This is also yet another way that satellites and space debris will impact Indigenous sky traditions and storytelling, which have had an increasing role in recent years in astrotourism tours and stargazing initiatives at International Dark Sky Parks designated by the International Dark-Sky Association.[8]

2.3. Rising diffuse night sky brightness from satellites and space debris

Concerns raised to date about the impact of large satellite constellations on the night sky have tended to focus on the streaks or trails of light they produce, whether observed visually as discrete, moving points of light or recorded on various electronic detectors. However, we are only beginning to examine the contribution of space objects in elevating the global diffuse brightness of the night sky[9], much as the collective light of millions of individual stars too faint to detect by the human eye yields the familiar, glowing clouds of the Milky Way. A recently published study estimates that, prior to the first SpaceX launch in 2019, these objects yielded an increase of "*approximately 10 per cent … over the brightness of the night sky determined by natural sources of light*", equivalent to a zenith luminance contribution of 20 µcd m^{-2}. Coincidentally, the IAU and the International Committee on Illumination consider an astronomical observatory site whose night-sky brightness exceeds 10% above background at zenith angles ≤ 70° to be light-polluted.[10]

According to the Union of Concerned Scientists, as of 1 April 2020 there were a total of 2666 satellites in orbit around Earth, of which 1918 were in LEO.[11] Assuming the number above for the total steady-state number of new LEO satellites in space in the 2020s, the total would reach about 50,000 satellites. If the population of debris objects increases according to the current size distribution, then the number of LEO objects in 2030 should be a factor of about 25 times higher than it is now. That would yield an average zenith luminance contribution from space objects of around 500 µcd m^{-2}, or 250% above the natural background. As we detail below, if this scenario were fully realized, it would cause significant degradation of detail in visual observations of the Milky Way, a diminution of the number of stars visible to the unaided eye by a factor of about two, the disappearance of roughly half of the meteors in major annual events like the Leonid meteor shower, and the inability to view faint auroral displays.

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8 ***National Parks Are Embracing Indigenous Astronomy***, Outside Online, 12 July 2021 (https://www.outsideonline.com/adventure-travel/national-parks/national-parks-indigenous-stars/).

9 Kocifaj, M., Kundracik, F., Barentine, J. C. & Bará, S. (2021). ***The proliferation of space objects is a rapidly increasing source of artificial night sky brightness***. Monthly Notices of the Royal Astronomical Society: Letters, 504(1), L40. https://doi.org/10.1093/mnrasl/slab030.

10 Cayrel R., et al. (1980). ***Guidelines for minimizing urban sky glow near astronomical observatories***. CIE 001-1980.

11 Geospatial World, ***How many satellites orbit Earth and why space traffic management is crucial*** (https://www.geospatialworld.net/blogs/how-many-satellites-orbit-earth-and-why-space-traffic-management-is-crucial/, accessed 23 August 2021)

At a combined total of natural plus space objects background of ~ 700 µcd m^{-2}, the brightness of the night sky at the zenith in this scenario would rival that at a site moderately impacted by terrestrial skyglow: 20.7 *V* magnitudes per square arcsecond, a value three times higher than the natural background alone. This condition is described by Class 4 on the qualitative Bortle Scale of night sky quality.[12] Only half the number of stars would be visible in the night sky relative to what would be visible in the absence of space-object light pollution.[13] This reduction in the visibility of stars is akin to a global view of the night sky that lies somewhere between typical suburban and rural skies.[14] We emphasize that this is only a lower limit to the stars being erased, assuming that crowded conditions in LEO lead to more frequent debris-generating collisions. This estimate further assumes that future satellites will have optical properties broadly like those of today. Although SpaceX has demonstrated a reduction in the total reflectivity of its Starlink objects through engineering innovations,[15,16] the long-term choices made by industry regarding mitigating solutions are not guaranteed. Without binding legal regulations that impose mitigation targets, it remains a purely voluntary matter whether operators pursue these solutions.

Other than the loss of stars, there is also the potential for increased target observation times for professional astronomy as higher backgrounds require longer integration times to reach a specific signal to noise ratio. Last but not least, there will be reduced viewing of celestial phenomena that have united human observations across the ages, including, e.g., the Milky Way, meteor showers and aurorae.

The brightest parts of the Milky Way become just visible to the unaided eye at the zenith around a brightness of 2000 µcd m^{-2} (~ 19.5 *V* magnitudes per square arcsecond, or m_v $arcsec^{-2}$). At 800 µcd m^{-2} (20.5 m_v $arcsec^{-2}$), depending on the presence of light domes on the horizon, most of the Milky Way is visible from horizon to horizon. But the visual appearance of the Milky Way with richness of detail does not begin until the zenith brightness is around 400 µcd m^{-2}, (~ 21.2 m_v $arcsec^{-2}$). In terms of factors above the assumed natural background of ~ 200 µcd m^{-2} (~ 21.9 m_v $arcsec^{-2}$), these represent thresholds of about 10, 4 and 2 times, respectively.[17]

Observing meteor showers and aurorae are also popular activities at dark-sky sites. While the brightest meteors are visible from even the most light-polluted cities, dark sites excel at providing the opportunity to see relatively large numbers of meteors during a given night. Faint meteors tend to dominate these numbers, and so the resulting effect is rather dependent on night-sky brightness. Keeping in mind that every step brighter in sky brightness in terms of magnitudes per square arcsecond is a factor of approximately 2.5 toward higher backgrounds, and given the brightness distribution of meteors in major

12 For a description of the Bortle Scale, see Bortle, John E. (February 2001), ***Gauging Light Pollution: The Bortle Dark-Sky Scale***, Sky & Telescope. Sky Publishing Corporation.

13 This assumes ~ 9000 stars brighter than the canonical unaided eye limit of magnitude +6.5 spread over the entire sky (Hoffleit, D.; Jaschek, C., eds. 1991. ***The Bright Star Catalogue***. New Haven: Yale University Observatory) and the relationship between the luminance of the night sky and limiting visual magnitude given in Schaefer, B. E. (1990). ***Telescopic limiting magnitudes***. Publications of the Astronomical Society of the Pacific, 102, 212. https://doi.org/10.1086/132629.

14 Note that Kocifaj et al. assumed the pre-Starlink rate of growth for new satellite launches to estimate a zenith brightness of 25 µcd m^{-2} in 2030 — some 20 times less than what we might more realistically expect in the age of mega-constellations.

15 Horiuchi, T., Hanayama, H. & Ohishi, M. (2020). ***Simultaneous Multicolor Observations of Starlink's Darksat by the Murikabushi Telescope with MITSuME***. The Astrophysical Journal, 905(1), 3. https://doi.org/10.3847/1538-4357/abc695.

16 Mallama, A. (2021). ***The Brightness of VisorSat-Design Starlink Satellites***, arXiv:2101.00374.

17 Conversions between SI (cd m–2) and 'astronomer' luminance units (mV arcsec-2) were made here according to the calibrations in Bará, S., et al. (2020). Magnitude to luminance conversions and visual brightness of the night sky. Monthly Notices of the Royal Astronomical Society, 493(2), 2429–2437. https://doi.org/10.1093/mnras/staa323 and Fryc, I., et al. (2021). On the Relation between the Astronomical and Visual Photometric Systems in Specifying the Brightness of the Night Sky for Mesopically Adapted Observers. LEUKOS, 1–12. https://doi.org/10.1080/15502724.2021.1921593.

annual showers, a brightening of the night sky from any source means a significant reduction in the number of observable meteors. For example, Brosch et al. (2004) found for the Leonid meteor shower (population index ~ 2) a broad distribution of apparent magnitudes peaking around +5.[18] For a site where the unaided-eye limiting magnitude equalled +5, corresponding to a night-sky brightness ~ 10 times higher than the natural background, approximately 40% of Leonids would be invisible.

The odds of seeing any particular auroral display are similarly decreased as the night-sky background brightens. This phenomenon is readily evident to aurora watchers impacted by the presence of moonlight, which even at relatively small lunar phases can quickly wash out faint auroral displays and those that are close to the horizon. Fainter aurorae (International Brightness Coefficients[19] I and II) have surface brightnesses comparable to that of airglow, and thus would be rendered invisible under a modest amount of sky brightness from any source. If the background were routinely elevated, whether from terrestrial skyglow or the diffuse glow of space objects, it would sharply reduce the potential to see the aurorae at moderately high northern/southern latitudes, reducing the number of nights a year when the phenomenon might be visible.

Figure 2. Starlink trails from objects deployed during Flight 6 are seen in this panoramic view of the night sky. Photo by Mike Lewinski, licensed under CC BY 2.0.

18 Brosch, N., et al. (2004). ***Meteor light curves: the relevant parameters***. Monthly Notices of the Royal Astronomical Society, 355(1), 111. https://doi.org/10.1111/j.1365-2966.2004.08300.x

19 A classification system introduced by Seaton, M. J. (1954) ***Excitation processes in the aurora and airglow 1. Absolute intensities, relative ultra-violet intensities and electron densities in high latitude aurorae***. Journal of Atmospheric and Terrestrial Physics, 4(6), 285, https://doi.org/10.1016/0021-9169(54)90060-4 and extended in Hunten, D. M. (1955) ***Some photometric observations of auroral spectra***. Journal of Atmospheric and Terrestrial Physics, 7, 141, https://doi.org/10.1016/0021-9169(55)90121-5.

