Federation of Astronomical Societies

Editor: Michael Bryce

Newsletter

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President's Spot: Dr Paul A. Daniels FRAS

Just when we all thought we'd seen the last of the daily news being dominated by a single topic along comes the COVID-19 pandemic! With everyone having their own ideas on what's more important (family, the economy or their political career) the government's response has, in equal measure, enraged and saddened more than one segment of the population. Whilst it still remains to be seen whether the so-called 'doom merchants' of the Tory Brexit were right, this virus has been more amenable to scientific and mathematical analysis by experts (remember them Mr Gove?) working on the best information available to them at the time as the virus has slowly revealed its truly appalling nature.

On behalf of the FAS and its members, our deepest condolences to all those of you who've lost friends or loved ones. Even though we passed the first peak of new daily infections in April, we must all continue to take care. Most of those who've sheltered from the virus by social distancing and the lockdown will *still* be vulnerable to infection. The government are encouraging society to resume business-as-usual earlier than many think prudent and it's likely we're in for a second and, perhaps, third peak in the months ahead. Please, please, everyone, take all precautions to stay safe and be especially vigilant with those over 65.

On 30th January I took part in a meeting, hosted at the Royal Astronomical Society in Burlington House, about the potential threat to astronomy from the SpaceX Starlink and other megaconstellations of satellites and, at that meeting, I principally represented the FAS and the interests of amateur astronomers. As the meeting opened there were about 30 UK and European astronomers from UK Universities, ESA, ESO, STFC, UKSA and others and, later, we were joined by Patricia Cooper from SpaceX and Timothy Maclay from OneWeb.

Frankly, I was horrified by what I heard. Some Starlink satellites had already been launched and the media (local newspapers being the worst) were treating them as some sort of harmless celestial firework display! Those that have been launched are but the thin end of the wedge. Every astronomer at the meeting (and all those I've spoken with since) was concerned about the impact on ground-based optical and radio astronomy. I decided I had to write an article for the newsletter so that all our members could be told of the problems ahead.

I wrote the first version of this 'President's Spot' back in late March and my intention was to write a short article for the newsletter that would bring everyone up-to-speed on SpaceX's Starlink satellites. Well… it turns out that there's really *quite a lot* to say about Starlink and all of the issues that surround megaconstellations in general and the details were changing even as I was writing them! So, my apologies to those of you who'd hoped for a newsletter sooner but, *mea culpa*, it's taken longer than I thought it would; I felt it important to be thorough. Anyway, the full article is in this newsletter and I hope you all take the opportunity to read it – if I say so myself, I'm quite pleased with how it (eventually) turned out!

After those gloomy openings it seems a bit mundane and self-absorbed to mention that your FAS Council has decided to postpone the FAS 2020 Convention & AGM that would have been on 19th September 2020. We're currently considering different options: (i) postpone both Convention and AGM until April next year, (ii) postpone the Convention until April but look at an online AGM in September/October this year (probably *via* Zoom) or (iii) have an online AGM in September/October, abandon the idea of a 2020 Convention altogether and prepare

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instead for a meeting in September/October next year. There's even the option of moving *all* future AGMs to be online which would simplify the Conventions (no AGM stuffed in the middle) and, with our practise at using the technology, would give us the option of interim online EGMs if we needed them and, perhaps, we could also host quarterly online meetings with regional representatives such as SAGAS, NWGAS, *etc*.

Our next Council meeting is on 4th July so, if you've got any preferences, please let me know *via* president@fedastro.org.uk and, as always, keep watching the FAS website, www.fedastro.org.uk, for the latest status.

The guidance documents we've been writing are now starting to appear on the member's pages within Membermojo. Login the same way as you did for membership renewal and follow the links to download them. Remember to check back from time-to-time as new documents will appear and existing ones may be updated.

Despite stepping down as PLI Secretary last September, Tony Questa has been very supportive and generous with his time *this* year in helping to get the PLI sorted – many thanks for all your work Tony! We had no response from my appeal for a member with experience arranging group insurance to join the FAS Council so a Council member has stepped forward to allow Tony to relinquish that baton with handover support. Tony remains on the FAS Council as the SAGAS representative.

