2

Mega-constellations

2.1 Introduction

As the COVID-19 pandemic preoccupied most of Earth's inhabitants in July 2020, the night sky provided a much-needed distraction. NEOWISE, the brightest comet seen in the northern hemisphere since the passage of Hale–Bopp in 1997, painted the heavens with its brilliant twin tails.

But NEOWISE was not the only new feature in the sky. 'Trains' of satellites crossed the sky in large numbers, with some widely shared images showing the comet being 'photobombed' by a dense overlay of white lines produced by SpaceX's Starlink satellites.[1] It might be tempting to dismiss this event as a one-off – an unlucky chance alignment between NEOWISE and a single payload of about 60 recently launched satellites undergoing orbit-raising manoeuvres. But consider Figure 2.1, a wide-field image showing a 'globular cluster' of stars and the comet C/2020 T2 (Palomar), which was produced from two hours of image stacking.[2] The image is full of both bright and faint streaks from Starlink and other satellites. Sadly, a clear picture of the sky is quickly becoming something of the past.

Until recently, those wanting to escape the effects of terrestrial light pollution could leave cities and travel to the countryside. Indeed, 'dark-sky spaces' have been recognised and protected around the world,

[1] See Julien H Girard, '17 30-second images of the comet added up by @cielodecanarias, completely photobombed by @elonmusk's #Starlink satellites. It's a few hundreds of them right now, there will be a few thousands in the near future. @SpaceX is committed to coating orienting them better but still . . .' (22 July 2020 at 17:41), *Twitter*, online: twitter.com/djulik/status/1286053695956881409.

[2] Globular clusters are old and massive star clusters, containing hundreds of thousands of stars, all held together by and orbiting each other through their mutual gravitational interactions. 'Stacking' multiple exposures to produce an image can provide many advantages over a single, long exposure. The multitude of satellite streaks is the result of each image in the 'stack' having a different set of streaks.

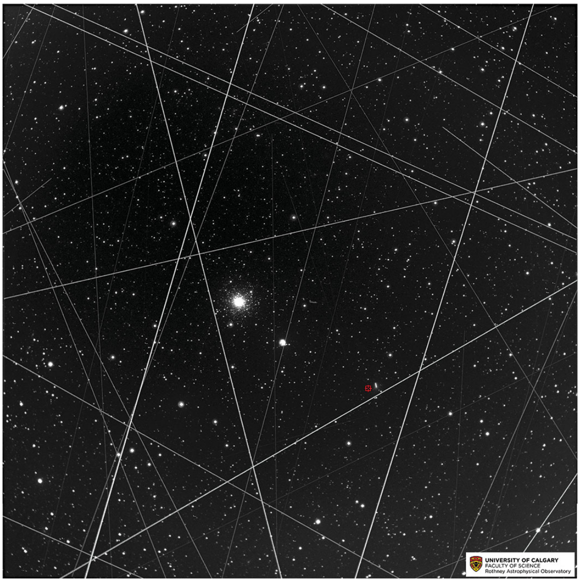

Figure 2.1 An image of M3 (NGC 5272), a globular star cluster, along with comet C/2020 T2 (Palomar), which is near the red cursor. The image was produced from a two-hour series of observations by the Rothney Astrophysical Observatory's Baker–Nunn telescope. The multitude of bright and faint streaks are individual satellites.

and stargazing has become a form of tourism.[3] But increasingly there is nowhere, and therefore no way, to escape the pollution from the thousands of satellites being launched each year.

Should Starlink and other so-called 'mega-constellations' come to fruition without brightness mitigation, the night sky as we know it could be lost. Indeed, anyone looking up at the stars as they had done in their youth could very well could see one in ten 'stars' moving – because they are not stars at all.[4] Adding to the confusion, such a dizzying dance of satellite movements could further create an optical illusion, so that suddenly all the lights in the sky appear to be in motion, making it difficult to track which are actual stars and which are something else.

[3] International Dark Sky Association Headquarters, 'International Dark Sky Place' (January 2022), International Dark-Sky Association, online: www.darksky.org/our-work/conservation/idsp.

[4] Samantha M Lawler, Aaron C Boley and Hanno Rein, 'Visibility predictions for near-future satellite megaconstellations: Latitudes near 50° will experience the worst light pollution' (2022) 163:1 *Astronomical Journal* 21.

Light pollution and a loss of natural and cultural heritage, however, are not the only problems that come with mega-constellations.

The era of mega-constellations began around 2019. Until then, the sight of a satellite was usually a cause of excitement – an ordinary person's glimpse at the marvel of Space exploration. Indeed, as of 2019 there were 'only' about 3,000 satellites in low Earth orbit (LEO), about half of which were functional. Moreover, before mega-constellations, there were just individual satellites and small 'constellations' – groups of satellites that work together to provide some kind of service, such as the global positioning system (GPS), with its 31 satellites. Iridium has provided satellite phone services for decades with a constellation that presently contains 76 satellites. Planet Labs provides Earth imaging for farmers, forestry companies, other businesses and governments from a constellation of 200 satellites, while SiriusXM satellite radio operates from just a handful of satellites. A mega-constellation,[5] by contrast, is designed to provide low-cost, low-latency, high-bandwidth Internet around the world from thousands or even tens of thousands of satellites in LEO.

SpaceX's Starlink constellation has been the first out of the gate. Its initial deployment phase was largely completed in 2020 with 1,440 satellites placed into a single 'orbital shell' – a collection of circular orbits having the same altitude, in this case 550 kilometres. SpaceX now operates more than 3,000 satellites or approximately 50 per cent of all active satellites in orbit (LEO to GEO, i.e. geosynchronous orbit),[6] and is well on its way to placing an already licensed 12,000 satellites into orbit.[7] Yet this is only its 'Gen1' design. The company has already filed for permission from the US Federal Communications Commission (FCC) to add a further 30,000 satellites, the

[5] Scientists often refer to mega-constellations as 'large constellations' or 'satcons', though both these terms downplay the order-of-magnitude change in numbers over early constellations. The nomenclature is further complicated by the fact that it would be more accurate to use the prefix 'kilo' rather than 'mega' for thousands of satellites.

[6] For updates, see Jonathan McDowell, 'Starlink statistics', *Jonathan's Space Pages*, online: https://planet4589.org/space/stats/star/starstats.html.

[7] For Gen1 of SpaceX's (Space Exploration Holdings, LLC) Starlink filings and modifications with the Federal Communications Commission (FCC), see the technical attachments of the following: Patricia Paoletta, 'Application for fixed satellite service by Space Exploration Holdings, LLC, SAT-LOA-20161115-00118' (29 March 2018), *FCC*, online: fcc.report/IBFS/SAT-LOA-20161115-00118; Patricia Paoletta, 'Application for fixed satellite service by Space Exploration Holdings, LLC, SAT-LOA-20170301-00027' (15 November 2018), *FCC*, online: fcc.report/IBFS/SAT-LOA-20170301-00027; William Wiltshire, 'Application for fixed satellite service by Space Exploration Holdings, LLC, SAT-MOD-20200417-00037' (27 April 2021), *FCC*, online: https://fcc.report/IBFS/SAT-MOD-20200417-00037.

so-called 'Gen2' design.[8] Other companies have similar plans for mega-constellations, including OneWeb (7,000 satellites, of which 394 have already been launched),[9] Amazon/Kuiper (3236 satellites),[10] and Guo Wang/StarNet (13,000 satellites).[11] In what could seem like a dramatic escalation, in 2021 Rwanda filed 'advanced publication information' with the International Telecommunication Union (ITU) for two constellations that would have more than 300,000 satellites between them – assuming the filing can be taken at face value. However, the Rwandan company in question, Marvel Space Communications,[12] might be planning to sell off all or some of any radio spectrum rights that it obtains, rather than placing that many satellites into orbit itself. It is also possible that at this time the company does not know exactly what its desired constellation will look like, but wants to lay claim to as much spectrum and orbital Space as it can while it sorts out the details. Since the Rwandan filing, other states have also filed advanced publication information for additional mega-constellations, including Canada for Kepler (114,852 satellites)[13] and the US for Astra Space (13,600 satellites).[14]

[8] For Gen2 of SpaceX's Starlink filing, see William Wiltshire, 'Application for fixed satellite service by Space Exploration Holdings, LLC, SAT-LOA-20200526-00055' (14 January 2022), *FCC*, online: fcc.report/IBFS/SAT-LOA-20200526-00055.

[9] For OneWeb's phase 1 and 2 filings, see Brian D Weimer, 'Application for fixed satellite service by WorldVu Satellites Limited, SAT-MPL-20210112-00007' (12 January 2021), *FCC*, online: fcc.report/IBFS/SAT-MPL-20210112-00007.

[10] For Amazon/Kuiper's filings, see Jennifer D Hindin, 'Application for fixed satellite service by Kuiper Systems LLC, SAT-LOA-20190704-00057' (30 July 2020), *FCC*, online: fcc.report/IBFS/SAT-LOA-20190704-00057.

[11] Larry Press, 'A new Chinese broadband Internet constellation' (2 October 2020), *CircleID*, online (blog): circleid.com/posts/20201002-a-new-chinese-broadband-satellite-constellation.