2.4. Other skywatchers and broad implications

This type of stakeholder may not have any specific scientific, cultural, hobby-related or religious connection to the night sky. They may not engage in astrotourism or participate in amateur astronomy, but they think of access to the night sky as something that adds value to their lives and may contribute positively to their overall sense of wellbeing.[20] They don't necessarily have any equipment to view the night sky, and typically do so with their unaided eyes. And they may have a sense that what makes the night sky special is that it is (literally) above Earthly concerns and that the value they perceive is independent of whether they understand any of it. In that way, its value is largely aesthetic, like visual art. But it isn't seen as a luxury or a frivolity; research suggests that people are willing to exchange things of value for access to nighttime darkness.[21]

What we all stand to lose as the night sky brightens around the world is the initial attachment to these ideas; in other words, if people never experience something first hand, it is less likely that they will assign it value, much less take any action to protect it when threatened.[22] In the case of both terrestrial light pollution and enhanced night-sky brightness attributable to space objects, viewers may see an unwelcome reminder of the extent to which humans have modified and transformed Earth, often for the worse. Although spotting individual satellites or the International Space Station can be entertaining or inspiring to some viewers, a steady stream of swarming artificial lights in the night sky diminishes the experience by making them routine or even perhaps annoying. A future transformation of the night sky in this way threatens to fundamentally rewrite the story of the relationship between humanity and the night sky, yet there has been virtually no outreach to this global community of night sky stakeholders. Often these communities are invisible to policymakers and have no seat at the tables around which policy decisions are made affecting the night sky; some authors have suggested that this amounts to a form of "astrocolonialism,"[23] while others have labeled it "cultural genocide".[24]

That this concern exists, requiring the attention of stakeholders through events like SATCON2, begs the question of who should bear the burdens associated with this fundamental paradigm shift in our approach to the use of orbital space near Earth. These are not old issues on newly expanded scales; rather, they are entirely new uses of near-Earth space whose scope and consequences we have barely begun to understand. Most launches now take place from US territory and are thus governed by US law and space policy; however, communities impacted by private commercial activities in space are being told to accept the consequences of these activities while the industry carrying them out faces a weak regulatory environment in the same regard. For example, it is arguable that a significant burden has already been placed on astrophotographers, whose work is adversely affected after the launch of only a few percent of the planned total of nearly 100,000 objects in LEO this decade.

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20 For one well-studied example, see Blair, A. (2016). ***Sark in the Dark: Wellbeing and Community on the Dark Sky Island of Sark***. Sophia Centre Press. http://sophia-project.net/SophiaProjectNews/issues/2016-vol10-sark-in-dark.php. .

21 Simpson, S. N., & Hanna, B. G. (2010). ***Willingness to pay for a clear night sky: use of the contingent valuation method***. Applied Economics Letters, 17(11), 1095, https://doi.org/10.1080/00036840902817508.

22 Amel, E., et al. (2017). ***Beyond the roots of human inaction: Fostering collective effort toward ecosystem conservation***. Science, 356(6335), 275, https://doi.org/10.1126/science.aal1931.

23 ***SpaceX's Satellite Megaconstellations Are Astrocolonialism, Indigenous Advocates Say***, Vice, 5 October 2021 (https://www.vice.com/en/article/k78mnz/spacexs-satellite-megaconstellations-are-astrocolonialism-indigenous-advocates-say)

24 Hamacher, D.W., de Napoli, K. & Mott, B. ***Whitening the Sky: light pollution as a form of cultural genocide***, arXiv:2001.11527 (10 January 2020)

It is clear at this point in time that we do not have a full accounting for all of the known and potential harms associated with a vast increase in the number of LEO satellites expected in the 2020s. It may be further argued that the current international space policy framework is inadequate to address these concerns, and combined with the advent of low-cost commercial launches it has led to a sense in which near-Earth space is the new Wild West where the priority of access is determined by who is the first to arrive. To the extent that near-Earth space represents a kind of commons, as implied by the language of the OST[25], there is now a strong possibility of a tragedy of that commons in which individual users of that space, unhindered by social strictures or meaningful international regulation, simply act in their own self-interest and diminish the resource through their largely uncoordinated activities.[26] Debate over the nature of this commons and the sustainability of its use has fragmented the participants into idealist and conformist factions[27], further muddying the waters as we collectively search for some kind of fair and amicable agreement on the shared use of the resource of near-Earth space. However, all sides seek ***regulatory clarity and certainty, which seems to be the best hope for achieving some kind of consensus moving forward.***

25 Resolution adopted by the United Nations General Assembly, 2222 (XXI). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies. (https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html)

26 See, e.g., Hardin, G. (1968), ***The Tragedy of the Commons***. Science. 162 (3859): 1243,https://doi.org/10.1126/science.162.3859.1243.

27 Verstegen, S. & Hanekamp, J. (2005), ***The sustainability debate: Idealism versus conformism—the controversy over economic growth***, Globalizations, 2 (3): 349

3. Survey of the Amateur Astronomy Community Regarding Impacts of Satellite Constellations

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3.1. Overview

Our working group pursued input from as wide a range of constituencies as possible regarding their views about the impact of large satellite constellations. This report summarizes information gleaned from the amateur astronomy community. As this is an international community, it seemed best to utilize a survey that could be broadly disseminated across the world, relatively rapidly accumulate information

that could be analyzed, and provide quantitative and open-ended qualitative information on viewpoints and attitudes.

3.2. Data Collection

A survey was created using the *Google Forms* tools, which was viewed as the quickest and easiest way to generate an instrument that could be broadly distributed and be compatible across many software platforms across the world. The survey questions are shown in the appendix. As the goal was to "take the pulse" of the amateur astronomy community as broadly as possible, and to allow for some level of analysis, the survey asked several key demographic questions: the primary type of observing of the respondent (visual, astrophotography, both); the level of participation in research activities; and the home country. Questions asked about the degree to which the observing activities of the respondent were impacted by satellite constellations, and the degree to which these satellites affected their appreciation of the night sky (each using a 5-level Likert scale). Open-ended questions for comments and a totally optional opportunity to supply an email address completed the survey.

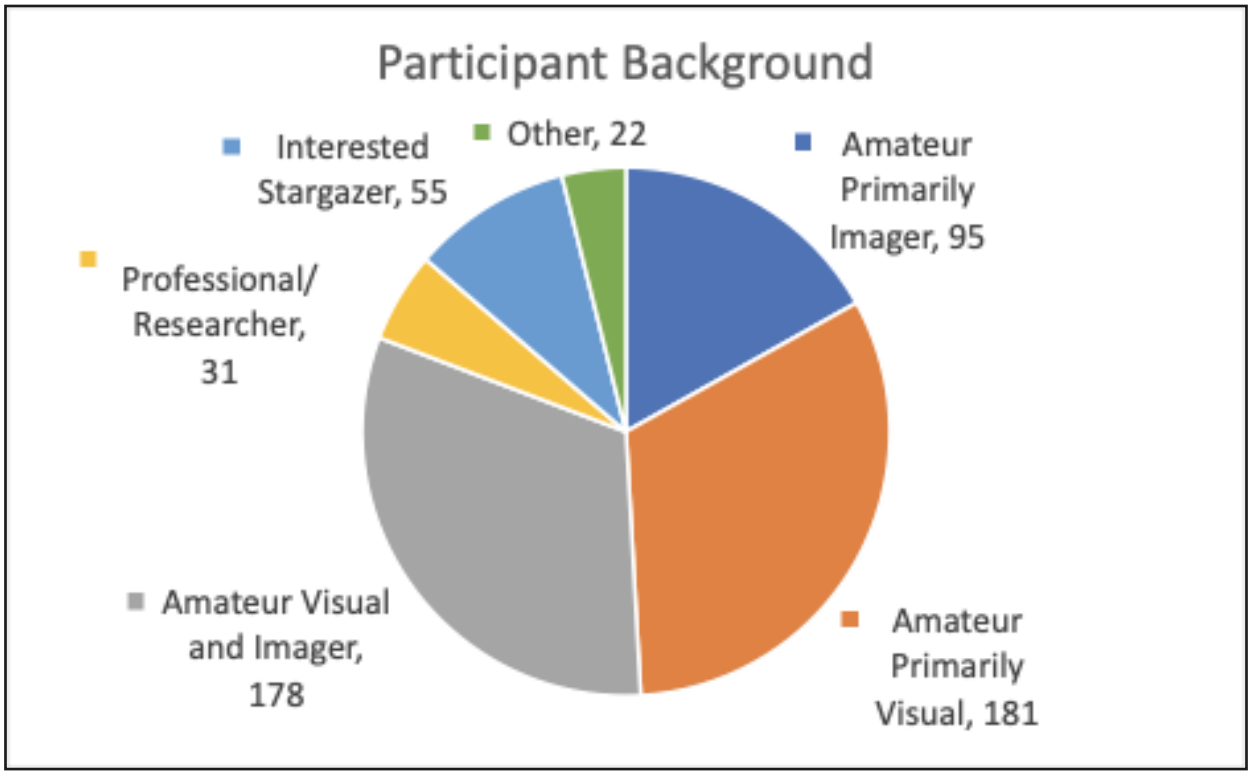
The link to the survey generated by *Google Forms* was posted on as many sites and distributed as widely as we could to reach a broad constituency of amateur astronomers across the world. The distribution was as follows:

- The website and Facebook page of the Mountains of Stars public science education and outreach program[28]
- Through the Night Sky Network, posted by the Astronomical Society of the Pacific both in their newsletter and on their social media sites
- Through the American Association of Variable Star Observers (AAVSO), via their online Forum and social media
- Posted to the Astronomical League for distribution to member clubs
- Posted to the Cloudy Nights online forum
- The e-mail lists of several astronomy clubs, including the Springfield Telescope Makers and the Amateur Telescope Makers of Boston.

