
The Impacts of Large Constellations of Satellites

Contact: Gordon Long — glong@mitre.org

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JASON
The MITRE Corporation
7515 Colshire Drive
McLean, Virginia 22102-7508
(703) 983-6997

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EXECUTIVE SUMMARY

Large numbers of communication satellites have recently been launched into low earth orbit (LEO). These include launches of hundreds of Starlink satellites destined for 550 km LEO orbits, as well as a smaller number (74) of OneWeb satellites destined for 1200 km LEO orbits. In 2020, Starlink announced plans to construct a constellation with a final size of 42,000 satellites, OneWeb has announced plans for 48,000, and there are many other less mature concepts under development for this market. If both of these constellations are completed there would be 5,000 satellites visible from most any point on the ground at all times. JASON was asked by NSF and DOE to assess the impact of current and planned large satellite constellations on astronomical observations, and in particular the impact on the Vera Rubin Observatory and its Legacy Survey of Space and Time (LSST).

In addition to the impacts on the Rubin Observatory, JASON also investigated potential impacts on optical astronomy generally, infrared astronomy, radio astronomy, cosmic microwave background (CMB) studies, and laser guide-star observations. JASON assessed the possible growth of future large constellations, and also evaluated the risk posed by large constellations from the possible increase of orbital debris.

Size and Economics of Constellations To understand the magnitude of the potential problems, JASON performed a simple analysis to determine the economic viability of satellite constellations for high speed data communications. This included looking at the minimum and maximum size for viable constellations from both an economic and technical point of view. The following are our findings and recommendations.

- We see no economic barriers to constellations of the size already proposed. There may be technical limits to maximum constellation size, for example resulting from sidelobe power from many satellites degrading link margin or the number of satellites in a given uplink beam, but these are likely to be insignificant for fewer satellites than the maxi-

mum size of the proposed constellations. There may also be ways to mitigate these issues, such as using higher frequencies.

- Judging from the size of the potential market and what people currently pay for broadband internet, this could be a profitable business as long as the cost of the satellites and launches are maintained at current levels or less. It appears that revenue currently exceeds cost for constellations comprising up to 100,000 satellites, and costs are currently coming down.

Rubin Observatory and Optical Astronomy. A very large amount of detailed work by others has gone into the topic of large constellations and their potential impact on optical astronomy, including journal articles and numerous panel reports, with particular emphasis on the impacts on the Rubin Observatory. JASON reviewed this work and has the following highest priority findings and recommendations. Most of these are non Rubin-specific and relate to optical astronomy generally.

- Our highest priority recommendation is: If at all possible, avoid orbits above 600 km. Orbits at 1000 km and higher are visible for a much longer fraction of the night. Satellites in orbits at 550 km reflect sunlight for only a few hours during and after twilight and consequently leave periods during the night that do not impact ground-based optical telescopes.
- Operators of large constellations should be required to provide continuous, accurate position information on their satellites so that planned astronomical observations can avoid directions in which satellites may be present and also so that any impacted observations can be identified. This is also extremely important for general traffic management and collision avoidance.
- The NSF should support efforts to mitigate the impact of large constellations on optical astronomy observations. These mitigations are likely

to involve software for both the community and optical astronomy facilities.

- The Rubin Observatory should undertake a comparative study of other known sources of systematic error due to saturation and cross-talk (e.g., bright stars or cosmic rays) and assess the *incremental* impact of satellite trails relative to these other sources of error. As soon as possible, the Rubin Observatory should begin to measure these impacts using on-sky observations during the engineering verification phase.
- The Rubin Observatory should consider using 2×15 second observations rather than a single 30 second observation because of the utility of mitigating systematic errors, including satellite trails, by taking advantage of two close-in-time observations. The loss in observation time of about 8% may be worth the gain from better control of systematics.

An important overall finding is that, absent significant regulation of large constellations, the astronomical community needs to prepare for a potential future which includes tens of thousands of LEO satellites bright enough to impact observations, many in orbits of 1000 km or higher.

Radio Astronomy. While much of the recent focus of the astronomical community has been on the impact of large constellations on optical astronomy, the radio astronomy community has been working for several years with companies such as SpaceX and OneWeb to determine the impacts of their gateway and user-terminal satellite downlinks on radio astronomy and what steps the operators of large constellations should take to ensure that their emissions satisfy existing regulations. The regulatory framework is well established by organizations such as the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) within the United States, as well as the International Telecommunication Union (ITU).

Unfortunately, the regulatory framework was developed at an earlier time when the impact of large constellations of internet communication satel-

lites was not an issue. The regulations mostly protect certain narrow bands for radio astronomy, while modern receiver and processing technology allow broad band radio astronomy observations, and much radio astronomy is done outside officially protected bands. In the opinion of JASON, the current regulatory framework is insufficient to protect many modern radio astronomy observations.

There is consequently a parallel with optical astronomy: there is no regulatory framework for satellite optical brightness and therefore optical astronomy is largely unprotected. For radio astronomy, the regulations may not be sufficient to protect radio astronomy. The impact on radio astronomy may be very significant, at least in the downlink bands used by the satellites in large constellations. In particular, radio astronomy relies heavily on sites that are as free from radio frequency interference (RFI) as possible, as recommended in radio regulations. These sites often have some protection from ground-based transmissions, but have little or no formal protections from spaceborne transmitters. Because of sidelobe and out-of-band emissions from the ubiquitous satellites of evolving large constellations, existing radio quiet zones are likely to be severely impacted by satellite RFI in the future.

Our principal findings and recommendations are:

- The NSF should support the radio astronomy community in documenting the impact of large constellations on radio astronomy, even if those impacts are allowed under the existing U.S. and international regulatory framework. Again a parallel exists with optical astronomy, which has taken the first steps in quantifying the harm done to its science.
- The NSF should support efforts in the spectrum management community to protect those bands that are allocated primarily to radio astronomy. With thousands of satellites in orbit, unanticipated out-of-band leakage in only a fraction may have significant impacts.

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- The NSF should support the radio astronomy community to make quantitative measurements of RFI both in protected and unprotected frequency bands. Baseline measurements should be done soon while the constellations are still small and large scale downlink activity has not yet been initiated. There is again a parallel with optical astronomy, which is organizing to make quantitative brightness measurements on Starlink and OneWeb satellites.
 - The NSF should support efforts to mitigate the impact of large constellations on existing and future radio astronomy facilities. These mitigations are likely to involve both hardware and software.
 - The NSF should support efforts to increase regulatory protection of radio astronomy sites, which are now vulnerable to emissions from satellites, including requirements for satellite vendors to power off transmissions over radio astronomy facilities.

CMB Astronomy. Measurements of the Cosmic Microwave Background (CMB) are especially sensitive to interference from large satellite constellations transmitting above 20 GHz due to their wide field of view, extremely broad frequency bands, their extreme sensitivity to polarization, and their use of bolometers. This will pose, at the minimum, a significant data reduction challenge.

- JASON recommends that satellite vendors should be required to power off any transmission above 20 GHz when they clear the horizon of several prime CMB/radio observing sites, especially the Atacama site of ALMA and the Simons Observatory and the South Pole. These sites in Chile and Antarctica are very remote, and this should have a minimal impact on their business model due to the low number of people and the continued availability of the sub-20 GHz gateway downlinks.

Collisions. It has long been understood that collisions and the resulting debris can endanger an object in orbit — the 2013 film *Gravity* won 7 Academy

Awards (although the collisions it portrayed were grossly exaggerated) – but there has been relatively little analysis of the collision and debris threats posed by the recently announced large constellations. The most recent NASA studies from 2018 included 8000 satellites at 1200 km, and showed significant dangers unless nearly all satellites are successfully de-orbited at end of life. OneWeb’s proposed constellation of 48,000 satellites at 1200 km is much larger, and the scaling for collision rates goes as the square of the number of satellites. JASON has created a simple analytical model that produces similar outputs to the much more sophisticated NASA numerical debris models, but trivially scales to larger constellation sizes.

In a JASON simulation with reasonable parameters OneWeb’s constellation leads to a runaway cascade of collision that renders orbits near 1200 km unusable within 25 years. A similar impact is possible with constellations at orbits below 600 km, but atmospheric drag causes the orbits of debris to decay on fairly short timescales (typically less than 5 years). A collision cascade initiated by a mistake in satellite design or operation of a 42,000 satellite constellation at 600 km will be extinguished in a few years. The threat to lower orbiting facilities such as the International Space Station during this time is very significant.

The key parameter in this analysis is what is known in the industry as the post-mission disposal (PMD) probability, which is the fraction of satellites that are successfully de-orbited after their primary mission lifetime. A very high PMD (at least 99%) is essential to avoid the worst environmental impacts, but PMD is very hard to predict ahead of time, especially for large constellations of satellites where satellite design is highly optimized to reduce unit cost. A formal process to evaluate and ensure high PMD is needed. We note that existing commercial constellations such as Iridium have fallen short of the required (1-PMD) for a large constellation by at least a factor of 30.

JASON recommendations that:

- The regulatory licensing should include a three step process to try to avoid catastrophic debris generation:

-
1. application, including details about the plan for fleet management and expected PMD probability,
 2. evaluation by an independent body of the PMD required for safe operations, and
 3. evaluation by an independent body whether the satellite design and build will meet this PMD requirement.
- The orbital debris community should be directed to run more accurate models of the current proposed constellations immediately in order to have a quantitative basis to evaluate the collision risk, and funding should be provided to do this analysis. It is important that the ascent and descent phases of a satellite's lifetime are not neglected in this analysis.
 - Satellite operators should be required to publish accurate (<50 m) locations of all their satellites continuously.

Due to the impacts on ground-based astronomy and concerns about debris generation and longevity, JASON's **highest priority recommendation is to eliminate or highly regulate large satellite constellations in orbits higher than 600 km.**

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1 INTRODUCTION

Large numbers of communication satellites have recently been launched into Low Earth Orbit (LEO). These include launches of hundreds of Starlink satellites destined for 550 km LEO orbits, as well as a smaller number (74) of OneWeb satellites destined for 1200 km LEO orbits. In 2020, Starlink announced plans to construct a constellation with a final size of 42,000 satellites, and OneWeb has announced plans for 48,000. If both of these, or constellations of similar size, are completed there would be 5,000 satellites visible from most any point on the ground at all times, and there are many other less mature concepts under development for this market.

JASON was asked by NSF to study the impacts of large constellations of satellites on astronomical observations. The scope of the JASON study requested by NSF can perhaps best be summarized by some of the key questions posed by NSF in its Statement of Work for the JASON Study:

- What are the expected trends, with uncertainties, in the population of satellites in Low Earth Orbit over the next 1-20 Years?
- What are the specific impact to be expected on the Rubin Observatory LSST program over time. including both the general survey activities and the detection of potentially hazardous Near-Earth Objects?
- What are the mitigation opportunities both for the Rubin Observatory LSST and for more general classes of astronomical observations in the future?
- What good practices could be put in place by satellite purveyors to minimize deleterious impacts on celestial observations.

In addition to addressing these questions, JASON also studied the important issue of the increased risk of generation of space debris if large constellations of satellites are put into low-Earth orbit, particularly at orbits of above 600 km.

JASON heard briefings from, and interacted with, a broad range of individuals in the U.S. government and the astronomical community. JASON

was briefed by both the NSF and the DOE. These briefings included: talks on the Rubin Observatory by project members; by members of the astronomy community on impact on optical observations; and by SpaceX on Starlink, and by Amazon on the Kuiper Project. We also separately interacted with individuals from OneWeb. In addition, JASON members listened to talks in workshops convened by the Astro2020 Panel on Optical Interference from Satellite Constellations (27 April 2020), and in the SATCON1 workshop organized by the NOIRLab and AAS Committee on Light Pollution, Radio Interference and Space Debris (30 June - 1 July 2020 and 25 August 2020).

During the summer, JASON produced a short letter report [29] for the NSF summarizing its conclusions with regard to the impacts of large constellations on optical astronomy generally, and the Rubin Observatory, in particular. Much of the material in the letter report is provided in Section 3.1 of this report. JASON and the SATCON1 working group briefed their reports to NSF on 24 August 24 2020. The two reports generally came to similar conclusions.

JASON members also interacted throughout the summer with individuals from the NSF, NRAO, and the astronomical community on radio astronomy impacts, with NASA individuals on satellite collisions and debris generation, and with members of the Cosmic Microwave Background (CMB) community.

JASON thanks all the many individuals who provided very informative input that helped shaped this final report.

The Executive Summary of this report contains our principal findings and recommendations. Additional findings and recommendations can be found at the end of specific subsections of the report.

2 LARGE SATELLITE CONSTELLATIONS

Advances in technology open new opportunities for commercial satellites. The advent of geo-synchronous Earth orbit (GEO) satellites that provided inter-continental radio communications and continent-wide television broadcast was a game changer that outstripped traditional trans-oceanic cables of the time and made radio tower broadcast of television obsolete. GEO satellites are extremely expensive, but their task is technologically quite simple.

The Iridium constellation was the first serious attempt to bring a constellation down to low Earth orbit (LEO) that could provide world-wide telephone communications. Iridium had to solve the problem of managing a dynamic constellation of satellites with ever changing inter-satellite links and downlinks, and was in many ways a failure. The satellites were too expensive for what they provided, the technology was too immature to make it cheap and easy.

We are at the dawn of a new era. Commercial providers have worked for 20 years to bring down launch costs with very significant success, and satellite and wireless communications advances have made it possible to build a capable and sophisticated satellite for a low price. Similar advances in computers and networks now make it feasible to manage an arbitrarily large constellation of satellites in LEO that act as though they are a static network of “cell towers in the sky”. Although it is bleeding edge technology right now, it is built on a solid technological foundation and will only become easier and cheaper as time goes by.

2.1 What is a Large Satellite Constellation?

For the purposes of this report, we consider a large constellation (LC) any satellite constellation that is at least an order of magnitude larger than the first generation constellations like Iridium (66 satellites), Globalstar (48 satellites), and Orbcomm (31 satellites), roughly 500 satellites.

2.2 Current Constellations

The first major satellite constellation, Iridium, was deployed by Motorola between 1997 and 2002. The launches took place on a heterogeneous group of launchers, including vehicles from the United States, Russia, and China. The constellation consists of 66 active satellites in an orbit of altitude 780 km and an inclination of 86.4° providing worldwide coverage. Iridium was primarily sold as a satellite-based voice phone service capable of using hand-held ground units, but the rise of affordable cell phones quickly invalidated this business case, resulting in Iridium filing for Chapter 11 protection. The company emerged from bankruptcy and focuses on niche businesses and military customers that require reliable communications and are not as price sensitive as consumers. After a 15 year delay with no new launches, a second generation constellation called Iridium-NEXT began construction in 2017.

Globalstar is another constellations similar in concept to Iridium that went into operation in 1999 with 48 satellites. It declared bankruptcy in 2002, but came out of bankruptcy and continues to operate. Its satellites operate at an altitude of 1400 km with an inclination of 52° .

Orbcomm operates a constellation of 31 satellites focused on global low bandwidth data connections for industrial hardware. Launched between 1995 and 1999, Orbcomm declared bankruptcy in 2000, but was reorganized and continues to provide service and began launching a second generation of OG2 satellites in 2014. Its satellites operate at an altitude of 750 km with an inclination of 52° .

2.3 Constellations in Construction

The existing constellations are fairly limited in size and don't present major challenges to ground-based astronomy. The constellations currently under construction, however, are an entirely different beast. The current and in construction constellations are shown in Table 1.

Table 1: Current and planned satellite constellations through the end of 2020.

Years	Entity	Satellites	Derelict	Deorb.	Al. (km)	Inc. (°)	Status	Total	Refs
1995-99	Orbcomm	31			750	52	On Orbit	31	1
1999	Global Star	48			1400	52	On Orbit	79	2
1997-2002	Iridium	95		2	780	86.4	On Orbit	172	3,4
2014-17	Orbcomm-OG2	17	5		750	52	On Orbit	184	5
2017-19	Iridium-Next	75			780	86.4	On Orbit	259	6
2019	OneWeb	6			1200	88	On Orbit	265	7
2019	Starlink	120	3		550	53	On Orbit	385	8
2003-2020	Iridium		8	58	780	86.4		327	9
2020	Starlink	418			550	53	On Orbit	745	8,10
2020	One Web	68			1200	88	On Orbit	813	7
2020	Starlink	234			550	53	Sched.	866	8
2020	One Web	36			1200	88	Planned	902	7

1. <https://en.wikipedia.org/wiki/Orbcomm>
2. <https://en.wikipedia.org/wiki/Globalstar>
3. https://space.skyrocket.de/doc_sdat/iridium.htm and https://www.google.com/search?client=firefox-b-1-d&q=How+many+Iridium+satellites+are+there%3F&sa=X&ved=2ahUKEwjDpd-r1fPqAhU_GDQIHdGRAFMQzmd6BAGLEA0&biw=1285&bih=729 includes 66 active plus 9 on-orbit spares
4. https://en.wikipedia.org/wiki/Iridium_satellite_constellation#Iridium_33_collision
5. <https://spacenews.com/three-orbcomm-og2-satellites-malfunctioning-fate-to-be-determined>
6. https://en.wikipedia.org/wiki/Iridium_satellite_constellation#Next-generation_constellation
7. https://en.wikipedia.org/wiki/OneWeb_satellite_constellation
8. https://en.wikipedia.org/wiki/Starlink#List_of_launches
9. <https://spacenews.com/iridium-to-finish-deorbiting-legacy-constellation-early-next-year/>
10. Contained darksat with reduced reflection & visorsat to lower visibility

SpaceX has currently launched over 560 satellites as part of the Starlink constellation. Regulatory permits have been filed that indicate a final constellation size of up to 42,000 satellites¹. Starlink satellites currently orbit at a final altitude of 550 km with an inclination of 53°, although the final configuration will likely include additional shells with several different altitudes and inclinations. Starlink satellites communicate to the ground using Ku (10.7-12.7 GHz) and Ka bands (17.8-18.6, 18.8-19.3, and 19.7-20.2 GHz) [1], and have side links to other satellites using laser communications. Most recent filings indicate that SpaceX has abandoned plans for higher orbital altitudes and plans to fly its entire constellations below 600 km.

Starlink plans to provide global broadband (up to 1 GSPS) internet through pizza-box sized ground terminals, focusing on rural areas where broadband connectivity is currently lacking. Starlink has recently filed with the

¹<https://fcc.report/IBFS/SAT-LOA-20200526-00055/2378669.pdf>

FCC to increase the number of licensed ground stations from 1M to 5M in response to significant demand².

Starlink satellites are very bright on initial launch and deployment to their final altitude, and caused significant consternation in the astronomical community. This is discussed in detail in §3.

OneWeb is building a constellation of 650 satellites, and has currently launched the first 74. While SpaceX has committed to flying all its satellites below 600 km, OneWeb has chosen an altitude of 1200 km with an inclination of 88°. At this altitude satellites are essentially permanent as the effects of atmospheric drag are negligible (see §5), and the satellites are visible much longer into the night (see §3). Regulatory filings submitted by OneWeb during its recent bankruptcy indicate it plans to eventually have up to 48,000 satellites³ in its “phase 2” constellation. We show in §3.1 this would have immense detrimental effects on wide field ground-based astronomy, as well as likely rendering the 1200 km orbit a veritable minefield in short order as shown in §5.

2.4 Planned Future Systems

While SpaceX and OneWeb have started launching the first shells of their LCs, there is significant interest from around the world in getting a share of this market. For LCs that have not launched hardware there is significant uncertainty about the viability of the business, as the first come-first serve system for communications licenses incentivizes notional filings to stake a claim.

²<https://www.cnbc.com/2020/08/01/spacex-starlink-extraordinary-demand-with-nearly-700000-interested.html>

³<https://www.oneweb.world/media-center/oneweb-seeks-to-increase-satellite-constellation-up-to-48000-satellites-bringing-maximum-flexibility-to-meet-future-growth-and-demand>

Table 2 contains a list of planned future constellations based on International Telecommunications Union (ITU) and Federal Communications Commission (FCC) filings, press releases, and news stories. In addition to Starlink and OneWeb, we judge the Amazon Kupier constellation as the next most mature, currently about 2500 satellites in 610-630 km orbits.

These filings and plans are constantly amended, with the number of satellites and the frequencies used seeming to shift in almost realtime. While the minimum number of satellites needed to provide global coverage is not high (around 500, see §2.7.2), there are significant economic incentives to grow to much larger constellations, as explained in §2.7.3. The most concrete conclusion we can draw from this table is that a lot of companies with deep pockets think that constellations of communication satellites are a profitable endeavor, and we could very quickly wake up on a world with over 100,000 communications satellites in LEO.

2.5 Regulatory and Bandwidth Considerations

Space is largely unregulated and satellites do not obey national borders. This has led to a parade of satellites for commercial, military, and even artistic purposes. The primary barrier to entry has been the cost of launching into Earth orbit, but modern launchers have brought this cost down significantly, and modern electronics have allowed far greater capabilities in a smaller satellite.

While launchers from the US are regulated by the Federal Aviation Administration (FAA), their payloads are not. A company who wanted to launch a dump truck full of sand into the same orbit as the International Space Station would have no formal barriers to doing so in many countries around the world.

Table 2: By the end of 2020 we expect a total of around 900 communications satellites to be in orbit that are part of constellations in LEO. This table shows planned future constellations. An entry in parenthesis next to the Number column indicates satellites already launched. M2M refers to Machine to Machine communications.

Entity	Origin	Number	Alt (km)	Status	Total	Op. Freq.	Refs
End 2020	All	902					1, 2
Starlink	USA	7518	340	FCC OK	8420	Ku Ka V	3, 4
Starlink	USA	828	550	FCC OK	9248	Ku Ka V	4, 5
Starlink	USA	2800	1150	FCC OK	12048	Ku Ka V	4
Telesat	Canada	298 (15)	1248	FCC OK	12346	Ka V	4, 7, 23
Telesat	Canada	1373	1000–1248	FCC request	13719	Ka	22
Kepler	Canada	140	575	FCC OK	13859	Ku	4, 18
Kepler	Canada	220	600	FCC request	14079	Ka	22
OneWeb	USA	720–2720	1200	FCC OK	16799	Ku Ka V E	4,6, 7, 20, 23, 29
OneWeb	USA	49128	1200	FCC request	65927	Ku Ka V E	22
SpaceX - Gen 1	USA	1500	550–1150	FCC OK	67427	Ku Ka V	4, 8,
SpaceX - Gen 2	USA	30000	328–614	FCC request	97427	Ku Ka V	22
Amazon Kuiper	USA	784–3236	370–630	FCC OK	100663	Ka	7, 11, 21
Amazon Kuiper	USA	1296	610	FCC OK	101959	Ka	7, 11
Amazon Kuiper	USA	1156	630	FCC OK	103115	Ka	7, 11
China Commsat	China	800 (8)	600	Unknown	103915	Unknown	7, 14
Hongyan China	China	320–864 (1)	1100	Unknown	104779	Ku	7, 13, 14, 21,
Astrocast	Switz.	64 (2)	540	M2M	104843	Unknown	29,30
ViaSat	USA	288	1300	FCC request	105131	Ka V	4, 9, 22
SES/O3b	Lux.	36	507	FCC request	105167	Ku Ka	22
Boing	USA	3016	1030	Dormant	105167	Ku Ka V	4, 7
STEAM-1	Norway	3993	LEO	Unknown	109160	Ku	27, 28
STEAM-2	Norway	3993	LEO	Unknown	113153	Ka	27, 28
LeoSat	Europe	108	1423	Shutdown	113153	Ka	4,7,19
Samsung	Korea	4700	2000	Proposed	117853	Unknown	7, 12, 29
China Xinwei	China	32	600	Unknown	117885	Unknown	7, 14, 15, 29
India AstroTech	India	600	1400	Unknown	118485	Unknown	7, 16
Helios Wire	Canada	30	LEO	Funded, M2M	118515	S	29
SatRevolution	Poland	1024	350	Notional	119539	Unknown	7, 14
Hongyun CASIC	China	156	1000	Notional	119695	Unknown	7, 14, 21, 24
Astromet Technol	India	150	LEO	In planning	119845	mm-Wave	29, 31
Xingyun	China	156	LEO	Unknown	120001	Unknown	26
Thales MCSat	France	774	LEO	Unknown	120775	Ka	26, 27, 28
Thales MCSat	France	7272	LEO	Unknown	128047	Ka	26, 27
3ECOM-1	Licht.	288	LEO	Unknown	128335	Ku Ka	26, 28
3ECOM-2	Licht.	288	LEO	Unknown	128623	Ku Ka	28
Sky&Space,Gl.	Britain	200	LEO	UK scrutiny	128823	Unknown	26, 29
Swarm Tech.	USA	157	LEO	Unknown	128980	Unknown	26
Fleet	Australia	102	LEO	Unknown	129082	Unknown	26
Yaliny	USA	135	600	Crowd Funded	129217	Cell	7,17, 29
102	Canada	774	LEO	Unknown	129991	Ka	27
Constellation	Canada	891	LEO	Unknown	130882	Ka	27, 28
TXIN	China	60	LEO	Unknown	130942	Ka	27
Amdromeda A	Cyprus	48	LEO	Unknown	130990	Ka	27
Courier-3	Germany	72	LEO	Unknown	131062	Ka	27
AST-NG-C-2	Germany	4672	LEO	Unknown	135734	Ka	27, 28
KasKilo	Germany	280	LEO	M2M	136014	Ka	29

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1. From Table 1.
 2. Magnitudes in Hainaut and Williams (2020) [22]
 3. Generally for SatCom Ku-band is 12–18 GHz, Ka-band is 18–31 GHz and V-band is 36–51 GHz. Specific bands for satellite communications for up and downlink vary for different countries, see <https://www.inetdaemon.com/tutorials/satellite/communications/frequency-bands/>
 4. <http://www.satellitemarkets.com/news-analysis/next-wave-low-earth-orbit-constellations>
 5. 1600 approved by FCC — 772 in orbit or scheduled for 2020 = 828
 6. <https://www.fiercewireless.com/tech/oneweb-gets-fcc-approval-for-720-low-earth-orbit-satellites-to-offer-global-internet-services>
 7. Hainaut and Williams (2020) [22]
 8. Approved SpaceX constellation totals 11,000, less specific, approved Starlink constellations at 340, 550 and 1150 km altitude, leaves 1500 headroom
 9. <https://spacenews.com/viasat-gets-fcc-approval-for-meo-constellation/>
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 11. <https://spacenews.com/amazons-kuiper-constellation-gets-fcc-approval/>
 12. <https://newatlas.com/samsung-satellite-network-internet-access/38971/>
 13. <https://www.spacetechnology.com/china-launches-first-hongyan-leo-comms-satellite/>
 14. <https://spacenews.com/chinas-commercial-satellite-sector-sees-boost-from-new-infrastructure-policy/>
 15. <https://www.haaretz.com/israel-news/business/chinese-firm-agrees-to-buy-israel-spacecom-for-285-million-1.5428911>
 16. No comsat constellations launched by India to 2019, <https://www.fresherslive.com/current-affairs/article/list-of-indian-satellite-launched-from-1975-17>.
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 30. https://space.skyrocket.de/doc_sdat/astrocast-0.htm
 31. <https://spacewatch.global/2018/09/indias-astrome-hopes-to-start-launching-hts-satellites-in-2019/>

This allocation includes small protected regions of spectrum for Astronomy, but these narrow slices of the spectrum tend to cluster around narrow spectral features like the hydrogen 21 cm line. This was very useful in the early days of radio astronomy when technical limitations prevented wideband instrumentation, but does little to protect the sort of observation performed with modern facilities like the Very Large Array (VLA) (Figure 2). More details on the impact of LCs on radio astronomy is detailed in §3.4.