[12] The name of the company may be linked to the film *Black Panther*, which was produced by Marvel Studios about a fictional country named Wakanda, located in roughly the same area as Rwanda. Wakanda is an extremely advanced country, disguising its wealth and capabilities as a small developing country.

[13] Jeff Foust, 'Satellite operators criticize "extreme" megaconstellation filings', *SpaceNews* (14 December 2021), online: spacenews.com/satellite-operators-criticize-extreme-megaconstellation-filings. Kepler is not planning to launch all these satellites itself. Rather, its business model involves installing small data terminals on 'smallsats' and 'nanosats' being launched by its customers. These terminals will connect to Kepler's own relatively small constellation of satellites, which will then pass signals onward to ground stations, creating 'always-on, real-time connectivity to space-based assets' that would otherwise lack this constant connectivity. Craig Bamford, 'Spire Global to test Kepler's Aether communication terminal and service', *SpaceQ* (20 December 2021), online: spaceq.ca/spire-global-to-test-keplers-aether-communication-terminal-and-service.

[14] Jeff Foust, 'Astra files FCC application for 13,600-satellite constellation', *SpaceNews* (5 November 2021), online: spacenews.com/astra-files-fcc-application-for-13600-satellite-constellation.

Although the current governance system for LEO is slowly changing, it remains ill-equipped to handle very large systems of satellites. In this chapter, we outline how the current direction of development – essentially the application of the 'consumer electronic product model' to satellites – could lead to multiple tragedies of the commons. Some of these are well known, such as a loss of access to certain orbits because of Space debris, while others have received insufficient attention thus far, including changes to the chemistry of Earth's upper atmosphere and increased dangers on Earth's surface from re-entered debris. The heavy use of certain orbital regions might also result in the de facto exclusion of other actors from them, violating the 1967 Outer Space Treaty, which among other things designates Space as 'free for exploration and use for all States without discrimination of any kind' and that this exploration and use of Space is 'the province of all [hu]mankind' (Art. I).[15] In the next chapter, we address some of the legal issues arising from collisions and Space debris, as well as from the effects of light pollution on astronomy.

We conclude that all these challenges associated with mega-constellations should be addressed in a co-ordinated manner through multilateral law-making, whether at the United Nations, at the Inter-Agency Space Debris Coordination Committee (IADC), or via an ad hoc process, rather than in an unco-ordinated manner through different national systems. Multilateral law-making has already delivered solutions to similar challenges regarding civil aviation in international air space and commercial shipping on the high seas.

Most importantly, mega-constellations require a shift in perspectives and policies. Instead of looking at single satellites, we need to evaluate systems of thousands of satellites, launched by multiple states and companies, all operating within a shared ecosystem. We use the term 'ecosystem' to underline an obvious but necessary point: the closer regions of Space are part of Earth's environment. Mega-constellations are on track to exceed the limits of that environment, with negative consequences for all of humanity.

2.2 Why Mega-constellations?

The thinking behind mega-constellations is simple, at least in general terms. Companies want to offer low-latency, reliable broadband Internet

[15] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 27 January 1967, 610 UNTS 205 Art. VI (entered into force 10 October 1967) (Outer Space Treaty).

connectivity regardless of user location. They are betting that, with enough users in remote and rural communities and on ships, trains, planes and automobiles, the winners in the race to industrialise LEO will create and capture a profitable long-term market. Whether these companies are right remains to be seen. It is possible that the difference between success and failure will ultimately be in the hands of military rather than civilian customers, since global low-latency connectivity delivered via thousands of satellites could offer a strategic advantage, for some applications, over higher-latency systems delivered by a much smaller number of satellites in higher orbits. For instance, it is widely assumed that the connectivity provided by a mega-constellation will be more resilient to attack, due to the large number of targets that would have to be struck to disrupt, disable or destroy the entire system.[16]

Another benefit cited by the proponents of mega-constellations is that connectivity will be brought to rural and remote communities, Indigenous peoples and those in the least-developed countries, places that often lack fibre-optic cables and other infrastructure that many of us now take for granted. Internet connectivity also creates opportunities for remote learning and 'telehealth', two services that have gained prominence during the COVID-19 pandemic. Yet some early analyses have questioned whether these promises are achievable. People who are not already well off may be prevented from accessing mega-constellations due to high subscription costs and the need for some ground-link infrastructure.[17] Iridium has built a successful business of providing satellite phones to emergency services and shipping and mining companies, but at several dollars per minute of connectivity, its customer base remains small. Larger constellations aim to find millions of customers, and it remains to be seen whether long-term profitability can be achieved – especially once multiple systems are offering the same service. Again, it may be that a single large customer, such as a military, is needed for any individual mega-constellation to succeed.

It is further possible that, as technology changes, the market for Internet connectivity from Space will flatten or contract. We see a hint of this already. The Hoh, an Indigenous people in northern Washington State, were among the first early users of the Starlink constellation.

[16] We question this assumption in the conclusion to this book.

[17] Meredith L Rawls, Heidi B Thiemann, Victor Chemin, Lucianne Walkowicz, Mike W Peel and Yan G Grange, 'Satellite constellation Internet affordability and need' (2020) 4:10 *Research Notes of the AAS* 189.

However, they see this as a temporary measure, with the long-term goal being fibre connectivity – for reliability reasons as well as a desire to be their own service provider.[18]

Space debris is also an issue. With several companies already launching thousands of satellites, the cumulative amount of all the material in orbit is increasing rapidly (and most importantly, in terms of collision risk, so too is the total cross-section). Elon Musk claims that billions of satellites can be operated safely in LEO,[19] but this is not generally true, particularly as more operators become involved, or if we take into account random events such as malfunctions, accidental explosions on orbit (of which there are about five each year) and meteoroid strikes. Musk also ignores the threat of lethal, non-trackable debris, which can only partly be addressed through improved detection-and-tracking technology. Over time, the cost of collisions could exceed the technological and economic advantages of LEO, pushing global satellite communications back to GEO.

2.3 Space Debris and Orbital Congestion

Figure 2.2 shows the growth of on-orbit infrastructure over time, including tracked debris, payloads (active and defunct satellites) and abandoned rocket bodies. The term 'tracked debris' refers to those pieces that are large enough to be catalogued and reliably reacquired through observations, with sizes typically ten centimetres in diameter or larger. For cataloguing purposes, and as discussed here, 'tracked debris' excludes defunct satellites and rocket bodies. The latter are, of course, forms of debris but are discussed separately on account of their significant mass, and correspondingly their potential to be sources for the 'tracked debris' population, as discussed further below. Debris numbers are also incomplete, in that some objects with diameters greater than ten centimetres will not yet have been identified and tracked. Nor do they include smaller debris, which is likely much more numerous, with about one million

[18] Joshua Sokol, 'The fault in our stars: Satellite swarms are threatening the night sky. Is low-Earth orbit the next great crucible of environmental conflict?', *Science*, 7 October 2021, online: www.science.org/content/article/satellite-swarms-are-threatening-night-sky-creating-new-zone-environmental-conflict.

[19] Richard Waters, 'Elon Musk rejects claims he is squeezing out rivals in space', *Financial Times* (29 December 2021), online: www.ft.com/content/18dc896f-e92f-41f7-9259-69cfd8d61011.

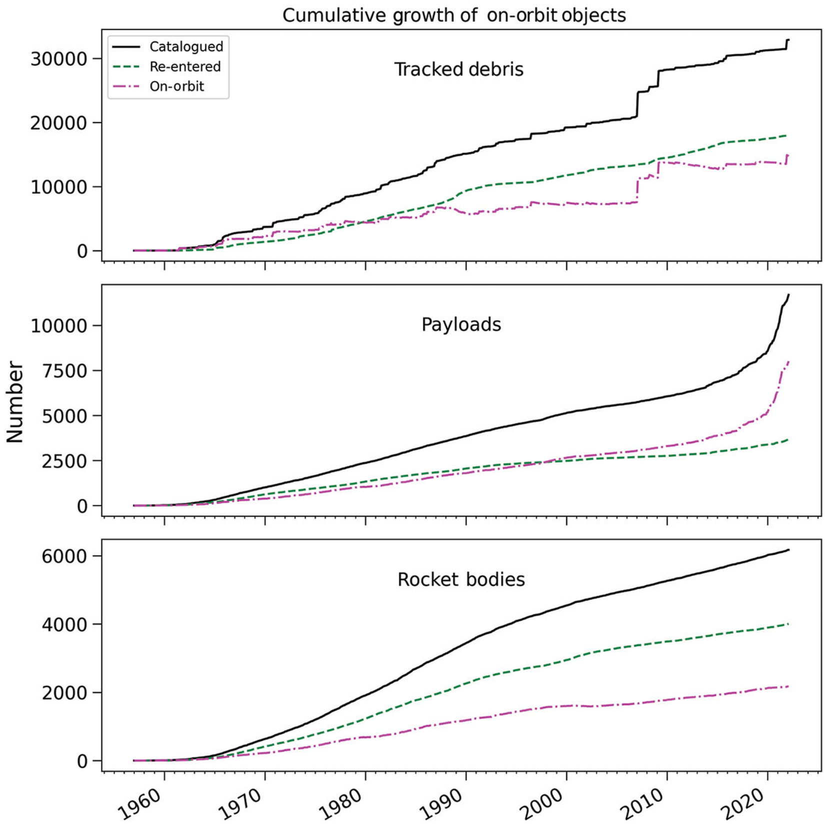

Figure 2.2 Cumulative on-orbit distribution functions (all orbits) for tracked debris (top), payloads (middle) and rocket bodies (bottom). The 'on-orbit' curves are just the difference between the 'catalogued' and 'decayed' curves. The 2007 and 2009 debris spikes are a Chinese anti-satellite test and the Iridium 33–Kosmos 2251 collision respectively, while the 2021 spike is the Russian anti-satellite weapon test. The recent, rapid rise of the satellite (payload) curve represents NewSpace. This figure was produced using data obtained from the USSPACECOM satellite catalogue (www.space-track.org) and cross-referencing with on-orbit fragmentation records (Phillip D Anz-Meador et al., *History of On-Orbit Satellite Fragmentations*, 15th ed (Houston: NASA, 2018). All orbits are included. Sudden rises in the debris curves are typically due to fragmentation events.