In each case, the postings also asked recipients to further distribute the survey link as broadly as possible.

As of this writing (19 August 2021) some 564 responses from 37 countries have been collected. A breakdown of respondents is summarized in Figure 3.

28 https://www.mountainsofstars.org; https://facebook.com/mountainsofstars



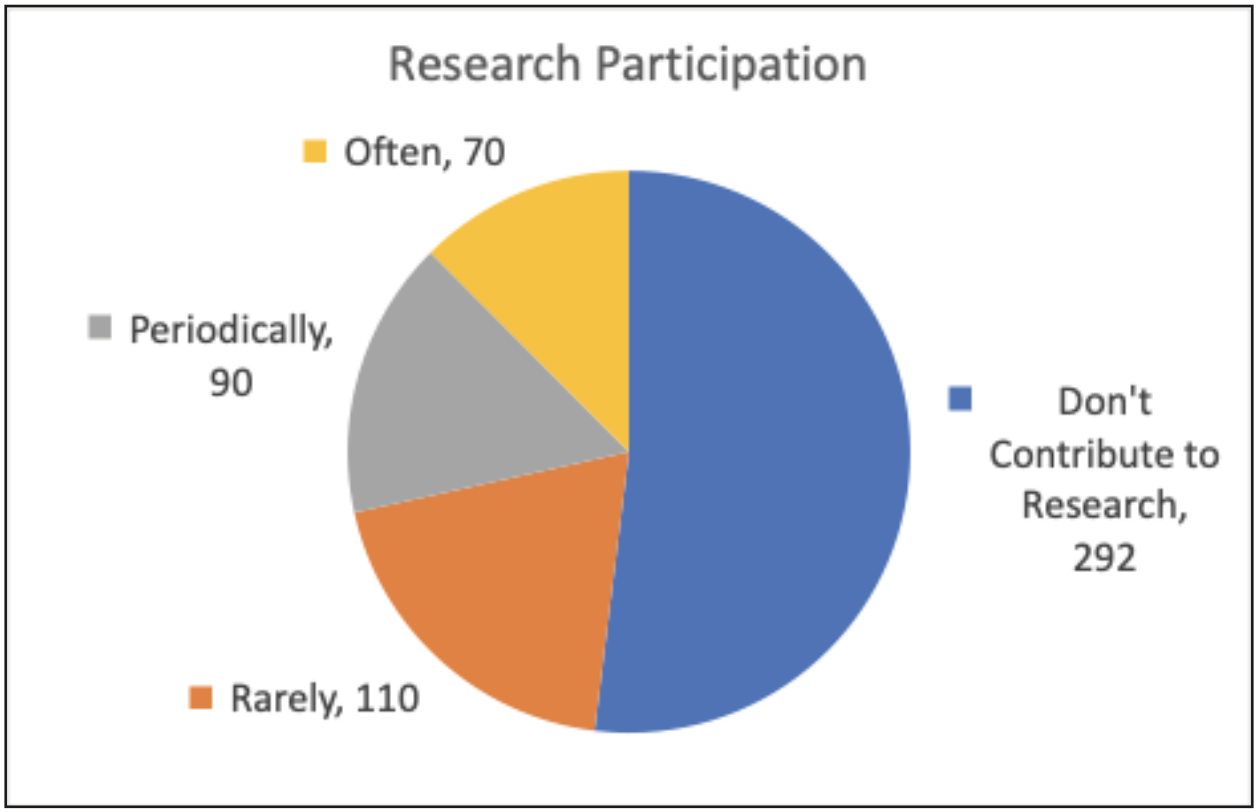


Figure 3. Breakdown of survey participant backgrounds and their contributions to astronomical research.

3.3. Summary of Results

In aggregate, respondents viewed the impact on their observing activities as moderate, with a mean value of 2.6 (+/- 1.3) out of 5 and the impact on their appreciation of the sky as moderate, but somewhat higher, 2.82 (+/- 1.5). The distributions are shown in Figures 4 and 5.

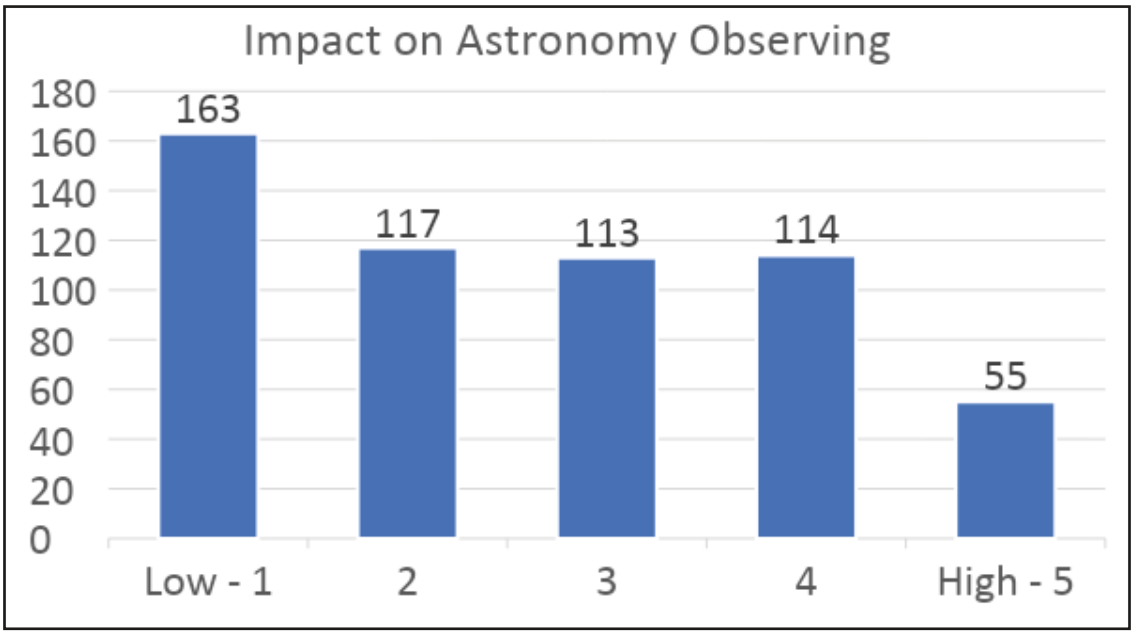


Figure 4. Bar chart displaying the number of survey participants reporting impacts on their observing activities.

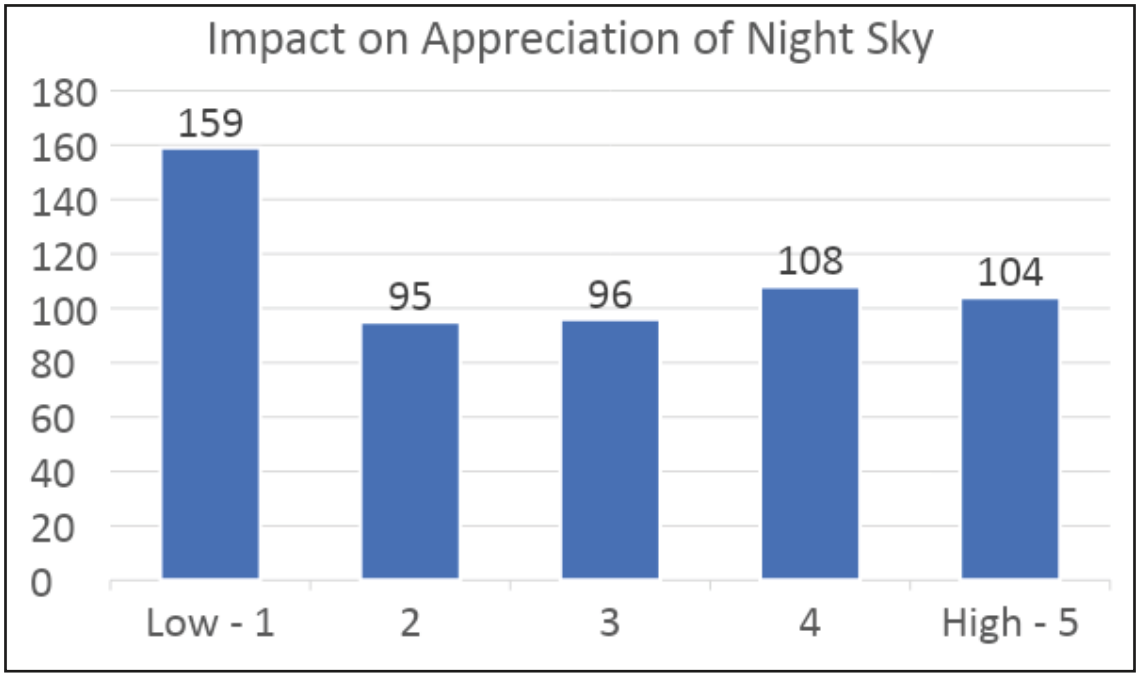


Figure 5. Bar chart displaying survey participants' perception of impact on their appreciation of the night sky.

3.4. Open Ended Comments

Respondents were given the option to submit open-ended comments on their view of both satellite constellations and the potential impact. Comments spanned a wide spectrum. A selection of comments, covering different viewpoints, are highlighted below:

I'm concerned about the current "gold rush" to populate space with micro satellites before governments across the globe put some form of control in place. Right now, it seems left to entrepreneurs with the wealth and means to do so. Commercial interests risk dominating scientific interests and the public good. There really needs to be some global coordination in this area. This could be a limit on the number of satellites, minimum standards for albedo and methods for retrieval such as space salvage — possibly a mix of all. Ultimately the space around our planet should be treated the same as a National Park, with a balance between usage and conservation.