Unfortunately, James Hannan, who's been our Deputy Webmaster and is a busy teacher in 'real life' has decided that, with the workload at his school and the extra demands of working through the Coronavirus outbreak, he has to step back from his position on the FAS Council. James and Martin Baker (our Webmaster) have been the dynamic duo most involved with the changes to our website and getting the new Membermojo membership system up and running in time for this years' renewals – many thanks to James and I'm sure we all wish him the very best for the future! His departure means that we have a vacancy on the FAS Council to work as Deputy Webmaster with Martin. If anyone with the right background for the position of Deputy Webmaster is interested in joining the FAS Council then please contact me at president@fedastro.org.uk.

National Astronomy Week 2020 is currently scheduled to be held the week of 14th-22nd November 2020: there's a meeting of the planning committee on 16th June to discuss our response to the COVID-19 threat. If the dates don't change then we're hoping that most societies will try to organise something for the public that week even if it's only online – the theme for the week is the planet Mars. See the website at astronomyweek.org.uk for the latest news.

Finally (and another sad item this month!), I'm sure we all lament the passing of astronomy writer and broadcaster, Dr Heather Couper. Heather was an inspiration to many of us and some of us took up astronomy because of her enthusiasm. I've written to pass on our joint condolences to Nigel Henbest, her lifetime business partner, friend and companion.

Clear skies!

Dr Paul A Daniels FRAS
FAS President

***Image Left**: Dr Heather Couper 1951—2020. Heather presented the 1981 ITV children's series Heavens Above and, in 1984, became the first female president of the British Astronomical Association.*

Image Courtesy Hencoup Enterprises/PA MEDIA

The Megaconstellation Threat

Abstract

The plummeting cost of launching small satellites has led to several companies having ambitions to place tens of thousands of satellites into low Earth orbit with, potentially, as many as 100,000 in orbit over the next couple of decades. This article discusses three serious threats posed by the projected growth in these satellites:

(i) The Optical and Radio pollution of the sky with the potential to end almost all professional ground-based astronomy over the next two decades, seriously hamper amateur astronomers' contributions to astronomy and their enjoyment of the night sky and contamination of the pristine natural sky that is the birth right of all the people of the world and which has inspired young and old for generations.
(ii) The vastly increased number of objects in Earth orbit will lead to a rapid growth in space debris that could endanger the lives of astronauts, damage existing satellites and, in worst case, potentially deny humanity access to space for any purpose for decades.
(iii) The lower cost of getting to space makes it, the Moon and asteroids prime targets for the next era of commercial exploitation and the rush to occupy large volumes of near-Earth space by powerful companies, backed by powerful military nations, will raise international tensions.

Introduction to Megaconstellations

Never since the launch of Sputnik 1 in 1957 has it been cheaper to make and launch satellites. The declining cost of miniaturised, space-quality components and the ability for several small satellites with the same form factor to be launched at the same time has brought down the total cost-to-orbit.

It used to be the case that the manufacture of a single large satellite weighing 6,000–8,000 kilograms would cost between $100–400 million and cost up to the same amount again for it to be launched. At typically $10,000–$40,000 *per* kg these were prices that only governments and large corporations could afford and, on top of that, there were the ongoing annual costs of the infrastructure for tracking and monitoring as well as licensing fees for the satellite radio bands and bandwidth used to communicate with the tracking stations.

The development of miniaturised satellites (often referred to as *nanosatellites*) such as the Cubesat, has made access to satellite technology viable for a much wider range of companies. A very basic Cubesat may have a size of just (10x10x10) cm and cost only $20,000 whereas a larger Cubesat at (30x30x30) cm may still only cost about $500,000. NASA have started their Cubesat Launch Initiative (CSLI) and made the prospect of small company space research entirely feasible.

Over time more powerful launch platforms, such as SpaceX's Falcon 9 or Roscosmos' Proton M, capable of lifting larger payloads to orbit have arrived and brought down the *per* kilogram cost. The higher payload capacity coupled with the mass production of small cheaper satellites has led to the idea of constellations of multiple satellites being placed into orbit in one or more launches.

Exactly where the division between a constellation and megaconstellation lies is subjective but a megaconstellation can be taken to mean a thousand or more similar satellites working as part of a single system. It is the sheer size of the megaconstellations and the multiple threats they pose that is the subject of this article.