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pieces being inferred for sizes greater than one centimetre in diameter. All these pieces pose a threat to satellites, spacecraft, and astronauts due to their orbits criss-crossing at high relative speeds. The debris is generated by accidental explosions, collisions and degradation in the harsh Space environment. Debris can also result from the intentional destruction of objects in orbit, as discussed in Chapters 7 and 8. Whatever the cause, fragmentation of objects in orbit increases the cross-section of orbiting material, and with it the probability of collisions over time. Eventually, collisions could become the dominant factor changing the orbital environment, a situation called the Kessler–Cour–Palais syndrome, which could in some scenarios lead to a collisional chain reaction – essentially, runaway Space debris.[20]

There is a natural clearing process for debris due to atmospheric drag, caused by the presence of some gas in the lower portions of LEO. This clearing action is highlighted by the fraction of debris that has de-orbited. However, the production of debris is outpacing this self-cleaning behaviour. More worrisome are the sudden jumps in the debris population, owing to the 2007 Chinese anti-satellite weapon test, the 2009 Iridium 33–Kosmos 2251 collision, and most recently the 2021 Russian anti-satellite weapon test. Unfortunately, these jumps might provide a glimpse of what to expect as we industrialise Earth orbits.

Also shown in Figure 2.2 are the growth and decay curves of rocket bodies, i.e. rocket stages that have been abandoned in orbit after use. While fewest in number, they have the greatest mass of all the derelict objects in orbit and are a major source of debris generation. We discuss rocket bodies at length in Chapter 4.

Finally, the payload curves represent the growth of active and defunct satellites. There was a steady rise in the number of satellites in orbit until 2015, which then transitioned to a sudden rise in 2019. This change in slope serves as an environmental definition for the start of 'NewSpace' – an era dominated by commercial Space actors and mega-constellations.

Simulations of the long-term evolution of debris suggest that LEO is already in the early and still slow-moving stages of the Kessler–Cour–Palais syndrome.[21] This could potentially be managed through active debris removal – a technologically feasible process, though very expensive

[20] Donald J Kessler and Burton G Cour-Palais, 'Collision frequency of artificial satellites: The creation of a debris belt' (1978) 83:A6 *Journal of Geophysical Research* 2637.

[21] J-C Liou and NL Johnson, 'Risks in space from orbiting debris' (2006) 311 *Science* 340.

and perhaps legally contentious.[22] But that potentiality does not reduce the seriousness of the current situation: the addition of mega-constellations and the general proliferation of 'small' satellites in LEO is stressing the orbital environment, and it is doing so at astonishing speed.[23]

Although the volume of Space is large, each individual satellite and every satellite system has specific functions, requiring specific altitudes and inclinations (Figure 2.3).[24] This increases congestion in certain regions of LEO and requires active management for station-keeping and collision avoidance.[25] Improved Space situational awareness is required, with data from satellite operators as well as from ground- and Space-based sensors being widely and freely shared.[26] Improved communication among satellite operators is also necessary. For example, in 2019,

[22] Legal contention might arise if one state attempted to retrieve a space object launched by another state without the launch state's permission. States retain jurisdiction and legal responsibility over spacecraft that have stopped functioning, or even have fragmented, with the Liability Convention defining 'space object' as including 'component parts of a space object as well as its launch vehicle and parts thereof'. Convention on International Liability for Damage Caused by Space Objects, 29 March 1972, 961 UNTS 187 Art. I(d) (entered into force 1 September 1972) (Liability Convention). But the retrieval would not entail returning the defunct object to the Earth's surface; rather, it would be directed onto a re-entry trajectory where it would 'burn up'. As a result, the 'launch state' would have little to be concerned about.

[23] A Rossi, A Petit and D McKnight, 'Short-term space safety analysis of LEO constellations and clusters' (2020) 175 *Acta Astronautica* 476; Samantha Le May, Steve Gehly, BA Carter and Sven Flegel, 'Space debris collision probability analysis for proposed global broadband constellations' (2018) 151 *Acta Astronautica* 445; J-C Liou, M Matney, A Vavrin, A Manis and D Gates, 'NASA ODPO's large constellation study' (2018) 22:3 *Orbital Debris Quarterly News* 4; D Vavrin and A Manis, 'CubeSat Study Project Review' (2018) 22: 1 *Orbital Debris Quarterly News* 6.

[24] Orbital inclination, in this context, describes how 'tilted' an orbit is relative to Earth's equator. An inclination of zero degrees means the orbit is in the same plane as Earth's equator, while an inclination of 90 degrees means the orbit goes directly over Earth's poles. An inclination greater than 90 degrees means the orbit of the object has a 'retrograde' orbital sense. For example, an orbiting object with an inclination of zero degrees and another with an inclination of 180 degrees would both orbit about Earth's equator, but one would do so in a clockwise motion and the other in a counterclockwise motion, as viewed from a pole.

[25] Nathan Reiland, Aaron J Rosengren, Renu Malhotra and Claudio Bombardelli, 'Assessing and minimizing collisions in satellite mega-constellations' (2021) 67:11 *Advances in Space Research* 3755.

[26] US Senate Committee on Commerce, Science, and Transportation, 'Statement of Dr Moriba K Jah on space missions of global importance: Planetary defense, space weather protection, and space situational awareness' (12 February 2020), online: www.commerce.senate.gov/services/files/F15B56A1-9134-43D8-B072-65F6CD2ADCEA.

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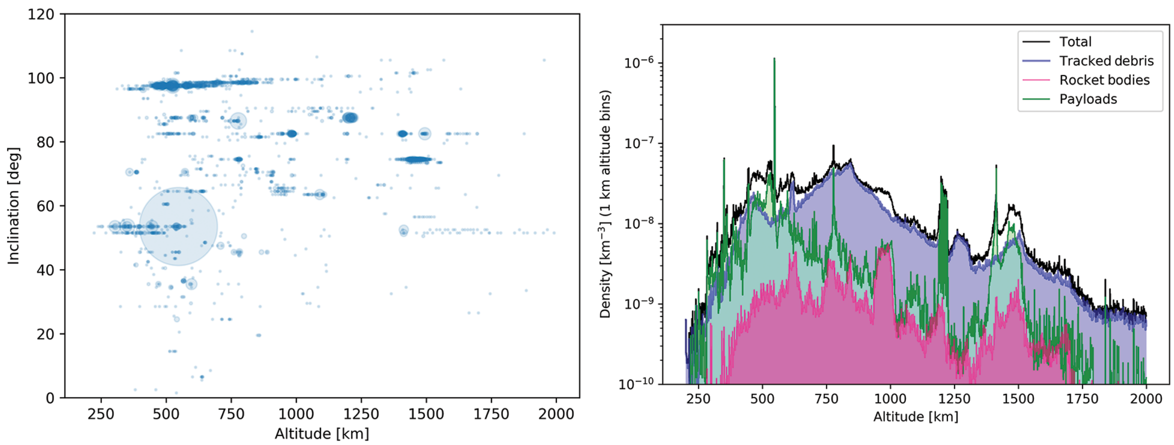

Figure 2.3 Orbital distribution and density information for objects in low Earth orbit. Left: distribution of payloads (active and defunct satellites), binned to the nearest kilometre in altitude and one degree in orbital inclination. The centre of each circle represents the position on the diagram, and the size of the circle is proportional to the number of satellites within the given parameter space. Right: number density of different resident Space objects (RSOs) based on one-kilometre radial bins, averaged over the entire sky. Because most RSOs are on at least slightly elliptical orbits, the contribution of a given object to an orbital shell is weighted by the time that object spends in the shell. Despite significant parameter space, satellites are clustered in their orbits due to mission requirements. The emerging Starlink cluster at 550 kilometres and 53° inclination is already evident in both plots. For more on the construction of these plots, see Aaron Boley and Michael Byers, 'Satellite mega-constellations create risks in low earth orbit, the atmosphere and on Earth', (2021) 11 *Scientific Reports* 10642.

the European Space Agency (ESA) moved an Earth-observation satellite to avoid colliding with a Starlink satellite, after failing to reach SpaceX by e-mail.[27]

Then, in December 2021, China reported that its Space station had manoeuvered on two occasions, on 1 July and 21 October 2021, to avoid potential collisions with Starlink satellites.[28] One of those satellites had moved into a nearby orbit, resulting in a 'close encounter', while the other was moving unpredictably. China emphasised that the United States was legally responsible for SpaceX's activities and for ensuring that they complied with the Outer Space Treaty.[29] There is insufficient information about these incidents to determine objectively what caused them. There may have been a breach in spaceflight safety, a possibility complicated by the lack of any rules concerning what constitutes a 'safe' distance for a 'conjunction' (i.e. a close approach). It is also possible, and possibly more likely, that SpaceX and the China National Space Administration (CNSA) have different decision matrices for ensuring on-orbit safety. Equally possible, as with the ESA incident in 2019, is that SpaceX and CNSA lack an effective channel of communication, one that would have enabled them to co-ordinate their actions.

