Megaconstellations of Satellites and Their Impact on Astronomy: A Potential Need for International Regulation

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Abstract

The recent activity of launching into low earth orbits (LEO) large constellations of satellites is posing a number of technical and regulatory issues. In particular, a totally unexpected issue has also emerged, which poses one of the most significant challenges: the visual impact that huge numbers of satellites placed in LEO is having on the Earth's night sky. The present paper will first examine the nature of this problem, and will then analyze it from the point of view of Space Law. The overall conclusion is that existing international regulation is insufficient, current efforts at self-regulation are giving at best limited results, and therefore new legal rules will be necessary in order to fully address this issue. International Space Law in force does provide some basic principles that could inspire a future regulation, in particular those contained in Articles I, III, VI, and IX of the Outer Space Treaty.

1. Megaconstellations of Satellites

1.1. Definition and Purposes

Over the past few years, a new human activity has quietly emerged in outer space. Large networks of artificial satellites, known as satellite constellations or satcons, have been designed and are already being deployed for a variety of purposes in Low Earth Orbit (LEO).

A satellite constellation is defined as "a number of similar satellites, of a similar type and function, designed to be in similar, complementary orbits for a shared purpose, under shared control."[1] This is certainly not a new concept: several constellations have been for years providing key services

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1 Wood, Lloyd, *Satellite constellation networks*, Springer 2003, p.13: https://link.springer.com/chapter/10.1007/978-1-4615-0431-3_2.

such as global navigation satellite services[2], satellite telephony and paging[3], or low-latency general communications[4].

What is new is that we are now considering hundreds, even thousands of satellites per constellation. Hence the name "megaconstellations" with which these new gigantic networks are referred to colloquially, to distinguish them from the first constellations that were launched in previous decades.

Megaconstellations have the aim to provide global communications services, in particular low-latency broadband internet connectivity to remote areas where terrestrial alternatives such as wired networks are limited or do not exist. Apparently there is a market for internet access via satellite. Unlike the global mobile telephony companies back in the 1990s, which found a much lower demand than expected and ended in bankruptcy, satellite broadband coverage has a potentially strong demand.[5]

Nowadays, around 60 percent of the world's total population uses internet.[6] However, there are many rural or remote areas on the planet that currently have no service or have a very low quality one, even in large swaths of developed countries like the US, Canada, or Europe; this is more so in developing countries. This means a potential market of three billion people worldwide who are currently without reliable internet access.

A global demand for internet and other services, however, does not explain by itself the new phenomenon: there are also technical and financial reasons. The advent of increasingly capable smaller satellites in the last twenty years has made much more feasible to build and launch into orbit lighter, cheaper satellites in high numbers. And venture capital and other sources of funding for NewSpace is more abundant than ever.[7] Finally, national security applications for global internet networks are also plentiful and inescapable.[8]

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2 Such as GPS (24 satellites in Medium Earth Orbit, MEO), Glonass (same) and Galileo (same).

3 Such as Iridium (66 satellites), Globalstar (about 48 satellites), or Orbcom (29 satellites).

4 Such as O3b (20 satellites in MEO), owned by SES, and operational since 2013.

5 Garber, S. J. and Vedda, J. A.,"Déjà vu or sea change? Comparing two generations of large satellite constellation proposals" The Space Review, July 1, 2019: https://www.thespacereview.com/article/3747/1. For a more up-to-date (and pessimistic) view, see Rusch, Roger, "What could happen to the LEO broadband constellations?" Space News, December 13, 2021: https://spacenews.com/op-ed-what-could-happen-to-the-leo-broadband-constellations/.

6 https://datareportal.com/reports/6-in-10-people-around-the-world-now-use-the-internet#:~:text=As%20we%20revealed%20in%20our,the%20start%20of%20April%202021.

7 https://www.thespacereview.com/article/3747/1; https://spacenews.com/op-ed-what-could-happen-to-the-leo-broadband-constellations/.

8 Foust, Jeff, "Handicapping the megaconstellations," The Space Review, March 2, 2020: https://www.thespacereview.com/article/3892/1; Erwin, Sandra, "DoD eager to leverage LEO broadband constellations," Space News, November 15, 2021: https://spacenews.com/dod-eager-to-leverage-leo-broadband-constellations/.