It's only the beginning and the real impacts may come when there are tens of thousands in the sky

The sky should be open for everybody worldwide and not only to those who sent up satellites

It's incredible. I am living at a latitude of 54° north ... and there are always up from 30% to 50% of my photographed single frames "infected" by satellite trails I can't remove by algorithm ... I have to eliminate them by hand ... it's terrible

I reject frames to mitigate the effect on stacked final images, but [it] is another source of data reduction to go with weather, seeing, light pollution etc.

I understand the issues (I'm a satellite engineer at NASA) that a large constellation will have on professional wide field ground based arrays but for the amateur astrophotographer this really isn't a problem. I shoot mainly wide field and I have only had the occasional run-in with Starlink. For the most part I'm just as likely to have a non-Starlink satellite pass through my 3–5-minute exposures. In 2020, I took more than 123 hours of data. This year, in just six months, I already have more than what I collected last year. I've rarely even removed a sub-exposure with a satellite trail because the modern pixel rejection algorithms are so good.

Astronomical research — especially photometry and spectroscopy of transient targets — will be/is being seriously impacted. Unlike pretty picture astrophotography, in which satellite trails can be removed through processing, time-series photometry requires all those sub-frames, and cannot tolerate pixel replacement algorithms to mask the satellites. There are sometimes transient events that happen before astronomical twilight, well over toward the western or eastern horizon, so the argument that the satellites will only be visible/detectable for a short period after sunset or before sunrise isn't valid for this type of research.

I also don't understand why each company needs its own constellation. Seems much more environmentally responsible to send up a much smaller fleet and share between companies.

I'm concerned with the interference to astronomical observations caused by these satellites. Also concerning is the amount of space satellites/debris to be managed to keep astronauts and those of us on the ground safe.

For now, my enjoyment of night viewing has been enhanced with Starlink satellite trains passing overhead. Looks like an alien invasion and at times, surprisingly bright.

I really think that complaining about satellites while ignoring ground based light pollution is just being penny wise and pound foolish. Light pollution makes a much more serious impact.

3.5. Analysis and Discussion

There is some correlation between those who conducted research or were regular imagers and the most negative views of satellite constellations and their impact on their observing programs. The comments made by respondents were generally targeted at limiting or eliminating satellite constellations — generally, approaches that are not likely to happen. Several asked that the satellites be painted black, or not be launched at all. A number of respondents noted that internet accessibility is, fundamentally, a good thing, and the astronomy community is a small, special interest group that should merely accept the satellites. There is no doubt a sampling bias in such surveys; those who have the strongest opinions (pro or con) are more likely to respond.

As there was a need to conduct this process over a relatively short time period, we recognize that there were questions that could have been asked but were not posed. These include (a) a measure of the familiarity of respondents with satellite constellations in general, and (b) a measure of the anticipated impact of satellite constellations as they grow in scale. A number of respondents addressed the latter on their own in their responses, noting that while satellite constellations *currently* may not pose a major barrier to their observing or astrophotography, they were concerned about what the future could bring. If a follow-up survey is administered when a larger number of satellites has been launched, these two questions will be valuable in parsing the responses and correlating the degrees of impact and attitudes about satellite constellations.

It is heartening that over 560 respondents around the world took the time to respond to this survey. Nevertheless, it would take substantial resources to fully analyze the data (using software such as SPSS) to identify potential correlations between observer type and attitude towards and impact of satellite constellations, for example, and the other cross-tabulations that such a data set offers, and must be weighed against any potential value such an analysis would have in addressing satellite constellations.

3.6. Input and follow-up from Town Hall discussion

The participants in the SATCON2 Town Hall Breakout Room offered both opinions on the current state of affairs and a number of concrete plans of action. There was concern that amateur astronomers are being blindsided; in particular, not enough information is being distributed to the community. Related to this, it was suggested that there has not been sufficient modeling of actual satellites since SATCON1. Concerns were voiced that the problem will become significantly enhanced in the future, as larger launch vehicles make it possible to launch hundreds of small satellites at a time. Discussion ensued around the fact that visibility of satellites depends on latitude and inclination of the orbit, so some regions will be more affected than others. More tracking is needed; the existence of a UK program was noted. Heavens Above

also shows which satellites are up, including Starlinks. It was suggested that this could be used to gauge the number/impact of them. In general, amateur astronomers may have to become more proactive (less "meek" in the words of one participant).

In terms of concrete actions, a suggestion was made to reorient satellites in order to lower their reflectivity when passing over major observatories. Another way of attacking the problem is to increase availability of broadband fiber optics and 5G internet, thus reducing the need for many of these satellites. In particular, politicians should be contacted and used as advocates (e.g., Senator Shaheen). Fiber optic technology is currently preferred to satellites in some locations (e.g., New Hampshire) because it is more durable, less weather-dependent, carries more kinds of data, provides better uploads, and is a better long-term investment. Therefore local economic development organizations could be helpful partners in finding a long-term solution to the explosion of satellite constellations. In turn, concerned citizens should be encouraged to make their preference for fiber over satellite known to their local governments, utility companies, and economic development agencies.

Returning to the issue of educating the amateur community (and beyond) about the problem, it was requested that a central information hub be created. Information about satellites that could be useful for planning observing runs would be helpful. It was suggested that the AAS provide follow-up to this meeting, for example creating an email list for attendees to stay in touch if desired. The leadership of the AAS should use their political and corporate connections to aid in the push for fiber over satellite; a partnership would serve both astronomical and corporate interests. It was also suggested that the amateur astronomy and astrophotography communities work together in educating their members, as they have shared interests and parallel concerns.

Finally, we need to hold the satellite constellation operators responsible; they should be more transparent with their plans, and explain to the general public and politicians clearly and honestly what the benefits, dangers, and trade-offs are of satellite constellation implementation. Politicians should hold operators to international agreements protecting the night sky at optical and radio wavelengths, not merely to the strict letter of the law, but to the spirit as well. Members of the general public should hold their elected representatives responsible in this regard.

While this survey and related public fora focused on the impact of satellite constellations on amateur astronomers, it must be noted that the division between amateur and professional astronomy is fuzzy, at best. Organizations such as the AAVSO and the Center for Backyard Astrophysics demonstrate the important follow-up work done by amateur astronomers, contributing literally millions of data points to our understanding of the Universe. A threat to amateur astronomy is therefore a threat to professional astronomy, interfering with our ability to both understand the Universe and effectively guard against unexpected threats from outer space (including both deorbiting satellites and near-Earth asteroids).

3.7. Survey Form

Here we include the text of the survey to the amateur astronomy community.

Impact of Large Satellite Constellations on Astronomy

As individuals engaged with the night sky, you are in an important position to help guide efforts to understand the impact of large satellite constellations on astronomy and enjoyment of the night sky. Data obtained through this survey will be used to inform the writing of the SATCON2 report - which will be used as part of our effort to address the impacts of satellite constellations on astronomy.

* Required

1. In what country are you located? *

2. I would characterize myself as: *

Mark only one oval.

- ◯ Professional astronomer/researcher
- ◯ Amateur astronomer - primarily visual
- ◯ Amateur astronomer - visual + imager
- ◯ Amateur astronomer - primarily imager
- ◯ Interested stargazer/appreciator of the night sky
- ◯ Other: _____

3. I contribute to research programs, such as variable star light curves, exoplanet confirmations, supernova searches, etc. *

Mark only one oval.

- ◯ Often
- ◯ Periodically/occasionally
- ◯ Rarely
- ◯ Don't contribute to professional research

4. My general sense of large satellite constellations (such as Starlink and Oneweb) is: *

Mark only one oval.

- ◯ A major issue impacting professional and amateur astronomy
- ◯ A modest issue impacting professional and amateur astronomy
- ◯ A minimal issue impacting professional and amateur astronomy

5. My observing has been affected by large satellite constellations (e.g., Starlink) *

Mark only one oval.

	1	2	3	4	5	
Little to no impact	◯	◯	◯	◯	◯	Substantial impact

6. My appreciation and enjoyment of the night sky has been negatively affected by large satellite constellations: *

Mark only one oval.

	1	2	3	4	5	
Very little	◯	◯	◯	◯	◯	Very much

7. Please provide any comments/suggestions you have regarding large satellite constellations, including additional information you would like to receive, ideas for mitigating effects, etc.

8. If you are willing to contribute additional thoughts/information to this project, please provide your e-mail address. This information is not required, and will not be shared outside of this study.

4. Perspectives from Indigenous Communities

The primary authors of this section and subgroup members are, in alphabetical order of last name:

Fernando Avila Castro (Mestizo / Universidad Nacional Autónoma de México)
David Begay (Diné, Indigenous Education Institute and U. of New Mexico)
Juan-Carlos Chavez (Yaqui/Sonora, affiliate at the Blue Marble Space Institute of Science)
Alvin Harvey (Diné, MIT)
Kaʻiu Kimura (Native Hawaiian, ʻImiloa Astronomy Center of Hawaiʻi)
Annette Lee (Ojibwe and D(L)akota, St. Cloud State University)
James Lowenthal (Smith College)
Nancy Maryboy (Diné/Cherokee, Indigenous Education Institute and U. of Washington)
Hilding Neilson (Mi'kmaw, University of Toronto)
Doug Simons (Canada France Hawaiʻi Telescope and U. of Hawaiʻi)
Aparna Venkatesan (U. of San Francisco)

International perspectives on this report's topics were offered by Hilding Neilson, Fernando Avila Castro and Michele Bannister (non-Indigenous (Pākehā), University of Canterbury, New Zealand).