Figure 2: The Karl G. Jansky Very Large Array in its most compact configuration. Image Credit: National Radio Astronomy Observatory (NRAO)

The ITU and FCC impose limits on which frequencies and at what received power on the ground that a satellite constellation can emit. In practice, the requirement of an FCC license to operate in the lucrative US market appears to be the only effective formal regulation of satellite vendors. Since 2004 FCC approvals for LCs have come contingent with requirements on things not related to radio spectrum, like orbital debris mitigation⁴. There appears to be no effective regulation in place for satellite constellations that launch outside the US and Europe and do not intend to serve those markets.

The ITU does impose milestones to ensure that satellite ventures do not squat on spectrum rights indefinitely. After the first seven years of a spectrum allocation by the ITU, Non-geostationary orbit (NGSO) constellation operators will need to launch 10% of their satellites in two years, 50% in five

⁴<https://docs.fcc.gov/public/attachments/DOC-363486A1.pdf>

years and 100% in seven years. If constellation ventures fail to launch enough satellites by the milestones, or within the total 14 years allotted, their spectrum rights are limited proportionally to the number of satellites launched before time runs out (14 years).

2.6 Number of Satellites in View

Satellites interact with ground-based astronomical observations differently in radio and in the optical/NIR. In the radio, satellites are actively transmitting at very high powers, often using downlink beams with very large footprints on the ground. In this case, it is often useful to calculate the number of satellites above the horizon at a given time since even the distant sidelobes of these bright beams can cause interference. A derivation of the number of satellites N above zenithal distance z ($z = 90^\circ$ for the horizon) for a constellation of $N_{\text{Const.}}$ is performed in [22]. In this calculation the distribution of satellites over the Earth is assumed to be uniform, but full simulations have shown that for reasonable constellation parameters this estimate is accurate to better than a factor of 2.

$$N = \frac{N_{\text{Const.}}}{2} \left(1 - \cos \left(z - \arcsin \left(\frac{R_{\oplus}}{R_{\text{Sat}}} \sin z \right) \right) \right). \quad (2-1)$$

where R_{\oplus} is the radius of the Earth, $R_{\text{Sat}} = (h + R_{\oplus})$, and h is the orbital altitude.

The number of satellites above the horizon calculated using this model is shown in Table 3. This number is especially useful for calculations involving radio downlink power, as shown in §3.4.

Table 3: The expected number of satellites above the horizon, above air-mass 2, and the average number per square degree for the largest planned constellations

Constellation	# Above Horizon	# Above Airmass 2	#per sq. deg. above horizon	# per sq. deg. above airmass 2
Starlink Phase 1 (12k)	476	46	0.006	0.0003
OneWeb Phase 1 (648)	51	8.5	0.0006	0.00005
Starlink Phase 2 (42k)	1667	162	0.02	0.001
OneWeb Phase 2 (48k)	3800	635	0.046	0.004

In the optical and infrared, satellites are bright due to reflected sunlight and to a lesser extent from thermal blackbody radiation. Most troubling are satellites that are well above the horizon but are still directly illuminated by sunlight, which is a steep function of satellites altitude – the lower the better for astronomy. This quantity can also be estimated analytically, but it is likely more instructive to look at simulations that produce more accurate results, such as the one shown in Figure 3. Additional results are discussed in §3.1.1.

2.7 Large Constellation Constraints

This section will explore the natural constraints on “large constellations” (LC): their orbits and the lower and upper limits on the number in the constellation that arise from coverage, crowding, collisions, and economics.

2.7.1 Orbit altitude and inclination

There are a number of constraints that arise naturally for creation of a LC of satellites. The first is simply the altitude at which the satellites orbit. The drag from the Earth’s atmosphere is a strong function of altitude, depending also on the area to mass ratio of the satellite and the solar cycle. For example, for a ballistic coefficient of 200 kg/m² (SMAD Fig 8-4 [42]) the lifetime of a satellite goes from a few years at 500 km altitude (depending on solar activity

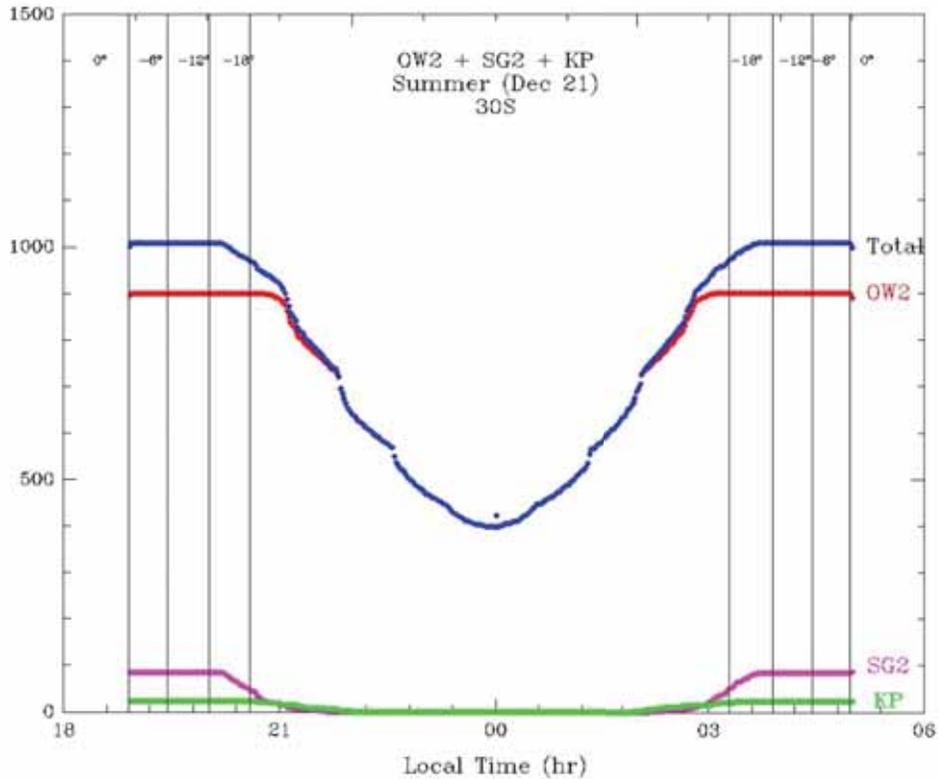


Figure 3: A simulation from J. McDowell showing the number of illuminated satellites from the OneWeb and Starlink Phase 2 constellations at the summer solstice. Even in the middle of the night over 400 satellites (all from the OneWeb constellation) are illuminated and visible from the Rubin Observatory.

phase) to more than 500 years at 1200 km altitude. Maintaining an orbit in the face of this drag requires some level of reboosting which costs mass and money.

The radiation environment also changes dramatically with altitude, increasing by a factor of 50 between 500 km and 1200 km as the orbit approaches the Van Allen belts (SMAD Fig 8-15 [42]). This assumes an orbit with 30° inclination that spends most of its time away from the equator, and commercial electronics will not survive at 1200 km without many millimeters of Al shielding. A satellite in a higher orbit requires more shielding and/or rad-hard electronics which costs capability and money.

Therefore the sweet spot for low Earth orbit (LEO) is between 500 km and 1200 km orbital altitude. The density of existing orbital debris has a broad maximum at ~ 800 km (partly from the 2009 Iridium collision⁵ and the 2007 Chinese ASAT test) and another peak between 1400–1500 km, so these altitude bands are less attractive from the standpoint of satellite security. We estimate below (§5) that the mean time for a catastrophic collision for an individual satellite with existing debris at 800 km is about 2000 years, which implies a significant yearly loss from a constellation of 48,000 satellites unless they succeed in maneuvering to avoid all collisions.

The choice of orbits for a LC in LEO is similarly tightly constrained. The requirement to provide continuous coverage for a user means that a given spot on the Earth must have at least one satellite in view at all times. Therefore the natural choice for orbits is to populate a set of circular orbits at some inclination that step in longitude (a “Walker constellation”). Orbits do not reach latitudes higher than their inclination, but picking an inclination that just reaches the highest latitude desired for service creates a denser satellite population at that latitude. Averaging $\sin \lambda = \sin i \sin \omega t$ (λ is the latitude, i is the orbital inclination, and ωt is the orbital phase) over an inclined orbit yields the fraction of time spent in a given latitude range. For example the recent Starlink launches at $i = 53^\circ$ spend about twice as much time in the latitudes of the US than a random sampling over the sphere. The satellite density for a constellation of size N is therefore

$$n = m(i, \lambda) \frac{N}{4\pi R^2} = 4.7 \times 10^{-5} \text{ km}^{-2} \frac{m(i, \lambda)}{2} \left(\frac{N}{12000} \right), \quad (2-2)$$

where $m(i, \lambda)$ is the latitude dependent density enhancement over random for inclined orbits.

Therefore the desirable configuration of satellites is spread evenly over the world up to some latitude, spaced so as to ensure overlapping coverage at all points on the globe at all times. Because the rotation period of the Earth and the orbits at LEO are so different it is not possible to tailor the

⁵<https://spacenews.com/u-s-satellite-destroyed-in-space-collision/>

population of orbits to avoid the Pacific Ocean and concentrate over a continent — even coverage is the best you can do at LEO.

2.7.2 Communications constraints on constellation size

Continuous coverage sets a natural lower limit N_{min} on the number of satellites that can create a LC. If h is the orbit altitude above the Earth, R_{\oplus} is the Earth radius, $R_{Sat} \approx R_{\oplus}$ is the orbital radius, and θ is the minimum elevation angle that a ground station may be required to track a satellite, the minimum number of satellites required is approximately (flat Earth approximation)

$$N_{min} \sim \frac{4R_{Sat}^2}{h^2} \tan^2 \theta \sim 550 \left(\frac{h}{550\text{km}} \right)^{-2} \tan^2 \theta \quad (2-3)$$

(550 km at 45° requires 550 satellites). Eq. 2-3 is a reasonable approximation for the purpose here: a LEO constellation and elevation angles high enough to stay within reasonable range. Eq. 2-1 can be used in other circumstances to estimate N_{min} .

In order to maximize the number of users covered by a given number of satellites it helps to make h as high as possible, for a given radiation tolerance, and to work to as great a slant angle (small θ) as possible. Iridium, for example, by choosing 780 km and working to $\tan \theta \sim 0.5$, was able to reduce N_{min} to 66.

Communications confusion sets one type of upper bound on the number of a LC. Assuming a phased array or dish antenna of the same size d for both satellite and customer and a customer service frequency of f , the area on the ground illuminated by a beam from the satellite and the area among the satellites seen in a customer's beam are

$$\begin{aligned} A &\sim \frac{\pi}{4} \frac{h^2}{\sin^3 \theta} \left(\frac{c}{fd} \right)^2 \\ &\sim 2400 \text{ km}^2 \left(\frac{h}{550\text{km}} \right)^2 \left(\frac{\sin \theta}{\sin 45^\circ} \right)^{-3} \left(\frac{d}{0.5\text{m}} \right)^{-2} \left(\frac{f}{10\text{GHz}} \right)^{-2}, \end{aligned} \quad (2-4)$$

where c is the speed of light.

If the product of the satellite density and this area is bigger than 1, more than one satellite will be in a customer's beam, and more than one satellite will necessarily have to illuminate the same area. As long as these do not happen at the same time the power received by the customer from the wrong satellite will be down by a sidelobe gain, perhaps $x = 0.01$ (-20 dB). (Using a value x that corresponds to the sidelobe peak instead of average may be appropriate if the communications must be robust in the face of changing interference as the sidelobes sweep across.) These constellations must operate with quite a few beams and/or spectral efficiency in order to get the advertised bandwidth out of the frequency allocation, so presumably a significant link margin y must exist for communications. We will therefore take as a soft upper limit the requirement that no more than one satellite exist in a customer's beam at the same time. (Of course the customer's field of regard is huge compared to the diffraction limited beam; her operation depends on being able to instantaneously switch between two satellites.)

This upper limit $nA = O$ from the number of satellites within a customer's main beam (or vice versa) O occurs when

$$N_{max,di} = 10^5 \frac{2}{m(i, \lambda)} O^{-1} \left(\frac{h}{550\text{km}} \right)^{-2} \left(\frac{\sin \theta}{\sin 45^\circ} \right)^3 \left(\frac{d}{0.5\text{m}} \right)^2 \left(\frac{f}{10\text{GHz}} \right)^2. \quad (2-5)$$

Thus a 48k OneWeb constellation at 1200 km altitude will have a direct-indirect occupancy $O = 2$ (i.e. main beam may connect with sidelobe). Whether or not this is tolerable depends on the sidelobes and requirements for link margin.

Another communications confusion occurs when the direct-direct channel (connecting main beams of satellite and customer) receives too much interference through sidelobes of satellite and sidelobes of customer terminal. The ratio of the power through sidelobes relative to the power from a direct overhead connection integrates to

$$\begin{aligned} P_{tot}/P_{direct} &\sim 3\pi n h^2 x^2 \\ &\sim 1.4 \times 10^{-2} \frac{m(i, \lambda)}{2} \left(\frac{N}{12000} \right) \left(\frac{h}{550\text{km}} \right)^2 \left(\frac{x}{0.01} \right)^2. \end{aligned} \quad (2-6)$$

Insisting this be greater than the link margin y^{-1} provides another upper limit,

$$N_{max,ii} = 9 \times 10^4 \frac{2}{m(i, \lambda)} \left(\frac{h}{550\text{km}} \right)^{-2} \left(\frac{x}{0.01} \right)^{-2} \left(\frac{y}{0.1} \right). \quad (2-7)$$

2.7.3 Economic constraints on constellation size

Microeconomics recommends that a constellation grow to the point where the marginal revenue from one new satellite is equal to its cost. We expect the marginal revenue to be a declining function as more and more capacity is introduced by more and more competitors, and although we expect the marginal cost to be a declining function as fixed costs are amortized over more units, at some point the profit margin is squeezed to zero.

As always in emerging markets the acceptable profit margin of revenue over cost may not be well defined. Some up front loss may be tolerable in order to establish a foothold and capture market share and customer inertia — we have seen this in the constellations to date. Many of the eventual, steady state costs or remediation for harm from unregulated effects may not be defined or levied at first. (For example satellite disposal and creation of space debris is not a cost levied on Iridium at all.) There is an out of equilibrium initial advantage to getting a constellation built and flying as quickly as possible, before costs are recognized and regulations are changed.

First of all, what is the expected market for a LC? The overall internet business is estimated to be \$1T/year⁶. Physical connection by fiber or wire is well established, but it has been unprofitable to bring a physical connection to many people in the world.

For example, the number of Americans who are currently underserved by internet service providers (ISP) is estimated to be 20–40 million,⁷ i.e. about 10% of the total population. On 20 Mar 2020 the media reported that

⁶<https://www.prnewswire.com/news-releases/the-global-internet-access-market-had-total-revenues-of-9814bn-in-2016-300553419.html>

⁷<https://www.bloomberg.com/news/articles/2020-02-19/where-the-u-s-underestimates-the-digital-divide>

the FCC approved 1 million Starlink user terminals for the 3% “hardest to reach customers”, in order to connect them with the Starlink constellation of 12,000 satellites that has already been approved.⁸ Evidently the LC internet business is aiming at a small fraction of the worldwide business, picking up the customers who are remote enough to lack internet and wealthy enough to pay for it. 3% of the worldwide business is \$30B/year.

The low density of customers who are not well served by physical connections is not a problem for a LC. The density of all Americans in the lower 48 states is about 40 persons per km², concentrated in cities, so apparently something like 4 persons per km² are potential large constellation internet customers. If there are 4 people per user terminal, the unserved market has a density of about 1 per km².

The area that a satellite can instantaneously service per beam is given by Equation 2-4, but the area over which a beam can be placed is larger by a factor of about 1000, $\sim(2fd/c)^2$. Therefore a LC could expect to support ~ 2400 terminals per beam even in the most isolated areas because it can pick and choose to put beams on the highest concentrations of customers (illuminate towns, avoid desert). Therefore a Starlink satellite can expect to have 100% duty cycle connecting to underserved customers while over the US.

A satellite does not spend all its time over the US, however. The continental US is about 1/64 the area of the world, but including a 550 km range around the edges the accessible US is about 1/36 of the world. Because of the latitude concentration effect, a Starlink satellite in an orbit inclined at 53° can access the US about 1/20 of its time. With only a US market, the Starlink satellites would have a duty cycle of 0.05.

The recent launches of Starlink satellites by SpaceX are advertised to provide a total of about 1 terabit per second (Tbps) per tranche of satellites, i.e. 10^{12} bits per second from 60 satellites with a mean satellite lifetime of 5

⁸<https://www.cnbc.com/2020/03/20/fcc-approves-spacex-to-deploy-1-million-antennas-for-starlink-internet.html>

years. We interpret this to mean that under ideal conditions a single satellite can process ~ 16 Gbps, which seem generally consistent with the radio bandwidth, spectral efficiency, plausible number of beams, and processing power available.

As a benchmark for revenue, a typical internet user in the United States pays about \$800 per year for an average of at most 10 megabits per second (Mbps, i.e. 10^7 bit per second).⁹ Competition between internet service providers (ISPs) generally takes place by offering “faster internet speed”, up to 1 gigabit per second (Gbps), i.e. 10^9 bit per second. But note that streaming an mpeg compressed movie whose typical size is 1 GB over 2 hours consumes only 1.4 Mbps, so providers statistically can support users with a bandwidth allocation that is much, much less than the advertised download speed. (Error correction usually allocates 10 bits per byte in a communications channel, so $1\text{GB/s} = 10\text{Gbps}$.) Experience in the early evening at most locations in the US suggests that the total capacity provided by ISPs is actually not much greater than 3 Mbps per household.

12,000 satellites can provide $16\text{Gbps} \times 12000 \times 0.05 = 9600\text{Gbps}$ to 1 million terminals in the US for an average delivered bandwidth of 1 Mbps (17 movies streamed per day). We may expect that the cost for 1 Mbps will be no less than \$1000 per year (the figure \$80/month is widely tweeted about), so the revenue to Starlink for the US service will be at least \$1B/year from a constellation of 12,000 satellites.

Other sources of revenue are certainly available. Those willing to pay a premium price for bandwidth will get preference in the US, but the most important consideration is to increase the duty cycle for a satellite to gather revenue.

- The total number of underserved people in the world must be 100 times the US numbers, and although their means to pay for internet may be less, it may exceed the marginal cost of communicating when the satellites are otherwise idle. Note that the cost of a user terminal antenna

⁹<https://www.numbeo.com/cost-of-living/country-price-rankings?itemId=33>

may not be prohibitive, given that it is very cheap to distribute the coverage to many customers over ~ 1 km using copper wires, switches, and wireless routers. 12,000 satellites can serve 60M people, if 1/3 of the orbit is over land and has customers within the field of regard. If the net value of internet is \$1T/year and Starlink can capture 3%, this is the \$30B/year mentioned above.

- There are 10^7 airline flights per year of which a substantial fraction are long-haul and provide (poor) internet connectivity through a combination of cell and satellite communication. Onboard customers are apparently willing to spend $\sim \$20$ for internet and $\sim \$5$ for streaming video which suggests that $\sim \$1,000$ might be available per flight for really good connectivity: \$2–3B/year. Transoceanic flights represent free revenue because satellites are otherwise idle.
- There are 50,000 ships on the ocean which are another set of customers that can be served when the satellite is otherwise idle: conceivably \$1B/year.
- Autonomous long-haul trucks might be safer and more reliable using satellite connectivity than local cellular connections. There are 2 million semi trucks on the road, and the cost of an antenna would not be prohibitive for an autonomous truck. This could conceivably be a \$1B/year market.
- Many US customers are not well pleased with their ISP (US customers are charged twice what Europeans pay for internet and 3 times more than Koreans, for example), so if a large constellation could compete on a price/performance basis, customers already equipped with fiber might switch \$800/year to the large constellation. On the other hand, the ISPs in the US apparently have substantial room to reduce prices in the face of competition.

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- The free-space travel time over 3000 km through LEO is about 2 msec faster than going through undersea fiber. High-speed traders have been willing to pay for ultra-low latency in the past and this might provide a small revenue stream.
 - It is arguable whether a LEO-based internet backbone is subject to regulations imposed on the ground-based internet such as net neutrality, advertising, packet-sniffing, and national control of internet content. This might be an attractive feature to some customers.

We also can speculate about the cost. Morgan Stanley estimated the satellite cost at \$1M and the launch cost for 60 satellites to be \$50M, but more current estimates are closer to \$0.5M per satellite and \$30M for the launch,¹⁰ so the cost of getting a satellite to orbit may be less than \$1M. This might come down by a factor of 2 as more satellites are manufactured and the launches shift to 180 satellites at a time on the Super Heavy Starship instead of Falcon 9. This cost of about \$12B to launch 12,000 satellites is consistent with numbers like \$10B that have floated out of SpaceX via twitter.

Construction and launch are not the only costs, but operations for a huge constellation becomes relatively minor per satellite. The customer has to pay for the ground terminal as well as monthly fees, and even if the satellite and internet management costs \$1B/year it is a fraction of the \$2B/year to construct and launch 10,000 5 year lifetime satellites.

Adding up the numbers, it seems quite possible for Starlink to bring in more revenue than expenses of \$3B/year for a constellation of 12,000 satellites.

Finally, where will microeconomics call a halt to LC expansion? A single Starlink satellite can support ~16,000 customers, but the duty cycle imposed by uninhabited areas means that approximately one satellite will be required per ~3,000 customers. At this optimum duty cycle the revenue would be

¹⁰<https://www.nextbigfuture.com/2019/12/spacex-starlink-satellites-cost-well-below-500000-each-and-falcon-9-launches-less-than-30-million.html>

\$3M/year, vastly greater than the costs so we may expect a successful LC to grow as fast as possible, and possibly get into the usual cycle of violent competition, bankruptcy, buyouts, consolidation, and comfortable oligopoly. It seems clear that the fixed internet business is not particularly competitive, so they could potentially lower their prices and erode the LEO internet market as well.

The only limit arises when the market saturates. There are approximately 4B internet users worldwide¹¹ which might translate to 1B connections. Capturing the stated goal of 3% of this market is 30 million customers, requiring a constellation of 10,000 satellites. This is apparently the Starlink Phase 1 and OneWeb Phase 2 plan.

Growth beyond a 10k constellation (or multiple 10k constellations) depends on the market. In principle there is a factor of 30 more growth by cutting into the the fixed fiber market. Economically feasible? If capturing 3% turns out to be wildly profitable there is clearly growth potential until an equilibrium is reached against the fixed fiber market.

Another growth market would be providing more bandwidth with more satellites. If the developing world becomes more prosperous, there may be a demand for more streaming at higher definition to fewer people, and this demand could be met with more satellites.

To summarize the economic constraints, the profitability is as yet unclear, and huge uncertainties remain such as liability from debris production, but it appears that if LEO internet is profitable at all for a 10k constellation, profitability could extend to a 100k constellation or larger.

¹¹<https://www.statista.com/topics/1145/internet-usage-worldwide>

2.7.4 Scaling relations for constellation size

The findings related to constellation size are summarized below.