Such channels of communication are needed between all spacecraft operators. Earlier in 2021, SpaceX and the National Aeronautics and Space Administration (NASA) announced that they would be co-operating to reduce the risk of collisions arising from their on-orbit activities.

[27] Mike Wall, 'European satellite dodges potential collision with SpaceX Starlink craft', *Space.com* (3 Sept 2019), online: www.space.com/spacex-starlink-esa-satellite-collision-avoidance.html.

[28] Permanent mission of China to the United Nations (Vienna), 'Information furnished in conformity with the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies', Note verbal, UN Doc A/AC.105/1262 (3 December 2021), online: www.unoosa.org/oosa/en/oosadoc/data/documents/2021/aac.105/aac.1051262_0.html. The report was made to the UN secretary general, pursuant to Article V of the OST, which provides that 'States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary-General of the United Nations of any phenomena they discover in outer space, including the Moon and other celestial bodies, which could constitute a danger to the life or health of astronauts.' Outer Space Treaty, Art. V.

[29] Permanent mission of China to the United Nations (Vienna), op. cit. Article VI of the OST reads, 'States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty.'

However, this agreement is between only one operator and one agency,[30] although, according to SpaceX, efforts to share data with other operators are now under way.[31] Such efforts at co-operation clearly need to include other governments, and especially China and Russia. Just as importantly, internationally adopted 'right-of-way' rules are needed to prevent games of 'chicken',[32] as companies, seeking to preserve thruster fuel and avoid service interruptions, wait for the other operator to move its satellite first.

2.4 Increased Collision Risk

Mega-constellations are composed of relatively low-cost, mass-produced satellites with few backup systems. This 'consumer electronic product model' allows for short upgrade cycles and rapid expansions of capabilities, but it also results in considerable amounts of discarded equipment and therefore increased collisional risks. Although SpaceX will actively de-orbit its satellites at the end of their five- to six-year operational lives, this process will take six months, so roughly 10 per cent will be de-orbiting at any time. If other companies do likewise, thousands of de-orbiting satellites will be slowly passing through the same congested region. Because satellites in higher orbital shells will by necessity pass through all lower shells, stresses on Space traffic management will be enhanced, raising the risk of collisions. Construction flaws and other malfunctions will increase these numbers, with the long-term failure rate being difficult to project. It should further be recognised that such congestion affects all orbital operations, including in GEO, due to the need to perform orbit-raising manoeuvres (i.e. 'GEO-transfer' orbits) that repeatedly pass through LEO for several weeks or months. Indeed, a collision between an LEO object and a GEO transfer object would create a debris 'family' that passes through all near-Earth orbital Space. Again, it is important to remember that SpaceX will be just one of many

[30] National Aeronautics and Space Administration (NASA), news release, 21-011, 'NASA, SpaceX sign joint spaceflight safety agreement' (18 March 2021), online: www.nasa.gov/press-release/nasa-spacex-sign-joint-spaceflight-safety-agreement.

[31] Jeff Foust, 'SpaceX emphasizes coordination with other satellite operators', *SpaceNews* (16 Sept 2021), online: spacenews.com/spacex-emphasizes-coordination-with-other-satellite-operators.

[32] On the oceans, such rules are known as 'rules of the road'. See Convention on the International Regulations for Preventing Collisions at Sea, 20 October 1972, 1050 UNTS 16 (entered into force 15 July 1977).

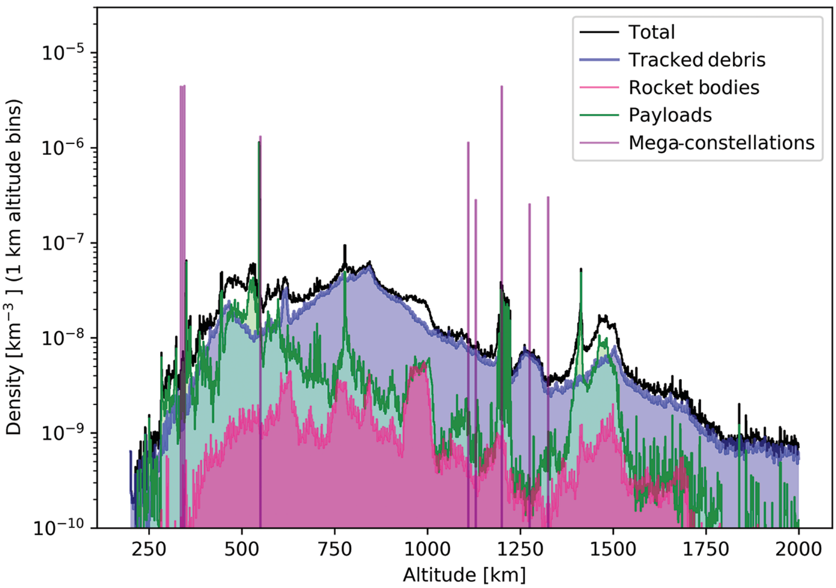

Figure 2.4 Satellite density distribution in LEO with 65,000 satellites from four mega-constellations (Starlink, OneWeb, Kuiper and StarNet). Areas of potentially high congestion and collision risk are represented by the large spikes in orbital density. The collision risk is further heightened by debris that is too small to be tracked or when collision avoidance manoeuvres are impossible for other reasons. For more on our methods, see Boley and Byers, op. cit.

companies engaging in such practices in a congested environment, creating a serious collective action problem with no easy fix.

Figure 2.4 depicts some of the congestion that we can expect to see. It is similar to the righthand plot in Figure 2.3, but includes the Starlink, OneWeb, Amazon/Kuiper and Guo Wang/StarNet mega-constellations as filed (and amended) with the FCC and/or ITU, for a total of about 65,000 satellites. The large spikes show the considerable density of satellites in orbital shells. The total cross-section within these regions is high, and a satellite fragmentation, for any reason, at one of those altitudes could lead to multiple collisions and large-scale debris generation.

De-orbiting satellites will be tracked while operational satellites can be manoeuvred to avoid close conjunctions with them, with other satellites and with trackable debris. But effective collision avoidance often depends on ongoing communication and co-operation between operators, which, as noted above, is at present ad hoc and voluntary. The situation could become more, not less, complicated, as autonomous collision avoidance systems are developed. In April 2021, SpaceX sent a letter to the FCC about how, in the face of one upcoming conjunction, OneWeb requested that SpaceX turn off its autonomous collision avoidance system so that OneWeb could safely manoeuver its satellite out of the way.[33]

SpaceX also points to its automatic collision avoidance technology to justify the high density of its satellites in individual shells. But in August 2021, it emerged that the system is currently entirely dependent on the standard (and not always accurate) conjunction warnings provided by the United States Space Command (USSPACECOM).[34] Unresponsive satellites add a further collision risk. Worse yet, SpaceX's collision assessments, at least according to their FCC filings, do not account for untracked, lethal debris (i.e. pieces with diameters of less than about ten centimetres and larger than a few millimetres),[35] including untracked debris decaying through the shells used by Starlink. Using simple estimates,[36] the probability that a single piece of untracked debris will hit any satellite in the Starlink 550-kilometre shell is about 0.003 after one year. Thus if, at any time, there are just over 200 pieces of untracked debris decaying through the 550-kilometre orbital shell, there is roughly a 50 per cent chance that there will be one or more collisions between satellites in the shell and a piece of untracked debris.[37] While not all collisions will lead to catastrophic failures, they will still degrade the orbital environmental by producing additional debris and wearing down satellites. And it only takes one collision with a significant fragmentation outcome to produce large amounts of debris, which in turn could produce widespread satellite failures within an orbital shell.

[33] Letter from David Goldman, SpaceX director of satellite policy, to Marlene H Dortch, secretary, FCC, regarding application SAT-MOD-20200417-00037 (20 April 2021). See also Joey Roulette, 'OneWeb, SpaceX satellites dodged a potential collision in orbit', *The Verge* (9 April 2021), online: www.theverge.com/2021/4/9/22374262/oneweb-spacex-satellites-dodgedpotential-collision-orbit-space-force.

[34] Jonathan McDowell, 'SpaceX have released a bit more info on the "automatic" collision avoidance that some people have been confused about. As suspected, what they mean is that they rely on conjunction warnings generated by SpaceForce radar tracking which are uploaded to the satellites' (22 August 2021 at 15:26), online: *Twitter* twitter.com/planet4589/status/1429525312577183746.

[35] Le May et al., op. cit.

[36] Aaron Boley and Michael Byers, 'Satellite mega-constellations create risks in low Earth orbit, the atmosphere and on Earth' (2021) 11 *Scientific Reports* 10642, 1 at 5–6.