This report shares a summary of perspectives and needs as directly stated by our Indigenous colleagues and conference participants at SATCON2, primarily through the Community Engagement Working Group. We emphasize that these speakers and participants speak for themselves and their own experiences only, not their whole community or all Indigenous peoples or tribal nations.

We also respectfully draw the reader's attention to the References and Further Reading section at the end, which includes a brief (incomplete) compilation of articles co-authored by this subgroup's members and others on Indigenous perspectives in space and related report topics, as well as recent articles featuring subgroup members that draw attention to the ongoing role of satellite constellations in "astro-colonialism" and space as an environmental commons.

Opening the workshop, Dr. Chavez began by drawing attention to our relationship with Mother Earth and Father Sky, asking that we honor their gifts and take responsibility for our actions and choices as we

began this conversation. He invited all those working on these issues to bring our best intentions to this journey, and to seek ways to heal and learn from the past so we can do better and be better as beloved communities. He ended by seeking permission to continue in a good way so that our desire to progress does not come at the cost of elders or with ideals of empire, but so we can proceed in ways that honor our interconnectedness.

4.1. Key Themes

Some key themes that emerged from the morning talks and the afternoon Town Hall and breakout room on Indigeous and international perspectives are described below.

Indigenous peoples are part of sovereign nations — they are not special interest groups. Satellite constellations that are visible by the unaided eye on Earth will impact Indigenous peoples. The SATCON1 report noted in passing that the satellites might affect wayfinding practiced by different Indigenous peoples. It is commendable that the SATCON2 working groups included greater discussion about how Indigenous peoples might be harmed by or benefit from these satellites, including the voices of some Indigenous peoples. However, Indigenous peoples were included in the discussion as a special interest group along with amateur astronomers, astrophotographers, and others. This is inappropriate because Indigenous peoples in Canada and the United States are groups of sovereign nations with rights highlighted by treaties and the United Nations Declaration of the Rights of Indigenous Peoples. Consulting and including Indigenous peoples in a working group is a positive step from the SATCON1 report, but more work is needed for that discussion to be nation-to-nation and not colonizer-to-Indigenous peoples.

Altered relationship with the cosmos. Indigenous workshop speakers shared that "*satellites literally interrupt our relationship with the stars and ceremonial ways of connecting with them*", "*Stars are our ancestors and erasing them is erasing our tellings and scientific-cultural traditions*", and "*Land, sky and oceans are relationships, a verb*". Speakers emphasized the need for a relational ethical approach to space built on consensus and consultation. There is also a profound shift in our view of the stars as a fixed sphere, as we introduce more human-made moving objects into this realm.

A new form of colonization. The perspectives of Indigenous peoples with respect to outer space and the expected rapid growth of satellite constellations are important and necessary. Indigenous peoples from around the globe have observed the night sky since time immemorial and have a sophisticated and complex relationship with the visible night sky. As sovereign peoples and cultures, the rapid growth of these satellite constellations can have a significant and negative impact on this relationship. Many Indigenous stories are written in the stars. Light pollution has acted to erase Indigenous stories and identities — again — disconnecting these peoples from the night sky, mirroring the painful history of colonization in which Indigenous peoples lost their land and water. Speakers viewed light pollution as erasing their stories and satellites as rewriting them. They shared successful collectives to honor and preserve ancestral knowledge about Indigenous star stories and sky traditions, including Pai Pai star stories[29] from the bilingual 68 Voices project[30] based in Mexico, and the highly successful nonprofit Native

29 https://68voces.mx/pai-pai-el-origen-de-los-celos
30 https://68voces.mx/

Skywatchers[31] founded by astronomer-artist Dr. Annette Lee. Speakers also raised the disproportionate impact of colonization, climate change and COVID19 on Indigenous communities.

Duty to consult. Indigenous peoples and nations must be consulted and their decisions should be respected. Many nations might view these satellites as inappropriate and as another form of pollution or colonization, but many nations might view the benefits of the satellites, such as access to broadband internet, as being valuable to their communities. However, it is not the purview of the workshop report authors, or academia and industry, to dictate the impact of these LEO satellites on Indigenous peoples. As such, the discussion would be better served as a nation-to-nation dialogue that includes consultation and consent.

Urgent need for cultural competency in space agencies and space actors. The accelerating situation with satellite constellations and the use of near-Earth space reveals an urgent need for space policy and scientific programs rooted in cultural competency and sensitivity to cultural traditions. NASA could lead the way by having an Office of Tribal Affairs or an Office of Cultural Protocol. Such an office could address ongoing practices around sensitive issues (e.g., what is heritage and who gets to define it; the thriving export business of human remains and ashes to near-Earth space). Several participants also suggested that NASA is missing an opportunity for due diligence on a major international issue: engaging sovereign nations in space exploration. NASA has much to learn from Indigenous ways of knowing and integrative scientific-cultural practices such as wayfinding, which have reflected for millennia the relatively new NASA values of Inclusion and Mission Success. Participants shared that a talking circle with NASA leadership is needed — something that has been very rich when allowed to happen — rather than the current approach of being sent in circles when Indigenous scientists and communities wish to be heard.

We can also learn from inclusive or creative approaches in other countries, e.g., in New Zealand, a small yet highly active spacefaring nation. Recent major national shifts in cultural competency include the official declaration[32] of the heliacal rising of Matariki (The Pleiades) as a national holiday honoring Māori calendrical and cultural traditions. In addition, national initiatives in New Zealand are required to protect and enact Māori principles and incorporate Māori in economic and cultural development, as per Te Tiriti o Waitangi | the Treaty of Waitangi. The New Zealand government has to consider how any policy affects Māori empowerment and communities, including for instance in science implementation and funding.[33] New Zealand has five dark-sky reserves at present, for culture, astrotourism, and science; iwi-owned astrotourism in the largest reserve contributes to rural economic development, and the increased visibility of satellites there has been noted.

Legal and policy issues in space in the context of treaties with Sovereign Indigenous Nations. A growing number of issues need legal clarification and explicit addressing[34]. These include: how do we define the environment of the Earth, where does Earth end and space begin, and what is the legal jurisdiction of Earth's laws? What are the legal obligations for state and private actors in space given existing treaties with sovereign Indigenous nations? We need written agreements between industry,

31 https://www.nativeskywatchers.com/
32 https://www.mbie.govt.nz/business-and-employment/employment-and-skills/employment-legislation-reviews/matariki/matariki-public-holiday/
33 http://www.maramatanga.co.nz/sites/default/files/Rauika%20Ma%CC%84ngai_A%20Guide%20to%20Vision%20Ma%CC%84tauranga_FINAL.pdf
34 E.g., https://www.nature.com/articles/d41586-021-01954-4

spacefaring countries and Indigenous nations that respect these treaties and these communities' sovereignty. Such agreements must be transparent and include cost analysis so that agreements are not dependent on a new generation of leaders and people. Looking at New Zealand's approach once more, Aotearoa (the Maori name for New Zealand) is a new Artemis Accords signatory with public statements[35] emphasizing Māori principles of sustainability and stewardship of natural resources, as applied to outer space, which is termed an environment. Legal scholars are yet to answer the broader legal question of whether night skies are implicit in the multiple existing agreements and treaties between state actors and Indigenous peoples.

Systematic studies are needed on the viability of satellite broadband and outcomes for economic development. Two of our subgroup members drew attention to the unfolding situation as regards satellite broadband in their countries.

In Mexico, as an example, Dr. Avila Castro shared that as of July 2021, according to official data[36] 31% of the working population earns 3700 pesos a month or less, or approximately a third of the population earns $185 USD or less a month at current exchange rates of $1 USD = 20 pesos. Only 2% of the working force earns 18,700 pesos ($925 USD) a month. The announced price of Starlink in Mexico is the same as in the USA: An initial $500 USD (10,000 pesos) and a monthly fee of $99 USD (2,000 pesos). With this information we can easily see that Starlink is completely out of reach of the vast majority of the population. On the other hand, Mexico has 84 million internet users which is around 70% of the overall population. In urban areas, internet coverage is acceptable and affordable through cellular (3G, 4G), and ground-based internet (DSL, cable, optic fiber). As with other services, rural areas are the ones left behind so it could be argued that Starlink could fill those gaps in coverage. However, rural areas have the lowest incomes meaning that satellite internet is completely unaffordable for them. Even if resources are pooled to share a satellite link for the whole community, infrastructure has to be acquired, installed, and maintained (routers, cables, WiFi antennas, etc) and at that point it makes more sense to solve the last mile problem through conventional internet access. But let's expand the scenario even further, e.g., that Starlink is installed and operating through a community effort. What is going to happen if the Starlink project doesn't pan out and has to shut down the service? Now the community has invested a lot of money, only to be left with some proprietary antennas that are no longer useful. This is what technological colonization means in a developing country. You no longer own the infrastructure or services — they are owned instead by a private company in a foreign country[37]. So for the developing world, satellite internet in this form does not have a real market to expand, nor does it have a long term benefit for the people. However, people in these countries will suffer the increase in light pollution, and the loss of their traditional tales and stories in the skies. Any short-term benefits from satellite broadband may therefore be eclipsed by long-term economic and other impacts, with no clear path of recovery.

35 https://www.beehive.govt.nz/release/space-exploration-soars-artemis-accords

36 Data come from the National Institute of Statistics, Geographical Information (INEGI), and the Federal Institute of Telecommunications (IFT).