- Orbiting at a higher altitude and having a greater reach is only a marginal advantage for a very large constellation. Customers are in reach slightly longer before a satellite passes out of range and no longer generates revenue. The fact that atmospheric drag is less is a minor benefit because the satellite has to station keep throughout its life, and the components and collision rate will limit the lifetime to something like 5 years anyway.
- Some constraints on constellation size from communications confusion start appearing for constellations larger than 10^5 at 550 km altitude and 2×10^4 at 1200 km altitude, but these can be managed by appropriate engineering and operations.
- The density of potential customers does not create a limit on the size of constellations. Starlink's 12,000 satellite constellation is designed to serve 3% of the world market. At least that many satellites are required to serve 1Mbs to the 1 million user terminals that Starlink planned for its first US rollout. By subdividing bandwidth into many channels, forming many beams, and if necessary packetizing and time sharing a satellite can use its 16 Gbps for a wide range of population density, and in principle a larger constellation could serve a much larger fraction of the population than 3%.
- There are many fixed costs such as development and tooling, operations, and personnel that do not increase much with the size of a constellation so there are strong advantages for larger constellations.
- There are so many unknowns right now in terms of cost and elasticity of the price-demand curve for internet bandwidth that it is not possible to say where the microeconomics limit comes in for constellation size. Evidently that limit is much greater than 10,000 satellites, very possibly 100,000 or more.

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- As we shall discuss below in §5, there appear to be strong constraints on constellation size in order to avoid creation of enough dangerous derelicts and debris to eventually destroy the constellation, *particularly* at 1200 km altitude. However there are no regulations that prevent a constellation from reaping profit for a few decades and then allowing it to disintegrate into debris, so this may not be an economic disincentive for very large constellations.

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3 IMPACT ON ASTRONOMY

3.1 The Impact of Large Satellite Constellations on Optical Astronomy

JASON was asked by NSF and DOE to assess the impact of current and planned large satellite constellations on astronomical observations generally, and in particular the impact on the Vera C. Rubin Observatory (Rubin) and its Legacy Survey of Space and Time (LSST). In this section, we discuss impacts and mitigations on optical astronomical facilities, including the Rubin Observatory. In the next section, we will discuss impacts on other areas of astronomy including infrared, radio, and CMB.

A very large amount of detailed work has gone into the topic of large constellations and their potential impact on optical astronomy [22, 35, 40, 37]. JASON was briefed on this topic by NSF and DOE, including talks on Rubin by project members and by Space-X on Starlink. In addition, JASON members listened to talks in workshops convened by the Astro2020 Panel on Optical Interference from Satellite Constellations (27 April 2020), and the AAS Committee on Light Pollution, Radio Interference and Space Debris (SATCON1: 30 June - 1 July 2020). The SATCON1 workshop circulated draft working group reports, including one from the Mitigations Working Group and one from the Metrics Working Group. All of these discussed various mitigations, including mitigations of the impact on the Vera Rubin Observatory. The work included simulations of large constellations of satellites and their appearance in optical telescopes when illuminated by sunlight at various latitudes and times of the year. The work also included discussion of the possibility of optical glints and flares.

3.1.1 Summary of results to date

The results on impact of large constellations of satellites on optical astronomy can be summarized as follows.

- The impact of large constellations of satellites is dependent on the brightness of the satellites in reflected light. A useful threshold for brightness is AB magnitude=7 (5.75×10^{-26} W/m²/Hz)¹². This magnitude will likely avoid most saturation problems in CCD detectors used on large telescopes with low-f number [40], and it is also a brightness that is below the visibility limit of the human eye (\sim magnitude=6.5). Starlink satellites currently in orbit have measured magnitudes of m=4-8 (e.g., [34, 14, 39]), see Figure 4.

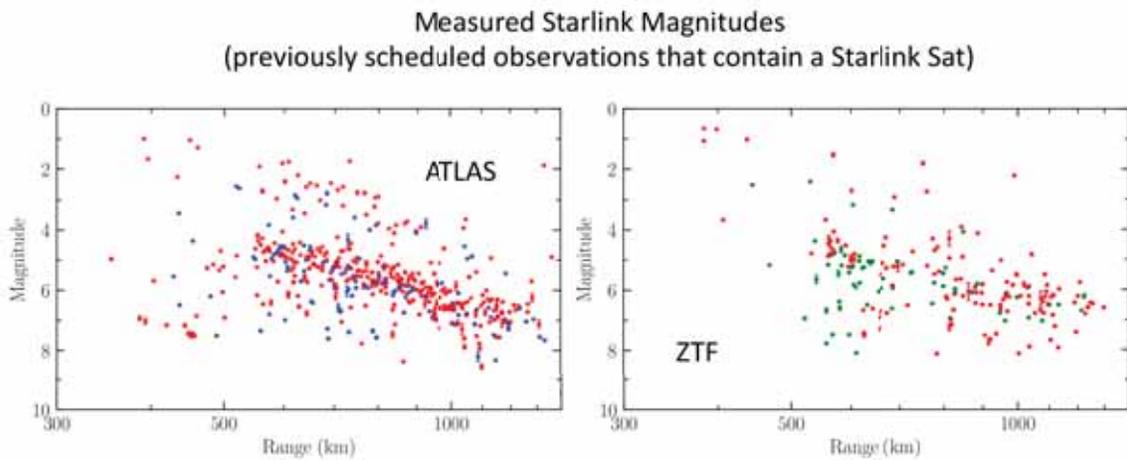


Figure 4: ATLAS and ZTF measurements of magnitudes of Starlink satellites. Using accurate SupTLEs provided by T.S. Kelso (<https://celestrak.com/NORAD/elements/supplemental/>), we identified archival images of ATLAS and ZTF containing Starlink satellite trails. Since these images were taken during normal operation of ATLAS and ZTF, they are representative of the brightness of the satellites that wide-area survey telescopes, such as the Rubin Observatory might have encountered had they been operating. Point color indicates the filter bandpass.

- Satellites in orbits below 650 km will also have less impact than satellites in higher orbits, e.g. 1000 km, because of the length of time that the satellites will be illuminated by the Sun: those in 650 km orbits will be illuminated during a few hours during and adjacent to twilight, while those at 1000 km can be illuminated the entire night depending

¹²We use the AB magnitude system which is calibrated in terms of spectral flux density. Conversion to other systems is discussed in, e.g., [?]

on latitude and time of year (see Figures 5, 6, and 7 for representative calculations).

Given these results, we recommend consideration of the following mitigations, separated into two categories: those that benefit a broad set of astronomical facilities and those that are more specific to the Rubin Observatory. While we do recommend mitigations that apply to satellite operators and encourage NSF and DOE to pursue these, we feel that it is best for the optical astronomical community to prepare for the worst, i.e., the possibility in the future of a mostly unregulated set of constellations from a variety of countries, with satellites numbering in the tens of thousands or more. Many additional mitigations have been recommended by various working groups. We list here those that we currently feel are high priority.

3.1.2 Optical astronomy: recommended mitigations

General recommendations listed in priority order, highest priority first – not necessarily specific to the Rubin Observatory

1. **Recommendation:** If at all possible, discourage or prevent large constellations with orbits above 600 km. There are two critical reasons:
 - (a) Impact on astronomical observations. Satellites orbiting at $\gtrsim 1000$ km are visible for a much longer fraction of the night. Satellites orbiting at 600 km or below reflect sunlight for only a few hours during and after twilight and consequently leave periods during the night that do not impact ground-based optical telescopes, see e.g., [35, 37]. While similar satellites will generally be fainter in 1000 km orbits than 600 km orbits¹³, this is not enough to offset the fact that satellites will be visible for a greater part of the night for higher orbits.

¹³Because streak SNR saturates as soon as the streak is longer than the point spread function, and because the angular rate at 1000 km is half that at 500 km, the satellite will be two times fainter at 1000 km altitude rather than 4 times fainter, as might be expected from range considerations.

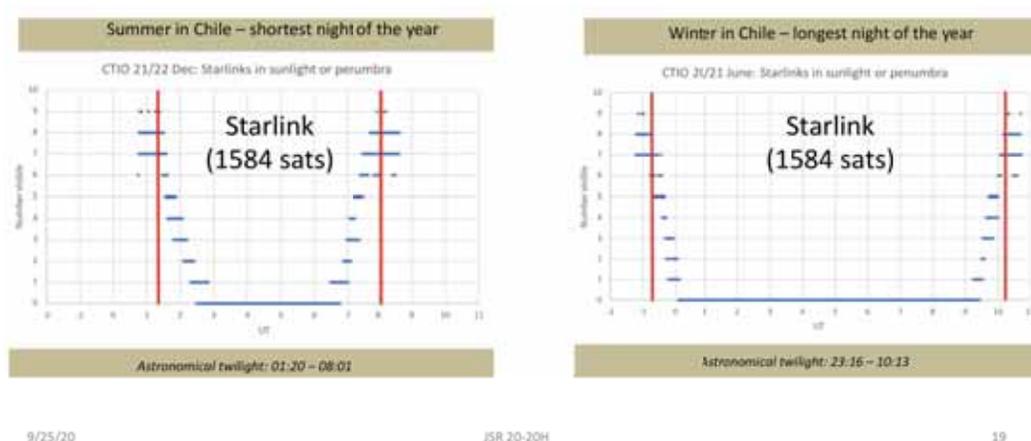


Figure 5: Example calculations taken from Patrick Seitzer talk to JASON. Plots show visible number of Starlink satellites for a constellation size of 1584. See also [37].

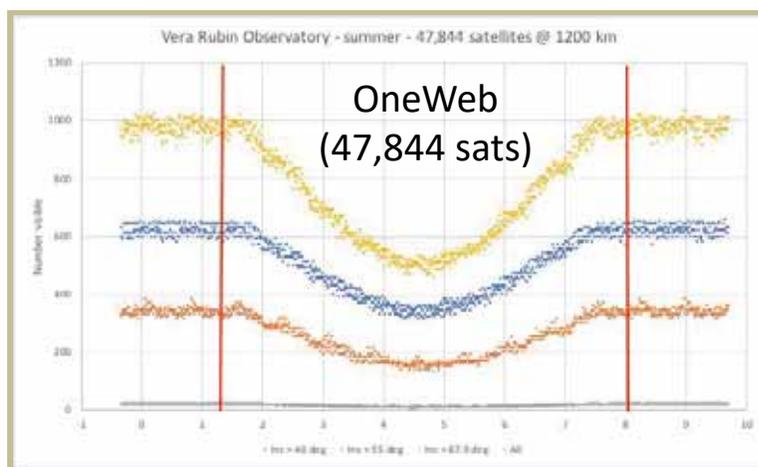


Figure 6: Example calculation taken from Patrick Seitzer talk to JASON. The figure shows the visible number of OneWeb satellites for a constellation size of 47,844, for summer observations at Cerro Tololo. Note that over 500 satellites in three planes would be visible even at midnight. Yellow indicates the total number of satellites over all planes; blue, orange, and gray specifies the orbital planes with inclinations 40, 55, and 87.9 degrees respectively. See also [37].

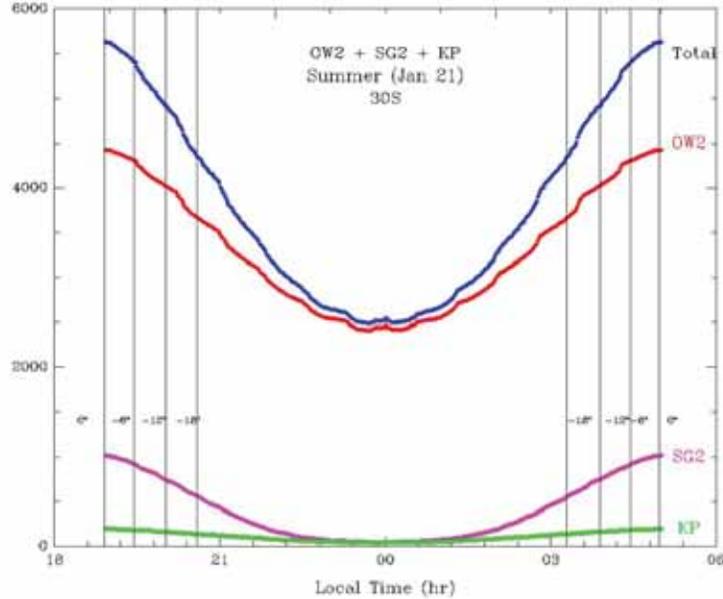


Figure 7: Example calculations taken from Jonathan McDowell talk to JA-SON. The figure shows the visible number of satellites for 3 constellations: 2nd generation OneWeb (OW2), 2nd generation Starlink (SG2), and Kuiper. See also [35].

- (b) Failure of satellites (or the company operating them) will jeopardize de-orbit and orientation control capability. Even if this happens in only a small fraction of cases, it will contribute to an increase in the semi-permanent population of non-maneuverable space junk. We note that a massive solar coronal mass ejection event disabled satellites in the past and could do so in the future [36]. At 600 km, the orbital decay time is $\sim 1\text{--}40$ yr (depending on ballistic coefficient and solar activity), at 800 km it is $\sim 40\text{--}500$ yr, at 1000 km it is > 300 yr. At 1000 km, any satellite failure will be a very long-lived problem. Failed satellites become a target for collisions with other space debris; such collisions can then produce many small pieces of debris, creating a hazard for any satellites whose orbits lie in or cross that altitude range *including astronomical and Earth science satellites*. Regarding failure of companies that have developed constellations, we note that Iridium, Globalstar, and Orbcomm, have been threatened with, or declared,

bankruptcy at some point. Although these companies survived in modified form, their examples illustrate the potential challenges of competing in the satellite constellation business. More recently, OneWeb experienced financial problems and was then purchased by the U.K and an Indian telecom company.¹⁴ The status of the constellations and the liability for their safe operation will be a serious long-term issue. The issues of collision and debris are addresses in §5.

As a specific case, NSF/DOE should work with elements of the U.S. Government, as well as U.K. and India governments to limit the negative impacts of OneWeb satellites, require OneWeb to operate only at altitudes below 600 km, and discourage other large constellations planning orbits above 600 km.

2. Satellite operators must bear the responsibility for all of their satellites at all times. Operators need to make accurate satellite orbital information available publicly. Organizations carrying out astronomical observations can then either: (1) Avoid times/pointings when satellites are present, or (2) Accurately determine what observations might be affected.

Recommendation: Publicly available software should be developed for use by observatories that will incorporate the most accurate orbital information and predict whether a given observation will be impacted by the presence of a satellite (see footnote [2]) . The accuracy of predictions and post-facto information requires further study, but as a starting point we suggest: Accuracy of 1 arcminute in the along track direction and 10 arcsec in the cross-track direction¹⁵, accurate to 10 seconds in time. A given prediction needs to be accurate for at least 10 hrs into the future to allow for timely planning of upcoming astronomical observations.

¹⁴<https://spacenews.com/bankruptcy-court-frees-payment-to-oneweb-satellites-to-restart-satellite-manufacturing/>

¹⁵1 arcsec = 1/3600 deg; 1 arcmin = 1/60 deg

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3. **Recommendation:** Steps should be taken by satellite operators to reduce the reflectivity of their satellites, following the example of SpaceX, which has taken significant steps to darken their satellites with the goal of an apparent visual magnitude $m=7$. Reduction in reflectivity is important in all orbital phases: parking orbits, orbit raise, operational orbit, and de-orbit.
 4. **Recommendation:** Operators should be required to have a well-defined, quantitative de-orbit plan that minimizes time for de-orbiting, both to decrease likelihood of a collision and to decrease time during which satellites may be brighter than in the operational orbit. Similarly, require operators to have a quantitative plan for residence time in parking orbits and the time needed for raising satellites to operational orbit. Minimize both of these.
 5. The long-term, 10-year evolution of the numbers of large satellite constellations is unknown, particularly since companies in countries other than the U.S. have announced intentions to launch large constellations. Therefore the baseline assumption should be that large number of satellites will be present in the future, possibly in orbits above 600 km. Many wide-field telescopes such as Rubin, ATLAS, and ZTF have developed software to mitigate the effects of satellite tracks in images.

Recommendation: NSF should support development of publicly available software tools and thus ensure that the wider community has access to the needed tools for both prediction of times and locations of satellites, and identification and removal of satellite artifacts in observations, and that funds for such mitigation be made available without taking away from the budget for science research.

Recommendations Specific to the Rubin Observatory

Some key science projects of the Rubin Observatory will ultimately be limited by systematics. However, it is not clear to us whether large satellite constellations will be the dominant systematic limitation on Rubin/LSST

investigations such as dark energy/weak-lensing. Many questions will only be answered when on-sky data become available during the engineering verification of the Rubin Observatory. Near-term investment of resources on the impacts of large constellations should be moderate until data are in hand. The process for fully understanding Rubin systematics will likely have a long time scale, probably several years.

1. **Recommendation:** The Rubin Observatory should undertake a comparative study of saturation and cross-talk effects from different sources (e.g., bright stars, satellite streaks) as well as the effects of “ghost” images on sensitive weak-lensing measurements. This will help determine the principal sources of systematic uncertainty. These estimates should be checked against on-sky data.
2. **Recommendation:** Rubin/LSST should consider 2 x 15s observations, even though they result in a reduction of $\sim 8\%$ in effective observing time. Paired observations have advantages in mitigating effects of, for example, cosmic rays, but also have useful science benefits, e.g., for fast moving near earth objects (NEOs) because the pair of observations provides directional information not necessarily available in single observations. In the context of mitigation of the effects of LEO satellites, in most cases, one of the two 15s images will be free of the track of a given satellite since a LEO satellite at 500 km will traverse the 3.5 deg field of Rubin/LSST in less than about 5 s, while the time gap between 15s exposures is about 4 s (2s for shutter open and close, and 2s for readout). Consequently, each pixel in the image will have one of the exposures free of the satellite track, albeit with a factor of $\sqrt{2}$ decrease in sensitivity (0.4 mag). One prompt processing possibility would be to release an image that contains the lesser flux for a given pixel between the two images, a product that would be largely free of satellite tracks, and sufficient for many types of prompt science. More extensive processing could be implemented later to regain most of the $\sqrt{2}$ decrease in sensitivity, if desirable.

Other mitigations for the Rubin Observatory have been suggested (see e.g., [40]), such as increasing readout time to reduce cross-talk or electronics modifications to mitigate saturation. These involve detailed knowledge of the Rubin/LSST readout electronics and are best evaluated by the Rubin Observatory project.

3.2 Near and Mid-Infrared

Satellites reflect sunlight and can be naked eye objects in the optical [22]. Communications satellites usually transmit coherent radiation in the radio, making them easily the brightest objects in the radio sky. The region between these wavelengths, the infrared, can also be impacted from both a satellite's reflected solar radiation but also from thermal blackbody radiation from the satellite itself. A simple calculation of the brightness of the Starlink and OneWeb satellites in the infrared from 1–26 μm is shown in Figure 8.

There are currently fewer ground-based surveys in the infrared than in the optical, but this is likely due to the cost and capabilities of optical vs. infrared detectors rather than for intrinsic scientific reasons. Successful ground based infrared surveys include 2MASS, UKIDSS, and VISTA [28, 32, 38]. These surveys have seen satellite trails in their images, as shown in Figure 9.

Large constellations are a concern for future ground-based wide field surveys. Unlike in the optical, the satellites will be visible all night regardless of their altitude not just during twilight. However, the brightness of the streaks compared to the sky background will not be as large, likely lowering or eliminating the kinds of saturation effects discussed in §3.1. The primary impact will likely be extra data processing to remove streaks, and the loss of a more substantial area of the focal plane due to light contamination from the streaks.

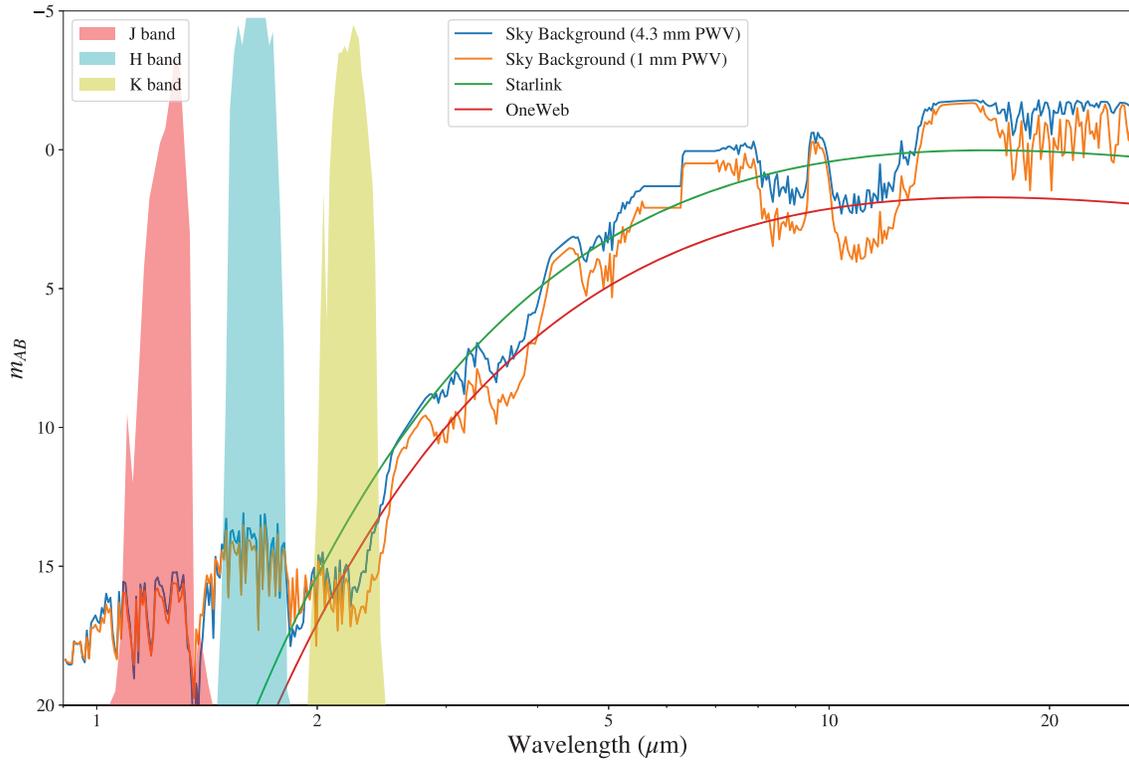


Figure 8: The expected blackbody thermal emission expressed as AB magnitudes from the Starlink and OneWeb satellites compared to the sky emission at an excellent observatory site with 1 mm of Precipitable Water Vapor (PWV), and a more typical site with 4.3 mm PWV. A Starlink satellite is expected to be about 0.5 arcsec diameter on the sky, which matches the typical seeing in the near-IR, so the sky background is calculated in a 0.5 arcsec circular aperture. Common NIR astronomical observing bands are shown as filled regions. Satellites become brighter than the sky in atmospheric windows astronomers typically observe in, especially K, L, M, and N band, and could impact astronomical surveys in these windows.

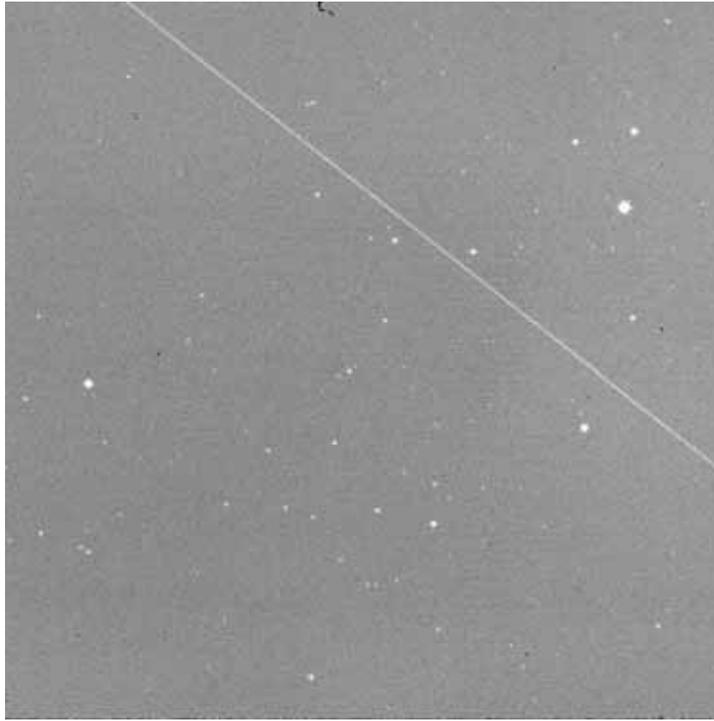


Figure 9: The SpaceX Starlink “Darksat” satellite observed in a 10 second exposure with the VISTA telescope’s VIRCAM in Ks-band. Image Credit: Boris Haeussler, Felipe Gaete and Angel Otarola (Tregloan-Reed *et al.*, 2020, *in prep*).

1. **Finding:** Satellite trails from large constellations will be visible in near- and mid-IR wide field images at all times, not just during twilight. They will likely not be bright enough to cause saturation or other artifacts that seriously degrade science output of future large ground-based surveys.

3.3 Laser Guide Star Adaptive Optics

Adaptive Optics (AO) systems compensate for blurring of telescope images due to atmospheric turbulence. AO systems are now installed on virtually all 8-10m imaging telescopes in the world, including the five that are most frequently utilized by US astronomers (two Gemini telescopes, two Keck telescopes, and the Large Binocular Telescope).

Adaptive optics is based on rapid measurements of atmospheric turbulence using light from relatively bright stars close to the target of interest. When a sufficiently bright star is not close by, one can make an “artificial star” using an upward propagating laser beacon to excite atomic emission or molecular scattering in a small spot high in the earth’s atmosphere. The five telescopes mentioned above all are equipped with laser guide stars for this purpose, with high-impact scientific results flowing from these LGS AO systems on a regular basis at spatial resolutions three to four times better than those of the Hubble Space Telescope at the same wavelengths.