1.2. Current Constellations

Starlink (based in Hawthorne, California), owned by Space X, has plans for the largest megaconstellation so far, with the goal of providing worldwide coverage of high-speed broadband internet.[9]

In 2016, SpaceX filed an application with the Federal Communications Commission (FCC) for a "non-geostationary orbit satellite system in the Fixed-Satellite Service using the Ku- and Ka- frequency bands".[10] Since 2019, SpaceX is launching successfully and repeatedly batches of 60 Starlink satellites aboard its *Falcon 9* rocket from Kennedy Space Center, Florida. Starlink currently has nearly 1,800 satellites orbiting at 550 km altitude, and the aim is to have nearly 12,000. Should demand for its service increase, it is possible to expand the network: SpaceX has requested authorization to launch up to 30,000 Starlink satellites.[11] Starlink already tested its satellite broadband internet system with hundreds of users, and in 2021 the company claimed to have 100,000 subscribers in 14 countries.[12]

OneWeb (based in London) also aims to provide global broadband internet coverage. The company started launching its initial 648-satellite constellation in February 2019 using *Soyuz* rockets from Baikonur. OneWeb uses higher orbits than its rivals, with satellites placed at an altitude of 1,200 km. In March 2020, OneWeb announced it had filed for Chapter 11 bankruptcy in a New York court. However, the company exited bankruptcy in November 2020, and it is now under ownership by a consortium consisting of the UK Government, Hughes Communication, Bharti Global Limited, SoftBank, and Eutelsat. This network is also scalable, first up to 6,372 and eventually to some 48,000 satellites.[13]

Kuiper. Amazon announced in April 2019 its own LEO satcon for providing broadband services, and has likewise filed paperwork and received FCC approval in July 2020 for its Project Kuiper, based in Redmond,

9 https://www.starlink.com/; https://en.wikipedia.org/wiki/Starlink.

10 https://licensing.fcc.gov/cgi-bin/ws.exe/prod/ib/forms/reports/swr031b.hts?q_set=V_SITE_ANTENNA_FREQ.file_numberC/File%20Number/=/SATLOA2016111500118&prepare=&column=V_SITE_ANTENNA_FREQ.file_numberC/.

11 Henry, Caleb, "SpaceX submits paperwork for 30,000 more Starlink satellites,", Space News, October 15, 2019: https://spacenews.com/spacex-submits-paperwork-for-30000-more-starlink-satellites/.

12 Lyons, Kim, "SpaceX CEO Elon Musk says Starlink internet service leaving beta in October," The Verge, September 18, 2021: https://www.theverge.com/2021/9/18/22681185/spacex-ceo-elon-musk-starlink-internet-service-leaving-beta-october.

13 https://oneweb.net/; https://en.wikipedia.org/wiki/OneWeb_satellite_constellation.

Washington.[14] Consisting of 3,276 satellites, Kuiper features three layers of satellites, one each at 590 km, 610 km, and 630 km orbital altitude. As of this writing, no Kuiper satellites had been launched into space yet, but launch agreements have already been concluded to that purpose.[15]

Telesat. The Ottawa-based company Telesat, one of the world's largest operators of commercial GEO comsats, is working on its own 298-satellites broadband LEO constellation, officially named Lightspeed. In 2020, Telesat filed plans that would allow it to launch to LEO over 1,600 satellites.[16]

Other constellations. In 2021, Boeing received FCC's approval to launch and operate 132 satellites to 1,056 kilometers (LEO) as part of a planned constellation for broadband communications.[17]

A Texas-based venture called AST Space Mobile is working on a network of up to 243 court-sized cellphone towers about 720 kilometers high, aiming to provide satellite connectivity to already existing mobile phones. AST received authorization for its project from Papua New Guinea, raising for the first time some concerns about the use of "flags of convenience" in space activities.[18] Lynk, headquartered in Virginia, is also developing a constellation to provide direct connectivity for regular cellphones. Lynk ultimately envisions operating as many as 5,000 satellites in LEO, communicating with mobile phones all over the world without the need for special antennas or other equipment.[19]
The Defense Advanced Research Projects Agency (DARPA) of the US Department of Defense (DoD) has considered a LEO constellation called Blackjack, which also aims to develop and demonstrate a global high-speed network in LEO.[20] Additionally, some LEO constellations such as PlanetLabs (150 satellites) are aimed at achieving continuous Earth observation for commercial purposes.[21]

14 https://spacenews.com/amazons-kuiper-constellation-gets-fcc-approval/; https://en.wikipedia.org/wiki/Kuiper_Systems.
15 https://www.bizjournals.com/seattle/news/2021/09/02/amazon-fcc-project-kuiper-redmond-satellites.html.
16 https://www.telesat.com/leo-satellites/; https://en.wikipedia.org/wiki/Telesat.
17 Rainbow, Jason, "FCC approves Boeing's 147-satellite V-band constellation", Space News, November 3, 2021: https://spacenews.com/fcc-approves-boeings-147-satellite-v-band-constellation/.
18 https://ast-science.com/spacemobile/; Dunstan, James, "Who wants to step up to a $10 billion risk?", Space news, June 25, 2021: https://spacenews.com/op-ed-who-wants-to-step-up-to-a-10-billion-risk/.
19 https://lynk.world/our-technology.
20 https://www.darpa.mil/program/blackjack.
21 https://www.satrev.space/; https://www.planet.com/our-constellations/.