37 More broadly, fiber optic cables can serve multiple data-carrying functions in multiple formats for multiple providers and users from individuals to corporations to governments for multiple decades. In contrast, satellite dishes to access satellite broadband internet are fixed to one household account with one private provider corporation using one format of data transmission, and are prone to rapid obsolescence.

In the case of the nation of Canada, Dr. Neilson shared that access to broadband internet has been promised by governments for years[38]. To that end the Canadian government has committed support to the satellite company Telesat[39] which currently has a constellation of about 300 LEO satellites in space to provide broadband internet access to almost two million Canadians who lack affordable access. Most of this access will impact large areas of Canada with small population densities who are disproportionately Indigenous. At the time of writing, it is unclear whether and how many communities have been consulted about this.

Nuanced approaches without appropriation are required. Indigenous peoples have their own governance, rights and needs. Both academia and industry should avoid statements emphasizing preferred narratives around satellite constellations. We must avoid such appropriations of Indigenous perspectives and needs, or misinterpreting them for pre-determined uses — this is a real issue now that astronomers are at the receiving end of colonization. Nuanced approaches that engage in long-term relationships and listening with communities are needed, recognising that consensus building happens differently in each community and culture. This is not a single issue across all Indigenous peoples (e.g., cultural sky traditions); rather, this is a complex tradeoff between broadband access, economic development, cultural heritage, and survival (many Indigenous peoples do not have access to clean water or other basic necessities).

We end by sharing that the co-Chairs of the Community Engagement Working Group were invited into extended dialogue with a circle of Oceania wayfinders ranging from Hawai‘i to Aotearoa and many Pacific communities, starting in the week of the SATCON2 workshop. It would be inappropriate to attempt to summarize these conversations this early in the process, but we honor the wayfinders’ gracious invitation into dialogue as we collectively move forward to preserve the health and integrity of the ocean above us as well as the ocean between our lands.

We express gratitude and support for these Indigenous perspectives offered at SATCON2. We hope that we can listen, consult, learn from the past and co-create an ethical sustainable future in space that honors our interconnection and does not come at the expense of things that belong to us all.

38 https://crtc.gc.ca/eng/internet/internet.htm
39 https://www.telesat.com/about-us/

5. Planetariums and the Satellite Constellation Challenge

The primary authors of this section are:

- James Sweitzer (Science Communication Consultants, USA; Subgroup member)
- Ryan Wyatt (California Academy of the Sciences)
- Ka Chun Yu (Denver Museum of Nature & Science)
- Michael McConville (Evans & Sutherland)

The primary attendees of the SATCON2 Community Engagement Working Group breakout session on planetariums were:

- Ryan Wyatt (California Academy of the Sciences)
- Ka Chun Yu (Denver Museum of Nature & Science)
- James Sweitzer (Science Communication Consultants, USA)
- Patrick Seitzer (University of Michigan)
- Rosemary Walling (Marie Drake Planetarium)
- David Galadi Enriquez (Calar Alto Observatory)
- Andreas Haenel (Museum am Schölerberg)

5.1. Introduction

Planetariums deliver accurate, dark, artificial starry skies on demand. In an era when the natural night sky is under threat from light pollution and now satellite constellations, planetariums could well become a leading method to communicate the satellite constellation challenge and educate a broad range of people, whether they live in urban or rural areas, about these problems. Unfortunately, some 83% of the world's population live under light polluted skies. Few have ready access to natural dark sky sites either. Planetariums might therefore be the only starlight refuges we have to educate the public. These "domed

cosmic classrooms" should not be regarded as a separate, threatened community, but rather as trusted voices for the protection of the night sky.

We are now approaching the 100th anniversary of the first modern planetarium, in Munich, Germany. Today, planetariums number 4000 worldwide in nearly 90 countries. They include fixed and portable domes with both digital systems and traditional opto-mechanical projectors. More than 1700 of the planetariums are now digitally fulldome capable. The advantage of fulldome video systems is that they can display either real-time simulations or pre-rendered videos of virtually anything that can be visualized for a hemisphere. Displaying simulations of artificial satellites and showing their impact should be a straightforward task for contemporary planetariums.

Aside from their technical capabilities and broad geographic reach, planetariums connect with larger in-person astronomical audiences than any other mode by nearly two orders of magnitude. Current pre-COVID estimates top out at over 100 million global planetarium attendees per year. In contrast, a quarter of a million students are enrolled in American introductory astronomy courses. Planetariums also reach a truly international audience with programs in their native language. And unlike online media, planetarium experiences generally include contact with real astronomers, educators and experts. For much of the world, planetarians *are* the face of astronomy.

5.2. Assessing satellite constellation impacts in planetariums

Along with their worldwide distribution and ability to reach large audiences, planetariums also offer four programmatic and technical opportunities and one organizational bonus for the community concerned about the impact of satellite constellations.

1 The technical capabilities of planetariums allow them to share visualizations that accurately illustrate satellite constellations. What better way to understand the problem than to see and compare for oneself? Planetarians have been teaching children and adults to identify constellations in the night sky for nearly a century. Simulating the challenge of light pollution has long been a staple of planetariums. Augmenting that natural sky with a new set of realistic-looking, artificial lights in motion is a straightforward task for planetariums.

2 Planetariums are natural venues to celebrate the many cultural dimensions of humanity's relationship with the night sky. They regularly present programming that addresses celestial practices and beliefs of diverse cultures today, as well as the traditional views of the past. This practice of featuring indigenous storytelling and culturally-rooted star shows and sky traditions is well developed in many planetariums. These programs have proven to be among the most popular with audiences. Planetariums offer a familiar and trusted venue to celebrate our common heritage and respect for the dark night sky. The planetarium world also realizes it must go beyond traditional approaches to cultural stories and instead become places for giving people and groups a chance to speak for themselves. The yearly Live Interactive Planetarium Symposium (LIPS) meetings are a natural forum for engendering such programs.

3 During the fulldome digital planetarium revolution of the past twenty years, ambitious shows have been developed with sophisticated visualizations able to tackle subjects that would never

have been approached in the past. Planetarium show content now ranges from storytelling for children to accurate visualizations of the bending of light around the supermassive black hole in M87. Storylines can be as complex as those seen on NOVA, the popular documentary television series. For example, Big Astronomy, an ambitious planetarium show with a broad perspective on the enterprise of research astronomy including a number of social and cultural themes, also includes Vera C. Rubin Observatory, which will be extremely vulnerable to satellite constellations because of its large etendue.

4 Many planetariums also offer live presentations that augment pre-recorded shows like Big Astronomy. This offers an opportunity for planetarians to contextualize the effect of satellite constellations in terms of topics addressed by the shows. A "live section" following Big Astronomy, for example, could highlight the effect of satellite constellations on the Rubin Observatory Legacy Survey of Space and Time (LSST) program, followed by tips on how audience members can act to preserve dark skies. Live segments can be considered as "rapid deployment presentations" for timely topics like satellite constellations.

5 Planetariums can deliver emotional astronomy experiences and be used for artistic performances. Although they are admittedly "second best" to stunning dark night skies in nature, they are on-demand and accessible to even the most light-polluted populations. They bring the night sky experience to the people. All planetarians, no matter what the show they are presenting, know the power of the stars. Ironically, this *affective* capability of planetariums might prove to be the most important factor for addressing the satellite constellation challenge. This is because we face a challenge to motivate the public similar to the one the environmental movement has had to deal with for decades. The British environmental writer Michael McCarthy argues that engendering an emotional connection to nature may prove to be the best approach for engaging the general public:

   We should offer up not just the notion of being sensible and responsible about [nature], which is sustainable development, nor the notion of its mammoth utilitarian and financial value, which is ecosystem services, but a third way, something entirely different: we should offer up what it means to our spirits; the love of it. We should offer up its joy.

The planetarium community also offers an organizational bonus. Although widespread and institutionally diverse, they are a relatively close-knit group. This means that any programming created for planetariums or for professional development programs can be distributed via well-established organizational channels. A prime channel is the International Planetarium Society (IPS). This organization can, with coordinated and adequately funded programs, reach nearly every planetarium in the world. The IPS has already connected with the SATCON2 Community Engagement Working Group and initiated the formation of an educational working group of their own. In addition, other planetarium communities of practice, such as LIPS, support professional development with a focus on how to engage audience members.

5.3. Recommendations

During the SATCON2 online meeting and subsequent discussions, the following specific thoughts regarding planetariums were offered, some of which can be used as action items for the coming months

and years. (Because planetariums operate primarily within educational, nonprofit organizations they will require financial, partnership, and in-kind support to legitimize and achieve the actions outlined below.)

- Convene a group of planetarians, astronomers, system operators and software developers who can begin the task of creating databases of orbital elements and algorithms for rendering satellite visibility that can be shared among the different software vendors. (Several in the breakout group volunteered to help and the list of others who need to be in this group, such as planetarium software vendors, has been assembled.)
- Produce short, "live presenter" planetarium content that can be added in the near future to shows that are already running in multiple planetariums. This can be done in the coming year. For example, Big Astronomy could be augmented with short live sections that might show how Vera C. Rubin Observatory would be impacted. Other add-on life segments could be developed and added to other pre-rendered programs.
- Begin production planning for a more comprehensive, pre-rendered show that includes a more complete discussion of satellites and the challenges of the commercialization of near space.
- Start creating content and activities for professional development opportunities for the planetarium community. As of late summer 2021, planetarians are still meeting remotely. The hope would be to have such content ready for the renewed in-person meetings in 2022 and beyond.
- Establish a "satellite event" portal where the planetarium and amateur astronomy communities could share the information they need to help their audiences learn about satellites first hand. This would also allow opportunities for these two communities to connect and collaborate.
- The IPS is interested in progressive ways to use planetariums to give agency and voice to many who have not had a chance to be represented in their theaters. The satellite constellation challenge could be a welcome catalyst for new discussions about the night sky we all share.
- Planetariums worldwide will be celebrating the 100th anniversary of the first planetarium between 2023 and 2025. In April of 2024 an important total solar eclipse will be seen in North America. The challenges presented by satellite constellations should be folded into the educational efforts over the coming years.