3.3.1 Laser clearing house

In some cases, it is possible that a laser guide star might unintentionally damage a satellite located or passing overhead. To avoid this, the Department of Defense has been operating the Laser Clearing House (LCH) under a series of DoD mandates. The LCH uses Predictive Avoidance to instruct laser operators to turn off their lasers at specific times when they are pointed in specific directions, if their lasers are thought to be capable of damaging the satellite in question. Although its main mandate applies to all DoD laser programs, LCH works with volunteer non-DoD laser US programs as resources allow, including all the 8-10m telescopes mentioned above. We understand that the NSF has committed all NSF-funded US observatories to continue working with the LCH in this manner.

Until now a laser guide star-equipped telescope such as Keck might be asked to turn off its laser a few to ten times a night or more, depending on the directions of their astronomical targets for the night. In general it has not been too onerous to work within the requirements of the LCH, and LCH turn-off times have been nicely integrated into telescope operations.

The reason for our concern about this topic is that if large constellations were to be included in the LCH “Protect List”, so that laser guide stars would have to turn off every time one of the Starlink or similar satellites is close by, the number of required laser turn-offs would increase by factors of up to 100.

This would make it virtually impossible for laser guide star adaptive optics to produce meaningful astronomical results because the laser would be turning off and on so frequently.

Our informal understanding is that to date, the StarLink satellites have not been added to the “Protect List” by the LCH. Indeed the briefers who described the StarLink system to us stated that their platforms were laser-safe and thus would not need to be “protected” by the LCH methodology. We are not privy to analogous information for the OneWeb or Kepler constellations.

The issues above have raised several questions in our minds, at least some of which stem from our less than perfect understanding of the inner workings of the LCH at its current home within JSpOC (Joint Space Operations Center) in the DoD:

1. We are familiar with the Predictive Avoidance process, in which the DoD uses sophisticated computer algorithms, fed by data on satellite materials and configurations, and determines whether a specific laser has a high probability of significantly damaging a specific type of satellite. If it is determined that the satellite is vulnerable for one of many reasons, that satellite is placed on the “Protect List” and instructions are given to Laser Guide Star-equipped astronomical observatories to shutter their laser in order to avoid that satellite. What we do not understand is the process by which a vendor such as StarLink or SpaceX can come at the deconfliction process from the other direction, by informing the LCH that they do not wish to be placed on the “Protect List” (a statement that presumably would be accompanied by appropriate documentation) regardless of the results of DoD’s Predictive Avoidance process. This would be highly desirable if it has not happened already.
2. President Trump issued Space Policy Directive 2 in 2018, which calls for functions pertaining to the regulation of commercial space activities (such as Space Situational Awareness data and Space Traffic Management) to be consolidated within the Office of the Secretary of Com-

merce. Thus regardless of the current policies of DoD’s LCH, it is unknown what the corresponding policies will be once the transfer to Commerce has taken place, nor is it known whether the LCH would be part of this transfer of responsibilities. Would it remain entirely within the DoD? Would it only transfer commercial satellites to the Department of Commerce?

3. In any case, it is our understanding that the issue of the appropriate administrative home for SSA and STM functions has been on hold due to lack of Congressional action. Earlier this year Congress requested an outside study to assess the feasibility, expected effectiveness, and funding implications of a transfer of space traffic management functions to the Office of the Secretary of Commerce as directed by SPD-2. This six-month study has been undertaken by the National Academy of Public Administration¹⁶. The study recommended that the Office of Space Commerce (OSC) in the Department of Commerce be selected to conduct the SSA/STM mission.

3.3.2 Laser guide stars: recommendations

Our recommendations for this section come in two parts:

1. **Recommendation:** For a modest number of Large Constellation satellites that require laser precautions, allow the vendor to “opt-in” to get onto the Protect List (with specific compelling evidence required). The remainder of the satellites in the Large Constellation would be responsible for protecting themselves. The vendor would do this by remaining cognizant of potential laser damage mechanisms throughout the design and test process. and/or
2. **Recommendation:** The Laser Clearing House should commit to keeping Large Constellations off their “Protect” list, while encouraging the

¹⁶<https://www.napawash.org/studies/academy-studies/united-states-department-of-commerce-office-of-space-commerce>

vendors to design all future satellites to minimize their vulnerability to ground-based laser guide star illumination.

Regardless of which of these options (or others) are chosen, it will be imperative to maintain a consistent policy, documentation, and corporate memory of how commercial Large Constellations are to be treated, as the Laser Clearing House responsibility is moved from the DoD to its future home in some other Federal Agency.

3.4 Radio Astronomy Impacts

Radio Astronomy. While much of the recent focus of the astronomical community has been on the impact of large constellations on optical astronomy, the radio astronomy community has been working for several years with companies such as SpaceX, OneWeb, and Amazon to determine the impacts of their gateway and user-terminal satellite downlinks on radio astronomy and what steps the operators of large constellations should take to ensure that their emissions satisfy existing regulations. The regulatory framework is well established by organizations such as the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) within the United States, as well as the International Telecommunication Union (ITU). However, as discussed below, this regulatory framework does not seem to be sufficient to protect radio astronomy in the era of large constellations of communication satellites.

3.4.1 Estimates of RFI from large constellations

Radio Frequency Interference, or RFI, may occur by main-beam or side-lobe illumination from a satellite. The RFI may enter the radio telescope's receiver either through the telescope's main beam or side-lobes. Furthermore the illumination may be in-band or out-of-band; in the latter case the imperfect nature of band-pass filters may be at fault, either in the receiver or the satellite's transmitter. The worst case is of course in-band main-beam

into main-beam where RFI may be measured in megaJansky; but this case is prevented by ITU regulations, if respected. Mitigations may be tried at the radio telescope, or on the satellite, or preferably both. An important difference between LEO and GEO is footprint size: Transmitted RF footprints on the ground may typically be much narrower for a LEO sat (~ 20 km) than for a GEO sat (~ 200 km); if so, satellite operators will be capable of finer control of keep-out zones; see Figs. 10,11.

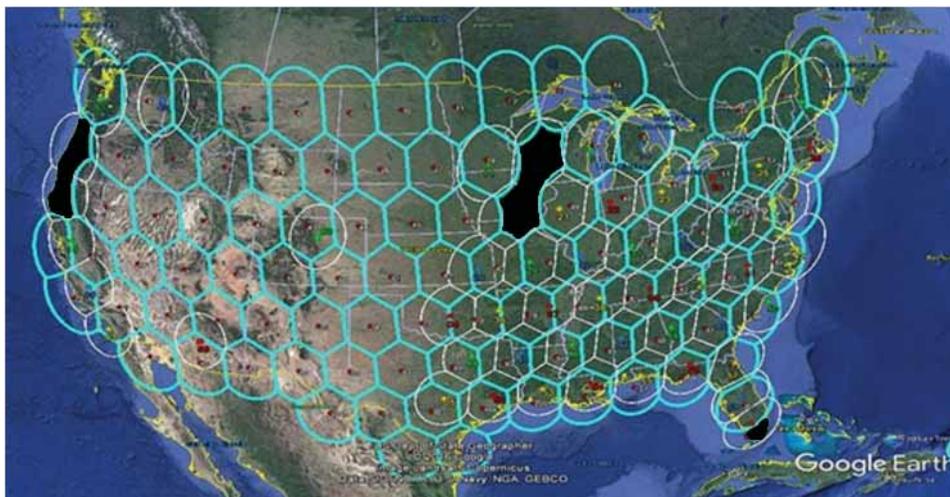


Figure 10: Beam footprints in Ka band for internet service provided by a GEO satellite (HughesNet Corp, in teal); each is about 300 km across. GEO satellite transmissions are generally moving from Ku band to Ka band. From [25]

We wish to estimate the Radio Frequency Interference (RFI) at ground level from a constellation of satellites, as received by a single-dish radio astronomy telescope. For large constellations, a detailed calculation of this is challenging, involving many factors: number of satellites in view at any given time, direction of the transmitted main beam(s), sidelobe structure of the satellite transmit antennas, and detailed positions of the satellites at any given time. For companies to demonstrate compliance with ITU regulations, detailed simulations are carried out, such as those given in [1] (see also [15]). Those simulations are different for each large constellation.

Such detailed simulations are beyond the scope of this study and in any case we do not have access to the detailed information on the operation

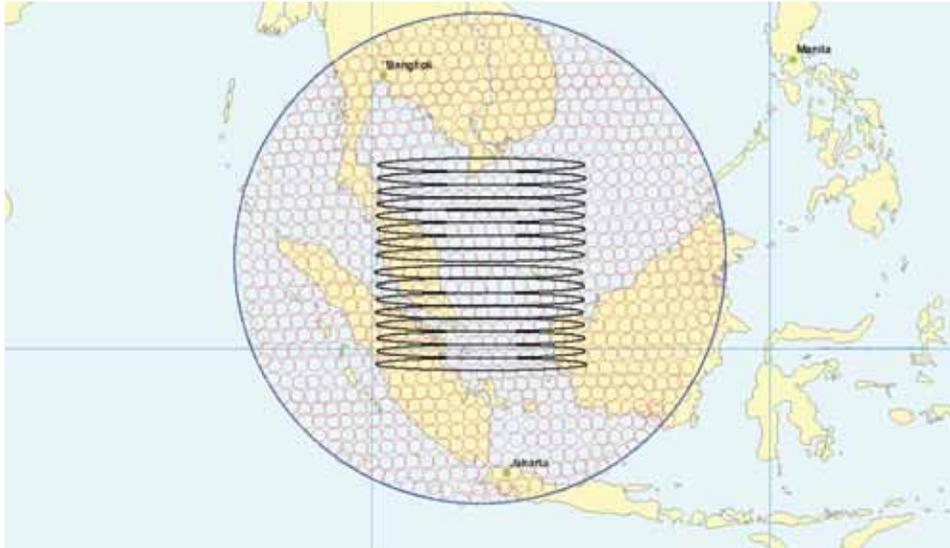


Figure 11: Beam footprints in Ku-band for internet service provided by LEO satellites (Starlink in orange, OneWeb in black). Beam footprints in Ka-band will be 3 times smaller, or as small as 20 km. From [44].

of the constellations that would be required to carry out such simulations. Here, we take a different approach. Since all large constellations are required to meet ITU regulations, we use the limits imposed by those regulations to estimate the RFI. Specifically, we use ITU Equivalent Power Flux Density (EPFD) limits, which pertain to the summed emission from a constellation of satellites. Although all operators must meet these limits, the economics of the constellation as well as the desire for providing maximum data rate to ground will push large constellations towards operating near the limits. Here we will assume that the constellations will be operating within 5-10 dB of the EPFD limits. Taking this approach avoids the necessity of knowing the many details of the constellation, and rather, simply estimates the RFI of a constellation operating somewhat below the ITU limits. As will be seen, the ITU limits are insufficient to protect radio astronomy in bands where some radio telescopes operate, for instance for X-band (8-12 GHz) and K-band (18-27 GHz) and particularly for single dish, single feed telescopes.

3.4.2 PSD and EPSD limits

For convenience, we will use Power Spectral Density (PSD) and Equivalent Power Spectral Density (EPSD) which can be calculated directly from the Power Flux Density (PFD) and the Equivalent Power Flux Density (EPFD), quantities that are used in ITU and FCC documents. EPFD takes into account the aggregate of the emissions from all non-GSO (non GEO Stationary Orbit) satellites in the direction of an Earth receiving antenna. In contrast, PFD applies to transmissions from a single satellite. For uniformity, we convert all levels to units of dB W/m²/MHz and also given Jansky equivalents (1 Jy = 10⁻²⁰ W/m²/MHz). PSD is sometimes called “spectral PFD” in ITU documents, e.g. in [4]. The PFD requirements correspond to a single satellite emitter, while the EPFD requirements correspond to the total emission from a constellation of satellites. A tutorial discussion of EPFD is given in [27]. Regulations for PFD are given in ITU Radio Regulations (RR) Article 21 [16] and EPFD regulations are given in ITU RR Article 22 [17]. The procedures for calculating RFI are given in the ITU Handbook on Radio Astronomy[11], see footnote.¹⁷

¹⁷ITU Handbook on Radio Astronomy - Section 6.4.3.2: “The potential for detrimental interference from non-geostationary LEOs is exacerbated by their operation in large numbers, which make it possible for many of them to be simultaneously above the horizon at a radio observatory, and within LoS of the radio telescope antenna. This leads to a situation where the radio telescope antenna can receive unwanted emissions from those visible non-geostationary LEOs through near and far side-lobes of the antenna beam, and also through the main beam. The interference problem is complicated by the continually changing directions of arrival of the interfering signals, and the need for the radio telescope antenna to track the celestial source under observation. Multiple inputs of strong signals may drive the operating point of the receiver into a non-linear region, resulting in the generation of intermodulation products.

The impact of unwanted emissions produced at radio astronomy sites by a constellation of satellites in (low) non-geostationary orbits may be determined using the epfd methodology described in Recommendation ITU-R S.1586. Calculation of unwanted emission levels produced by a non-geostationary fixed-satellite service satellite system at radio astronomy sites, or Recommendation ITU-R M.1583, Interference calculations between non geostationary mobile-satellite service or radio navigation satellite service systems and radio astronomy telescope sites, and the antenna gains given in Annex 1 to Chapter 4. These Recommendations may be used to determine the percentage of data lost during observations made at a particular radio astronomy site due to interference from a given satellite system. The maximum acceptable percentage of data lost is defined in Recommendation ITU-R RA.1513.”

Table 4: ITU Limits on Power Spectral Density (PSD) and Equivalent Power Spectral Density (EPSD).

Frequency (GHz)	PSD (dB W/m ² /MHz)	Starlink Emitted PSD (dB W/m ² /MHz) (10.7-12.7 GHz)	EPSD Limits (dB W/m ² /MHz) (=10 ^{5.4} Jy)	Detrimental ITU RFI Threshold (dB W/m ² /MHz) (=100 Jy)
10.7-11.7	-116 ^[1]	-122 ^[4]	-146 ^[2] (=10 ^{5.4} Jy)	-180 ^[3] (=100 Jy)
17.7-19.3	-105 ^[1]	-116.3 ^[4]	-150 ^[2] (=10 ⁵ Jy)	-172 (=630 Jy)
19.7-20.2	NA	-116.3 ^[4]	-140 ^[5] (=10 ⁶ Jy)	-171 ^[3] (=800 Jy)

The second column gives the ITU PSD limits. The third column gives the SpaceX Starlink single satellite main-beam PSD levels for comparison. Emissions from the sidelobes of a satellite constellation need to meet the EPSD limits given in the fourth column. The fifth column gives the ITU detrimental RFI threshold for radio astronomy observations. The last column gives threshold levels detrimental to radio astronomy continuum observations.

^[1] R-ACT-WRC.12-2015-PDF-E: Article 21 Summary [16]

^[2] R-ACT-WRC.12-2015-PDF-E: Article 22 Summary [17]

^[3] ITU-R RA.2131, Figure 1 (approximate) [26]

^[4] FCC Filing: SpaceX Non-Geostationary Satellite System, Attachment A, Technical Information to Supplement Schedule S. The Starlink RFI levels are assumed to be constant over the 17.8-20.2 GHz range.

^[5] ITU Article 22

LEO constellations of communication satellites propose to broadcast in the X-band (8-12 GHz) and K-band (18-27 GHz), and in the future possibly at Ka-band (26.5-40 GHz) and V-band (40-75 GHz), so the problems for radio astronomy are mostly for high-frequency observations at or above about 10 GHz ¹⁸.

¹⁸There appears to be a rather confusing difference in nomenclature between the bands quoted for satellite downlinks and the band nomenclature of the Institute of Electrical and Electronics Engineers (IEEE) used for most radio astronomy observations. For radio astronomy, X-band covers 8-12 GHz, while satellite downlinks in this band are called Ku-band. Similarly, for radio astronomy, K-band covers 18-27 GHz, while satellite downlinks in this band are called Ka-band. The IEEE defines Ku as 12-18 GHz and Ka as 26.5-40 GHz.

Several conclusions can be drawn from the table.

- EPSD limits are generally stricter than PSD limits and since these limits are for a constellation of satellites, the average individual satellite emission limits are therefore even more constraining.
- Starlink main beam emissions are generally 5-10 dB below the PSD requirements. SpaceX presents both PFD and EPFD calculations in [1].
- The ITU Detrimental RFI thresholds in the table are taken from ITU-R RA.769-2 and RA.2131. Even though these are more stringent than the EPSD requirement, even these are very large in terms of Jy units. They are derived assuming a *constant* signal integrated for 2000 s. For a 10 MHz bandwidth, the statistical fluctuations in the power are down by $\sqrt{\Delta ft}$ (Eq 1 in [26]) or about 50 dB down from the nominal detrimental power spectral densities, i.e., at mJy levels. If the fluctuations in the satellite constellation EPFD are on the order of a mJy, this can have significant impacts on a radio astronomy observation. However, the RFI levels will not be steady when satellites are potentially detectable in antenna sidelobes. In this case, the noise will be time variable and will be dominated by statistical fluctuations in the number of satellites and their sidelobe contributions at any given time.
- While the ITU regulations concerning EPSD limit the *average* power in satellite RFI, it is actually the *fluctuations* in RFI power that are most damaging to astronomical observations. To understand this, note that the EPSD of the sky at temperature T_{sky} observed at wavelength λ is $kT_{\text{sky}}/\lambda^2$ per polarization.¹⁹ For representative values $T_{\text{sky}} = 10$ K and $\lambda = 3$ cm, $\text{EP}_{\text{sky}} \approx -128$ dB re $\text{Wm}^{-2}\text{MHz}^{-1}$ (10^7 Jy). This is about two orders of magnitude larger than the limits on the EPSD of satellite constellations in Table 4. So if satellite RFI were uniform in space (i.e., position on the sky), in time, and in frequency, it would be an almost

¹⁹This presumes that the energy per photon $hc/\lambda \ll kT_{\text{sky}}$, or $\lambda \gg 1$ mm at $T_{\text{sky}} = 14$ K.

negligible contribution to the noise background against which astronomical sources are detected. On the other hand, the power spectral densities of astronomical sources are typically also orders of magnitude below the thermal noise background. What makes a weak astronomical source detectable is that it is *not* uniform but rather concentrated either in frequency (as with radio-frequency emission and absorption lines of atoms or molecules), in time (e.g. pulsars), or in position on the sky. Thus if the uniform thermal-noise-background level is sufficiently well determined via integration over a large time-bandwidth product, the spatio-temporally compact astronomical source can be detected by subtraction of this background from the data. Similarly, in radio interferometry diffuse sky noise does not correlate between distinct radio dishes, but sufficiently compact astronomical sources do (see later discussion in Sections 3.4.3 and 3.4.4). Unfortunately, most RFI is also nonstationary in space, time, and position, and therefore easily entangled with natural astronomical sources.

3.4.3 RFI fluctuations

To estimate the fluctuations, we assume operation of the constellation at 5 dB below the EPSD limits of Table 4. Because we do not know the pointing characteristics of the satellites in the constellation and therefore do not know the distribution of emitted power into the sidelobes of the satellite phased arrays, we simply divide the EPSD contribution equally among all satellites visible to a given radio telescope using Eq. 2-1. For the radio telescope, we use the prescription for gain vs angle off the telescope pointing direction as given in ITU documents such as [2, 3]. This is an approximation of the response of a generic radio telescope. We used 11.2 GHz as the fiducial frequency of our estimates.

The contribution of individual satellites randomly distributed according to Eq. 2-1 is then estimated using the gain vs angle response of the telescope. We do a Monte Carlo calculation of 5000 trials, each trial sampling from a

Poisson distribution of satellites within 10 degrees of the axis of the radio telescope. Typically only a small number of satellites contribute measurable flux into the near sidelobes of the radio telescope. We choose a telescope zenith angle of 45 degrees as representative.

The results are shown in Figure 12. Several conclusions can be drawn from these estimates.

- The total RFI contribution from a constellation of satellites operating within 5 dB of the EPSD regulation limits is $10^{4.9}$ Jy (Table 4). For a constellation of 40,000 satellites, using Eq. 2-1 the number of satellites visible 10 degrees above the horizon is about 700. The average EPSD contribution per satellite is therefore about 100 Jy. However, single dish radio telescopes generally have small fields of view with response that drops significantly off the telescope axis. Taking the telescope response into account indicates that the RFI into the near main beam and sidelobes of the telescope can be at the mJy level (Figure 12). Note that for constellations smaller than 40,000 satellites, the total EPSD contribution will remain roughly constant, the average emission per satellite will grow larger, as will the relative fluctuations in the RFI.
- The fluctuations in the RFI contribution can span an order of magnitude: ~ 1 -10 mJy for a 25 m telescope; ~ 0.5 -5 mJy for 50 m; and ~ 0.1 -1 mJy for a 100 m telescope. They therefore can be comparable to or larger than the mJy-level statistical fluctuations used to determine levels of RFI detrimental to radio astronomy as described in [26].
- The fluctuations will occur on about a minute time scale, i.e. the crossing time for satellites through the sidelobes of the telescope (taken to be within a radius of 10 degrees for the estimates presented in Figure 12).

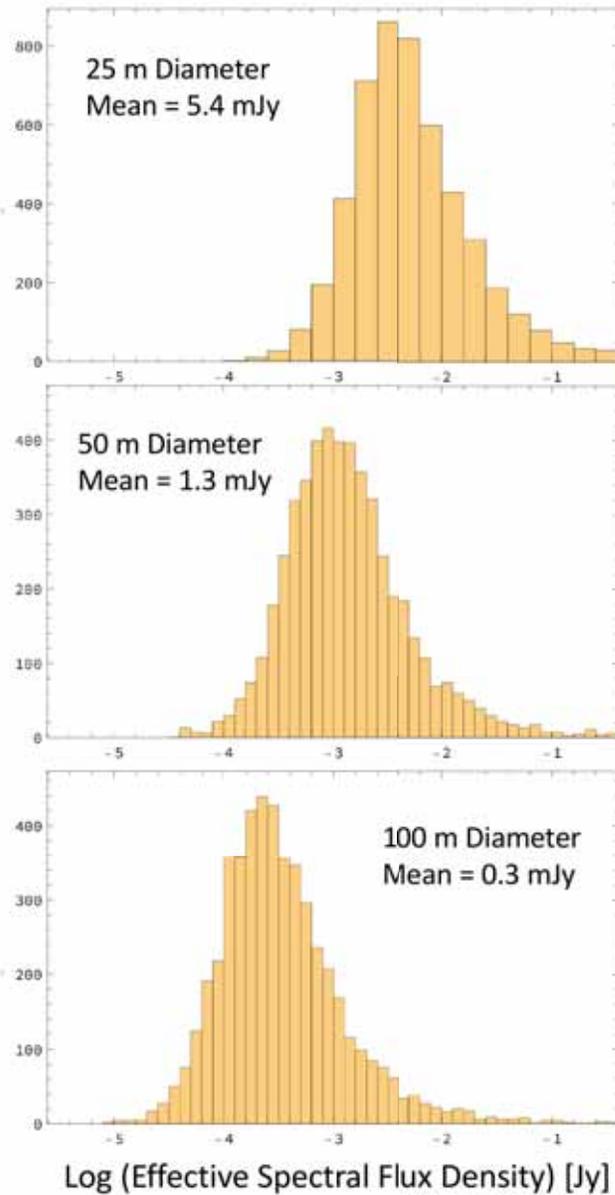


Figure 12: Estimated distributions of power spectral density from a telescope pointed at 45 degrees zenith angle. The telescope will see a different RFI contribution level approximately every minute, sampled from the indicated power spectral density distributions. Distributions are for telescopes of 25, 50, and 100 meters in diameter, and a total constellation size of 40,000.

-
- However, the estimates do not include the variations in the downlink power emitted by the satellites, nor any changes in pointing direction of the phased array beams. These can significantly change the side-lobe emission pattern, possibly on very short time scales depending on operation.

The estimates discussed above are indicative of the possible RFI impact of a large constellation of satellites. For Starlink, the Gateway downlink band covers 2 GHz of the radio astronomy X-band (8-12 GHz) and are therefore problematic for broad-band radio astronomy observations at X-band. While this band is not protected for radio astronomy, it is a band frequently used for radio astronomy observations.

The estimates provided above are no substitute for detailed simulations of RFI and we encourage the radio astronomy community to publicly document the possible impacts on radio astronomy, *even if those impacts are outside the current narrow protected radio astronomy bands*. Our conclusions are consistent with earlier assessments by NRAO for the ngVLA. See footnote²⁰ from pg. 7 of [19].

Radio astronomy relies heavily on radio-quiet “protected” sites that are as free from RFI as possible, as recommended in radio regulations [4, 5]. These sites often have some protection from ground-based transmissions, but have little or no formal protections from spaceborne transmitters. Be-

²⁰From [19]: “Hundreds of these satellites will be visible simultaneously to any antenna in the array through primary beam and sidelobes. With many of these constellations employing spot beams for regionally high Signal-to-Noise Ratio (SNR), power levels will be quite significant even outside the primary lobe. It should be expected that astrophysical data will be corrupted at all times in any frequencies on which the constellations are transmitting. Beam hits can be expected to increase in number proportional to orbit occupancy. In addition to downlinks, satellites will have ISLs (Inter Satellite Links) that ngVLA will see. ISL experiments have included UHF, S, C, X, Ka, and V bands (as well as optical), but should be expected to generally move up or remain in high-frequency bands such as V.

Satellite downlinks will be visible, transmitting, and powerful at all times, and the same signal will be received by most or all of the antennas in the array. No signal mitigation strategies are currently known that are likely to recover signal from underneath these transmissions. Therefore, any frequencies used by these satellites for downlink or ISL are likely to be lost to radio astronomy.”

cause of sidelobe and out-of-band emissions from the ubiquitous satellites of evolving large constellations, existing radio quiet zones are likely to be severely impacted by satellite RFI in the future. Even if a satellite turns off its transmitters directly above a radio astronomy site, satellites hundreds of km away can still have sidelobe emission that produces RFI at the position of the radio telescopes.