The most frequently-discussed threats are to ground-based radio and optical astronomical observations and also the risk of a rapid increase in space debris which, in an extreme case, could lead to the use of near-Earth space, as a resource for communications, living, research and commerce, being denied to us for several decades.

Another threat that's less often discussed is that megaconstellations, due to the large number of satellites involved, the complexity of their operation and the wide range of orbital altitudes, inclinations and ascending nodes, occupy a large volume of the near-Earth space 'real estate' and pose the major problem of how to share that space safely and fairly with other satellite operators (including those operating other megaconstellations). By international treaty, space is a 'global commons', not owned or controlled by any single nation and, as we move into an age of growing exploitation of space for potentially lucrative commercial purposes, there's the risk of raised international tensions if one company or country monopolises its use of those shared commons to the detriment of others and especially if they're prepared to use military power to support that monopoly.

Types of Orbit

Table 1 shows that geocentric orbits can be divided into a few basic categories.

Description	Abbr.	Altitude range (km)	Active Satellites[1]
High Earth Orbit	HEO	More than 35,786	15?
Geosynchronous Earth Orbit Geostationary Earth Orbit	GEO GSO	35,786	562
Medium Earth Orbit	MEO	2,000 to 35,786	132
Low Earth Orbit or Near Earth Orbit	LEO[2] NEO	Less than 2,000	1,468

Table 1 Orbit categories

1 Satellite count correct up to 30th September 2019, UCS Satellite Database [1]

2 Note that Very Low Earth Orbit (VLEO) is sometimes used but definitions vary. I have seen 'below 300 km', 'below 450 km' and 'below 500 km' which all have very different atmospheric drag considerations.

Traditionally, communications satellites have been launched into circular orbits at an altitude of 35,786 km above the Earth's surface. Those having an orbital plane parallel to Earth's equator are known as *geostationary* satellites while those inclined to the plane of the Earth's equator are termed *geosynchronous* satellites. The principal characteristic of both of these orbits, and what makes them useful, is that satellites in those orbits always stay above the same line of longitude on the Earth's surface because their orbital period exactly matches the Earth's rotation rate on its axis.

In the case of the inclined, geosynchronous, orbits the satellite stays above the assigned longitude but cycles North and South of the equator over the course of an orbit. If the orbit is slightly eccentric (elliptical) then, at perigee (closest point to the Earth), the satellite orbits slightly *faster* and is slightly in *advance* of the Earth's rotation so it moves to be above a slightly more easterly longitude and, conversely, at apogee (the furthest point), the satellite moves more slowly and so returns to a more westerly longitude. The effect of this is that the track of the satellite above the ground is a stretched figure-of-eight with the height of the '8' dependent on the orbital inclination and the width dependent on the orbital eccentricity.

The Earth isn't spherical but is flatter at the poles, an approximately *oblate spheroid*, with an equatorial diameter 43 km greater than it's polar diameter. This small bulge at the equator applies a torque or twisting force to inclined orbits and, in the same way that twisting the axis of a spinning bicycle wheel creates gyroscopic forces at right-angles to that axis, the torque due to Earth's bulge causes the points where the satellite's orbit crosses the equator (the ascending and descending nodes) to precess in an easterly or westerly direction at a rate dependent on how close it is to the bulge (*i.e.* the altitude of the satellite) and the inclination of the orbit.

Communications satellites placed in GEO have the advantage that they can see about 40% of the Earth's surface, can 'see' more ground stations and so fewer such satellites are needed for global coverage. There are two principal disadvantages: (a) they are further away and so the satellites have to use more power to communicate which means they're generally bigger and more expensive (as well as more expensive to launch into GEO) and (b) the distance to the satellite and repeater delays on the ground introduce a typical but unavoidable 600 milliseconds or more round-trip delay in communications signals – which is simply irritating for audio or video conversations but a more significant issue for high-speed digital communication between computer systems.

It's common for some satellites to be placed in an MEO with an altitude of 20,200 km where they have a 12 hr orbital period. There's also a highly-elliptical, highly-inclined, 12 hr period type of orbit (commonly called a *Molniya* orbit) where the satellite, typically used for surveillance, moves at its slowest at apogee above a 'continent of interest'.