All in all, the FCC alone has authorized at least ten satellite constellations to be launched in the next few years[22]. And China (Guo Wang or 'National Network,' with 12,992 satellites[23]) and the European Union[24] have also announced plans for creating new broadband internet megaconstellations on their own.

1.3. The Impact of Megaconstellations in Space Activities

As a result, since 2019, the number of satellites placed in orbit is increasing rapidly, with plans to deploy potentially tens of thousands of them. At the present rate, satcon satellites will soon outnumber all previously launched satellites.[25] One report predicted that there may be up to 100,000 satellites launched into LEO in the coming decade.[26]

Large satcons are posing a number of challenges. Some of them are already familiar to space lawyers: registering large batches of satellites; avoiding harmful radioelectric interference between satcons and other space and terrestrial stations; enhancing space situational awareness amidst a growing orbital crowding; and managing increasingly larger amounts of space traffic and orbital debris. In addition to all that, a totally unexpected issue has emerged, one which may pose one of the most significant problems: the visual impact that huge numbers of satellites placed in near earth orbits is having on the night sky.

2. Initial Impact on the Night Sky. Reaction of the Astronomical Community

On 23 May 2019, SpaceX launched a first packet of sixty Starlink satellites, deploying them in an initial orbit of 440 kilometers high. These satellites immediately started causing unintended consequences for astronomy. Some amateur astronomers caught pictures or even videos of a "train" of satellites flying together across the night sky and shining as bright as the Pole Star. Though the visual brightness of the spacecraft shortly after launch is not representative of their brightness once they reach their final positions, the pictures and videos that were uploaded in mass media generated a discourse

22 Werner, Debra, "Will megaconstellations cause a dangerous spike in orbital debris?" Space News, November 15, 2018: https://spacenews.com/will-megaconstellations-cause-a-dangerous-spike-in-orbital-debris/.

23 https://spacenews.com/china-is-developing-plans-for-a-13000-satellite-communications-megaconstellation/; https://techcrunch.com/2021/06/06/chinas-drive-to-compete-against-starlink-for-the-future-of-orbital-internet/.

24 https://www.forbes.com/sites/jonathanocallaghan/2020/12/23/europe-wants-to-build-its-own-satellite-mega-constellation-to-rival-spacexs-starlink/?sh=5a42b8de1252.

25 As a way of comparison, in early 2019, right before Starlink's first launch, there were only about 1,950 operational satellites in orbit.

26 https://www.thespacereview.com/article/3747/1 (see note 5 above).

on the effect of space commercialization on astronomical research and society more generally.[27]

The truth is that, even though plans for these constellations had been in the work for years, the brightness of the satellites came as a shock to astronomers and to the general public.[28]

The International Astronomical Union (IAU)[29] first showed its concern about the new satellite megaconstellations in a public statement issued on 3 June 2019:

> The IAU embraces the principle of a dark and quiet sky as not only essential to advancing our understanding of the Universe of which we are a part, but also as a resource for all humanity... We do not yet understand the impact of thousands of visible satellites scattered across the night sky... Despite the huge growth in space-based astronomy that has happened in the last few decades, (as exemplified by the Hubble Space Telescope and many other recent missions), as of today most astronomical research is still ground-based, both types (space-based and ground-based) being fundamental to astronomy. (…) The IAU urges appropriate agencies to devise a regulatory framework to mitigate or eliminate the detrimental impacts on scientific exploration as soon as practical.[30]

Other institutions that issued statements in 2019 about the deployment of large constellations of bright satellites into Earth orbit were the International Dark Sky Association (IDA),[31] the National Radio Astronomy Observatory of the United States of America (NRAO),[32] the American Astronomical Society (AAS)[33], and the European Southern Observatory (ESO)[34]:

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27 Young, Monica, "The New Space Race", *Sky & Telescope*, March 2020, p. 15. See also Langbroek, Marco, "SpaceX Starlink Objects train 24 May 2019," at https://vimeo.com/338361997.
OneWeb also started launching its first satellites in 2019, although it did so more discreetly than Starlink.

28 *Sky & Telescope*, March 2020, p. 15. See also Wall, Mike, "Why SpaceX's Starlink satellites caught astronomers off guard", Space.com, January 10, 2020: https://www.space.com/spacex-starlink-satellites-megaconstellation-surprise-astronomers.html.