[37] Ibid.

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Moreover, fragmentation events are never confined to their local orbits. As Chapters 7 and 8 explain, India's 2019 anti-satellite weapon test was conducted at an altitude below 300 kilometres in a good-faith effort to minimise long-lived debris. Nevertheless, some tracked debris (and presumably a larger amount of untracked but still lethal debris) was placed in orbits with apogees greater than 1,000 kilometres. As of January 2022, there was one piece of tracked debris from that test still in orbit. Pieces of such long-lived debris have high eccentricities and thus can cross multiple orbital shells twice per orbit. Yet all these collision risks associated with mega-constellations have not received due consideration, in part because of the FCC's practice of considering only the per-satellite collision risk when issuing licences for mega-constellations composed of thousands of satellites.[38]

The collision risks associated with meteoroids have also been largely ignored, presumably because the cross-section of on-orbit infrastructure has, until recently, been relatively low. Moreover, unlike collisions with debris, collisions with meteoroids are unavoidable, which reduces the options available to any government or company wishing to reduce the risks.

Meteoroids are composed of natural material that is between about 30 microns and one metre in diameter.[39] Their main source is ejected pieces of asteroids and comets. Much smaller objects are called 'dust', and larger objects are thought to be more asteroid-like, although this is a definition of convenience more than anything else. In any event, the cumulative meteoroid flux for masses of greater than 0.01 gram is about 1.2×10^{-4} meteoroids per square metre per year.[40] Such masses could cause significant damage to satellites, even if they do not result in catastrophic fragmentation,[41] in part because meteoroids can attain

[38] Mike Lindsay (chief technology officer, Astroscale), 'Another thread about sat collision probability. This time let's talk about regulations, as the FCC has just solicited input about how to regulate collision risk. As we know, risk can be computed as = 1–(1–Pc)^N where Pc = each sat's collision probability and N = # of sats' (19 October 2020 at 8:55), online: *Twitter* twitter.com/mikeclindsay/status/1318174030583656449.

[39] International Astronomical Union, 'Meteors & meteorites: The IAU definitions of meteor terms' (2022), online: *International Astronomical Union* www.iau.org/public/themes/meteors_and_meteorites.

[40] Eberhard Grün, Herbert A Zook, Hugo Fechtig and RH Giese, 'Collisional balance of the meteoritic complex' (1985) 62:2 *Icarus* 244.

[41] Althea V Moorhead, Aaron Kingery and Steven Ehlert, 'NASA's meteoroid engineering Model 3 and its ability to replicate spacecraft impact rates' (2020) 57:1 *Journal of Spacecraft and Rockets* 160.

much higher impact speeds than orbital debris. Assuming a Starlink constellation of only 12,000 satellites (i.e. the Gen1 design), there is about a 50 per cent chance of 15 or more meteoroid impacts (or a 99.7 per cent chance of one or more meteoroid impacts) per year at a mass of more than 0.01 gram.[42] Adding more satellites will only increase the number of events per year.

Many satellites are designed with shielding, but damaging events that might be rare to a single satellite will become common when measured across all orbital infrastructure. Therefore, while orbital debris will likely remain the most significant threat to mega-constellations, we can also anticipate regular satellite failures due to meteoroid impacts. Again, this is a result of the total cross-section on orbit, and not strictly the total number of satellites. So even small satellites in sufficiently large numbers – such as the 114,852 satellites for which Kepler has filed advanced publication information – could give rise to regular debris-generating events from collisions with either debris or meteoroids.

One response to all these concerns about congestion and collisions is for operators to construct mega-constellations out of fewer satellites. But with more and more operators entering LEO, even this would only provide a partial solution. For this reason, it is critically important that spacefaring states and satellite companies, individually and collectively, take an all-of-LEO approach to evaluating the effects of the construction and maintenance of any one constellation, and then to mitigating the cumulative effects of all constellations.

2.5 Surface Impacts

Re-entering rocket stages pose growing safety and environmental risks on the Earth's surface, as we explain at length in Chapter 4. SpaceX is a relatively responsible actor in this regard, as the first stages of SpaceX rockets are usually landed and reused, while second stages are usually controlled through re-entry and deposited in remote areas of ocean. Unfortunately, these best practices are not being followed – or cannot yet be followed – by other launch providers. For example, the first stages of the Soyuz rockets employed by OneWeb until February 2022 (when Russia invaded Ukraine) are not reusable, nor are the second-stage re-entries controllable. OneWeb has since signed a contract to use India's

[42] This calculation assumes that each satellite has a cross-section of about four square metres.

Geosynchronous Satellite Launch Vehicle,[43] which is similarly limited. The Vulcan Centaur rockets that will be used by Amazon/Kuiper suffer from the same limitations, as do the Long March rockets that will likely be employed by Guo Wang/StarNet.

Satellite re-entries pose their own risks – including that of killing people – since re-entering orbiting material often does not demise ('burn up') completely in the atmosphere.[44] To get a feel for the numbers, consider the early FCC filings made by SpaceX for its Starlink satellites. The typical 'casualty risk' per satellite was listed as about 1:20,000 (the highest risk was 1:17,400),[45] meeting NASA's risk threshold of 1:10,000 per object. The satellites were (and still are) expected to last between five and six years, with a full replacement of the constellation occurring on that timescale. This meant that every replacement cycle of the 12,000 satellites in Starlink Gen1 carried a 45 per cent probability of one or more casualties from the re-entering satellites ($P = exp(-12000/20000) \approx 45\%$). If this were extended to Starlink's full 42,000 satellites (Gen1 and Gen2 taken together), the probability of one or more casualties per replacement cycle would be 88 per cent. Again, we are talking here about the statistical likelihood of people getting killed by a satellite impact. Fortunately, the issue was identified during the FCC's 'open consultation' process.[46] SpaceX responded by changing some components to make its satellites fully demisable and therefore of no threat to people on the Earth's surface. However, the effects of these changes will have to be verified, and it remains to be seen whether other operators will follow this new best practice.

Even controlled re-entries can be problematic if the re-entering rocket stage or satellite contains hazardous materials.[47] In 1978, a Soviet

[43] Jonathan Amos, 'OneWeb: UK satellite firm does deal to use Indian rockets', *BBC* (21 April 2022) online: www.bbc.com/news/science-environment-61175261.

[44] William H Ailor, 'Large constellation disposal hazards' (20 January 2020), Center for Space Policy and Strategy, *The Aerospace Corporation*, online: aerospace.org/sites/default/files/2020-01/Ailor_LgConstDisposal_20200113.pdf.

[45] Patricia Paoletta, 'Application for fixed satellite service by Space Exploration Holdings, LLC, SAT-LOA-20170301-00027' (15 November 2018), *FCC*, online: fcc.report/IBFS/SAT-LOA-20170301-00027.

[46] William Wiltshire, 'Application for fixed satellite service by Space Exploration Holdings, LLC, SAT-MOD-20200417-00037' (27 April 2021), *FCC*, online: https://fcc.report/IBFS/SAT-MOD-20200417-00037.

[47] Carmen Pardini and Luciano Anselmo, 'Uncontrolled re-entries of spacecraft and rocket bodies: A statistical overview over the last decade' (2019) 6 *Journal of Space Engineering Safety* 30; Michael Byers and Cameron Byers, 'Toxic splash: Russian rocket stages dropped in Arctic waters raise health, environmental and legal concerns' (2017) 53:6 *Polar Record* 580.

surveillance satellite malfunctioned, re-entered the atmosphere in an uncontrolled manner, and spread radioactive material over 120,000 square kilometres of northern Canada.[48] In 2008, the United States Navy used a ship-based missile to destroy a malfunctioning military satellite just before it entered the atmosphere.[49] The mission, named Operation Burnt Frost, was justified on the ground that it prevented 450 kg of unspent highly toxic hydrazine thruster fuel from reaching the surface.

Cumulative impacts must also be considered, especially in the ocean environments where most controlled re-entries end up.[50] In the 1990s, Pacific island states opposed the Sea Launch project because of environmental concerns, including from discarded rocket stages.[51] In 2016, Inuit in the Canadian Arctic protested the Russian practice of disposing hydrazine-fuelled rocket stages in Pikialasorsuaq (North Water Polynya), a biologically rich area of year-round open water.[52]

2.6 Atmospheric Effects

2.6.1 Re-entering Satellites

The demise of satellite components during re-entry introduces a further problem since none of their material actually disappears. It is, instead, converted into very large numbers of fine particulates, atoms and molecules having the same cumulative mass. To get a sense of this, again consider Starlink satellites, which have an estimated dry mass of about

[48] Canada presented a claim of CDN$6 million for the cleanup, citing the Outer Space Treaty and the Liability Convention. After three rounds of negotiations, the Soviet Union, while not admitting liability, agreed to pay half that amount 'in full and final settlement of all matters connected with the disintegration of the Soviet satellite Cosmos-954'. Olga A Volynskaya, 'Landmark space-related accidents and the progress of space law' (2013) 62 *Zeitschrift für Luft- und Weltraumrecht* (German Journal of Air and Space Law) 220 at 226; Protocol between the Government of Canada and the Government of the Union of Soviet Socialist Republics, E103429, Can TS 1981 No 8, online: www.treaty-accord.gc.ca/text-texte.aspx?id=103429.