The focus in recent years has shifted more towards use of LEOs and, in particular, placement of satellite constellations in LEOs. The ability to manufacture miniature satellites with smaller solar panels and low power requirements and, consequently, less available power for transmitting signals means that these satellites have to be closer to the Earth's surface. However, a satellite at 550 km altitude can only see about 4% of the Earth's surface so there have to be many more satellites working together (a *constellation*) to provide global coverage.

Satellites in a LEO have a much shorter round-trip time delay for communication signals (25–35 ms) providing the potential for low-latency, high-speed, global internet access. Since the signals travel most of the distance in air and vacuum (refractive index ≧1) the delays can actually be shorter than on the ground when using glass optic fibre (refractive index ~1.5) where the speed of light is about two-thirds of its speed in a vacuum.

Proposed Megaconstellations

In addition to those in Table 2, Virgin Orbit are planning to launch bespoke payloads from Boeing 747s using an air-launch system mounted on a spare engine pylon already present under the wings of all 747s (used to transport engines). The system is in the late stages of development but the first flight test on 25th May 2020 failed. Virgin Orbit claim that their mobile launch platforms make it: easier to deploy small satellites and satellite constellations into a wide range of inclinations, able to launch more safely over the ocean, not be reliant on a spaceport for launches and able to change the launch location to avoid bad weather. One of their spaceports will be based at Cornwall Airport Newquay in the UK[3].

Company	Project Name	No. of Planned Satellites	Orbit Altitude (km)	Radio Bands
SpaceX (USA)	Starlink	16,518 13,500 9,084 2,825	325–350 480–500 515–580 1,110–1,325	V K_u & K_a K_u & K_a
Amazon[1] (USA)	Kuiper	784 1,296 1,156	590 610 630	K_a
Samsung (KOR)		4,700	2,000	?
Boeing (USA)		3,116	1,030	V, C & K_a
Sat Revolution (USA)		1,024	350	R, G B, NIR
Commsat (CHI)		800	600	Optical
Roscosmos (RU)		640	870	L – X
Astro Tech (IND)		600	1,400	C
Telesat (CAN)		512	~1,000	K_a
Others…		>2,000	550–1,500	
Facebook[2] (USA)	*Athena*	*10k, 40k,100k?*	*550*	*E*
OneWeb[3] (UK)		*716* *47,844*	*1,200* *1,200*	K_u & K_a
Lynk[4] (USA)		*Thousands?*	*500*	
TOTAL	(Excluding OneWeb, Facebook & Lynk)	**>58,600**		

Table 2 Proposed Megaconstellations

1 The Amazon satellites will be in 98 orbital planes and will be designed to de-orbit themselves after 10 years (autonomously if necessary).

2 The numbers of satellites to be launched by Facebook's new subsidiary company, PointView Tech LLC, isn't known but, given the size and history of the parent company, it will probably have ambitions to match the order of size of SpaceX's Starlink constellation.

3 On 27th March 2020 OneWeb filed for Chapter 11 bankruptcy with several thousand creditors. A Chapter 11 bankruptcy gives a company a chance to remain in business, debt-free with a different management structure, so it's possible the satellite launches may proceed as planned under new ownership. Just two months later, 26th May 2020, OneWeb filed an application with the FCC for a change in their first application to reduce their proposed number of satellites from 720 to 716 and make some minor orbital changes but also, in a second phase, applied to launch 47,844 satellites[2]. All of these new satellites would be at 1,200 km altitude with two sets of satellites each of 720 satellites for each of 32 planes at 40° and 55° inclination and a further set of 49 satellites in each of 36 planes at 87.9° inclination. It's widely considered that this application may be to boost the sale value of OneWeb rather than a serious intent to launch those satellites.

4 The Lynk system will allow unmodified Android mobile phones to communicate directly with the satellite.

So far only Elon Musk's SpaceX company has placed a significant number of constellation satellites in orbit and it may be that other operators are watching to see how SpaceX cope with the technical, financial, legal and political hurdles before they commit investment. However, the political, commercial and legislative advantage of SpaceX's early entry into the megaconstellation business has given them a potentially unassailable lead that their competitors may find hard to usurp.

The rest of this article will principally discuss the proposed Starlink megaconstellation but bear in mind that the total number of all such satellites *could* eventually grow to be several times greater than the size of the constellations proposed by SpaceX.