Satellite constellations pose threats to our celestial commons and heritage in ways that are unprecedented. Good decision making and effective solutions will require a well-informed and educated public. The planetarium community has the capacity to be an important contributor to this effort. They have been trusted conveyors of the messages of the stars for over three generations. Now is the time for them to begin to prepare future generations for a more sustainable and equitable space habitat.

6. Environmental and Ecological Impacts of Satellite Constellations

The primary authors of this section and subgroup members are:

James Lowenthal (Smith College)
Diana Umpierre (Sierra Club)
Erika Nesvold (JustSpace Alliance)
Sally Carttar (National Park Service)

The Environmental Impacts subgroup of the SATCON2 Community Engagement Working Group researched and discussed numerous aspects of environmental and ecological impacts of satellite mega-constellations, held a virtual listening session with the Sierra Club, held dedicated presentation and discussion sessions during the SATCON2 workshop, and reached out to numerous individuals with expertise in environmental conservation and related concerns. Here we report the main issues and themes that surfaced from those inquiries and discussions.

We offer three main recommendations, summarized here and expanded below:

1. Earth-orbiting space should be considered part of Earth's environment, legally and otherwise.
2. Satellite constellations should not be exempt from NEPA review.
3. Sovereignty should be respected with regard to space and the night sky.

6.1. Historical, political, and environmental context

Just as the SATCON2 conference got underway to grapple with the challenges posed by Elon Musk's SpaceX Starlink and other mega-constellations of LEO satellites, news headlines around the world highlighted the race to space by two other billionaires, Jeff Bezos of Blue Origin and Richard Branson of Virgin Galactic. At the same time, much of the American and Canadian west was suffering from record-breaking heat waves and wildfires, as was Greece, while other areas, including parts of Germany and Belgium, saw massive and fatal flooding following unprecedented torrential rainfall, all exacerbated by anthropogenic climate change. Several members of the Community Engagement Working Group and people interviewed pointed out the ironic contrast between the dire material needs of the vast

majority of the Earth's population and the indulgences of some of the richest men in the world, as if the wealthy were literally escaping a planet on fire by means unavailable to most people. Others drew parallels between the current space race, including the development of satellite constellations, and the long history of colonial imperialism over the last millennium: the new natural resource up for grabs is space itself, to be exploited and capitalized by the highest bidders and the quickest and largest private corporations.

International legal and philosophical conception of the need to protect space for all humanity was enshrined, soon after the advent of the Space Age, in the OST. The OST lays the foundation for peaceful international cooperation and universal access to space, but it contains no explicit reference to the need for environmental protection against harm from human activities in space. More than 50 years later, facing the prospect of a rapid and manifold expansion and commercialization of activity in space, the United Nations Office of Outer Space Affairs (UNOOSA) issued the first Guidelines for the Long-Term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space (UN COPUOS 2021). Guideline A.2 reads in part:

> *In developing, revising or amending, as necessary, national regulatory frame- works, States and international intergovernmental organizations should...:*
>
> > *b: Implement space debris mitigation measures, such as the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, through applicable mechanisms;*
> > *c: Address, to the extent practicable, risks to people, property, public health and the environment associated with the launch, in-orbit operation and re-entry of space objects;*

Gilbert & Vidaurri (2021) study existing national and international case law and conclude that consideration of the NEPA should be applied to space activities — contrary to the practice of the US Federal Communications Commission (FCC), which is to disregard environmental impacts when considering applications by satellite operators for licenses to launch and operate satellite constellations. Sutherland (2021) describes the process by which NASA applies NEPA, in contrast to the FCC. Cirkovic (2021a,b) argues for a new "cosmolegal" conception of space and space law that recognizes the limitations of traditional terrestrial legal frameworks and the potential risks from overcrowding of orbits, space debris, and possible contamination of other planets by human activity in space. Comparisons between the problems of space debris, satellite constellations, and climate change become even more concrete given the prediction that increasing levels of atmospheric CO_2 will reduce drag on LEO satellites, making them stay in orbit longer (O'Callaghan, 2021).

Thus there is growing concern about the environmental impacts of satellite constellations, and precedent for implementing regulation and national and international law to control, mitigate, minimize, or eliminate those impacts.

6.2. Environmental harm from satellite constellations

Environmental harm from satellite constellations occurs during all three phases of satellite constellation lifetimes. Below we summarize the major impacts we found in the literature and from our discussions.

I. Impacts to the natural and human environment identified or predicted from launching satellite constellations include**:**

   a. Large quantities of CO_2, NOx, water vapor, and other greenhouse gases and toxic substances are produced by combustion of liquid and/or solid fuel during rocket launches (see Dallas et al., 2020 for a comprehensive review). Depending on the type of fuel used and the size of the launching rocket, up to 300 tons of CO_2 can be produced per launch. The breakdown of water vapor released in the stratosphere leads to depletion of the ozone layer (Marais, 2021).
   b. Combustion of kerosene fuel produces black carbon, and combustion of solid rocket fuel produces soot and alumina, both of which can affect the albedo (reflectivity) of Earth's atmosphere to sunlight (Lawler & Boley, 2021).
   c. Pollution associated with rocket launches, including over sensitive habitats such as the Gulf Coast in Texas and Cape Canaveral in Florida, negatively impacts humans and wildlife alike. Rocket launching facilities that are placed in environmentally delicate areas and/or near low-income or marginalized people raise questions about environmental justice and equity, e.g., the SpaceX spaceport near Boca Chica, TX (Sandoval & Webner, 2021).
   d. Falling debris and explosions associated with failed rocket launches have raised concerns and protest among neighbors of proposed launching sites, e.g., Little Cumberland Island, Georgia, where Camden County plans a new spaceport (Marvar, 2021).

II. Impacts on the natural and human environment identified or predicted from operating LEO satellites at orbit-raising and final station altitude include**:**

   a. Possible disruption of various species' ability to navigate using the stars. A wide range of species are suspected or known to use the stars and even the Milky Way to navigate (e.g., Foster et al., 2018; Sokol, 2021; Fritts 2021), from dung beetles (Foster et al., 2021) to bats (Stone, Harris & Jones, 2015), harbor seals (Mauck et al., 2008), and migratory songbirds (Emlen, 1967; Wiltschko et al., 1987; Pakhomov, Anashina & Chernetsov, 2017). The possibility that the proliferation of bright artificial LEO satellites could lead to the disruption of migration by many millions or billions of individual animals (Lintott & Lintott, 2020) is still new enough just two years after the first launch of Starlink satellites that no peer-reviewed studies have been published yet reporting confirmed impacts of satellite constellations on animals; however, numerous members of the working group felt that there was sufficient reason to be concerned about such possible effects on animals that the precautionary principle should apply, and that launches should be halted unless and until the effects are demonstrated to be negligible.
   b. Interference with the timeless and profound human experience of regarding the starry sky. The night sky is a fundamental part of nature, and one that provides us with solace, inspiration, and connection with countless generations before us and, one hopes, yet to come. The human right to see the naturally dark, unpolluted, starry night sky has been articulated in the Declaration in Defense of the Night Sky and the Right to Starlight (Starlight Foundation, 2007), and Resolution B5 in Defence of the Night Sky and the Right to Starlight (International Astronomical Union, 2009), and by the US National Park Service, which operates an extraordinarily popular Night Skies program whose motto is "Half the Park is After Dark" and whose philosophy is that naturally dark skies are, like clean air and clean

water, a natural resource to which every human has a right (National Park Service, 2021). Satellite constellations have the potential to dramatically and irrevocably alter the naked-eye appearance of the night sky (e.g., Lawler, Boley & Rein, 2021; Lawler and Boley, 2021; Skibba, 2021).

c. Earth-orbiting satellites know no national boundaries, and several Community Engagement Working Group members pointed out the need to respect the sovereignty of other nations, including Native American and other Indigenous peoples, who may regard outer space and the night sky as part of the environment, even if the FCC does not.
d. The rise in overall night-sky brightness due to the combined light from many thousands of satellites, even if individually invisible to the naked eye, may already be a significant new form of light pollution; Kocifaj et al. (2021) calculate that the night sky may already be as much as 10% brighter than natural as a result of the integrated reflected light from all artificial objects currently in orbit, including fewer than 2000 Starlink satellites out of more than 10,000 planned; that contribution to overall sky brightness will inevitably grow as more satellite constellations are put in orbit. Reasonable estimates based on planned satellite constellations just in the 2020's imply that the night sky could be artificially brightened by as much as 250%, erasing the view of the Milky Way and more than half of naked-eye visible stars (see the Astrophotography subgroup report of the Community Engagement Working Group). The circadian rhythms of humans and animals are generally thought to be controlled by the perception of integrated and diffuse light such as from the sky (Brown, 2016), rather than from individual light sources, and many species are sensitive to extremely low levels of light, well below 1 lux (e.g., Walbeek et al., 2021). Therefore an overall elevation of night sky brightness by satellite constellations may have profound and negative effects on many or most species of flora and fauna on Earth. Again, the field is too new for there to be published empirical studies yet, but Community Engagement Working Group members argued that the precautionary principle should apply.
e. Some interviewees indicated that any potential impacts on the integrity and continuance of Earth Observation (EO) satellites from orbital debris collisions and especially a potential debris cascade (the Kessler syndrome) due to overcrowding of orbits would be points of major concern to the environmental and ecological justice community, from scientists and activists to policy makers. Many of those EO satellites operate in LEO. For decades, EO satellites have provided data that have helped humanity understand, appreciate and protect the planet's atmosphere and ecosystems. They have exposed the vulnerability of our planet and the limits of our natural resources. They provided evidence and now the means to monitor our progress, or lack thereof, in tackling the climate and biodiversity crises. Whether directly or indirectly, whether knowingly or not, these constituents have benefited from EO observations in their work on ecosystems, natural resources, wildlife biodiversity, agriculture, food security, transportation, weather, water and air quality, light pollution, wildfires, disaster response, smart growth, climate adaptation, energy transition, social justice, and much more.