[49] Nicholas L Johnson, 'Operation Burnt Frost: A view from inside' (2021) 56 *Space Policy* 101411.

[50] Vito De Lucia and Viviana Iavicoli, 'From outer space to ocean depths: The "spacecraft cemetery" and the protection of the marine environment in areas beyond national jurisdiction' (2019) 49:2 *California Western International Law Journal* 345.

[51] Colin Woodward, 'High-seas launch worries islanders', *Christian Science Monitor* (22 September 1999), online: www.csmonitor.com/1999/0922/p5s1.html.

[52] Bob Weber, 'Inuit angered by Russian rocket splashdown in the Arctic', *Globe and Mail* (3 June 2016), online: www.theglobeandmail.com/news/national/inuit-angered-by-russian-rocket-splashdown-in-the-arctic/article30273826.

260 kg. Although we do not know their composition, we assume that most of the mass is an aluminium alloy. If 80 per cent of the mass is aluminium, and Gen1 includes 12,000 satellites, there will be 2,500 tonnes of aluminium in total. A five-year cycle would thus see on average about 1.4 tonnes re-entering Earth's atmosphere daily. While small compared to the 54 daily tonnes of meteoroid material,[53] most meteoroids contain less than 1 per cent aluminium by mass.[54] Thus, depending on the atmospheric residence time of material from re-entered satellites, each mega-constellation could produce fine particulates that greatly exceed natural forms of high-altitude atmospheric aluminium deposition, especially if the full numbers of envisaged satellites are launched. Gen1 and Gen2 of Starlink combined, with 42,000 satellites, would lead to about five tonnes of aluminium entering the atmosphere each day, an order of magnitude above natural levels.

Anthropogenic (i.e. human-caused) deposition of aluminium in the atmosphere has long been proposed in the context of geoengineering as a way to increase Earth's albedo – essentially, reflecting solar energy back into Space to slow global warming.[55] Recent work, however, suggests that alumina, the most typical product of aluminium reacting with the molecules naturally present in the atmosphere, might have a net warming effect through the absorption of longer-wavelength radiation.[56] Said differently, it reflects visible light but absorbs infrared. In any event, these geoengineering proposals have been scientifically controversial because of the identified and as yet unidentified risks, with controlled experiments encountering substantial opposition.[57] Mega-constellations will now begin this process as an uncontrolled experiment.[58] One could

53 Gerhard Drolshagen, Detlef Koschny, Sandra Drolshagen, Jana Kretschmer and Björn Poppe, 'Mass accumulation of earth from interplanetary dust, meteoroids, asteroids, and comets' (2017) 143 *Planetary and Space Science* 21.

54 Katharina Lodders, 'Solar system abundances of the elements', in Aruna Goswami and B Eswar Reddy, eds., *Principles and Perspectives in Cosmochemistry* (Berlin: Springer, 2010) 379.

55 David W Keith, 'Geoengineering the climate: History and prospect' (2000) 25 *Annual Review of Energy and the Environment* 245.

56 Martin Ross and Patti Sheaffer, 'Radiative forcing caused by rocket engine emissions' (2014) 2:4 *Earth's Future* 117.

57 Edward A Parson and David W Keith, 'End the deadlock on governance of geoengineering research' (2013) 339 *Science* 1278.

58 Debra Werner, 'Aerospace Corp. raises questions about pollutants produced during satellite and rocket reentry', *SpaceNews* (11 December 2020), online: https://spacenews.com/aerospace-agu-reentry-pollution.

imagine Elon Musk, whose concerns about both climate change and government interference are well known, being comfortable with the geoengineering aspect of Starlink, as well as with the unadvertised and unilateral manner in which it is being done. But again, the overall effects of alumina on the climate are not settled. There is also the not insignificant issue of Musk lacking any legitimacy or authority to make decisions for the rest of humanity.

Our calculations above are rough but bolstered by the more detailed work of Leonard Schulz and Karl-Heinz Glassmeier. They calculate the current annual influx into the atmosphere as *already* involving 0.89 kilotonne per year (kt/yr) of anthropogenic material, of which 0.09 kt/yr is injected in atomic form and 0.26 kt/yr as aerosols.[59] The rest of the material (0.54 kt/yr) reaches the surface, at least for the situations they explore. Of the injected elements, they find aluminium to be the most abundant (0.21 kt/yr or about 0.6 tonne per day).

Schulz and Glassmeier then calculate the influx in a 'Scenario 1' involving 19,400 satellites. Here, the annual anthropogenic influx increases to 2.7 kt/yr, with 1.6 kt/yr being injected into the atmosphere: 1.2 kt/yr as aerosols, 0.4 kt/yr in atomic form. Again, aluminium is the largest part of the injection (0.8 kt). They further calculate the influx in a 'Scenario 2' involving 75,000 satellites. Here, the annual anthropogenic mass influx increases to 8.1 kt/yr, with 4.9 kt/yr being injected into the atmosphere: 3.7 kt/yr as aerosols, 1.2 kt/yr in atomic form. Once again, aluminium is the largest part of the injection at 2.5 kt/yr or about seven tonnes per day. Making satellites fully demisable for safety reasons will tend to increase these values, creating an apparent trade-off between protecting people from being struck by Space objects, on the one hand, and climate impacts – which have their own safety implications – on the other.

Schulz and Glassmeier also warn that:

> There are many different possible effects on the atmosphere that are caused by an increased injection. Aerosols, respectively dust particles affect the stratosphere and mesosphere by acting as condensation nuclei contributing to the formation of high-altitude clouds. Additionally, they impact the chemistry in the upper atmosphere with possible effects on the D layer ion chemistry and the ozone layer. The large amount of aerosols injected by the ablation of anthropogenic material may also have an effect

[59] Leonard Schulz and Karl-Heinz Glassmeier 'On the anthropogenic and natural injection of matter into Earth's atmosphere' (2021) 67:3 *Advances in Space Research* 1002.

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> on Earth's climate as aerosols in the high-altitude atmosphere have a negative radiative forcing effect. Injected atoms partially ionize during ablation and thus contribute to the ionospheric layers. Furthermore, injected metal atoms form metal layers where the injected particles can have various different chemical reactions with other injected material, as well as atmosphere atoms and molecules.[60]

One thing is clear: the deposition of large amounts of aluminium into the upper atmosphere from re-entering mega-constellation satellites will affect the upper atmosphere, even if we do not yet know the scale of those impacts or understand all the complex interactions involved.

2.6.2 Rocket Launches

The act of putting satellites into Space can itself affect the atmosphere. While cumulative carbon dioxide emissions from rocket launches are currently small compared to other sources, CO_2 alone is a misleading metric. Black carbon produced by kerosene-fuelled rockets such as SpaceX's Falcon 9 and alumina particles produced by solid-fuelled rockets lead to instantaneous radiative forcing. As we discuss in Chapter 1 above with regard to Virgin Galactic's *SpaceShipTwo*, modelling of the cumulative effect of emissions from 1,000 annual launches of hydrocarbon-fuelled rockets found that, after one decade, the black carbon would result in radiative forcing comparable to that from all subsonic aviation.[61] Although 1,000 launches annually is ten times the current rate, the construction and renewal of multiple mega-constellations will require dramatic increases in launches. Current launches likely cause significant radiative forcing already.[62]

Rockets fuelled with liquid hydrogen do not produce black carbon but require larger tanks and therefore larger rockets, with solid-fuelled boosters often being used to increase payload capacity. SpaceX's new Starship, which could soon be launching 400 Starlink satellites at a time,[63] will be fuelled by methane, the combustion of which still produces

60 Ibid. at 1015 (citations omitted).

61 Martin Ross, Michael Mills and Darin Toohey, 'Potential climate impact of black carbon emitted by rockets' (2010) 37:24 *Geophysical Research Letters* L24810.

62 Martin Ross and Patti Sheaffer, 'Radiative forcing caused by rocket engine emissions' (2014) 2:4 *Earth's Future* 117.

63 Eric Ralph, 'SpaceX CEO Elon Musk says Starship will take over Starlink launches', *Teslarati* (11 June 2021), online: www.teslarati.com/spacex-starlink-launches-starship-takeover.

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black carbon that will contribute to radiative forcing, although it is expected to do so to a lesser extent than kerosene rockets. All liquid fuels will affect mesospheric cloud formation,[64] with potential impacts on the upper atmosphere.

Rockets threaten the ozone layer directly by depositing radicals into the stratosphere,[65] with solid-fuelled rockets causing the most damage per launch because of the hydrogen chloride and alumina they contain.[66] Amazon's recent purchase of Vulcan Centaur rockets to launch its Kuiper satellites poses a particular concern,[67] since each rocket will include multiple boosters,[68] each composed of 48,000 kg of solid fuel composed of hydroxyl-terminated polybutadiene mixed with aluminium.[69] As before, a single rocket has a negligible impact, but rocket launches in sufficient numbers could well be problematic. The radicals from rocket launches can also indirectly affect the ozone layer by altering the radiation balance and thus the temperature of the upper atmosphere, which in turn alters the reaction rates of ozone chemistry. A hotter stratosphere will tend to result in more ozone depletion.