The Starlink Project

Planned Satellites

SpaceX announced the formation of their satellite network project in January 2015 and, in November 2016, they filed an application with the USA's Federal Communications Commission (FCC) for a "non-geostationary orbit (NGSO) satellite system in the Fixed-Satellite Service using the K_u and K_a frequency bands" allowing them to place 4,425 satellites in orbits at between 1,160 km and 1,325 km altitude with full-deployment by the end of 2024.

In March 2017 an application was made for a further 7,518 satellites to be placed into Very Low Earth Orbits (VLEOs) at between just 335 km to 346 km altitude and to operate using the hitherto under-used V-band. This application was eventually granted in November 2018 with the condition that half of the fleet of satellites would have to be deployed in six years and fully deployed in nine years to satisfy the terms of the FCC spectrum allocation license assignment. The same month SpaceX asked for a change in the earlier granted license to permit and prioritise 1,584 of the higher-orbit satellites to instead be placed in a new 550 km orbit in 24 separate

Phase	No. of Satellites	Altitude (km)	Inclination (°)	No. of Planes
1[1]	1,584	550	53	72
	1,600	1,110	53.8	32
	400	1,130	74	8
	375	1,275	81	5
	450	1,325	70	6
Total	4,409			
2[2]	2,493	335.9	42	
	2,478	340.8	48	
	2,547	345.6	53	
Total	7,518			
3	1,500	580.0	97.7	?
	1,500	539.7	85	
	1,500	532.0	80	
	1,500	524.7	75	
	1,500	517.8	70	
	4,500	498.8	53	
	4,500	488.4	40	
	4,500	482.8	30	
	3,000	345.6	53	
	3,000	334.4	40	
	3,000	328.3	30	
Total	≤ 30,000			
TOTAL	**≤ 41,927**			

Table 3 Summary of approved and proposed Starlink satellites

1 Phase 1 must be at least half-completed by 29th March 2024 and fully completed by 29th March 2027.

2 Phase 2 must be at least half-completed by November 2024 and fully completed by November 2027.

orbital planes (66 satellites *per* plane) different only in the longitude of their ascending nodes (known as a Walker Constellation) – this request was approved by the FCC in April 2019.

In September 2019 another request was made to the FCC to change the 550 km orbits to use 72 planes (instead of 24) with only 22 satellites *per* plane in order to obtain better coverage although the number of satellites would remain the same – this was approved in December 2019.

In October 2019 the FCC, on behalf of SpaceX, filed 20 separate requests to the ITU of 1,500 satellites each for permission to launch a total of an *additional* 30,000 satellites into VLEO & LEO orbits between 328 km and 580 km (see Table 4). At the time of writing this hasn't yet been approved and it may be that not all of the filed requests will be approved or, if approved, not fully taken up by SpaceX. It has been suggested that SpaceX will need to launch all or most of them to provide competitive broadband speeds. There may also be an element of SpaceX trying to gain permission to reserve a set of VLEO/LEO orbits in an attempt to make it difficult for possible competitors, *e.g.* OneWeb, to make use of the same near-Earth space.

Assuming that all ~42,000 satellites shown in Table 3 are approved and launched (*i.e.* completion of Phase 3), Figure 1 shows the number of satellites *per* 100 deg^2 (square degrees) of sky at the zenith from the point of view of a ground-based observer. However, as a cautionary note, not all of those satellites may be visible as the elevation of the Sun below the horizon will affect which are illuminated and which are in the Earth's shadow and, for those that *are* illuminated but are in the higher orbits, they may be faint.