Simulations of RFI impact are also needed for interferometric arrays such as the VLA, and future ngVLA. Such simulations were beyond the scope of the current study. They involve consideration of imaging of “near-field” sources since the distance between individual elements of an interferometric array can be non-negligible given the few-hundred km distance to a satellite in a 550 km orbit. The satellite signal will not be coherent across the array, however non-standard processing will be needed to remove or reduce the RFI of the satellites.

3.4.4 RFI Mitigations

As remarked above, it is the intermittency of RFI rather than its mean level, that damages astronomical observations: that is to say, the concentration of RFI energy in the four dimensions defined by time, frequency, and sky position. This very intermittency also creates opportunities for removing the RFI from the data, at least in principle, if one knows where in the four-dimensional space the RFI lies, and if those parts are distinct from those occupied by the astronomical source being observed. We discuss some of the possibilities in this subsection.

We assume that the instantaneous positions of the satellites are known. Unlike many terrestrial but mobile sources of RFI (such as aircraft), satellites follow predictable ballistic trajectories—orbital paths. While orbital elements will change from time to time, one of the recommendations of this report is that the ephemerides of the satellites should be published at least a few hours in advance of when they might need to be used, and ideally with accuracy such that the satellite position can be predicted to better than the beamwidth of a

typical astronomical telescope. Unfortunately, it is not reasonable to expect satellite operators to publish (even retrospectively, let alone in advance) the “externals” of every downlink transmission, such as where the beam was pointed, what frequency band was used, and when the transmission started and stopped. Therefore, the location of RFI in the time-frequency plane will have to be discovered from the data itself.

There are techniques for coherently subtracting RFI at the level of individual time series collected by an individual radio receiver. These are dependent on the statistical properties of the interfering signal. They work best if the RFI has a periodic or other low-entropy pattern, or has non-gaussian statistics, such as a radar with a repeating pulse [20, 21, 10, 18, 6].

Such coherent time-frequency methods may be difficult to apply to the RFI expected from satellite constellations, unfortunately. The mean RFI levels shown in Figure 12 are equivalent to an increment in noise temperature $T_{\text{sat}} \approx 1 \text{ mK}$ (or twice this, if the RFI occurs in only one polarization). The time-bandwidth product necessary to detect this increment is $t_{\text{int}} \Delta f \gtrsim (T_{\text{sky}}/T_{\text{sat}})^2 \approx 10^8$; for transmission bandwidth $\Delta f = 10 \text{ MHz}$, the required integration time becomes $t_{\text{int}} \gtrsim 10 \text{ s}$. This may allow that part of the time-frequency plane to be identified and excised (which is apparently the go-to method of RFI mitigation currently), but as long as $T_{\text{sat}} \ll T_{\text{sky}}$, the Shannon-Hartley channel-capacity theorem says that it will not be possible to recover the transmitted waveform and perform a coherent subtraction.

We therefore discuss below mitigation methods that require combining time series from two or more apertures. While these methods also involve a form of coherent subtraction, they do not attempt to recover the satellite waveform. Instead, they rely on the fact that signals—even noise signals—from a pointlike source are correlated at distinct receivers.

Nulling or subtracting interferers

Many radio observatories are interferometric arrays: ALMA (Atacama Large Millimeter/submillimeter Array), VLA (Very Large Array), SMA (Submillimeter Array), ATCA (Australian Telescope Compact Array), MERLIN

(Multi-Element Radio-Linked Network), etc.; and intercontinental very-long-baseline interferometers such as the recently celebrated EHT (Event-Horizon Telescope), which imaged the black hole in M87. Such observatories consist of not one but several to many radio dishes, whose signals are coherently combined to obtain angular resolutions on the sky that are limited not by the diameters of the individual dishes/antennas, but by the distance (*baseline*) between pairs of such.²¹ Insofar as the interferer is angularly unresolved by the individual dishes²², signals received from a given single RFI emitter at two or more dishes will be coherent with one another, differing only in time delay of arrival (TDOA), strength (PSD), and possibly frequency difference of arrival (FDOA). The TDOA is caused by the different ranges R_1 and R_2 from the emitter to the two dishes; the different strengths are due to this range difference but also to different placements of the receivers within the antenna pattern radiated by the satellite; and the FDOA by different projections of the satellite's orbital velocity onto the lines of sight toward the two receivers. Thus if $s_1(t)$ and $s_2(t)$ represent the voltage time series received by that emitter at each of the two dishes, there is in principle some combination (τ, σ, δ) of delay, amplitude scaling, and time dilation such that

$$s_1(t) - \sigma s_2(\delta(t + \tau)) = 0. \quad (3-8)$$

The full time series $S_1(t)$ and $S_2(t)$ at each dish will (hopefully) contain, in addition to these RFI signals, additive contributions from astronomical sources of interest, plus, of course, noise. By taking the same linear combination of S_1 and S_2 , one can in principle cancel the interferer from the data; the astronomical signal will not cancel (or not completely) because its sources lie in different directions and with different relative dopplers. Note that the cancellation (3-8) does not depend on the details of the RFI signal, as long as it is coherent between the two receivers.

²¹The sizes of the individual dishes are important for the sensitivity of the array, however, and for its field of view.

²²i.e., the emitter size $\ell < \lambda R/D$, where λ is the wavelength of the RFI, D the diameter of the receiving dish, and R the range from dish to interferer. For $\lambda \geq 1$ cm (frequency 30 GHz), $D = 18$ m as for the ngVLA, and $R \geq 540$ km as for the altitude of the Starlink satellites, the right side of this inequality is ≥ 300 m.

This is the principle of nulling. It has been used since the early days of radio (e.g. for direction finding). There are many elaborations and methods of implementation, which go under various names. In a military context where one is trying to defeat jammers with locations that are *a priori* unknown, it is called “adaptive beam forming.” In recent radio-astronomical literature, it is sometimes called “subspace projection” [33, 12].

There may be practical difficulties in discovering the correct choices of (τ, σ, δ) , which will vary slowly with the orbital motion of the satellite. Putting these difficulties aside for the moment, it is clear that even if the three parameters were perfectly known, they would be specific to the emitter. If there are two or more RFI sources, they cannot all be cancelled by a single linear combination of the sort (3-8). To cancel N emitters exactly, one needs a minimum of $N + 1$ dishes and received signals. Suppose now a constellation of K satellites uniformly distributed over the globe at a common altitude h . The average number of satellites in a LEO constellation visible above the horizon will be $N \sim Kh/2(R_{\oplus} + h)$, $R_{\oplus} \approx 6370$ km being the Earth’s radius.²³ See also, Eq. 2-1. Taking $K \sim 4 \times 10^4$ and $h \sim 600$ km as for Starlink’s aspirations, one has $N \approx 3400$, much larger than the number of dishes in any current or near-future radio-astronomical array. Of course, not all of these satellites will be transmitting simultaneously in the same band, and some of them may be at such extreme ranges (up to 2800 km for this altitude) and/or with such faint sidelobes as not to matter. An individual null may suppress, if not entirely eliminate, several RFI sources that lie in similar directions and have similar dopplers. Finally, and most importantly, the individual radio dishes with aperture area A resolve a solid angle in their main beams $\Omega = \lambda^2/A$ ($\approx 4 \times 10^{-7}$ sterad for the 18-meter dishes of the ngVLA at 30 GHz); interferers outside the main lobe enter the receiver with reduced strength. Even with megaconstellations of tens of thousands of satellites in LEO, there is not likely to be more than one within the instantaneous field of view (main beam of a single dish) of the ngVLA.

²³Notice that this reduces to $K/2$, as it should, in the irrelevant (for LEO) limit $h \gg R_{\oplus}$.

However, even in principle, the degree to which an RFI signal can be coherently subtracted from the data after digitization is limited by the dynamic range of the analog-to-digital converter (ADC). We turn to this topic next.

Quantization noise

Let $s(t)$ be the exact signal received from an angularly unresolved RFI source at some dish, i.e. the signal that comes out of that signal’s receiver; the signal may have been reduced to baseband or to some intermediate frequency by mixing with a local oscillator, but it is still an analog signal—not yet digitized. For the purposes of this discussion, we pretend that the receiver and its local oscillator are perfect apart from inevitable additive thermal noise that is independent of the RFI signal strength. Now let $\hat{s}(t_n)$ be the version of this signal that emerges from the ADC. This differs from the analog signal in at least two respects:

1. The digital signal has been sampled at some finite rate f_s , so that instead of a continuous waveform, one has a sequence of numbers corresponding to discrete times $\{t_n\}$ separated by the reciprocal of the sampling rate, $t_{n+1} - t_n = f_s^{-1}$.
2. The individual numbers $\hat{s}(t_n)$ are not arbitrary real or complex numbers, but rather integral multiples of some constant amplitude or “quantum” q (which is determined by an adjustable gain in the system) in the range $-2^{N/2}q$ to $(2^{N/2} - 1)q$ for an N -bit ADC.

The first reduction—sampling—entails no loss of information if the sampling rate is larger than the full two-sided bandwidth of $s(t)$; if these samples were not quantized, the full original signal $s(t)$ could be recovered exactly from its samples. This is Nyquist’s theorem. Given two versions of the *sampled* RFI signal at two different dishes/receivers, we could reconstruct their exact analog waveforms, and then scale, delay, and stretch one of them so as to achieve the cancellation (3-8).

But quantization of the samples does lose information. The error $\hat{s}(t_n) - s(t_n)$ between the quantized and exact samples can be regarded as a random variable even for some definite signal $s(t)$ if the time t_0 of the first sample is random. To clarify this, suppose again that we are dealing with two versions $s_{1,2}(t)$ of the RFI signal as received at two radio dishes, with different delays, dopplers, and strengths. Each dish will have its own ADC, with sampling times slaved to some local clock. Even if these clocks could be perfectly synchronized, since the delay (τ) between the two versions $s_1(t)$ and $s_2(t)$ of the RFI signal is not knowable to the required accuracy ($\Delta\tau \ll f_s^{-1}$)—not to mention the relative doppler and strength—the difference between t_0 and some fiducial point in the waveform transmitted by the satellite is effectively random.

Insofar as the error $\hat{s}(t_n) - s(t_n)$ is uniformly distributed in the interval $[-q/2, q/2]$, q being the value of the least significant bit emerging from the ADC, the variance of this error will be $|q|^2/12$. If we are comparing the signals measured at two dishes for the purposes of nulling, the variance should be multiplied by 2. On the other hand, to avoid saturation of the ADC,

$$2^{N-1}|q| \gtrsim \max |s(t)|, \quad (3-9)$$

presuming that the RFI dominates the power of the received signal.

Thus the variance of the difference between the reconstructed versions of the signals at the two dishes—the residual in the cancellation (3-8) caused by quantization—will be roughly

$$|q|^2/6 \gtrsim 2^{1-2N}(\max |s(t)|)^2/3. \quad (3-10)$$

Clearly this is proportional to the received power in the RFI signal, but reduced by a factor $\sim 2^{1-2N}$. It would be unimportant if it were smaller than the thermal noise power. However, we have estimated above that the flux density at Earth from the downlink sidelobes of a single satellite will be $\sim 10^4$ - 10^5 Jy. If this is within the field of view (the main lobe) of the individual array dishes, it has to be compared to the system equivalent flux density due to thermal noise, $SEFD = 2kT_{\text{sys}}/A_{\text{eff}}$, which is about 400 Jy

for the ngVLA dishes and receivers at 27 GHz, as already mentioned. In the absence of RFI, the most significant bit would optimally be set in proportion to \sqrt{SEFD} so that thermal voltage fluctuations would marginally saturate the ADC. In the presence of RFI in the main beam, it will have to be set higher by the square root of the ratio of the RFI flux density to the SEFD, or about a factor of 5-16 for the numbers above. However, the lowest-order bit is smaller than the higher by $2^{-7} = 1/128$ with 8-bit quantization, which is of course smaller than 1/16. Put differently, the residual quantization-noise power due to imperfect nulling of RFI can be smaller than the thermal noise power by a factor

$$\frac{PSD_{\text{RFI}}}{SEFD} \times 2^{1-2N}/3, \quad (3-11)$$

which is not more than 2×10^{-3} or -26 dB for the numbers above. Even if the main beam of an ngVLA dish were to cross swords with the main downlink beam of a satellite ($PSD_{\text{RFI}} \approx 6 \times 10^7$ Jy instead of 10^5 Jy), the factor (3-11) becomes only $+2$ dB, which is not so bad.

A few caveats are in order:

- In focusing on quantization noise, we have idealized other parts of the telescope system that may limit the ability to place effective nulls on interferers, such as uncompensated drifts in local oscillators, imperfectly calibrated variations in antenna gain across the signal band or integration time, and atmospheric fluctuations.
- Briefers to JASON characterized the state of the art in subspace projection (nulling) and other methods for coherent subtraction of RFI in software as “immature” and “not robust.” It is not clear to JASON whether this is due to some underlying fundamental difficulty (we do not believe that quantization noise is such), or simply because the motivation for putting such methods into practice has not yet been strong. Apparently, simple flagging and excision of RFI has usually been possible at an acceptable level of data loss, up to now.

Reference antennas and adaptive filters

RFI from megaconstellations is projected to be strong, pervasive, and difficult to avoid or mitigate, so that radical mitigations may be required. One possible mitigation is removal of the RFI in signal processing; not surprisingly this has been tried and we understand that, currently, it is found not to be robust. This subsection will concentrate on methods of cancellation of RFI from a single radio-astronomical antenna's output; this case is an example of the famous "cocktail party problem": isolation of a single voice (signal) from a single recording of all the simultaneous conversations (noise) at a crowded party, an example of blind signal separation (BSS)[13]. Although many approaches exist to BSS, they depend on details of both the signal and the noise, are often empirical, and often depend on higher-order statistics.²⁴ Use of BSS in radio astronomy is therefore likely to be difficult.

In a pioneering paper, Barnbaum and Bradley [7] proposed the addition of a reference antenna to capture a sample of the interfering signal r , in addition to the signal s received from the astronomical source through the main antenna; such a reference antenna can help greatly in RFI cancellation.²⁵ The reference signal r feeds into an "adaptive filter" which seeks to null out the contribution of r in the desired signal s_{out} . This combination of a reference signal with an adaptive filter can provide deep nulling of RFI in s , not requiring detailed analysis of the properties of the RFI. Nulling depends principally on the SNR of s , the SNR of r , and the lack of any correlation between s and r , and lack of correlation between either of the noises n_s and n_r and any other signal; see Figure 13.

Algorithms for such adaptive filters are highly developed and effective [43]. They are well explained in the literature [7, 43] and need not be reviewed here. The principle of operation is to minimize the normalized correlation $E(s_{\text{out}}, r)$ ($0 \leq E \leq 1$) between output signal

$$s_{\text{out}} = s + r' + n_s - Wr - Wn_r \quad (3-12)$$

²⁴In fact, it is easy to see that BSS is impossible if all the signals are white Gaussian noise.

²⁵Here all signals r , s , ... are understood to be functions of time $r(t)$, $s(t)$, ..., either discrete or continuous.

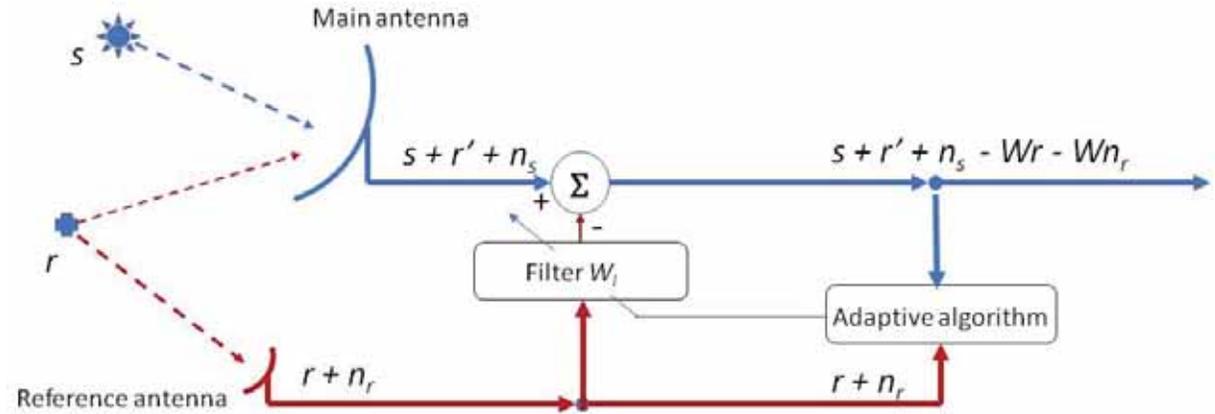


Figure 13: The astronomical signal s is corrupted by RFI from a satellite signal r' . The reference antenna captures signal r from the satellite. An adaptive filter W then cancels the RFI by subtracting $Wr = r'$ from s , with accuracy limited by noise n_s and n_r .

and RFI r . The correlator is the most important component of the box labeled “Adaptive algorithm” in Fig. 13, the output of which the algorithm seeks to minimize by adjusting W to an optimal value. Its performance depends principally on second-order statistics of s and r , *i.e.*, on their power and correlation, although in specific cases convergence time can be improved by consideration of higher-order statistics. Note that the RFI r' and the reference signal r do not need to be identical, they just need to be correlated with each other. The filter W itself is often implemented as an impulse-response filter

$$(Wr)(t) = \int^t dt' W(t - t') r(t') \quad (3-13)$$

where the function $W(\Delta t)$ (where $\Delta t = t - t'$) is to be adjusted to minimize the correlation and hence interference. The dominant contribution to W will be caused by the difference $\Delta\ell$ in propagation path from the satellite to the reference antenna and the main antenna, respectively. If the satellite ephemeris is known, as well as the pointing of the main antenna, then ℓ can be modeled as a known parameter, and the filter can be written as

$$W(t - t') = a\delta(t - t' - \ell/c) + W_2(t - t') \quad (3-14)$$

where the adaptive parameters are now an amplitude ratio a and a residual filter W_2 .

The adaptive filter W does *not* model, or need to model, the satellite signal, nor does it need to demodulate it. The adaptive filter’s job is to model the EM transfer function relating two propagation paths from the satellite, namely the path to the main feed (for r') and the path to the reference feed (for r), respectively.

For RFI sufficiently “loud” as to dominate the instantaneous noise field, the reference antenna can be implemented as a small omni antenna. For satellite RFI, however, the reference antenna should be a phased array with sufficient gain when beamforming in the (known) direction of the satellite so that the SNR of the satellite signal, though small, is at least as large as that which enters the main antenna through its sidelobes. This is necessary so that when the adaptive filter subtracts the reference signal from the main one, it does not more than double the noise. For the simulations shown in Figure 12, the main-dish sidelobes are typically ~ 40 - 50 dB below the main lobe. Therefore the diameter of the reference array can be smaller than that of the main dish by a factor $\sim 10^{-2}$ - $10^{-2.5}$, in principle, to satisfy the equal-SNR requirement. One can therefore probably use the same arrays as are used by the satellite ground stations.

The reference antenna’s distance from the main antenna should be small enough for the arriving wavefronts from the satellite to be uniform; this means small fraction of a beam footprint, or $<$ few km distant. It should be nearer to the satellite than the main antenna, or else $\ell < 0$ for which W becomes acausal and harder to implement. A suitable location would be a mount on the main dish, in particular atop the main feed, or perhaps at the rim of the dish.

Some astronomical radio telescopes already have dual-beam or even multi-beam feeds so that a given beam could feasibly serve as “reference antenna” for other beams. For instance the Parkes telescope has a 13-feed dual polarization multi-beam receiver operating at 1.2-1.5 GHz which has been used for RFI suppression [30]. However, multi-beam systems are not

common at X-band and would require new feeds to be built for most single dish telescopes wishing to carry out X-band observations.

As a LEO satellite moves across the sky, the optimal filter must adjust, on timescales of seconds to minutes. Therefore the convergence time of the adaptive algorithm needs to be seconds or shorter, which appears to be feasible.

If N satellites in the sky ($N > 1$) are simultaneously causing RFI, then N separate reference antennas are required, or a phased array with N beams. However these antennas or beams need not be individually pointed at different satellites; the N -dimensional formulation of adaptive filtering automatically handles the diversity. Needless to say, if N is too large, the system becomes unwieldy.

In radio astronomy, the signal s from the main antenna is often digitized, perhaps at low bit depth b ; for interferometry this is almost always done. See Fig. 14, where r is likewise digitized. From the discussion of nulling and subtracting interferometers above one might fear that, accordingly, the adaptive filter's accuracy would be limited by quantization, and so the depth of null would be limited to $O(2^{-b})$. However the null can be actually be far deeper, as follows. The adaptive filter's performance depends on the accuracy of correlator within the box labeled "Adaptive algorithm" in Fig. 14. A sizable radio-astronomical literature exists [41, 31, 8] on correlation after digitization, due to its importance in interferometry. The main result is this: As long as the output of the correlator is implemented at high accuracy (by analog, or at high digital bit-depth $b_{corr} \gg b$), the correlation can be measured accurately to low levels, *e.g.*, $O(2^{-b_{corr}})$, even though the signals have been digitized at lower bit depth b . For the case $b = 1$ (full clipping of the input signals), the true normalized correlation $E(s_1, s_2)$ of two signals s_1 and s_2 is related to the normalized correlation of the post-ADC signals as [41]

$$E(\hat{s}_1, \hat{s}_2) = \arcsin\left(\frac{2}{\pi}E(s_1, s_2)\right) \quad (3-15)$$

where \hat{s}_1 and \hat{s}_2 are the digitized, post-ADC signals. This relation is unique and invertible; at small correlation we have

$$E(\hat{s}_1, \hat{s}_2) \approx \frac{2}{\pi} E(s_1, s_2) \approx 0.64E(s_1, s_2). \quad (3-16)$$

Similar results hold for bit depth $b > 1$ [31] (though analytic solutions are not available); the numerical coefficient approaches 1 as b become large. Therefore, high-precision adaptive nulling is feasible even for digitized signals.

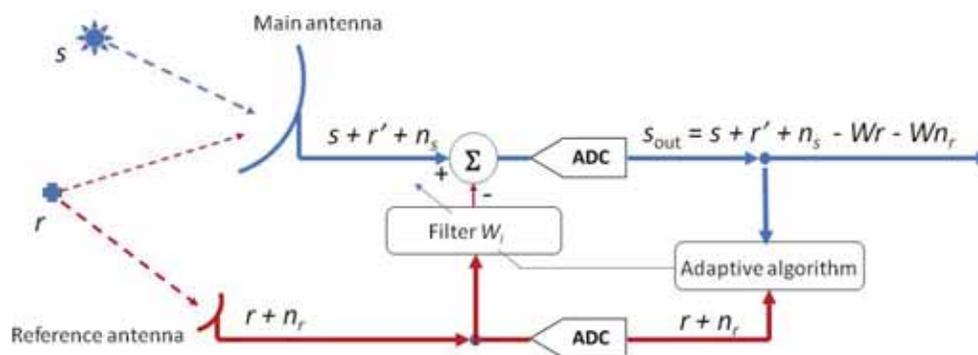


Figure 14: Same as Figure 13 except that the two signals pass through an ADC (analog-to-digital converter), perhaps to low bit depth b , before correlation.

3.4.5 Radio astronomy recommendations

Our principal findings and recommendations are:

1. **Recommendation:** The NSF should support the radio astronomy community in documenting the impact of large constellations on radio astronomy, even if those impacts are allowed under the existing U.S. and international regulatory framework. A parallel exists with optical astronomy, which has taken steps in quantifying the harm done to its science.
2. **Recommendation:** The NSF should support efforts in the spectrum management community to protect those bands that are allocated primarily to radio astronomy. With thousands of satellites in orbit, unanticipated out-of-band leakage in only a fraction may have significant impacts.

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3. **Recommendation:** The NSF should support the radio astronomy community to make quantitative measurements of RFI both in protected and unprotected frequency bands. Baseline measurements should be done soon while the constellations are still small and large scale downlink activity has not yet been initiated. There is again a parallel with optical astronomy, which is organizing to make quantitative brightness measurements on Starlink and OneWeb satellites.
 4. **Recommendation:** The NSF should support efforts to mitigate the impact of large constellations on existing and future radio astronomy facilities. These mitigations are likely to involve both hardware and software. Among the hardware mitigations that should be studied for inclusion on future facilities, or for retrofitting existing facilities, are:
 - Offset feeds.
 - Small reference antennas.
 - Multi-beam feeds.
 5. **Recommendation:** The NSF should support efforts to increase regulatory protection of radio astronomy sites, which are now vulnerable to emissions from satellites.

3.5 CMB Observations

Observations of the Cosmic Microwave Background (CMB) have given us some of the most sensitive probes in all of Cosmology. This work is pushing forward rapidly, with the upcoming deployment of large facilities like the Simons Observatory (SO) and the CMB S4 Project to look for the signature of inflation using CMB B-mode polarization.