29 Founded in 1919, the IAU is an international non-governmental organization that brings together more than 13,500 professional astronomers from more than 100 countries worldwide in order to protect and develop astronomy. See https://www.iau.org/administration/about/.

30 See the complete IAU statement at: https://www.iau.org/news/announcements/detail/ann19035/.

31 See at: https://www.darksky.org/starlink-response/.

32 See at: https://public.nrao.edu/news/nrao-statement-commsats/.

33 See at: https://aas.org/posts/news/2019/06/aas-issues-position-statement-satellite-constellations.

34 ESO is an international intergovernmental organization composed of 16 European nations plus Chile, devoted to conducting ground-based astronomical research in the Southern hemisphere: https://www.eso.org/public/about-eso/.

> ESO and other observatories are evaluating the effects that these satellite constellations will have on ground-based optical and infrared astronomical observations. ESO… is taking measures to raise the awareness of this issue in global fora such as COPUOS, while exploring practical solutions with space companies that can safeguard the large-scale investments made in cutting-edge ground-based astronomy facilities. ESO supports the development of regulatory frameworks that will ultimately ensure the harmonious coexistence of highly promising technological advancements in low Earth orbit with the conditions that enable humankind to continue its observation and understanding of the Universe.[35]

3. Actual Impact of Mega-Constellations in the Night Sky

The primary concern of astronomers so far has been the Starlink constellation, as it is already operating and it involves several thousands of medium-sized satellites. Hundreds could be in view at any given time, producing streaks in images that could affect observations.

Starlink satellites' visual brightness at their operational altitude makes them all but invisible for the average citizen living in an urban or suburban area. But they will have a noticeable effect on the night sky in rural areas or as observed through a telescope. Given that the satellites will be distributed in 24 orbital planes, with 66 satellites in each plane, "if you happen to look into one of these planes, you will see one satellite after another, much as the recurring overhead jets that are seen and heard near a major airport."[36]

Satellites (whether in a constellation or not) can be seen only when they are reflecting sunlight: as the night advances, they fall into the Earth's shadow and cease to be visible. Simulations show that the visibility of a satcon will depend on the time of the day, the season of the year, and the height of the orbit.

The hours following sunset and preceding sunrise are particularly bad in terms of optical interferences from satellites. This is because the satellites flying up high are still (or are already) receiving the solar illumination even though on the ground it is already (or still) night time. However, astronomers do use those so-called twilight hours for observing, because all large professional telescopes have a demand that is much bigger than the available time, and all the night time proper is always assigned to many different observers.

In terms of seasons, summer nights are shorter and therefore satellites tend to stay visible for longer periods of time. Finally, orbital height very much influences both the brightness of a satellite and the duration of its interference with astronomical observations. Satellites at lower altitudes are

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35 See the complete ESO statement at: https://www.eso.org/public/announcements/ann19062/.

36 *Sky & Telescope*, March 2020, p. 16.

brighter as seen from the ground, but on the other hand, they dissapear earlier from view. As the altitude is raised, brightness is reduced, however satellites are visible for longer periods during the night. Satcons orbiting at altitudes higher than 600 km, such as OneWeb, are particularly problematic: they look fainter, but they will be reflecting sunlight for a larger fraction of the night, and in summertime they could be visible all night long.[37]

In March 2020, ESO published a study that examined the effects of satellite constellations on its Very Large Telescope (four 8-meter telescopes) and the upcoming Extremely Large Telescope (with a primary mirror 39 meters in diameter), all located in Chile. The ESO study considered a total of 18 satcons under development by SpaceX, Amazon, OneWeb and others, together amounting to over 26 thousand satellites. It concluded that both telescopes would be "moderately affected," with up to 3% of long-duration exposures ruined by passing satellites around twilight. The effects would be less severe for shorter exposures and those taken later at night, as the satellites would be in the shadow of the Earth and therefore not visible. The impact could be lessened by making changes to the operating schedules of ESO telescopes, though these changes come at a cost in terms of time and money.[38]

Prospects are worse for another telescope that is currently under construction in Chile: the US National Science Foundation's Vera C. Rubin Observatory. That 8-meter telescope, designed for taking wide-field images of the whole sky every three nights with the idea of recording any visible changes, could have 30% of its twilight observations "severely affected" by satellite constellations, according to the ESO study. One of Rubin's mandates is to seek out between 60 percent and 90 percent of all near-Earth asteroids that may pose a collision threat to the Earth and thus serve a key warning function for planetary defense. This task will be more difficult to do under the new circumstances.[39]