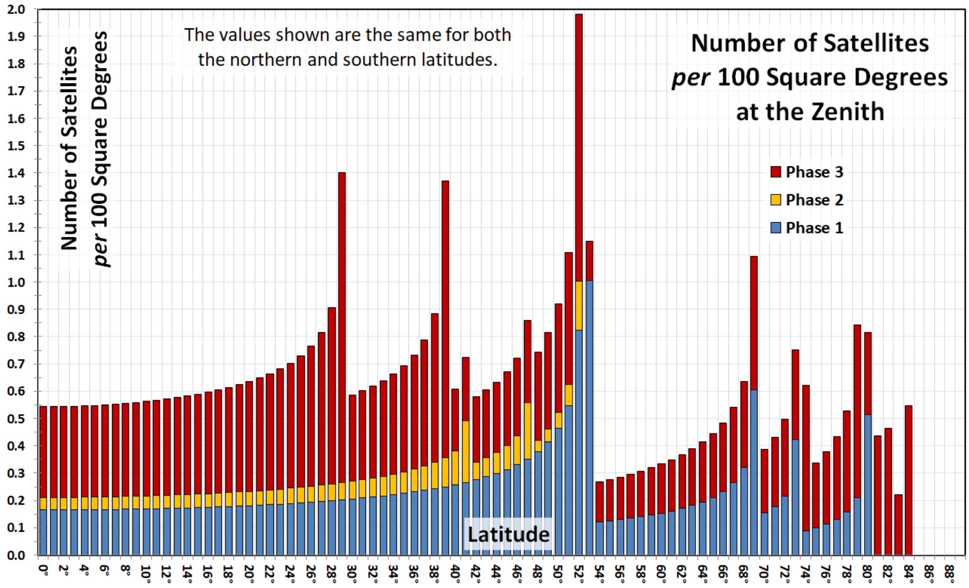

Figure 1 Using the orbit data shown in Table 3, the number of satellites *per* deg^2 at the zenith *per* 1° interval in latitude.

A moment's consideration reveals that an observer further north than a specified latitude on the graph and looking southwards would be looking through the swarm of satellites above that latitude (and similarly for further south and looking northwards). For example, with 1° of latitude corresponding to a distance of about 111 km on the Earth's surface, satellites in a 550 km altitude orbit overhead at latitude 52°N would be at an approximate elevation of 45° looking southwards from a latitude of 57°N. Therefore the peaks in the graph at latitudes 29–30°, 39–40° and 52–53° suggest problems for observers at latitudes up to a few degrees further north and observing celestial objects towards the south (and *vice versa*).

To get an idea of what 100 deg^2 looks like, the Square of Pegasus has an area of 207.4 deg^2, the 'bowl' of Ursa Major's dipper has an area of 43.7 deg^2, the quadrangles of Orion above and below the belt total 81.8 deg^2 and the Solar disk occupies about 0.2 deg^2. So, for example, at 52°N (including up to 53°N) and after Phase 3 is complete there would be approximately two satellites *per* 100 deg^2 at the zenith. So at latitude 52–53°N and looking up towards the zenith, the Square of Pegasus would, on average, contain about four satellites within the square and the bowl of Ursa Major would contain about one satellite.

Again, note that Figure 1 is simply showing the density of satellites at the zenith for a given latitude but the number *actually* visible will depend on (i) the elevation of the Sun and the consequent angle of the Earth's shadow, (ii) the amount of light reflected from the satellite (if illuminated) and (iii) its distance from the observer. Those observing in the infra-red may still detect a satellite after it passes into the Earth's shadow because the satellite may continue to emit some IR radiation even as it cools down in the shadow. Of course, the issues of illumination/cooling are irrelevant to radio astronomers as it's the satellite's own emissions that are the problem not the effects of sunlight.

The Satellites and Ground Stations

There are currently two versions of Starlink satellite, v0.9 and v1.0. Table 5 lists and compares the features of each:

Starlink v0.9	Starlink v1.0
Mass of 227 kg	Mass of 260 kg
Use of the K_u-band	Use of both K_u- and K_a-bands
95% destroyed on re-entry	100% destroyed on re-entry
Common to both	
Hall-effect thrusters using Krypton gas for orbit raising, station keeping and de-orbit	
Multiple, high-speed, beam-steerable phased-array antennae	
A single solar panel array of approximately 1 m x 9 m size	
A star-tracker navigation system for precise pointing	
Use of US DoD data to actively adjust orbits to avoid collisions with debris and other satellites	

Table 5 Characteristics and comparison of Starlink satellites

The current versions don't communicate satellite-to-satellite but a new version planned for later this year will use four optical inter-satellite laser links to improve connectivity and reduce latency. Without the optical link a satellite must currently be within line-of-sight of a ground station.