One of the primary technical challenges to measuring the CMB is subtracting out intervening signals, called foregrounds. These foregrounds are in general much brighter than the CMB signal that is being measured, but they tend to have different spectral signatures, as shown in Figure 15. This

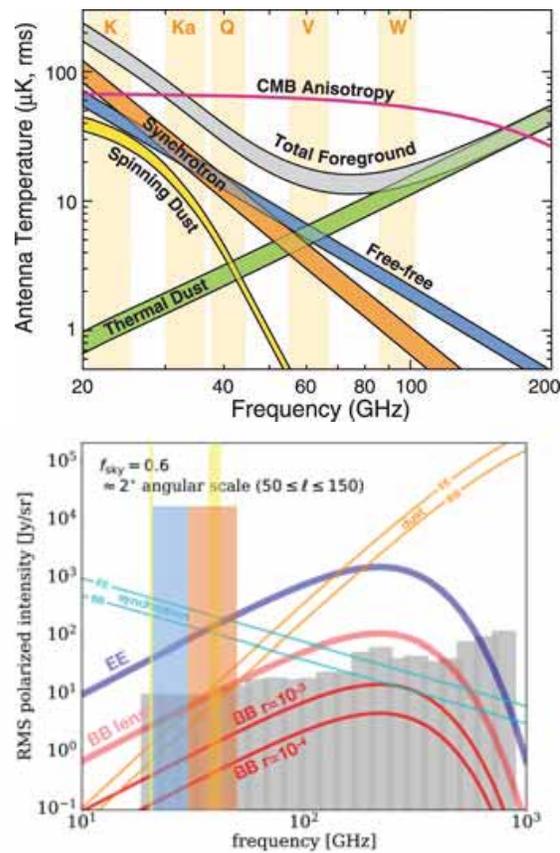


Figure 15: Left: The expected unpolarized foregrounds [9] relevant to CMB measurements. The primary CMB anisotropy is shown in magenta. Right: The expected polarized intensities [23] relevant to CMB B-mode measurements. Especially relevant are the backgrounds from synchrotron and dust, shown with expected intensities in both EE and BB modes. The SO low frequency bands are shown as blue and orange boxes, and the proposed SpaceX and OneWeb downlink bands are shown as yellow vertical bars.

allows instrument builders to design cameras with multiple filter bands across the 30–200 GHz range that allow these foreground signatures to be quantified and removed. The characteristic scale of the CMB fluctuations, as well as the low frequencies, means that CMB experiments tend to have a large field of view covered by a relatively small number of pixels. Of these foregrounds, Ka band (26.5–40 GHz) is especially important for subtracting out the bright polarized signature of synchrotron emission from the galaxy as well as spinning dust.

SpaceX’s ITU filings indicate it will downlink user data in the 10.7–12.7 GHz range with a received ground power flux density (PFD) of -122.02dB ($\text{W}/\text{m}^2/\text{MHz}$), and downlink to its ground stations over a variety of bands in the 10.7–20.2 GHz range with a PFD of -116.30dB ($\text{W}/\text{m}^2/\text{MHz}$). OneWeb will primarily downlink in the same 10.7–12.7 GHz band, but has numerous ITU filings about using many bands up to at least 50 GHz.

The Simons Observatory (SO) has incorporated two bands to measure these foregrounds, spanning 20–30 GHz and 30–46 GHz, as shown in Figure 16. There is currently marginal overlap between the SpaceX ground station downlinks and the lowest frequency SO band. As these constellations grow, competition for limited spectrum and improved technology will push operators to use higher frequencies, potentially including other designated space-to-earth designated bands at 66–74 GHz (high atmospheric opacity), 123–130 GHz, and 158–164 GHz. All of these bands lie in important spectrum for CMB observations.

With a 35° diameter FOV (950 sq. deg.) and only observing above air-mass two, we estimate using the calculations in §2.6 that there will be roughly five satellites in the FOV of the SO Small Aperture Telescopes (SATs) at all times if the Starlink and OneWeb phase 2 constellations are completed. Of these, 4 will be OneWeb satellites and one will be a Starlink satellite due to the higher altitude of the OneWeb constellation. Assuming that the side-lobes of the ground station downlink beams are -30 dB , this equates to a received power of 0.65 pW (0.03 pW in the detector assuming 5% transmis-

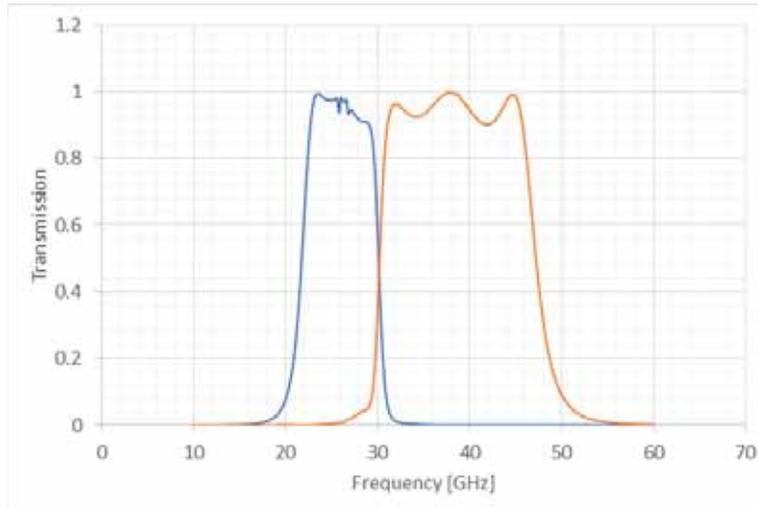


Figure 16: The low frequency filter bands of the Simons Observatory.

sion through the band-defining filter) from a 2 GHz wide satellite downlink band contained in the 20–30 GHz band (shown in orange in Figure 16) of the Simons Observatory 0.42 cm SATs. This compares to a total power of roughly 0.2 pW expected from sky and thermal loading on the detector. The signal being measured is a small fraction of this total power, so the additional signal from the satellites will need to be identified and subtracted out. The signal will likely also be polarized, potentially causing systematic issues for B-mode searches. The magnitude of the problem rises quickly as satellite operators push beyond 30 GHz, which they have filed plans to do. For example, OneWeb has submitted a FCC filing about using a V band downlink to a gateway at 37.5–42.5 and to user terminals at 40–42 GHz²⁶. Another potential concern are the satellite to satellite crosslinks, and there is limited information about these plans except that Starlink is currently using radio but is planning to move to Near-IR laser communications. If radio is used, frequencies that do not penetrate the atmosphere would have significantly less impact on CMB Astronomy.

Other potential problems include out-of-band transmissions, especially as components age and fail. Higher harmonics could easily contaminate higher frequency CMB bands, especially in the critical region around 90

²⁶http://licensing.fcc.gov/myibfs/download.do?attachment_key=1190495

GHz. It is possible that the satellite makers will not even have tested existing spacecraft for unexpected emission at 90 GHz due limitations in their test equipment.

1. **Finding:** The impact on CMB science increases dramatically as the frequency of the downlink beams increases beyond 20 GHz.

Finding: Currently planned constellations will pose a significant data reduction challenge to the Simons Observatory and the CMB S4 Project. Future expansions to higher frequencies will exacerbate the problem. Out-of-band transmission, especially as satellites age, could be detrimental to CMB observations.

Recommendation: Satellite vendors should be required to power off any transmitters over 20 GHz when they clear the horizon of several prime CMB/radio observing sites, especially the Atacama site of ALMA and SO and the South Pole. These sites in Chile and Antarctica are very remote, and this should have a minimal impact on their business model due to the low number of people and the continued availability of the sub-20 GHz gateway downlinks.

Recommendation: Future CMB experiments should consider attempting to design their detector bandpasses to mitigate the impact of satellite downlink beams.

2. **Finding:** Very little is known about the out-of-band emission of satellites in the 20–200 GHz range.

Recommendation: The FCC should mandate extensive testing for out-of-band emission covering the 20–200 GHz range. If a satellite begins emitting significant out-of-band power it should begin de-orbiting maneuvers immediately.

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4 LSST AND FAINT SATELLITE TRAILS

The Vera Rubin Observatory has unparalleled sensitivity for astronomical transients and asteroids. It will also have substantial sensitivity for detecting Earth-orbiting satellites. We discussed above the effects of *bright* satellite streaks. In this section we provide some estimates for the detectability of *faint* satellite streaks which might be confused with asteroids or could create systematic error for some of the LSST science objectives.

Because many astronomical transients are fleeting or evolve rapidly, the Rubin Observatory will have a Prompt Processing Pipeline (PPP) whose latency for reporting events is specified to be less than 60 seconds. In order to find and report asteroids, the PPP must detect and summarize transients that are streaked to some degree: data will include endpoints, uncertainties, and postage stamp images that encompass the streak.

In addition to the PPP release of event descriptions and postage stamps, the Rubin Observatory also intends to make images available for enhanced or non-standard processing with minimal delay (the current plan is ~ 24 hours). The project is considering collecting data as a back-to-back pair of 15 sec exposures or a single 30 sec exposure (this choice has a substantial effect on satellite detection).

Artificial satellites will appear as long streaks in LSST images (which are tracked at sidereal rate), with length that depends on satellite velocity and distance, for example $\sim 10^\circ$ per 15 sec exposure (0.7 deg/sec) in low Earth orbit (LEO), $\sim 0.06^\circ$ per exposure (360 deg/day) in geosynchronous Earth orbit (GEO), etc. LEO satellites traverse the Rubin Observatory's 3.5° field of view in much less than an exposure time.

Despite the streaking of an artificial satellite (and the defocus of a satellite in LEO), the Rubin Observatory is capable of detecting quite a small object. A fully illuminated, white, 1 m diameter sphere at GEO is bright ($m \sim 13.6$), but the Rubin Observatory is capable of detecting white objects that are $20\times$ smaller than this or 1 m objects that are $400\times$ darker than

this. In LEO these numbers are $200\times$ smaller than 1 m or $40000\times$ darker, but it is extremely unlikely for a LEO satellite to leave two endpoints in an image, which are necessary to make an estimate of the satellite’s orbit.

The LSST 10 year survey will not deliberately target satellites as it periodically covers half the sky. A given satellite will therefore typically be imaged infrequently, and detections may be a nuisance for astronomy, but not sufficient to disclose orbital parameters. A streak with both endpoints captured on an image provides only 4 parameters for a 6 parameter orbit, and a prediction of the future location of a satellite becomes uncertain over a fraction of the orbital time. Without reobserving the same satellite or identifying *two* unassociated detections of the same satellite quickly, the predictability of future satellite location rapidly degrades. If a streak crosses an image entirely or one or both endpoints are missing, the orbital information from the observation becomes very uncertain.

4.1 Detection Sensitivity

JASON has evolved a number of rules of thumb that can be useful for understanding the detectability of satellites by Rubin Observatory. The V magnitude of a satellite is approximately

$$V = 13.6 + 5 \log(r/38\text{Mm}) - 5 \log(D/1\text{m}) - 2.5 \log(a) + 4 \min(\phi/90^\circ, 1) \quad (4-17)$$

where r is the range, D is the satellite diameter, a is its albedo, and Φ is the Sun-object-observer phase angle. This phase angle term is broadly consistent with Cognion (2013). Given physical and orbital parameters, Equation 4-17 provides a magnitude. (A V magnitude is approximately the same as an AB magnitude m measured at 555 nm.)

Streak detection and fitting can be difficult for a computer, although the human eye has evolved to be remarkably good at seeing them. In the face of uncorrelated Gaussian noise the optimal statistic for fitting a streak is a matched filter, meaning a sum of image pixels weighted proportional to

the streak intensity. Note that such a long matched filter output is most emphatically **not** part of the normal LSST pipeline processing and will **not** be provided as a standard data product. Users who care to search images for long streaks need to acquire the images and do the computation themselves.

Since streaks vary in position, length, and orientation each streak has its own optimal matched filter. It is computationally trivial to do a search for the best position of the matched filter, but the search over possible length and orientation is computationally very expensive and false alarms abound.

Given this matched filter correlation kernel, in the limit of a background limited (true for LSST images), long streak (true for all satellites for contemplated LSST exposure times), the SNR of a streak contained entirely within an image is approximately (JSR13-420, App. A)

$$\text{SNR} \sim 1200 N^{1/2} f f_{\mu}^{-1/2} (A \delta d \ln \nu)^{1/2} (w \dot{\theta})^{-1/2}, \quad (4-18)$$

where $f = 10^{-0.4m_{AB}}$ is the object flux in units of AB magnitudes, f_{μ} is the sky flux per square arcsecond in AB units, N is the number of averaged exposures, A is the unvignetted telescope aperture in cm^2 ($3.3 \times 10^5 \text{ cm}^2$ for Rubin Observatory), δ is the throughput and quantum efficiency (~ 0.35 for Rubin g), $d \ln \nu$ is the bandpass in log frequency (~ 0.2 for Rubin filters), w is the point spread function (PSF) full width half maximum (arcsec), and $\dot{\theta}$ is the object's angular velocity (arcsec per second). This equation is independent of exposure time and streak length: both the signal and the noise of the ever lengthening background underneath the streak grow proportional to exposure time.

Note that in a general blind search for a streak there will typically be a multimodal merit function as different streak lengths are tested. Another JASON rule of thumb Equation 4-19, gives the probability that a streak of SNR s will yield well constrained parameters:

$$P(s) = (1 + \exp(6.5 - s))^{-1}. \quad (4-19)$$

4.2 From Streaks to Orbits

Given a streak detection, it is easy to understand qualitatively how streak parameter accuracy depends on SNR, and how orbit determination and prediction depends on streak parameter accuracy. Given a low SNR streak of length L , all of the pixels average to the cross-track position, the difference in cross-track position along the streak provides the angle, but only the pixels at the very ends contribute to the endpoint locations. Therefore we may expect that the uncertainty in the cross-track position is approximately the PSF full width half maximum w divided by the total SNR of the streak, $\Delta x \sim w/\text{SNR}$, the uncertainty in the streak angle, arising from the difference in the cross-track position along the streak, is $\Delta\varphi \sim 4w/(L * \text{SNR})$. At low SNR the uncertainty in an endpoint is approximately the length of the portion of the streak that provides a signal-to-noise of 2, i.e. $\Delta\epsilon \sim 4L/\text{SNR}^2$; at higher SNR the uncertainty is the PSF divided by the signal-to-noise of a PSF-length portion of streak, $\Delta\epsilon \sim \sqrt{2wL}/\text{SNR}$.

These uncertainties are critical for an initial orbit determination, especially the endpoints, because they create an uncertainty in angular velocity. The uncertainty in the future location of a satellite can be approximated to first order as the quadrature sums (\oplus)

$$\begin{aligned}\delta s(t) &\sim \Delta x \oplus \sqrt{2}\Delta\epsilon (t/\Delta t) \\ \delta x(t) &\sim \Delta x \oplus \sqrt{2}\Delta\epsilon (t/\Delta t) \Delta\varphi\end{aligned}\tag{4-20}$$

where Δt is the exposure time, $\delta s(t)$ is the uncertainty in along-track position and $\delta x(t)$ is the cross-track uncertainty. Evidently the cross-track position is known much better than the along-track position; the factor of $\Delta\varphi$ is typically quite small. For example, absent any priors, the along-track uncertainty of a single $\Delta t = 15$ sec streak of length $225''$ at $\text{SNR}=5$ (low SNR regime) will reach 0.5° in about 10 minutes. At $\text{SNR}=15$ it takes about about 90 minutes to reach 0.5° uncertainty.

We now provide explicit code for estimating the SNR of satellite detections and other parameters, using the Unix/Linux command *awk*. An *awk*

script that incorporates the LSST sensitivity parameters for the 6 filters and solar colors can be used to estimate the SNR, fit probability, the exposure time, and the fractional angular velocity uncertainty. For this script, V is the V magnitude, ω is the angular velocity in arcsec/sec, and the exposure time in seconds is embedded as dt . (For Pan-STARRS $A=3.14*78*78$, $dnu=0.6$, and $\delta=0.6$ for its w filter.)

```
awk -v V=21.0 -v omega=15 'BEGIN{dt=15; L=omega*dt; A=3.14*325*325; dnu=0.2;
  filt[1]="u"; sky[1]=22.8; psf[1]=0.98; Vx[1]=-1.63; delta[1]=0.20;
  filt[2]="g"; sky[2]=22.1; psf[2]=0.92; Vx[2]=-0.28; delta[2]=0.35;
  filt[3]="r"; sky[3]=21.1; psf[3]=0.87; Vx[3]=+0.16; delta[3]=0.60;
  filt[4]="i"; sky[4]=20.2; psf[4]=0.84; Vx[4]=+0.32; delta[4]=0.70;
  filt[5]="z"; sky[5]=18.6; psf[5]=0.83; Vx[5]=+0.37; delta[5]=0.72;
  filt[6]="y"; sky[6]=17.9; psf[6]=0.81; Vx[6]=+0.41; delta[6]=0.20;
  printf "F    V    omega    m    mu    delta    psf    SNR    Prob    Len    dv/v\n"
  for(i=1;i<=6;i++) { m=V-Vx[i];
    f=exp(-0.4*log(10)*m); s=exp(-0.4*log(10)*sky[i]);
    snr=1200*f/sqrt(s)*sqrt(A*delta[i]*dnu)/sqrt(psf[i]*omega);
    prob=1/(1+exp(6.5-snr));
    d1=4/snr/snr; d2=sqrt(2*psf[i]/L)/snr; domega=sqrt(2*(d1*d1+d2*d2));
    printf "%s %5.1f %6.1f %6.2f %6.2f %5.2f %5.2f %5.1f %6.3f %5d %6.4f\n",
    filt[i],V,omega, m, sky[i], delta[i], psf[i], snr, prob, L, domega} }'
```

A few examples illustrate the use of this.

- A 1U cubesat with body-mounted solar panels with $a = 0.1$ at GEO will have a $\phi = 0$ brightness of $V = 21.1$ according to Equation 4-17, and Equations 4-18 and 4-19 give a detection probability of 0.13 in r band: it will seldom be detected by LSST.
- A 12U cubesat with the same body-mounted solar panels at GEO has a $\phi = 0$ brightness of $V = 19.2$, and is detectable with $P = 1$ in $griz$ bands. The detection probability falls to $P \sim 0.9$ in gri at $V = 20.3$

which corresponds to a phase angle of 25° away from opposition (anti-sun direction). This is the output from the awk script for $\phi = 0$:

F	V	omega	m	mu	delta	psf	SNR	Prob	Len	dv/v
u	19.2	15.0	20.83	22.80	0.20	0.98	6.1	0.400	225	0.1539
g	19.2	15.0	19.48	22.10	0.35	0.92	20.9	1.000	225	0.0143
r	19.2	15.0	19.04	21.10	0.60	0.87	26.6	1.000	225	0.0092
i	19.2	15.0	18.88	20.20	0.70	0.84	22.4	1.000	225	0.0125
z	19.2	15.0	18.83	18.60	0.72	0.83	11.5	0.993	225	0.0444
y	19.2	15.0	18.79	17.90	0.20	0.81	4.6	0.130	225	0.2692

Pan-STARRS could also detect this 12U cubesat, but only within a few degrees of opposition.

- A Starlink satellite at a range of 1000 km, diameter $D=2$ m, and albedo $a = 0.2$ evaluates to $V = 6$ from Equation 4-17. The same satellite at GEO has $V = 17.8$ at phase angle $>90^\circ$, and is visible in all 6 filters, with maximum SNR 97 in r filter and fractional angular velocity uncertainty of 0.0014. The output from the awk script with $V=17.8$ and $\omega=15$ looks like

F	V	omega	m	mu	delta	psf	SNR	Prob	Len	dv/v
u	17.8	15.0	19.43	22.80	0.20	0.98	22.1	1.000	225	0.0130
g	17.8	15.0	18.08	22.10	0.35	0.92	75.9	1.000	225	0.0020
r	17.8	15.0	17.64	21.10	0.60	0.87	96.7	1.000	225	0.0014
i	17.8	15.0	17.48	20.20	0.70	0.84	81.4	1.000	225	0.0017
z	17.8	15.0	17.43	18.60	0.72	0.83	41.6	1.000	225	0.0044
y	17.8	15.0	17.39	17.90	0.20	0.81	16.7	1.000	225	0.0216

Pan-STARRS could also easily detect this Starlink satellite, with a SNR that is $\times 2.5$ lower.

Given this mechanism to evaluate the detection probability as a function of phase angle for a given satellite size, albedo, range, and angular velocity, we can now evaluate the fraction of sky around opposition where the detection

probability is significant. Finally we can estimate what fraction of the time both the satellite and the LSST survey pattern both lie within this area of sky, and the fraction of time they overlap.

4.3 Other Surveys

Although Rubin Observatory is more sensitive for detecting streaks, there are many sky surveys already in steady operation in the United States (CSS, Pan-STARRS, ASASSN, ATLAS, ZTF, to name a few), Europe, and elsewhere.

- The two Pan-STARRS telescopes combine to a bigger field of view than Rubin with a filter that is 3 times wider, so for streaks Pan-STARRS is only 1 magnitude less sensitive than LSST.
- The Zwicky Transient Facility (ZTF) is 2.5 magnitudes less sensitive than LSST but the ZTF sky coverage is 5 times greater per exposure so its ability to provide useful orbit determination information for bright satellite streaks is *much* greater than LSST.
- The Brazil-Russia-India-China-South Africa (BRICS) consortium has announced their intention to deploy 72 telescopes of 1 m aperture with 25 deg² fields of view and a limiting magnitude of 21.²⁷ This combination of telescopes is much more powerful than LSST for satellite detection, and the fact that $\sqrt{72} \sim 8.4$ matches the aperture of Rubin Observatory is probably not an accident.

4.4 Streak Length and Science

One of the LSST science goals is to find dangerous asteroids. Congress issued a mandate to NASA in 2005 (George E. Brown, Jr. Near-Earth Object Survey Act) to find at least 90% of all potentially hazardous asteroids (PHA) of size 140 m or larger. A particularly difficult place to find PHAs is when

²⁷<http://lnapadrao.lna.br/eventos/brics-astronomy-working-group-2019/presentations>

they lie inside the Earth's orbit because they only show a crescent of illumination and can be $\times 100$ fainter than when fully lit. By looking into the evening and morning twilight sky LSST can find these PHAs. These should be detectable by LSST to a distance of 0.3 AU, where a typical transverse velocity of 10 km/s translates to an angular rate of 1 deg/day, a short streak. Although there are cases where LSST will first observe an asteroid when it has an angular velocity greater than, say, 10 deg/day, these will typically be very small asteroids; large asteroids will typically be discovered at distances such that the angular velocity is much less than 10 deg/day.

There is a huge difference in angular velocity of most satellites and most asteroids. Even the moon and cis-lunar satellites are moving at 12 deg/day. It is also extremely uncommon for an asteroid of size 140 m or larger to rotate faster than 2.4 hours, the gravitational breakup rate, and so an asteroid is unlikely to vary significantly in brightness over a 30 sec exposure. Conversely, the majority of satellites show photometric variability on a timescale of 30 sec. Therefore photometric variability is another useful discriminant for whether a streak is a satellite or an asteroid, and could be used to extend an angular velocity limit.

LSST will have a substantial increment in sensitivity over other surveys such as Pan-STARRS and ZTF. Faint satellite streaks will be present, may be confused with asteroid streaks, and may leave behind systematic residuals that interfere with other LSST science. JASON believes that the wide disparity between the angular velocity of most asteroids and most satellites permits LSST to distinguish asteroid from satellite with very high probability, even when the LSST cadence does not provide enough information to ascertain whether the object is bound to the Earth or not. The very long and very faint streaks can only be detected by specialized image processing, not part of the LSST Prompt Processing Pipeline. Presumably the image combination that leads to the deep LSST view of the static sky will be robust against contamination from faint, undetected streaks, although that should be tested.

5 COLLISION/DEBRIS CONSIDERATIONS

5.1 Introduction

There are currently about 20,000 “trackable” ($L \gtrsim 10$ cm) objects in LEO, of which $\sim 3,000$ are operational satellites. Both NASA’s ORDEM 3.1²⁸ (Orbital Debris Engineering Model) and ESA’s MASTER²⁹ model (Meteoroid and Space Debris Terrestrial Environment Reference) maintain detailed models of the distribution of debris in size and orbit. These can be used to estimate the flux of debris onto a target in a given orbit.

Sophisticated tools exist such as NASA’s LEO-to-GEO Environment Debris software (LEGEND) or JAXA’s NEODEEM that propagate existing objects, debris, and possible new objects along orbits for centuries, evaluating collisions, new debris creation, and post-mission disposal along the way. For the purposes of this section we only need to understand order of magnitude risks and when a large constellation becomes so big as to warrant a detailed look by LEGEND.

Although 20,000 might seem a large number, the volume in LEO is also large ($> 10^{11}$ km³), so the probability of collision on a given satellite in a year is quite low. Horstmann et al. [24] provided an evaluation of the MASTER model in 2018 of the density of objects in LEO, and we obtained from J-C Liou at the NASA Orbital Debris Program Office (ODPO) the ORDEM densities as of 2020 (Figure 17).