Another study came out in January 2022 which looked at the number of Starlink trails seen in images captured by the Zwicky Transient Facility (ZTF) at Caltech's Palomar Observatory (California). The study found that from November 2019 to September 2021, there were 5,301 streaks seen in ZTF images. In 2019 only half a percent of twilight images had streaks, but they are now seen in about 1 of every 5 twilight images. This is concerning because twilight images are critically important to the search for near-Earth asteroids. The study also pointed out that the mitigation strategies used by Starlink are not sufficient to avoid an impact on astronomy.[40]

37 *Sky & Telescope*, March 2020, pp. 16-7.
38 https://www.eso.org/public/news/eso2004/.
39 https://www.eso.org/public/news/eso2004/; *Sky & Telescope*, March 2020, pp. 17-18.
40 https://www.caltech.edu/about/news/palomar-survey-instrument-analyzes-impact-of-starlink-satellites.

4. Mitigation Measures Taken So Far. The Role of Self-Regulation

4.1. Mitigating measures Taken So Far

Beyond evaluating the environmental impact of megaconstellations in terms of light pollution of the night sky, the astronomical community undertook early on an effort to approach the corporations that are establishing these networks, in particular SpaceX, OneWeb, and Amazon. As a result, all three companies have been in contact with astronomers to collaborate and find ways to mitigate the problem.

There are several mitigating measures that companies can take. The first obvious solution is to make satellites less reflective to interfere less in astronomy. SpaceX has worked to reduce the brightness of Starlink satellites in several ways. The first step was to give them a different orientation so that they would reflect less sunlight downwards. SpaceX is using a roll maneuver twice per orbit that puts the solar panel in line with the Sun, presenting a "knife's edge," and ultimately keeping it hidden from the ground.[41]

Another early approach adopted at the request of astronomers was to paint in black the bottom part of the satellites so that they would reflect less sunlight. The US and other countries have been using these low-tech invisibility cloaks for decades for many military satellites to make detection more difficult.[42]

Accordingly, SpaceX put a dark coating on the earth-facing parts of one Starlink satellite, dubbed "Darksat", launched in January 2020. However, while the experimental darkening made the satellite less visible to backyard astronomers, the dimming was not enough to help professional observatories. In any case, this tactic had to be abandoned because the black paint made the satellite absorb more sunlight and become thermically "hot", which affected its primary function as an internet transmitter.[43]

After April 2020, a "sunshade" or what amounts to a sun umbrella was instead added to each of the Starlink satellites, shielding the spacecraft from the Sun, and thus preventing sunlight from being reflected downwards. The sunshade is securely attached to the comsat and it does not need to be deployed, so it is a simple solution, while avoiding the thermal balance problems. This approach has been nicknamed "Visorsat". Preliminary analyses show that, at least during the night hours, Visorsats become virtually invisible. Occultations of stars by the satellites themselves will be still a nuisance for astronomy, but it is not nearly as problematic as reflected sunlight.[44]

41 https://skyandtelescope.org/astronomy-news/details-spacex-starlink-visorsat/.

42 Foust, Jeff, "Stars and Starlink", The Space Review, March 30, 2020: https://www.thespacereview.com/article/3911/1.

43 https://skyandtelescope.org/astronomy-news/starlink-astronomers-update/.

44 https://www.thespacereview.com/article/3911/1; https://skyandtelescope.org/astronomy-news/starlink-astronomers-update/; https://skyandtelescope.org/astronomy-news/details-spacex-starlink-visorsat/.

In addition, SpaceX is making public the orbital elements of all its already launched spacecraft in order to help astronomers track and avoid them; and it is also now providing predictive data before every new launch for the same purpose.[45] Starlink trajectories have been published through space-track.org[46] and celestrak.com[47], which many astronomers use in timing their observations to avoid satellite streaks.[48]

Astronomers themselves can take some measures to mitigate the effects of megaconstellations. They may schedule their observations out of the twilight hours. They might even program their observations so as to avoid catching the streaks of the satellites in their images; however, this requires a very precise knowledge of the position of the satellites and their times of overflight. Another approach would be to use software that eliminates the satellite streaks from celestial images after these have been taken. Removing trails of satellites and airplanes in astrophotos is possible, and software and techniques exist that are already well established in this regard. However, the brightest satellites generate echoes or noise bands that saturate all the pixels; images so affected must be completely discarded. Additionally, any adjustment taken by the professional observatories will cost money both in operational time and in the additional researcher effort needed to fix data contaminated by satellites.[49]

4.2. The Role of Self-Regulation

As described above, a number of mitigating measures have been taken so far by the operators, which is encouraging. Eventually, this information-sharing and cooperation channel that has been opened between industry and scientists may enable the creation of best practices aimed at ensuring the compatibility of ground-based astronomy and LEO constellations.