   Unfortunately, because the focus on identifying and communicating impacts and mitigations related to satellite mega-constellations has been primarily on astronomy, most of the communities working on environmental, ecological and social justice issues (including

non-profit organizations) are largely unaware of the challenges that thousands of new LEO satellites, and associated space debris, could pose to current and future EO satellites.

While intentional and meaningful outreach to these communities has only recently started, questions from them so far have included:

- Who is bearing the burden of costs associated with tracking these many objects, mitigating potential issues, and the loss or reduction of public benefits, if the operations of EO satellites are compromised?
- Will future launches of EO satellites be affected or reduced by more congested LEOs?
- How will cascading collision events, especially with untracked debris, affect the EO satellites we have come to depend on in respect of issues of great environmental importance, such as monitoring pollution and land cover changes affecting people and wildlife?
- What sustainability and carrying capacity studies are being carried out, if any, to ensure the safety and health of the planet's atmosphere and the equitable access to near-Earth orbits, especially among marginalized communities?

f. Community Engagement Working Group members pointed out that even with sophisticated decommissioning plans in place, individual satellite operators can go, and already have gone, bankrupt, potentially leaving thousands of satellites stranded in orbit, perhaps for thousands of years. This is perhaps analogous to leaving wrecked cars by the side of the highway indefinitely, a practice no modern society accepts.

III. Impacts on the natural and human environment identified or predicted from decommissioning LEO satellites include:

a. Aluminum and rare-earth metals deposited mostly in the atmosphere and the oceans but also on land during re-entry of satellites, either planned or accidental. Boley & Byers (2021) estimate that from the eventual re-entry of the fewer than 2000 Starlink satellites already in orbit as of this writing, the deposition of aluminum into the atmosphere will exceed that from all natural causes, primarily the steady rain of small asteroids and micrometeoroids (roughly 50 tons per day), that Earth collects (e.g., Rojas et al., 2021).

b. The greatly increased likelihood, given the numbers of satellites planned in LEO, of unplanned or uncontrolled re-entries resulting in the direct impact of satellites or satellite fragments with the ground, possibly causing direct injury or loss of life to humans or animals. Residents of the Pacific Northwest got a dramatic demonstration of such a scenario when a SpaceX Falcon 9 made an uncontrolled re-entry into the atmosphere, producing a spectacular fireball witnessed by thousands (Ives, 2021).

The Community Engagement Working Group makes the following recommendations regarding the proven or plausible impacts on the human and natural environment of launching, operating, and decommissioning LEO satellite constellations:

1. **Earth-orbiting space should be considered part of Earth's environment, legally and otherwise**. There was a strong consensus that the region of space occupied by Earth-orbiting satellites and the night sky should be considered an integral part of the environment and of the human experience of the natural world. To limit the concept of the environment to the surface of Earth and its atmosphere but to exclude the starry night sky or even objects passing through the atmosphere en route to or returning from LEO is to make an arbitrary distinction that defies common sense and universal experience.
2. **Satellite constellations should not be exempt from NEPA**. There was strong consensus that NEPA, which the FCC has so far declined to invoke in considering licence applications by potential operators of satellite constellations, should in fact be applied, and that environmental impact studies should be required components of such license applications.
3. **Sovereignty should be respected with regard to space and the night sky.** Even if the FCC does not consider space to be part of the environment or subject to NEPA review, other nations can and do consider space, the starry sky, the Milky Way, the planets and the Moon to be part of the environment, nature, cosmology, cultural and spiritual heritage and practice. Introducing satellite constellations to the night sky, especially if bright enough to be seen naked eye, thus threatens the autonomy and wellbeing of people of other sovereign nations including Indigenous and First Nations people, and undermines the concept of space as a commons as enshrined in the OST.

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Acronyms & Abbreviations

Acronym/ abbreviation	Meaning	First appears on page
OBSERVATIONS chapter		
AO	adaptive optics	27
BRDF	Bidirectional Reflectance Distribution Function	20
COPUOS	(UN) Committee on the Peaceful Uses of Outer Space	18
D&QS Report	Dark & Quiet Skies Report	3
EIRP	effective isotropic radiated power	20
FCC	Federal Communications Commission	18
IAU	International Astronomical Union	3
ITU	International Telecommunications Union	18
LEO	low-Earth orbit	1
LEOsat	LEO satellite	1
NIR	near-infrared	2
OEM	orbit ephemeris message	19
OMM	Orbit Mean-elements Message	24
STK	Systems Tool Kit	26
TLE	two-line element	2
WCS	World Coordinate System	9
ALGORITHMS chapter		
18SPCS	US Space Force 18th Space Control Sqn.	20
API	applications programming interface	13
BRDF	bidirectional reflectance distribution function	17
CADC	Canadian Astronomy Data Centrer	12
ESA	European Space Agency	12
GNSS	Global Navigation Satellite System	22
GPU	Graphics Processing UNit	17
ICRS	International Celestial Reference System	6
ILRS	International Laser Ranging Service	20
ITC	International Telecommunications Corporation	22

IVOA	International Virtual Observatory Alliance	5
JSON	software protocol	17
LEO	low-Earth orbit	3
TAP	Table Access Protocol	17
TLE	two-line element	19
WCS	World Coordinate System	6
ITRF	International Terrestrial Reference Frame	20
CCSDS	Consultative Committee for Space Data Systems	22
COMMUNITY ENGAGEMENT chapter		
AAS	American Astronomical Society	6
AAVSO	American Association of Variable Star Observers	21
IPS	International Planetarium Society	40
LEO	low-Earth orbit	2
LIPS	Live Interactive Planetarium Symposium	39
NEPA	National Environmental Policy Act	5
OST	Outer Space Treaty	5
UNOOSA	UN Office of Outer Space Affairs	43
FCC	Federal Communications Commission	44
IAU	International Astronomical Union	6
EO	Earth Observation	47
POLICY Chapter		
AAS	American Astronomical Society	5
AP	National NEO Preparedness Strategy and Action Plan	28
ATLAS	Asteroid Terrestrial-impact Last Alert System	41
BRDF	Bi-directional Reflectance Distribution Function	102
CBD	Convention on Biological Diversity	60
CE	Categorical Exclusion	48
CEQ	Council on Environmental Quality	8
CNEOS	Center for Near Earth Object Studies	41
COPUOS	(UN) Committee on the Peaceful Uses of Outer Space	4
COSPAR	Committee On Space Research	29
CSLA	Commercial Space Launch Act	23

EIA	Environmental Impact Assessment	48
EOL	end of life	10
EPFD	Equivalent Power Flux Density	99
FAA	Federal Aviation Administration	7
FCC	Federal Communications Commission	7
FEMA	Federal Emergancy Management Agency	39
GSO	geostationary orbit	25
IAA	International Academy of Astronautics	42
IAU	International Astronomical Union	9
IAWN	International Asteroid Warning Network	27
IDA	International Dark Sky Association	31
IES	Illuminating Engineering Society	31
IRTF	Infrared Telescope Facility	41
ITU	International Telecommunications Union	25
LEO	low-Earth orbit	12
LRTAP	Convention on Long-Range Transboundary Air Pollution	66
LTSG	Guidelines for the Long-Term Sustainability lof Outer Space Activities	7
MANOS	Mission Accessible Near-Earth Objects Survey	41
MLO	Model Lighting Ordinance	31
NASA	National Aeronautics and Space Administration	23
NEO	near-Earth object	27
NEOWISE	NEO Wide-field Infrared Survey Explorer	41
NEPA	National Environmental Policy Act	7
NOAA	National Oceanic & Atmospheric Administration	7
NPS	National Park Service	36
NRAO	National Radio Astronomy Observatory	44
NRQZ	US National Radio Quiet Zone	44
NSF	National Science Foundation	11
ODMSP	Orbital Debris Mitigation Standard Practices	10
OST	Outer Space Treaty	4
PDCO	[NASA] Planetary Defense Coordination Office	39
PIERWG	Planetary Impact Emergency Response Working Group	40
PP	precautionary principle	58

PPD	(AAS) Public Policy Department	90
PPP	planetary protection policy	3
RQZ	Radio Quiet Zone	7
SIA	Satellite Industry Association	91
SMPAG	Space Mission Planning Advisory Group	27
SPD	Space Policy Directive	21
STM	space traffic management	7
TLE	two-line element	103
UN	United Nations	4
UNDRIP	UN Declaration on the Rights of Indigenous Peoples	8
UNESCO	United Nations Educational, Scientific and Cultural Organization	85
UNFCCC	UN Framework Convention on Climate Change	60
UNOOSA	UN Office of Outer Space Affairs	27
US NSPP	National Strategy for Planetary Protection	30
VCPOL	Vienna Convention for the Protection of the Ozone Layer	59