If we integrate the collision rate from the densities shown in Figure 17, assuming a 10 m² cross section for the 10% of the objects which are active satellites and near zero for the rest, we find that there should be a collision on an active satellite once every 50 years. The biggest contribution to this rate comes from altitude ~ 800 km where the density is the highest, of course. LEO is a big volume, but we are just now at the dawn of experiencing frequent

²⁸<https://orbitaldebris.jsc.nasa.gov/modeling/ordem-3.1.html>

²⁹<https://sdup.esoc.esa.int>

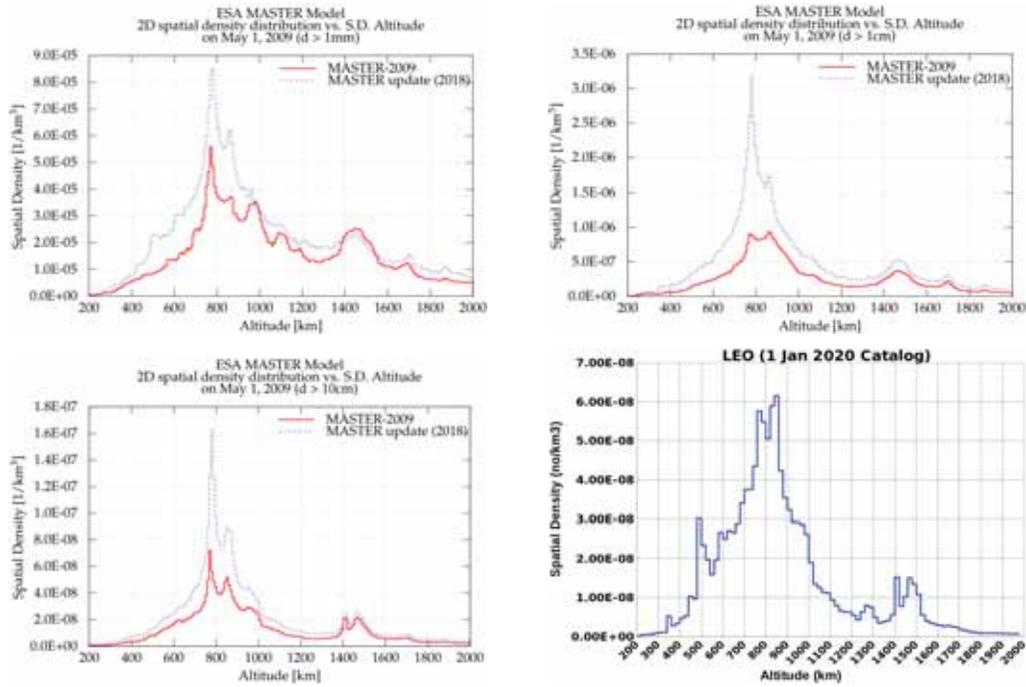


Figure 17: Figure 7 from Horstmann et al. [24] shows the density of objects in the ESA MASTER model larger than 1 mm (top left), 1 cm (top right), and 10 cm (bottom left) as a function of orbital altitude. The red curve dates from 2009 and the blue curve is a 2018 update. The bottom right panel shows the equivalent counts of >10 cm objects from NASA ORDEM at the beginning of 2020 (courtesy J-C Liou). The density of >1 mm objects is roughly 1500 times that of >10 cm debris, and the density of >1 cm debris is approximately 20 times higher. This is crudely consistent with $N(>L) \sim L^{-1.6}$. The density of >10 cm debris in 2020 is approximately $2.5e-8 \text{ km}^{-3}$ at 600 km altitude and $7e-9 \text{ km}^{-3}$ at 1200 km altitude.

destruction from collisions. Since the rate of collisions goes as n^2 , it doesn't take a big increase in n before collisions happen every decade or every year or every month.

There are a number of useful observations and heuristics that have been developed by NASA and others.

- A collision or explosion tends to produce a power law distribution of fragments in mass $N(>m) \sim m^{-0.8}$ or length $N(>L) \sim L^{-1.7}$. Note how m scales with L for fragments, $m \propto L^2$: a mass to area ratio (ballistic coefficient) of $m/A \sim 10 \text{ kg/m}^2$ is typical.³⁰
- The distribution of all detected components in LEO also tends as $N(>L) \sim L^{-1.9}$ from micron to meter scale.³¹
- There is a threshold energy deposition of 40 J/g where a “catastrophic” collision completely disrupts a target into a power law distribution of fragments. (From “Orbital Debris Modeling” J.C. Liou 2012.)³²

From a physics standpoint, since the failure stress of aluminum is about 0.3 GPa which is 300 J/cm³ or 100 J/g, provided an impactor has a comparable surface mass relative to the column of satellite it's hitting and does not tear through with much of its initial velocity intact, this seems a very reasonable value.

- At a velocity of 10 km/s the threshold mass ratio between target and impactor for “catastrophic” dissolution is 1250.
- An impact with less energy is termed “non-catastrophic” from the standpoint of debris creation because it does not produce a full collisional cascade of fragments, although it may do a great deal of harm to the target. For a non-castrophic collision about 100 times the mass of the impactor appears as debris (Kessler et al, 2010). Thus, an im-

³⁰<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120003286.pdf>

³¹<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19990041784.pdf>

³²Available from <https://ntrs.nasa.gov/citations/20120003286>

pactor of 10^{-4} the mass of a satellite might not disrupt it, but it might create 10 fragments that could disrupt it in a future collision.

- NASA espouses a “25 year” rule for spacecraft disposal, which is chosen to be much shorter than the mean time for a collision to create more than one significant fragment. An update to this Orbital Debris Mitigation Standard Practices³³ now suggests no more than 100 object-years for disposal per mission that disperses a constellation of objects smaller than a 1U cubesat.
- A “trackable” piece of space debris is about 10 cm and 1 kg, the size required to catastrophically destroy a satellite of mass 1000 kg. Telescopes and radars are certainly capable of detecting much smaller objects, but the incompleteness with which smaller pieces of debris are known and tracked (especially given unpredictable non-gravitational forces) grows rapidly for sizes smaller than 10 cm.

Figure 18 shows the effect of atmospheric drag on satellites as a function of ballistic coefficient, starting altitude, and solar activity. A satellite that is launched at solar maximum at an altitude where the atmosphere is distended has a much shorter lifetime than at solar minimum. At solar minimum a satellite with ballistic coefficient 20 kg/m^2 survives about 5 years at 600 km; the survival at 1200 km is about 500 years. At 400 km the satellite descends from atmospheric drag at a rate of about 200 km/year which leads to reentry in about 0.8 year.

5.2 Illustrative Collisions and Near Collisions

In 2007 China launched an anti-satellite (ASAT) missile that destroyed a defunct, 750 kg, polar-orbiting Fengyun 1C satellite at 863 km, creating a debris cloud of more than 3,000 trackable fragments.³⁴ Unfortunately at this altitude it will take many decades for a significant fraction of the debris to

³³https://www.orbitaldebris.jsc.nasa.gov/library/usg_od_standard_practices.pdf

³⁴https://en.wikipedia.org/wiki/2007_Chinese_anti-satellite_missile_test

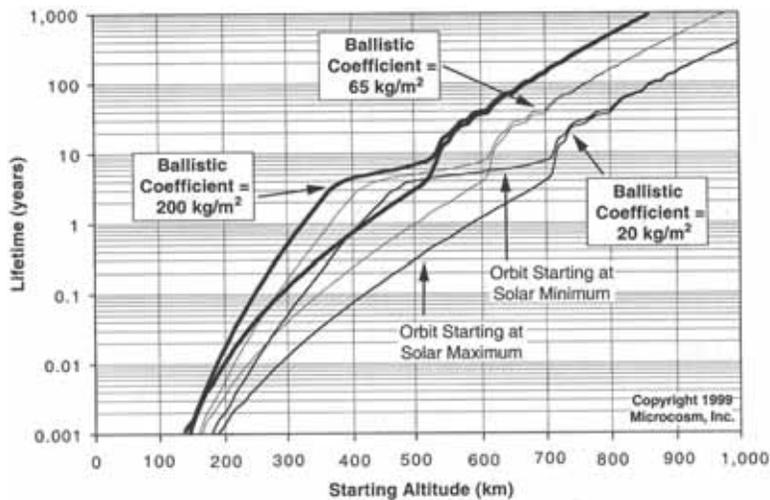


Figure 18: Figure 8.4 from Satellite Mission Analysis and Design [42] shows the reentry time from atmospheric drag for various ballistic coefficients.

reenter (Figure 18). This ill-advised test alone nearly doubled the risk to satellites.

In 2009 operational satellite Iridium 33 (560 kg) struck the defunct Cosmos 2251 (950 kg) at 789 km altitude, creating a shower of more than 1,000 trackable debris fragments of at least 10 cm.³⁵ Although Iridium 33 was active and could have avoided Cosmos 2251, nobody was looking. Celestrak website’s SOCRATES software predicted a passage within 600 m, but it did not make the top-10 list for that week. Apparently it was known to the US DoD that there would be a close approach, but a detailed conjunction analysis was not carried out. According to a 2009 NASA presentation “No requirement exists for the U.S. to conduct conjunction assessments for non-U.S. Government satellites; however, conjunction assessment requests from commercial and foreign satellite operators are satisfied on a noninterference basis... At the time of the collision of Iridium 33 and Cosmos 2251, no request for conjunction assessments for either satellite had been submitted to the JSpOC.”³⁶

³⁵https://en.wikipedia.org/wiki/2009_satellite_collision

³⁶<https://ntrs.nasa.gov/citations/20100002023>

As a result of this collision, the DoD and JSpOC (now CSpOC) changed their procedures, at least temporarily. “Although there was no prior warning of the collision, procedures could have been put in place by either the U.S. or Russian military to provide such warning... Since the collision, the U.S. military has developed a process to perform daily screenings of close approaches between the almost 1,000 active satellites in Earth orbit, and is providing warning to all satellite operators of potential collisions.”³⁷

The Iridium LLC operations office must weigh the probability of an impact against the cost of moving the satellite far enough out of the way to be certain to avoid it. Such a maneuver costs fuel and therefore satellite lifetime. However the Iridium operation office was strongly criticized for a lax approach to collision avoidance, as reported by Space.com.³⁸ Part of the problem is that orbital elements exist in the form of obsolete two-line elements (TLEs) which are convenient but which are typically not updated frequently nor very accurate. The Space.com report concluded: “For a constellation in low Earth orbit, two-line-element data would present potential collision alerts so often that Iridium cannot respond to each one with a detailed examination and possible evasive maneuver, industry and government officials said.”

The ESA Copernicus Sentinel A1 satellite (2300 kg, 5.9kW) solar panel was hit by a small piece of debris on 23 Aug 2016. It suffered only a small loss of power, a slight change in orientation, and 5 pieces of new debris were tracked from the collision. The satellite’s camera revealed a ~40 cm area damaged from the impact of a “few millimeter” sized object on one of the solar panels.³⁹

On 2 Sep 2019, an ascending Starlink satellite nearly collided with the ESA Aeolus satellite.⁴⁰ In an emailed statement, a SpaceX spokesperson said

³⁷https://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf

³⁸<https://www.space.com/2386-satellite-collision-avoidance-methods-questioned-space-crash.html>

³⁹http://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Copernicus_Sentinel-1A_satellite_hit_by_space_particle

⁴⁰<https://www.cnet.com/news/esa-spacex-starlink-satellite-nearly-collides-with-european-aeolus-satellite>

the company missed an update from the US Air Force showing an increase in the probability that the two satellites could collide to greater than 1 in 10,000, which is the industry threshold at which evasive maneuvers are recommended. “A bug in our on-call paging system prevented the Starlink operator from seeing the follow on correspondence on this probability increase,” the statement said. “Had the Starlink operator seen the correspondence, we would have coordinated with ESA to determine best approach with their continuing with their maneuver or our performing a maneuver.”

Further discussion of the Aeolus near collision in Forbes said “SpaceX also clarified that their satellite was operational and was capable of performing avoidance maneuvers if necessary. The company added that in three months since launch on May 23, the Starlink fleet has performed 16 autonomous collision avoidance maneuvers without any manual input.”⁴¹

These four examples illustrate a number of points

1. The space environment is fragile and even a rare collision, deliberate or accidental, creates so many fragments that a growing cascade becomes possible. If the rate of fragment production which goes as $(N^2/2)\sigma v N_0$ (N is the number of suitably large pieces from collisions, σ is the collision cross section, v is the typical relative encounter velocity, and N_0 is the number of suitably large pieces from a collision) exceeds the disposal rate from atmospheric drag or post mission disposal, the debris density grows.
2. It is critical that active satellites dodge impending collisions if they can, but the Iridium collision occurred because a) JSpOC was waiting for someone to ask whether a conjunction might occur and b) the Iridium operations center did not maintain adequate awareness of the hazard to their constellation.

⁴¹<https://www.forbes.com/sites/jonathanocallaghan/2019/09/03/spacex-says-a-bug-prevented-its-starlink-satellite-avoiding-europes-aeolus-satellite-in-orbit/#36b42d657ff5>

-
3. It is not uncommon for a satellite to be hit by a small piece of space debris, rates are usually estimated as 0.1–0.01/year, but in congested regions the flux of >1 mm pieces of debris may be as high as 0.03/year/m².
 4. Software and operations mistakes occur. An autonomous collision avoidance system is only as good as its inputs (a maneuver to avoid a collision must begin when the incoming impactor is on the other side of the planet from the threatened satellite). Presumably autonomous collision avoidance might better be termed “station keeping” because sufficiently accurate information to flag an impending collision is apparently kept private within a constellation fleet.

5.3 Collision Rates and Debris Production

In this section we will explore the collision rates that might occur in a large constellation. Although we are attempting to be realistic, this is *not* a substitute for a real study by people whose business it is to understand debris and collisions. The following will provide scaling relations that identify the limits of orbital density that may be safely achieved without starting a runaway debris cascade.

We will assume a uniform density of debris at some altitude. Although the density in space and velocity is very complex, on timescales much longer than an orbit this should not be too inaccurate. The delicate adjustments made in phase space by satellite operators to avoid collisions we will handle by assuming that no live satellite is ever struck by a tracked piece of debris (Iridium notwithstanding). Given this, a satellite will potentially be struck at a rate of

$$r = 3 \times 10^{-5} \text{ yr}^{-1} \left(\frac{n}{10^{-8} \text{ km}^{-3}} \right) \left(\frac{\sigma}{10 \text{ m}^2} \right) \left(\frac{v}{10 \text{ km/s}} \right), \quad (5-21)$$

where we use typical LEO values for n , the number density of impactors, σ , the cross section for an impact, and v , the typical relative collision velocity. A Starlink satellite of mass ~ 250 kg at 600 km will probably receive little damage by impact from a 1 mm object (~ 10 mg at $m/A=10$ kg/m²), may

suffer disabling damage by impact of a 1 cm object (~ 1 g), and a 10 cm impactor ($\gtrsim 0.2$ kg) can cause a catastrophic disruption.

Scaling from the 907 kg Solwind destruction by a US ASAT test, we may expect catastrophic disruption of a Starlink satellite to create ~ 100 debris fragments of >10 cm size and sufficient mass to destroy another Starlink satellite in turn. If 100 fragments are spread over a 25 km altitude range near 600 km they contribute a density of $7e-9$ km^{-3} , approximately $1/4$ of the current debris density at 600 km for >10 cm. (The full width half maximum of the density spikes created by the Chinese ASAT test and the Iridium-Cosmos collision in Figure 17 is roughly 3 histogram bins of 9km each, or about 25 km.)

A OneWeb satellite at 1200 km is similar, except that 100 fragments spread over a 25 km range at 1200 km altitude is equal to the existing debris density for >10 cm: a single OneWeb disruption will double the debris density for the constellation.

Referring to Figure 17 and Equation 5-21, at current debris densities a Starlink satellite at 600 km altitude with cross-section $\sigma \sim 10$ m^2 will be struck by a >1 mm object every 10 years, i.e. it has a 50% chance of a minor hit during its 5 year lifetime. The rate for a >1 cm impact is about one per 600 years, i.e. a 1% chance of potentially disabling damage during its lifetime. The rate for a >10 cm impact is about 10^{-4} /year, i.e. a 0.05% chance over its lifetime, assuming it does not maneuver to avoid tracked debris. The rate at which a >10 cm object passes within 180 m of each Starlink satellite (10^{-4} probability of impact) is ~ 1 /year, and the rate for a 1 km approach distance is 25/year.

For OneWeb at 1200 km these rates are lower by about $\times 6$ because the satellite cross section is about 5 m^2 and the debris density about $\times 3$ lower than at 600 km.

Now consider a simple model for a constellation of many satellites in a narrow range of altitudes (see Figure 19). Let S be the number of live satel-

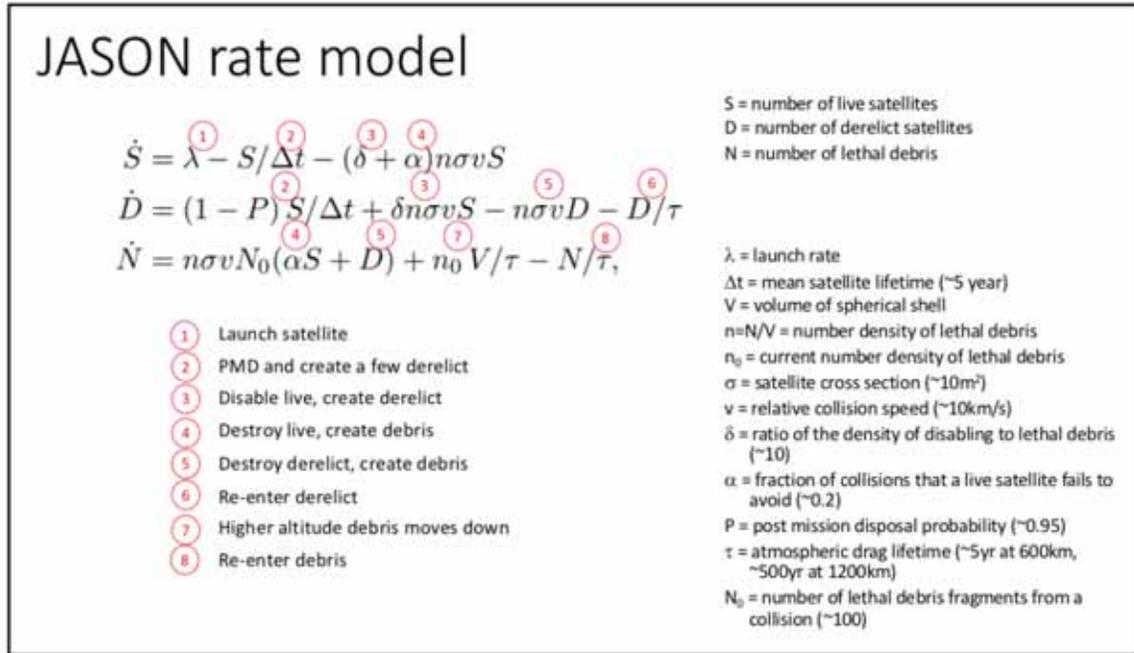


Figure 19: Explanation of terms in the JASON rate model.

lites, D be the number of intact but derelict satellites, and N be the number of objects capable of disrupting a satellite (>10 cm) within a spherical shell of thickness Δh and volume V . The population evolution is given by a couple of simplified rate equations:

$$\begin{aligned} \dot{S} &= \lambda - S/\Delta t - (\delta + \alpha)n\sigma vS \\ \dot{D} &= (1 - P)S/\Delta t + \delta n\sigma vS - n\sigma vD - D/\tau \\ \dot{N} &= n\sigma vN_0(\alpha S + D) + n_0 V/\tau - N/\tau, \end{aligned} \quad (5-22)$$

where λ is the launch rate, Δt is the mean satellite lifetime (~ 5 year), $n = (N + D)/V$ is the number density of disrupting objects, n_0 is the current number density of disrupting objects, σ is the satellite cross section (~ 10 m²), v is the relative collision speed (~ 10 km/s), δ is the ratio of the density of disabling objects to disrupting objects (~ 10), α is the fraction of disruptive collisions that a functioning satellite fails to avoid, either because the debris was not tracked or a successful avoidance maneuver does not happen (~ 0.2), P is the post mission disposal probability (PMD, ~ 0.95), τ is the atmospheric

drag lifetime, and N_0 is the number of catastrophic fragments from a collision (~ 100 for a Starlink or OneWeb satellite). We treat the contribution to \dot{N} from decay of debris from higher altitudes with the $n_0 V/\tau$ term, assuming the neighboring space environment stays more or less unchanged. P does not appear explicitly in \dot{S} because end of life is what drives \dot{S} , P governs whether the result is a successful disposal or creation of a derelict or debris. Inclusion of D in the expression for n is an approximation that tries to balance increased cross section for D on S or D , double counting of D on D , and the presumable dependence of δ and α on D versus N collisions.

We take τ to be 5 years (600 km) or 500 years (1200 km) until at least 2035 from Figure 18, using a ballistic coefficient of 20 kg/m² and knowing that the solar activity at maximum in ~ 2025 is likely to be very weak.

The PMD probability includes internal failures of all sorts: infant mortality, component failures, solar flares, failure to apply adequate thrust for disposal, etc. To date (24 Apr 2020) Starlink has 538 operational and 9 dead satellites (1.65% after $\sim 10\%$ of the nominal satellite lifetime), so we may expect infant mortality to contribute at least 0.01 to $(1 - P)$, no matter what happens during the rest of the lifetime. If it turns out that active debris removal becomes possible and cost effective, it is possible that PMD could be improved after launch, perhaps selectively, but we are skeptical that active debris removal will ever become economically feasible, at least for companies that need to make a profit or fold.

Also note that there are single point failures that are worrisome, for example a solar flare that permanently disables a substantial fraction of satellites or a design flaw that does not reveal itself until a satellite lifetime has elapsed and 10,000 copies are on orbit, or a software error or security breach with malicious damage to the constellation. A single point failure of a significant fraction of a constellation implies $\alpha \sim 1$, and that implies a runaway production of debris for almost any size constellation that would persist until atmospheric drag brings all the pieces down.

In principle there are means to ensure a high PMD at end of life through

robust components, redundancy, and shielding, but if the disposal process depends on a functioning satellite for power and attitude (electric propulsion) or communications, it may be challenging to meet a high PMD requirement and still achieve a high function to cost performance metric. **PMD redundancy and robustness is critical!**

We assume that live satellites sometimes are subject to catastrophic collisions because not all disruptive debris is tracked (we assume 80% are tracked with sufficient precision) and satellite operations are not perfect. Iridium has suffered 1 collision in ~ 1600 satellite-years. Equation 5-21 suggests that the total number of collisions from random intersections is about 1 per ~ 1600 satellite-years for a 25 m^2 cross section between two satellites at 780 km, so Iridium's track record does not inspire confidence.

Setting the derivatives to zero in Eq. (5-22) and treating n as constant gives us equilibrium values for S and D . The equilibrium number of satellites is $S_{eq} \approx \lambda \Delta t$, of course, and the equilibrium number of derelict satellites is

$$D_{eq} \sim \lambda \tau (1 - P + \delta n \sigma v \Delta t) \quad (5-23)$$

(neglecting the $n\sigma v$ collision rate on D which is currently negligible relative to $1/\tau$).

With these assumptions and the current n , Equation 5-23 gives the equilibrium number of derelict Starlink satellites as $0.054S$ for a constellation with equilibrium number S . For example, a desired constellation of $S = 10^4$ requires $\lambda = 2000/\text{year}$ and $D \sim 540$. However, the constant n assumption is not valid for much larger constellations. The $n\sigma v$ term for collisions at 600 km altitude is currently about 10^{-4} yr^{-1} and $\alpha + 0.054 = 0.254$, so a catastrophic collision will fragment a satellite from a 10k constellation about once per 4 years with a production of $100 > 10 \text{ cm}$ debris fragments per collision.

The increase in debris has a profound effect on the result; S and D may not reach equilibrium values if N keeps rising. Figure 20 shows what happens to constellations at 600 km with $\lambda = 2000/\text{yr}$ and $\lambda = 10000/\text{yr}$ as

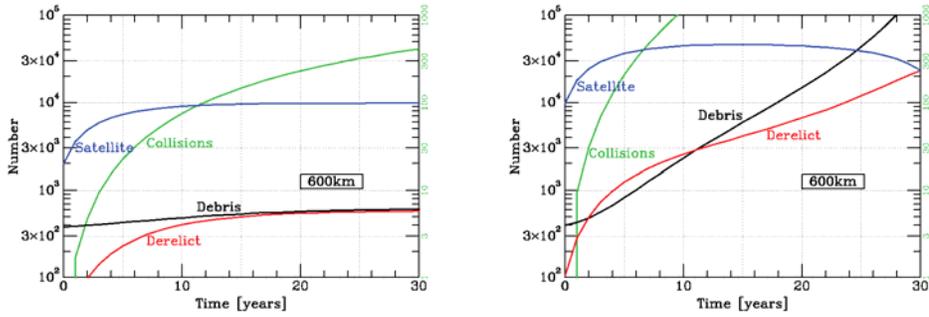


Figure 20: The solution of Equation 5-22 for $\lambda = 2000/\text{yr}$ at 600 km (left panel) shows asymptotes for S and D of 10000 and 540 as expected and the debris number also rises slowly to an asymptote. By contrast the right panel shows the solution for $\lambda = 10000/\text{yr}$. Once S passes the threshold of 40,000 the debris density starts running away, with the effect that after 50 years satellites are destroyed faster than they are launched. The cumulative number of collisions that disable or disrupt live satellites is shown by the green curves and green scales on right.

a function of time. The number of satellites rises toward an asymptotes of 10,000 and 50,000, and the number of derelicts rises toward an asymptotes of 540 and 2,700. For $S = 10000$ the debris density rises very slowly above the replenishment from higher altitudes, but for $S = 50000$ the debris density runs away: satellites and intact derelicts are destroyed faster than new ones are launched. This runaway happens when $\dot{N} > 0$, i.e. at 600 km

$$S_{max} \sim \frac{V}{(\alpha + 1 - P)\tau\sigma v N_0} \sim 40,000. \quad (5-24)$$

where we approximate the solution for D as its stable asymptote.

For OneWeb at 1200 km the results are a bit different because the atmospheric drag is so weak. The runaway occurs for $S_{max} > 900$, and the timescale for destruction of the environment is about 25 years for $S = 50000$ and 50 years for $S = 10000$, as illustrated in Figure 21.

Although the 10k constellation at 1200 km looks not much worse than the one at 600 km over the 30 year timespan of Figure 21, Figure 22 shows how durable the damage is, even if the constellation is ended after 20 years.