Advanced self-regulatory measures such as codes of conduct approved by all the industry would be particularly useful and could even have an indirect legal relevance by exposing non-compliers.

Starlink claims in their website that:

> While it will not be possible to create satellites that are invisible to the most advanced optical equipment on Earth, by reducing the brightness of the satellites, we can make the existing strategies… dramatically more effective. SpaceX is committed to making future satellite designs as dark as possible. (…) As launch costs continue to drop, more constellations will emerge and they too will need to ensure that the optical properties of their satellites do not create problems for

45 https://skyandtelescope.org/astronomy-news/details-spacex-starlink-visorsat/.
46 http://space-track.org/.
47 http://celestrak.com/.
48 https://www.spacex.com/updates/starlink-update-04-28-2020/index.html.
49 *Sky & Telescope*, March 2020, p. 17.

> observers on the ground… [W]e are working to make this problem easier for everyone to solve in the future.[50]

This approach is consistent with the present era, which favours de-regulation and evaluation by market forces. Governments may prefer to allow the space industry to regulate itself, while maintaining some vigilance over the effectiveness of the approach. External pressures such as enforcement of best practices or new legal rules would be introduced only if necessary.[51]

However, self-regulating attempts may fail, given the inherent conflict of interest in asking any organization to police itself. Not all businesses and countries may voluntarily meet best practice standards in the absence of binding norms compelling them to do so.[52] And astronomers face the risk of a change of mind by SpaceX and the other operators. As more ventures enter this market, will they all be motivated and resourced to make similar efforts? One unethical or incompetent actor would have disastrous consequences.[53]

We also suffer the lack of clear rules. For instance, one vital goal is to reduce the brightness of satellites, but how much brightness is adequate? The astronomers have been quick in proposing a first standard[54]: luminosity should in no case exceed the seventh magnitude[55], which so far has been acknowledged by the operators. But it would be much more reassuring to have that standard (and others as well) adopted as a legal norm.

5. The Need for Regulation

The current absence of rules preventing light pollution of the night sky by orbiting spacecraft is an obvious legal void, one that must be addressed by the space community. In the longer term, some kind of national and international regulation seems necessary that sets suitable levels of reflectivity, height, and orbital data-sharing for the largest satcons.

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50 https://www.spacex.com/updates/starlink-update-04-28-2020/index.html.

51 Neil Gunningham and Joseph Rees, "Industry Self-Regulation: An Institutional Perspective", *Law & Policy*, Vol. 19, No. 4, October 1997, pp. 363-414.

52 Gunningham and Rees, *op.cit.*, pp. 388-9, 406; Wikipedia, "Industry Self-Regulation": https://en.wikipedia.org/wiki/Industry_selfregulation.

53 *Sky & Telescope*, March 2020, p. 21.

54 Standards for the industry were first outlined by the two Satellite Constellations (SATCONS) workshops organized in 2020 and 2021 by the US National Optical-Infrared Astronomy Research Laboratory (NOIRLab) and the AAS to bring together astronomers, operators, and policy-makers to discuss the impact of large satcons on astronomy and society. See https://noirlab.edu/science/events/websites/satcon2/publications.

55 The scale of magnitudes is a logarithmic scale used by astronomers whereby the brightest stars are first magnitude, and the faintest stars visible without optical aid are about sixth magnitude. Accordingly, the proposed standard means that the brightness of megaconstellation satellites should always be below naked-eye levels.

Some examples can be found in the past when the interests of astronomers and other concerned groups were given due consideration. US Congress passed in 2001 legislation prohibiting American companies and individuals to conduct "obtrusive advertising in outer space". Now contained in the United States Code, it mandates that no license will be issued and no launch will be permitted for activities that involve obtrusive space advertising.[56] The latter is defined as "advertising in outer space that is capable of being recognized by a human being on the surface of the Earth without the aid of a telescope or other technological device."[57] Rationale for this law included aesthetic reasons as well as the protection of the night sky and astronomical observations.[58] Besides this federal law, nineteen US states plus Washington DC and Puerto Rico have enacted laws to reduce light pollution.[59]

Another important precedent is the decades-old dialogue conducted between radio astronomers, telecom operators, and national and international regulators, as a result of which harmful interferences have been prevented between commercial networks and the exploration of the sky by radio telescopes. This has been done by reserving for radio astronomy a number of frequency bands that have "remained quiet", that is, have not been subject to commercial exploitation.