Re-entering rockets, even reusable ones, require some consideration too. The intense heat of atmospheric re-entry will create radicals of NO_x (the generic scientific term for nitrogen oxide and nitrogen dioxide), a process that does not require any ablation from the rocket.[70] Radicals have an unpaired electron and are therefore very chemically reactive, and

64 JA Dallas, S. Raval, JP Alvarez Gaitan, S Saydam and AG Dempster, 'The environmental impact of emissions from space launches: A comprehensive review' (2020) 255 *Journal of Cleaner Production* 120209.

65 Ross, Mills and Toohey, op. cit.

66 Ibid.

67 United Launch Alliance, 'Amazon signs contract with United Launch Alliance for 38 Project Kuiper launches on Vulcan Centaur', 5 April 2022, online: www.ulalaunch.com/about/news/2022/04/05/amazon-signs-contract-with-united-launch-alliance-for-38-project-kuiper-launches-on-vulcan-centaur.

68 Sandra Erwin, 'Northrop Grumman expects a $2 billion order from ULA for solid rocket boosters', *SpaceNews* (28 April 2022), online: https://spacenews.com/northrop-grumman-expects-a-2-billion-order-from-ula-for-solid-rocket-boosters.

69 Northrop Grumman, GEM MOTOR SERIES, GEM 63XL, n.d., online: www.northropgrumman.com/wp-content/uploads/GEM-Motor-Series.pdf.

70 Erik JL Larson, Robert W Portmann, Karen H Rosenlof, David W Fahey, John S Daniel and Martin N Ross, 'Global atmospheric response to emissions from a proposed reusable space launch system' (2017) 5:1 *Earth's Future* 37; Seong-Hyeon Park, Javier Navarro Laboulais, Pénélope Leyland and Stefano Mischler, 'Re-entry survival analysis and ground risk assessment of space debris considering by-products generation' (2021) 179 *Acta Astronautica* 604-618.

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when formed or mixed into the stratosphere they will deplete ozone. So far, meteoroids account for most of the NO_x production from atmospheric entries, but near-future uses of Space could see this natural process, too, surpassed by anthropogenic production.

In short, when it comes to launching satellites and other spacecraft, there is no such thing as a 'green' rocket. At best, there is an environmental budget, so to speak, of launches that the Earth–Space system can handle before human activity will have a large disruptive effect. At worst, that threshold has already been reached.

2.7 Occupying Orbital Shells

From 1848 to 1855, the California Gold Rush brought 300,000 people to the newest part of the United States. The miners found themselves in a situation of relative lawlessness since Mexico's laws no longer applied to the territory and no new laws had yet been adopted to regulate access to gold. The result was an informal system of 'staking claims' whereby the first to begin mining a location could exclude others through his presence, though he would risk seeing his claim 'jumped' if he left, even briefly.[71] Later, when laws on gold mining were finally adopted, they perpetuated this system of 'free mining'. Not until 1866 and 1870 were shaft miners and placer miners respectively able to register and thus protect their claims.[72]

Today, the occupation and use of orbital shells appear to bear certain similarities. National regulators such as the FCC are assigning orbital shells to mega-constellations on a first-come–first-served basis, without assessing the effects on other states. These effects could include making any addition of further satellites to those shells too dangerous to contemplate. This de facto occupation of orbital shells may violate Article I of the 1967 Outer Space Treaty, which designates the exploration and use of Space as 'the province of all [hu]mankind' and 'free for exploration and use for all States without discrimination of any kind'. Article II further states, 'Outer space … is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.' Although regulators are not claiming sovereignty over orbital shells, allowing national companies to saturate them with

71 Donald J Pisani, '"I am resolved not to interfere, but permit all to work freely": The gold rush and American resource law' (Winter 1998–1999) 77:4 *California History* 123.
72 Ibid.

satellites could easily be considered appropriation by 'other means'. Lastly, Article IX requires that Space activities be conducted 'with due regard to the corresponding interests of all other States Parties to the Treaty'.[73]

Mega-constellation operators and their regulators could respond that they are exercising the right to explore and use Space without discrimination, that the use of an orbital shell is time-limited as a result of the licence, and that the satellites will be actively de-orbited.[74] They could also argue that some states have been using slots in geostationary orbit for decades, resulting in the de facto exclusion of others from any given slot without this being considered appropriation. However, the use of slots in geostationary orbit is mediated by the ITU, which does not play the same role in LEO.

Single states and operators should not be allowed to de facto occupy orbital shells by saturating them with satellites. Of course, what constitutes saturation will depend on technologies as well as different tolerances of risk. But the challenge of defining acceptable levels of use, while preserving access for others, is a reason for international governance and not a convincing argument against it. No single state is likely to handle this matter appropriately unless it co-ordinates with other spacefaring states, in the absence of which tragedies of the commons could easily arise. Institutionally, the easiest option may be to extend the ITU's role to LEO. Other options might include assigning the regulation of different orbital shells to different states, much like air traffic control in busy regions of international airspace, where reciprocity is the primary incentive for reasonable behaviour.[75] Even then, something like the International Civil Aviation Organization (ICAO), which co-ordinates international air traffic control, might be needed. The development of internationally accepted 'right-of-way' rules could also help, similar to the priority

[73] Outer Space Treaty, Art. IX.

[74] Christopher D Johnson, 'The legal status of megaLEO constellations and concerns about appropriation of large swaths of Earth orbit', in Joseph N Pelton and Scott Madry, eds., *Handbook of Small Satellites* (Cham: Springer, 2020) 1337.

[75] For example, air traffic control in the North Atlantic region is shared, through geographically assigned 'control areas' (CTAs), between the United States, Canada, the United Kingdom, Portugal, Denmark, Norway and Iceland, with the 'Reykjavik CTA' extending from 61°N to the North Pole and from 76°W to the Greenwich meridian. See Government of Iceland, 'About the Reykjavik Control Area: Oceanic Control Area' (2022), online: *Isavia* www.isavia.is/en/corporate/air-navigation/reykjavik-control-centre/reykjavik-control-area.

rules that have long guided ships and boats on the world's oceans,[76] though such rules only help to prevent imminent collisions and do not address the larger issue of congestion.

2.8 Radio Spectrum

Another 'rush' is occurring over radio spectrum. The ITU is involved in the allocation of frequencies to communications satellites. Under its binding instruments, namely the ITU 'Constitution and Convention',[77] as well as the subsidiary 'Radio Regulations',[78] states must treat frequencies as limited resources to which others have equitable access. At the same time, however, the ITU clearly sees the Radio Regulations as facilitative rather than constraining, writing that they 'enable the introduction of new applications of radiocommunication technology while ensuring the efficient use of radio-frequency spectrum, i.e. the operation of as many systems as possible, without interference.'[79]

Satellite companies are not party to these instruments and do not deal directly with the ITU. They apply for and obtain licences from their national regulator, which early in the planning process files a general description of the satellites with the ITU, including the frequencies and orbits they will use.[80] Under the Radio Regulations, a company is required to co-ordinate with any satellite system that might be affected

[76] Most of these rules were codified in the Convention on the International Regulations for Preventing Collisions at Sea, 20 October 1972, 1050 UNTS 16 (entered into force 15 July 1977). For a similar suggestion, see Neel V Patel, 'To solve space traffic woes, look to the high seas', *MIT Technology Review* (23 August 2021), online: www.technologyreview.com/2021/08/23/1032386/space-traffic-maritime-law-ruth-stilwell (reporting on the views of Ruth Stilwell).

[77] The most recent 1992 version of the Constitution and Convention is available at treaties.un.org/doc/Publication/UNTS/Volume%201825/volume-1825-I-31251-English.pdf. The Constitution and Convention is a treaty that, so far, has been ratified by 193 states, i.e. virtually all, including all of the spacefaring states. Constitution and Convention of the International Telecommunication Union, 22 December 1992, 1825–26 UNTS (entered into force 1 July 1994).

[78] The most recent version of the Radio Regulations is available at International Telecommunication Union (ITU), 'Radio Regulations' (2020), *ITU*, online: www.itu.int/pub/R-REG-RR-2020.

[79] International Telecommunication Union (ITU), 'Non-geostationary satellite systems' (June 2021), *ITU*, online: www.itu.int/en/mediacentre/backgrounders/Pages/Non-geostationary-satellite-systems.aspx.

[80] Tony Azzarelli, 'Obtaining landing licenses and permission to operate LEO constellations on a global basis', in Joseph N Pelton and Scott Madry, eds., *Handbook of Small Satellites* (Cham: Springer, 2020) 1287.

by its own planned system; indeed, such filings are identified as 'co-ordination requests'. Under the Rules of Procedure,[81] the two companies are then required to work with the ITU Radiocommunication Bureau to find a way for both systems to coexist. The highly technical character of these requirements and procedures reflects the advanced nature of the ITU as an international organisation, albeit one with a limited mandate – i.e. radio spectrum – that constrains its ability to address the fast-growing problems of physical congestion and debris.