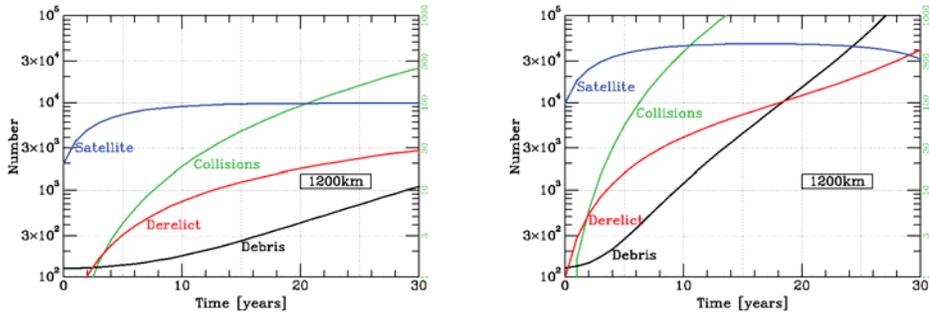


Figure 21: The solution of Equation 5-22 for $\lambda = 2000/\text{yr}$ at 1200 km (left panel) shows an asymptote for S at 10000, but D and N steadily rise until after about 40 years the loss from collision starts bringing S down. The $\lambda = 10000/\text{yr}$ case is similar except that the timescale is half as long. The cumulative number of collisions that disable or disrupt live satellites is shown by the green curves and green scales on right.

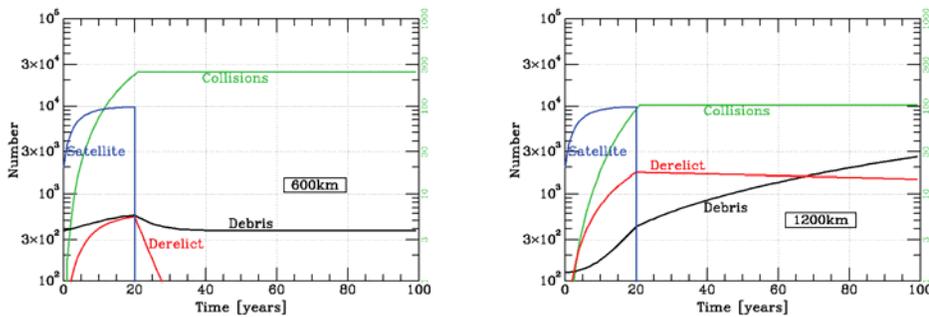


Figure 22: The solution of Equation 5-22 for $\lambda = 2000/\text{yr}$ at 600 km (left panel) shows the decay from atmospheric drag if the live satellites are all removed after 20 years. By contrast the right panel shows the solution for 1200 km, where the debris density continues to rise for the atmospheric drag time of 500 years.

This non-linear runaway of N is actually faster than exponential. Because $\dot{N} \sim N^2$ it diverges in a finite time: $N \sim 1/(t_c - t)$. Therefore if a runaway gets underway it may not be possible to prevent it by active debris removal, all satellites will be broken down into fragments, and this will persist until atmospheric drag brings everything down again.

The awk script we used to integrate these rate equations is given below.

```
# atm_decay_time[year] altitude[km] cross_section[km^2] current_debris
# _density[km^-3]
starlink="5 600 10e-6 2.5e-8"
oneweb="500 1200 5e-6 0.7e-8"

echo $oneweb | \
awk -v lambda=2000 -v atmdrag=1 -v deleteallsat=1000 '
  BEGIN{ R=6378; dh=25; year=365.25*86400; totyear=100;
    v=10; delta=10; N0=100; designlife=5; alpha=0.2; PMD=0.95;
    printf "  Year      Nsat Nderelict Ndebris  Accident  Totacc\n" }
  { tau=$1; h=$2; sigma=$3; n0=$4;
    S=D=Loss=0; n=n0; V=4*3.1416*(R+h)*(R+h)*dh; N=n*V;
    for(t=0; t<totyear; t++) {  n=(N+D/2)/V;
      accident=(delta+alpha)*n*sigma*v*S*year;  Loss+=accident;
      S+=lambda-S/designlife-accident;  if(t>deleteallsat) S=0;
      D+=(1-PMD)*S/designlife+delta*n*sigma*v*S*year-n
        *sigma*v*D*year-D/tau;
      if(atmdrag==1) N-=N/tau;  N+=n*sigma*v*N0*year*(alpha*S+D)
        +n0*V/tau;
      printf "%5d %8d %8d %8d %8.2f %8.1f\n", t, S, D, N,
        accident, Loss;
    }
  }'
```

5.4 JASON Comments on Collision Rates

We are at a peculiar moment in time. We feel like we have a lot of experience with satellites flying around (20,000 tracked objects!), but we don't. The total experience with Iridium amounts to less than 2000 satellite-years, and a large constellation will experience that every two weeks. Most of the debris and satellites that make up the current count of 20,000 are either inactive or were built to the most exacting standards of robust components and redundancy, but building satellites to that standard will not lead to a profitable business. Virtually all the active satellites have a team of people paying close attention to the specific health and well being of each and every satellite, whereas operating a large constellation will depend on software to keep track of the operation and status of each satellite and to manage many avoidance maneuvers every day for the constellation.

Therefore it is essential that we shake off any feeling of complacency and closely examine assumptions and potentially lethal effects from carrying on “business as usual”.

The simple calculations of the previous section yielded preliminary results that were quite unexpected and sobering to JASON. The exact results for S_{max} and debris numbers depend on a number of assumed numbers. S_{max} is inversely proportional to $(1 - P)$ (we assume 0.05) and α (we assume 0.2), δ (we assume 10) comes in via disabling collisions that diminish the PMD.

Nevertheless the results for the case of 10,000 satellites at 1200 km are broadly consistent with the 2018 results from the NASA ODPO for 8,000 satellites between 1100–1300 km.⁴² Debris rises non-linearly for ~ 200 years with ~ 100 catastrophic collisions over that time in both models, so we think our simplified model provides useful guidance.

The FCC is well aware of the hazard from debris and the new threat created by large constellations. On 2 April 2020 the FCC released a fact

⁴²<https://www.orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv22i3.pdf>

sheet⁴³ which proposed some rather dramatic changes to regulations including requirements for maneuverability and liability for damage. On 23 April 2020 they released updated regulations to start to manage orbital debris.⁴⁴ Almost all the regulations in Appendix A are requirements on satellite applicants for disclosure, including but not mandating suggested quantitative thresholds. We closely paraphrase some of these:

- 2(b)(2): The applicant should indicate whether they have assessed the probability of disabling collisions and whether the probability is less than 0.01.
- 2(b)(4)(i)(A): The applicant should demonstrate the collision probability is less than 0.001 (but it may be assumed to be zero while the satellite can be maneuvered).
- 2(b)(4)(i)(D): All systems must describe the extent of satellite maneuverability.
- 2(b)(4)(i)(E): Satellite operators must certify they will act on a conjunction warning.
- 2(b)(5): Satellite operators must reveal the extent to which they plan to share ephemeris information with entities responsible for space traffic management.
- 2(b)(7)(iv)(A): The applicant must demonstrate that the probability of post mission disposal is at least 0.9. For space systems consisting of multiple space stations the demonstration must include information regarding efforts to achieve a higher PMD probability, with a goal of 0.99 or better.

These new regulations fall well short of what the FCC evidently thinks are required for safe traffic management in space, the new constraints on

⁴³<https://docs.fcc.gov/public/attachments/DOC-363486A1.pdf>

⁴⁴<https://www.fcc.gov/document/fcc-updates-orbital-debris-mitigation-rules-new-space-age-0>. See also, Federal Register, 85,165,52422 & 52455.

applicants are minimal, and they are not retroactive for existing licenses. We note that for our assumed parameters the probability of a disabling impact on a given satellite is about 0.01, the probability of a disruptive event is 0.0005, and we assume a PMD probability of 0.95 so an applicant could meet these new FCC regulations and still suffer the catastrophic runaways seen in our rate equations.

Obviously the PMD probability is an unknown, and normally should be an engineering design requirement to meet a constraint, not just an unverified disclosure. We are skeptical that PMD can be better than 0.95 without a lot of transparency and review of the design by outsiders, and single point failures have a huge consequence even if rare. There is also a strong economic incentive for satellite companies to operate as close to the point of failure as possible.

For example, of the 95 satellites Iridium satellites launched between 1997 and 2002, 30 malfunctioned and remain in orbit (PMD probability 0.68). Of these, 7 have low enough perigees that they will reenter within a decade, but 23 will remain derelict for a century. Iridium CEO Matt Desch told Space News that “paying to de-orbit Iridium’s dead satellites would have little financial benefit to the company”. “Incremental ops cost saved is zero. Decreased risk to my network equals zero (all are well below). Decreased regulatory risk is zero (I spend the \$\$, and someone else runs into something). Removing 1 or 2 things from a catalog of 100,000 is perhaps worth only PR value.”⁴⁵

Use of the α term (probability of failed avoidance) and δ term (ratio of disabling to disruptive collisions) does not seem to be standard practice in the debris modeling community, who appear to assume non-disruptive collisions are harmless or can simply be folded into a PMD contribution, and that active satellites always succeed in avoiding all collisions.

⁴⁵<https://spacenews.com/iridium-would-pay-to-deorbit-its-30-defunct-satellites-for-the-right-price>

To date it has been possible to ignore these terms. However, experience so far at much lower densities indicate that $\alpha = 0.2$ may be an underestimate if anything, both because of lax fleet management and imperfect and incomplete knowledge of lethal debris and their orbits. There have been many avoidance maneuvers to date, but statistically speaking virtually none has been necessary, and the one that was evidently necessary (Iridium 33) was ignored. Also, large constellation satellites are smaller and more fragile than most satellites in orbit right now, so even facing the debris density that exists today, there will be an increased probability of disabling or disruptive collision.

We believe it is critical to include the α and δ terms in any models of large constellation evolution, and they cannot just be treated as a component of PMD, because their dependence on debris densities is important.

We neglect the possibility of active debris removal. Although this is a technology that is being actively pursued, it has never been demonstrated and it has many challenges. The cost to remove an item of debris is essentially independent of the mass of the debris item, so once a large satellite has disrupted into a number of lethal fragments it is much more expensive to mitigate its hazard. The Iridium CEO (jokingly) suggested in the statement above that Iridium might be willing to pay \$10,000 to have one of their derelict satellite de-orbited, more than three orders of magnitude less than the most optimistic cost estimated for active debris removal.

The best way to think of active debris removal is as a possibility for a constellation to improve PMD even in the face of satellite failure. As such it can be subjected to serious engineering rigor and analysis as well as economic analysis for insurance and liability. We suspect that active debris removal simply does not make economic sense for large constellation business plans, although in the future governments may be required to undertake expensive projects to manage the existing derelicts and debris, because the companies who created the debris are bankrupt and their profits have been distributed to shareholders.

The most sobering fact is that, although active debris removal is in its infancy, launch for 20,000 satellites has been approved and apparently companies intend to file applications to the FCC that would see multiple constellations of 50,000 satellites. It does not take long for these satellites to produce a runaway of debris fragments that will not be economically feasible to remove.

5.5 Autonomous De-Orbit Systems

Although the α parameter depends on debris tracking and alert fleet management, PMD depends on good engineering. For those satellites which fail PMD it is worth considering whether auxiliary “Bring Down Safely” (BDS) hardware is worthwhile. For example a satellite could be equipped with a small autonomous box that will deploy a balloon or sail if it is not told to go back to sleep on a weekly basis. A functional satellite could jettison a failed BDS balloon, and a BDS could be equipped with a low bandwidth transmitter for independent control from the ground.

A balloon or sail that expands to an area x times larger than the cross section of the satellite will come down x times faster at the cost of a collision probability that is also x times greater. However, a collision with a thin balloon or sail might be damaging but survivable (or not generate much debris) whereas a collision with the solid satellite would not be, so the collision consequence may be improved when a BDS is deployed. It is conceivable for a satellite with BDS to jettison the balloon as a collision avoidance maneuver. A physically modest balloon and mass can make a big difference: the 500 year decay at 1200 km could be reduced to 5 years by using a 25 m balloon.

The visual impact on astronomy would also be worsened by a factor of x , of course, so the steady state, smaller number of satellites in more rapid descent would come at the cost of brighter objects. It is conceivable that the balloon could be very transparent or very black, so that its visual impact might be less than the full factor of x , however.

Electrodynamic tethers have also been discussed as a PMD option for derelict satellites at high altitudes (e.g. Kawamoto 2019⁴⁶ at the First Int'l Orbital Debris Conf). The technology does not seem particularly mature, but it could outperform a balloon in terms of force to cross section.

A BDS mechanism might also be important in case of a design flaw that causes a satellite to misbehave badly after failing PMD. For example a malfunctioning transmitter or a threat of thermal disassembly (explosion) from aging batteries might create certain harm that is worse than the possibility of collision.

5.6 Ascent and Descent Phases

In a steady state constellation there is always a concentration of derelict satellites, even for Starlink at low altitudes. The asymptote for derelict number is nearly 3000 even for a 48k constellation that has a 5 year de-orbit time from atmospheric drag. For a constellation at 1200 km the number of derelicts grows proportional to time without end, passing 10,000 after 20 years for a 48k constellation.

Derelict satellites whose brightness was previously mitigated by attitude control (for example the Starlink “visorsat”, and its “sharkfin” solar panel orientation) will become uncooperative with ground observers and much brighter. We will also see “Iridium flares”, except much more frequently and quite possibly much brighter depending on the planarity and reflectivity of the solar arrays.

We take it for granted that reentry and disposal is done graciously, but in fact it has been the Starlink satellites on ascent that have been so bright and problematic for astronomy. Figure 23 shows an attempt to image Comet NEOWISE that coincided with the passage of a new set of Starlink satellites. Currently Starlink has a launch rate of about $\lambda \sim 800/\text{yr}$, to create a constellation of $S \sim 4,000$. A 48k constellation would have 24 times more

⁴⁶<https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6100.pdf>



Figure 23: An attempt to image Comet NEOWISE on 21 Jul 2020 with a set of 17 30 sec exposures was spoiled by the passage of a flock of 58 Starlink satellites launched on 13 Jun 2020. These images were taken by Daniel Lopez with a Canon Ra astrophotography mirrorless camera and a 200mm lens; a video at www.facebook.com/watch/?v=302865147496785 illustrates the successive passes of Starlink satellites. With 17 images it is possible to photo-edit out the satellite streaks, but a small individual cost times a large number of afflicted photographers and astronomers is significant and should be part of the economics that decide the cost-revenue calculations for a large constellation.

satellites in the process of going up or coming down so it such events will be much more common. Satellites on station will make fainter streaks similar to the one in Figure 23 that is close to horizontal. In a field of view such as this there will be 10's or 100's of such streaks within an hour of twilight, depending on how close to the horizon the image is taken. Of course, a 48k OneWeb constellation would make an similar contribution except that it takes considerably longer to climb to and descend from 1200 km, and satellites will be visible all night long during the summer.

The ascent and descent creates a flux of objects through populous regions, and they are accelerating so their trajectories are not easy to propagate accurately from observations. In addition derelict satellites and debris de-

scending by atmospheric drag pass much more slowly through lower regions than satellites undergoing active de-orbit.

A 48k constellation at 600 km will see 20,000 bodies ascending or descending per year at a controlled de-orbit altitude rate of something like 2,000 km/yr, i.e. a density in altitude of about 10/km of controlled satellites. It will generate an increasing number of derelicts per year, averaging 750/year over a 20 year span, and if they reenter at a descent rate of 200 km/year at 400km this is a density of about 4/km of uncontrolled satellites. There is also an increasing number of >10 cm debris particles, amounting to about 20,000 over a 20 year lifespan, and these create about a density of 5/km of uncooperative debris. The area these things spread over is about $5 \times 10^8 \text{ km}^2$ so the net density is $2 \times 10^{-8} \text{ km}^{-3}$ for each of the maneuverable and uncooperative particles.

This sums to an order of magnitude more than the current density at 400 km altitude of the International Space Station (ISS), so the rate at which it is forced to maneuver to avoid collision and the damage to equipment and risk to human life caused by the untracked component of debris will be higher by an order of magnitude. Right now ISS maneuvers every year; with this new flux of objects it will have to maneuver every month to avoid collision with a non-cooperative body.

5.7 Accurate Satellite Positions and Fleet Operations

Managing any large constellation will be challenging from an operations standpoint because the alerts about and actions to avoid possible collisions (which may also require human judgment) will become common. If all >10 cm debris and satellites are tracked to a $1\text{-}\sigma$ accuracy of 60 m, every satellite will have 1 conjunction per year at the 10^{-4} probability level that needs to be sorted out: refining the accuracy of the orbit of the two bodies and deciding whether a maneuver is required. With this sort of accuracy a 48k constellation needs to consider 130 possible conjunctions per day and perform 130 >200 m avoidance maneuvers.

This seems a daunting task, but the frequency grows as the square of the metric accuracy, and 60 m is a very high standard for propagating an orbit forward from observations a day or two prior. The question is not whether this fleet management can be automated, the question is how to maintain enough knowledge of all satellites and debris at a high enough accuracy that satellites do not expend all their time and fuel avoiding collision.

We have assumed above that 80% of disruptive collisions are detected and avoided, and this is the most critical number from the standpoint of debris generation and space security. Clearly in this new era of large constellations knowledge of where objects are is crucial. An active satellite with a Global Navigation Satellite System (GNSS) system knows its position to much better than that 60 m accuracy, but of course that knowledge needs to be broadly disseminated to be useful because not all active satellites are run by a single operator.

No matter how many active satellites exist there will always be more pieces of >10 cm debris, and tracking them is a difficult job because their orbits are wildly non-Keplerian at the 60 m level. It appears that a combination of the US DoD with SpaceFence and the US Commerce Department will take on the job of maintaining and disseminating accurate coordinates.

It is time for all satellite companies and operators to step up to the task of publishing accurate (<50 m) positions at all times. Inter-operator agreements for data sharing are only helpful insofar as all operators are cooperating, and even then the operators require help from someone who is tracking the debris for them. This has until now been DOD and CSpOC, but the responsibility for tracking debris will apparently transition to the US Commerce Department. It makes no sense whatsoever to require Commerce to observe satellites with known positions and fit orbits to them, particularly when the satellites are accelerating to and from station and for station-keeping and collision avoidance.

5.8 Collision/Debris: Findings and Recommendations

1. **Finding:** Large Constellations pose a significant risk for collision and degradation of the space environment. Our simple calculations indicate that the threshold for serious harm is 40,000 satellites at 600 km altitude and 1,000 satellites at 1200 km. However, our calculations are necessarily simplified and can only provide preliminary guidelines for PMD requirements.

The single most important factor for constellation safety is the PMD probability. This is widely recognized by the professional debris community, but there is no serious attempt to link constellation parameters (orbit, number) to a minimum PMD, nor any attempt to verify the satellite and constellation plans and hardware can meet the required PMD.

SpaceX Starlink is to be *strongly* commended for abandoning 1200 km in favor of a constellation at 550 km. In these uncertain, initial phases this is an extremely good and wise decision.

Recommendation: When the FCC/ITU receives an application for a satellite constellation, it should engage a professional group such as the NASA Orbital Debris Program Office or equivalent to conduct an independent analysis of what PMD is required for constellation safety. The FCC/ITU should then engage a professional group to perform an independent engineering analysis on the design and construction of the applicant's PMD plan and hardware to verify that it meets PMD requirements. Only when these two conditions have been met should the FCC/ITU grant an operating license.

JASON believes that the FCC/ITU should not license operation of a large constellation at 1200 km altitude until extremely stringent requirements on the post mission disposal probability have been demonstrated, and even then JASON believes that a large constellation (more than 1000 satellites) at 1200 km is inadvisable, given unforeseen factors and unavoidable collisions.

2. **Finding:** There is an active and capable community in various space agencies concerned with space debris. The 1st International Orbital Debris Conference which was held on 9 Dec 2019 brought together many interested parties to discuss the problem.⁴⁷ The NASA Orbital Debris Program Office publishes a quarterly newsletter that has reported on the effects of large constellations and the requirements on PMD in 2018. It is very concerning, however, that the debris community appears to be two steps behind the internet satellite companies: the NASA large constellation study looked at 8k satellites, not the 48k requests headed for filing with the FCC and assumed that no active satellite will ever suffer any collision. There also appears to be no requirements to ensure that companies comply with PMD probabilities that are obvious to the debris community.

It seems clear to JASON that currently neglected terms to express the frequency of disabling collisions (δ) and disruptive impacts on operational satellites (α) are important and should be incorporated in professional calculations, as well as policy formulation for space traffic management.

Recommendation: This professional debris community is the closest thing we have to a technical resource for safe use of space. They should immediately run simulations of constellations of at least 48k satellites at a full range of altitudes and parameters so that the consequences of FCC filings by satellite companies can be immediately and publicly assessed. Satellite companies should demonstrate that their designs and applications make sense in terms safe operation and debris generation. Of course JASON wants companies to respect other users of the dark sky such as astronomers and photographers, but debris is a much more direct and immediate problem if not well managed.

⁴⁷<https://www.hou.usra.edu/meetings/orbitaldebris2019>

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3. **Finding:** Fleet operations will soon become impossible if competing companies continue to depend on the US Department of Commerce to maintain accurate satellite and debris positions, propagate orbits, and assess conjunctions.

Recommendation: Satellite operators should publicly publish daily ephemerides of all satellites in their constellation to an accuracy of 20 m, along with public software to automatically access and evaluate the apparent position from a given location and time. This should be a requirement for obtaining a license to fly a constellation.

4. **Finding:** Large Constellations spend a significant fraction of their lifetime in ascent and descent, and an important fraction of the satellites launched to sustain a large constellation are doomed to become uncontrolled derelicts (both from internal failure and unforeseen, disabling collisions).

Management of satellite attitude and trajectory during ascent and descent is important from the standpoint of collision hazard and harm done to ground observations. SpaceX and Starlink have made significant and appreciated improvements over their initial operations, but this phase of lifetime creates a major component of the total harm and must not be ignored.

Recommendation: Publish a full lifespan plan that affected parties can accept, and abide by it. Attitude control during ascent and descent and appearance of a derelict with uncontrolled attitude are just as important as behavior on station.

5. **Finding:** Although the atmospheric drag at 600km ensures that all debris will reenter within ~ 5 years, in the steady state of a replenished constellation the post-mission disposal probability is still critical. The NASA 25 year rule is really intended to ensure against runaway disruptive collisions, but is not a guarantee against many other deleterious effects such as debris and derelict rain at lower altitudes.

At 1200km the drag is so low that there will be a steady growth in space debris for any reasonable PMD probability, so active debris removal or a “bring down safely” subsystem is essential unless an extremely high PMD can be demonstrated.

Recommendation: Satellite companies should consider the merits of a BDS unit. By increasing the drag cross section and shortening the disposal time the number of derelicts in this steady state is reduced, at the cost of a greater cross section for collision and a brighter optical appearance.

A ACRONYMS

Table 5: Partial list of acronyms used in this report.

AAS	American Astronomical Society
ADC	Analog to Digital Converter
ALMA	Atacama Large Millimeter Array
AO	Adaptive Optics
ATCA	Australian Telescope Compact Array
ATLAS	Asteroid Terrestrial-impact Last Alert System
ASAT	Anti-Satellite
ASASSN	All-Sky Automated Survey for Supernovae
awk	Aho, Weinberger and Kernighan
BDS	Bring Down Safely
BSS	Blind Signal Separation
CCD	Charge Coupled Device
CMB	Cosmic Microwave Background
CSpOC	Combined Space Operations Center
CSS	Catalina Sky Survey
DOD	Department of Defense
DOE	Department of Energy
EHT	Event-Horizon Telescope
EPFD	Equivalent Power Flux Density
EPSD	Equivalent Power Spectral Density
ESA	European Space Agency
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDOA	Frequency Difference of Arrival
FOV	Field of View
GEO	Geosynchronous Earth Orbit
GNSS	Global Navigation System
GSPS	Giga-Samples Per Second
ISL	Inter Satellite Link
ISP	Internet Service Provider
ISS	International Space Station
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
JSpOC	Joint Space Operations Center
LC	Large Constellation
LCH	Laser Clearing House
LEGEND	LEO-to-GEO Environment Debris (software)
LGS	Laser Guide Star

Table 5: Partial list of acronyms used in this report.

LEO	Low Earth Orbit
LGSAO	Laser Guide Star Adaptive Optics
LSST	Legacy Survey of Space and Time
M2M	Machine to Machine
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MERLIN	Multi-Element Radio LInked Network
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NGSO	Non-Geostationary Orbit
ngVLA	Next Generation Very Large Array
NIR	Near Infrared
NOIR	National Optical Infrared
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
ODPO	Orbital Debris Program Office
ORDEM	Orbital Debris Engineering Model
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PFD	Power Flux Density
PMD	Post Mission Disposal
PPP	Prompt Processing Pipeline
PSD	Power Spectral Density
PSF	Point Spread Function
PWV	Precipitable Water Vapor
RFI	Radio Frequency Interference
SAT	Small Aperture Telescope
SEFD	System Equivalent Flux Density
SMA	Sub-Millimeter Array
SMAD	Space Mission Analysis and Design (book)
SNR	Signal to Noise Ratio
SO	Simons Observatory)
SSA	Space Situational Awareness
STM	Space Traffic Management
TDOA	Time Delay of Arrival
TLE	Two Line Element
US	United States
VLA	Very Large Array
ZTF	Zwicky Transient Facility

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