However, this success is due largely to the fact that, since the beginning, there was international and national regulation of radio frequencies. Thanks to the work of the International Telecommunication Union (ITU), all radio transmitters and receivers are protected from interference from other sources. The problem that arises now is due to the fact that there are no regulations at all covering optical interference from spacecraft.

In any case, these two legal precedents are significant, as they seem to indicate a policy adopted in the past by the US and many other nations in the sense of taking the interests of astronomy into account.

6. Towards a Future Regulation

In the case of the United States, there are two agencies in the US Government that are in charge of authorizing space activities. Any of them could be given the power to grant licenses to megaconstellations in the future subject to the condition of having under control the issue of the reflectivity of satellites:

56 51 U.S.C. § 50911. See at: https://www.law.cornell.edu/uscode/text/51/50911.

57 51 U.S.C. § 50902. See at https://www.law.cornell.edu/uscode/text/51/50902 at (12).

58 https://foundationsoflawandsociety.wordpress.com/2016/12/04/51-usc-%C2%A7-50911-space-advertising/.

59 https://baas.aas.org/pub/2021i0205/release/1?readingCollection=b956c163.

- The Office of Commercial Space Transportation of the Federal Aviation Administration (FAA)[60] authorizes and supervises commercial launches to space, and ensures that all payloads that are placed in space by US nationals are in conformity with international and national space legislation in force –for instance, the FAA is in charge of restricting any payloads that might be destined to do obtrusive advertising in outer space.
- The Federal Communications Commission (FCC)[61] authorizes all satellite telecommunication networks, making sure that they comply with national and international rules on the use of radio frequencies. The FCC also requires that the proposed networks do not pollute terrestrial orbits with space debris and do not interfere with the radio-quiet zones where radio observatories are located.

Similarly, the United Kingdom also has agencies involved in the licensing of satellite networks, such as the Civil Aviation Authority (CAA)[62] and the UK Telecom regulator (OFCOM)[63]. It is noteworthy that, in the case of the UK, Section 5 of the Outer Space Act 1986 expressly requires from any licensee to prevent the contamination of outer space.[64]

However, the night sky belongs to all of humanity, and it cannot be regulated by one or two countries alone. Besides, governments and corporations from other nations are also studying the possibility of establishing megaconstellations. Therefore, it would be preferrable to have an international regulation on this matter.

The natural forum to create such regulation would be the United Nations, as the only international organization that covers space activities in general; and more precisely, the UN's specialized body, the Committee on the Peaceful Uses of Outer Space (COPUOS). Established in 1959, this Committee currently has 100 Member States, including all space-faring nations in the world.[65]

Numerous international organizations have the status of observers in COPUOS, such as the IAU (since 1995) and ESO (since 2008).[66] Both organizations are actively engaged now in the discussions of the Committee, and both have already made declarations referring to the effects of large

60 https://www.faa.gov/about/office_org/headquarters_offices/ast.
61 https://www.fcc.gov/about/overview.
62 https://www.gov.uk/transport/spaceflight.
63 https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/satellite-earth/non-geo-fss.
64 https://www.legislation.gov.uk/ukpga/1986/38/section/5.
65 https://www.unoosa.org/oosa/en/ourwork/copuos/index.html.
66 https://www.unoosa.org/oosa/en/ourwork/copuos/members/copuos-observers.html.

satcons in the night sky and requesting from COPUOS the adoption of mitigating measures.

However, while observer organizations can make statements and even recommend a regulation, they cannot themselves introduce or support any proposed regulation: only Member States of COPUOS can do that. Since COPUOS works under the rule of consensus, once a proposal is made by a State, all other Member States must agree to proceed on any such proposal.

At the 58th session of COPUOS' Scientific and Technical Subcommittee (STSC), held in February 2021, a group of countries submitted, together with the IAU, a conference room paper entitled "Recommendations to keep dark and quiet skies for science and society".[67] At the same session, the STSC decided to add to its agenda an item entitled "General exchange of views regarding satellite system effects upon terrestrial-based astronomy", in order to allow delegations in future sessions to provide their views on both the issue of the impact of satcons on astronomy and its potential relevance on the work of COPUOS.[68]

Currently, the goal is to engage the STSC to issue some guidelines about protecting the night sky that will reflect a reasonable compromise between the satellite operators and the needs of astronomers. Those guidelines could then be picked up by national governments as licensing regulations that would require from operators *inter alia* to design their spacecraft to be as dim as possible, to keep them preferably at altitudes lower than 600 kilometers, and to share the orbital data pertaining to their satcons.