In 2019, the ITU responded to the development of mega-constellations by adopting a 'milestone-based regulatory approach', whereby listing a 'non-geosynchronous (non-GSO) satellite system' in its Master International Frequency Register requires the deployment of certain percentages of the system by certain times.[82] Simply put, operators must deploy 10 per cent of the proposed satellites within two years 'of the end of the current regulatory period for bringing into use', 50 per cent within five years, and 100 percent within seven years. The idea is to ensure that the Register 'reasonably reflects the actual deployment of such non-GSO satellite systems in specific radio-frequency bands and services', to prevent 'radio-frequency spectrum warehousing', and to facilitate the 'coordination, notification and registration of frequency assignments'.[83] The hope is that operators will now delay having their national regulator file for radio spectrum until the designs, funding, manufacturing capability and a launch provider for their satellites are all in place.

This new approach has its problems, the first of which is that the two-, five-, and seven-year milestones come after 'the end of the current regulatory period for bringing into use' – a period that is itself seven years long and begins after the first satellite in the system has been launched. This means that a company can launch a single satellite as a 'placeholder' and immediately obtain spectrum sufficient for the entire system, even if it then does nothing for seven years. That spectrum is then unavailable to others. In fact, a company can place *any* satellite as a placeholder – i.e. not necessarily one that will become part of the system.

[81] International Telecommunication Union (ITU), 'Rules of Procedure' (2021), *ITU* , online: www.itu.int/pub/R-REG-ROP/en.

[82] International Telecommunication Union, press release, 'ITU World Radiocommunication Conference adopts new regulatory procedures for non-geostationary satellites' (20 November 2019), *ITU*, online: www.itu.int/en/mediacentre/Pages/2019-PR23.aspx.

[83] International Telecommunication Union (ITU), 'Non-geostationary satellite systems' (June 2021), *ITU*, online: www.itu.int/en/mediacentre/backgrounders/Pages/Non-geostationary-satellite-systems.aspx.

Third parties are already offering the placement of a temporary satellite as a contractable service.[84]

A second problem concerns the penalty for failing to meet the milestones, which is simply a reduction in the number of satellites approved by the ITU. As a result, companies might be incentivised to apply for spectrum for a much larger number of satellites than they intend ultimately to launch.

A third problem is that a company that obtains spectrum may sell all or part of it to another company during the seven-year 'bringing-into-force' period or at any point during the subsequent seven years of milestones. In other words, a company might seek and obtain spectrum for the sole purpose of selling it to the highest bidder. Or it might seek and obtain more spectrum than it needs, with a view to selling the excess.

These problems could all converge in Rwanda's 2021 filings for 327,320 satellites on behalf of Marvel Space Communications – more than 50 times the total number of satellites currently in operation. The satellites are to be placed in elliptical orbits with perigees around 280 kilometres and apogees around 600 kilometres. They will weigh about ten kilograms each, have antennas extending 3.5 metres, be connected optically to each other, and cost less than €10,000 each to manufacture. Achieving these design and cost parameters would be quite an accomplishment, especially for a country that does not yet have its own Space industry or launch capacity. All this suggests that Marvel Space Communications does not intend to meet the ITU milestones, and that something else is going on.

According to *The Telegraph*, the filing 'has triggered concern and speculation in the space industry. If the plans are approved by the UN [i.e. the ITU[85]], even if Rwanda never launches a satellite, it could sell its rights on. One source said the project was "strategically very serious . . . 300,000 satellites with minimal regulation up for sale to the highest bidder".'[86] Another report suggests that the plan is targeted at the European Commission, which may have as much as €6 billion available

[84] See e.g. Surrey Satellite Technology Ltd (SSTL), 'Bring-into-use satellites' (2022), *SSTL*, online: www.sstl.co.uk/what-we-do/bring-into-use-spacecraft.

[85] The ITU is a 'specialized agency' of the United Nations.

[86] Matthew Field, 'OneWeb founder wants to flood space with 300,000 satellites from Rwanda', *The Telegraph* (7 November 2021), online: www.telegraph.co.uk/technology/2021/11/07/oneweb-founder-wants-flood-space-300000-satellites-rwanda.

for a Europe-based mega-constellation.[87] Such a system could, presumably, help European Union (EU) states avoid becoming overly dependent on the mega-constellations currently under development in the UK, the USA and China. The fact that Rwanda made the initial filings with the ITU would pose no impediment to this becoming a European project.

Adding to the mystery, multiple reports suggest that the Rwandan filings were instigated by Greg Wyler,[88] who founded OneWeb and served as its CEO until 2020 , when the United Kingdom rescued the company from bankruptcy – reputedly under the impression that a broadband mega-constellation in LEO could serve as a global positioning system and thus replace the EU's medium Earth orbit-based Galileo system for post-Brexit Britain.[89] In 2020, Wyler's connections with the Rwandan government were the subject of investigative journalism by European Investigative Collaborations, a group of media organisations that includes *Der Spiegel*, *El Mundo*, *Le Soir*, *Politiken* and the Croatian newsmagazine *Nacional*, where an eyebrow-raising report on Wyler's activities was published.[90]

On a more positive note, satellites having such a relatively low mass, large surface area and low perigee would easily comply with the Inter-Agency Space Debris Coordination Committee (IADC) 25-year de-orbiting guideline without needing active de-orbiting technology.[91] But such an approach would mean that this de-orbiting process is largely uncontrolled. The satellites would still pose a collision risk, in part because of their very large number and therefore high cumulative cross-section. Moreover, if we take the ITU filings at face value, the orbits are elliptical rather than concentrated into orbital shells, and so each of these 327,320 satellites would cross the orbits of the International

[87] Michel Cabirol, 'Greg Wyler: Le come-back fracassant de l'enfant terrible du spatial', *La Tribune* (5 November 2021), online: www.latribune.fr/entreprises-finance/industrie/aeronautique-defense/greg-wyler-le-come-back-fracassant-de-l-enfant-terrible-du-spatial-895751.html.

[88] Field, op. cit.

[89] Alex Hern, 'We've bought the wrong satellites': UK tech gamble baffles experts', *The Guardian* (26 June 2020), online: www.theguardian.com/science/2020/jun/26/satellite-experts-oneweb-investment-uk-galileo-brexit.

[90] Blaž Zgaga and Yann Philippin, 'The offshore schemes of the American satellite king', *Nacional* (13 October 2020), online: www.nacional.hr/the-offshore-schemes-of-the-american-satellite-king.

[91] See Inter-Agency Space Debris Coordination Committee, 'IADC Space Debris Mitigation Guidelines' (March 2020), *NASA*, online: orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf.

Space Station, China's new Tiangong Space station, all of SpaceX's Starlink satellites and many other satellites as well. And they would each do so twice every 90 minutes or so!

It might be tempting to think of this Rwandan filing as being a special case. In some respects, it is, most obviously in the conspicuously large number of satellites involved. However, as noted above, the Kepler filings are also for more than 100,000 satellites, of which Kepler envisages only a small fraction will be its own satellites. The plan is for the rest of the constellations to be made up of third-party satellites with Kepler transmitters attached.[92] Regardless, this distinction of ownership should not distract us from the main issue, which is that these companies might actually use all or a large fraction of their filed orbits, adding literally hundreds of thousands of new satellites to LEO. And even these ambitious filings hide the full scale of what is occurring, since cumulative use must also be considered.

Between 1 January 2021 and 31 January 2022, over 1.5 million satellite slots were filed in the ITU's 'as-received' database.[93] Interpreting these numbers must be done cautiously, as many slots will be left unused and there are some duplications in the database. But even if only a small fraction of these systems succeed in moving from paper to orbit, it could fundamentally change orbital congestion. To put this in perspective, only about 0.4 per cent of the proposed satellite slots (for this one year alone) would need to be used to exceed the current number of active satellites. Moreover, some of the most highly sought-after orbital altitudes are between 500 and 600 kilometres, with potential congestion extending to 1,200 kilometres. Thus, interwoven with the larger and manoeuvrable mega-constellation satellites, including Starlink and OneWeb, will be a potentially much larger number of small, cheap, unmanoeuvrable satellites.

In summary, the ITU system for allocating spectrum to 'non-geosynchronous satellite systems' creates multiple incentives for companies to seek as much spectrum as possible as quickly as possible. The system feeds a gold-rush mentality, and, with it, the overpopulation of LEO with low-cost, mass-produced satellites, adding to the already high collision risks and thus the Space debris crisis. Moreover, some of these systems may well be abandoned after construction if one or more companies goes

[92] See discussion at *supra* note 13.

[93] These numbers are based directly on the ITU 'as-received' filings, compiled by Outer Space Institute junior fellows Andrew Falle and Ewan Wright.

bankrupt in what is likely to be a highly competitive market. And yet the ITU seems to be encouraging rather than seeking to slow these developments, or otherwise to steer them in a sustainable direction. Unless something changes, we may well see upwards of 100,000 satellites in LEO by 2030. This would constitute a massive change in the orbital environment, the consequences of which are not yet fully understood.

Fortunately, states will soon have an opportunity to expand the scope of the ITU's mandate so that it can address these new and growing challenges. The next World Radiocommunication Conference will begin in the United Arab Emirates in November 2023. Under Article 55 of the ITU Constitution, any member state may propose any amendment to that instrument.[94] If more than half of the delegations to the conference concur, the proposal will then be debated and put to a vote – with two-thirds support being required to make the change. The revised constitution is then opened for ratifications.

[94] Constitution and Convention of the International Telecommunication Union, 22 December 1992, 1825–26 UNTS (entered into force 1 July 1994), Art. 55.