However, the process of creating new rules and standards for space activities is usually slow. For instance, it took thirteen years from the time when the issue of space debris first entered the agenda of COPUOS (in 1994) until the first adoption of UN guidelines on this matter (by the STSC in 2007).

Accordingly, astronomers will have to be patient and devote one part of their precious time and resources to diplomacy. This situation is a new one for the astronomy community, which so far had not gotten involved much in space-governance issues.[69]

Should COPUOS' Legal Subcommittee (LSC) decide one day to formally open the debate on a new international regulation addressing the light pollution of satcons, existing international space law could already provide the basic principles underpinning such regulation.

67 https://www.unoosa.org/oosa/en/oosadoc/data/documents/2021/aac.105c.12021crp/aac.105c.12021crp.17_0.html.

68 https://www.unoosa.org/oosa/oosadoc/data/documents/2022/aac.105/aac.1051257_0.html.

69 https://www.space.com/satellite-megaconstellations-threat-dark-skies-un.

The basic norm is the Outer Space Treaty (OST)[70], in force since 1967, to which all space-faring nations are parties. It provides some principles that could inspire a future regulation, in particular those contained in Articles I, III, VI, and IX of the OST:

1) Free access to outer space and free use of outer space without discrimination (Art. I).
2) Application of international law to outer space activities (Art. III). This would open the way to the application of e.g. international environmental law in outer space.
3) Need for State Parties to authorize and supervise all national actors in outer space, including non-governmental entities –such as private companies– that are conducting space activities (Art. VI).
4) Duty of conducting one's activities with due regard for the space activities of other States and without interfering with those activities (Art. IX first part). 'Due regard' means taking into consideration the interests of others when conducting your own activities.
5) Duty to maintain international consultations at the request of another state party, when one's space activity may cause prejudice to the activities of that state party (Art. IX second part).

Other paths for redress under international law have been suggested:

- Introducing the issue of dark skies in the current work of COPUOS regarding Long Term Sustainability of Outer Space Activities.
- Giving the ITU authority on optical frequencies and interferences, same as it has now for radioelectric frequencies and interferences under the Radio Regulations.
- Recognizing the uncontaminated view of the night sky as a non-renounceable human right and as a natural heritage under the protection of UNESCO.[71]

All these avenues merit further study and consideration, if we want to protect the night sky from unwanted light pollution.
The process of initiating a debate on this topic was helped by the two "Dark and Quiet Skies for Science and Society" Conferences held online in October 2020 and October 2021[72]. Jointly organized by the United Nations Office for

70 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, in force since 10 October 1967, 610 UNTS 205.

71 These proposals are outlined in Bharadwaj, Tejas, "Protecting the Dark Skies of the Earth from Satellite Constellations under International Space Law", *2020 Proceedings of the International Institute of Space Law*, Eleven 2021, pp. 19-32.

72 http://www.unoosa.org/oosa/en/ourwork/psa/schedule/2020/2020_dark_skies.html.

Outer Space Affairs (UNOOSA), the IAU, and the Government of Spain, the meetings had the purpose of analyzing the threats posed by light and radio pollution to astronomy and to the night sky. The Conferences produced a number of recommendations that governments and private enterprises can follow in order to mitigate the negative impact on astronomy of large satellite constellations, without diminishing the effectiveness of the services they provide. The final reports of the second Dark and Quiet Skies Conference, encompassing scientific and technical as well as legal and policy considerations, were presented to COPUOS in early 2022 in the form of a working paper, in order to become a reference for every future analysis of the situation.[73]

7. Conclusion

As noted presciently back in 1996, the situation for astronomy, which is already bad, is likely to get worse, since technology is leading to a growing degradation of the conditions for astronomical observation, even to the point where certain types of astronomical observation may be irretrievably lost. Still, the existence of rules to protect optical and radio observatories shows that astronomical concerns have been listened to and accommodated in the past. Such efforts must be actively sustained and promoted.[74]

Arguably, international conventions protecting the quality of the night sky have already become a necessity. A reasonable compromise must be attained between enjoying the benefits of our technological civilization and recognizing that traditional ground-based astronomy is an essential activity that must continue to exist. Our right to a pristine night sky, the progress of our science, and perhaps our very own survival are at stake.

73 https://www.unoosa.org/oosa/oosadoc/data/documents/2022/aac.105/aac.1051255_0.html. For the full reports, see https://www.iau.org/news/announcements/detail/ann22002/.

74 McNally, D., "Adverse Environmental Impacts on Astronomy", *Quarterly Journal of the Royal Astronomical Society* Vol. 37 (1996), pp. 129-151: http://articles.adsabs.harvard.edu/full/1996QJRAS..37..129M.