The Starlink satellite deployment will also have to be accompanied by construction of a very large number of ground stations as the low altitude produces a small beam 'footprint' on the Earth's surface so SpaceX, on 1st February 2019 and through sister company SpaceX Services Inc., filed an application to the FCC for a blanket license to operate up to 1,000,000 fixed ground stations within the USA. The ground station will use advanced phased-array beam-forming and digital processing technologies to steer highly directional antenna beams that will track the satellites.

Starlink Launches

On 22nd February 2018 SpaceX launched two test satellites, Tintin A and Tintin B; these were placed in a 514 km altitude orbit with a 97.5° inclination but were MicroSat-2a and -2b satellites for testing equipment rather than the design that would eventually be used.

All Starlink production design (v0.9 and v1.0) launches to-date have been on a Falcon 9 launch vehicle with re-usable boosters simultaneously carrying 60 Starlink satellites into an interim very low altitude orbit of just 290 km with a 53° inclination. At this altitude the atmospheric density, though very low, is the satellite's most significant perturbing force such that the flat solar panel array needs to face downwards to reduce the atmospheric drag in the direction of travel along the orbit.

The strength of the drag force is strongly dependent on the level of solar activity; high activity 'swells' the atmosphere and increases the drag. A 2016 preliminary investigation by Khalil & Samwel[4] concluded that the effect on an LEO satellite's orbital elements is generally about three orders of magnitude greater during solar maximum than solar minimum and the range of variation is even greater for very low altitude (VLEO) satellites.

The purpose of the interim low-altitude orbit is to test there's reliable command communication with the satellite and then to test its on-board systems. At that altitude the lifetime of an unresponsive satellite is about three months or, if the satellite *can* be commanded but has faults in its other systems, it can be forcibly de-orbited using the satellite's own Krypton Hall-effect ion thruster.

Following testing, if the satellite is found to be serviceable it's then gradually boosted to its target orbit altitude. Compared to the short, relatively powerful 'blasts' of chemical thrusters, ion thrusters produce a very low but continuous thrust so the transfer to a higher orbit takes about 45 days. NORAD tracking data has shown that SpaceX are raising the orbit of some of the satellites at 10 km *per* day and others at 5 km *per* day[5].

Starting with the Starlink #0 mission on 24th May 2019, SpaceX began launching v0.9 of the Starlink production design with an eventual target orbit altitude of 440–550 km. These are non-operational satellites, *i.e.* they won't be a part of the final network service, and are being used for test purposes including the ability to de-orbit. Five weeks after the launch three of the satellites were unresponsive and will passively de-orbit due to atmospheric drag and another two were intentionally de-orbited to test the de-orbiting process.

With the Starlink #1 to Starlink #8 missions on 11th November 2019, 7th January, 29th January, 17th February, 18th March, 23rd April, 3rd June and 13th June 2020, there have been eight more launches each of 60 v1.0 Starlink satellites totalling 540 satellites launched and 538 currently in orbit. Starlink mission #9 will launch on 23rd June 2020 with plans for subsequent launches at 2-4 week intervals: all of these will each launch another 60 satellites and have a target altitude of 550 km.

Once SpaceX have completed development of their new Starship launcher the launch rate can increase; Gwynne Shotwell, SpaceX President and COO, has said that it will be able to launch 400 satellites at a time[6].

Collision and Explosion Avoidance

One obvious concern with placing so many satellites in orbit at the same altitude is ensuring that they don't collide with each other, with other satellites or with space debris. Similarly precautions have to be taken to ensure that no part of the satellite might explode, *e.g.* battery, electronic or pressurised gas components, as any collision or explosion might either directly cause an increase in the amount of orbital debris or cause the satellite to become 'adrift' and/or unresponsive and so represent a threat of future collision.

ESA Estimates		NASA Estimates	
>10 cm	34,000	Bigger than a softball	20,000
1 cm to 10 cm	900,000	Bigger than a marble	500,000
1 mm to 1 cm	128,000,000	Too small to track	>100,000,000

Table 6 ESA and NASA estimates of space debris

The European Space Agency (ESA) has estimated that, as of January 2019, there were about 5,000 satellites in orbit of which about 1,950 are still working and the other 3,050 are now 'dead' space debris. They also estimate that there have been over 500 break-ups, explosions, collisions or other events resulting in fragmentation. Such catastrophic events would likely have generated many fragments travelling at speeds of several kilometres *per second* at which speed the kinetic energy carried by even small fragments (2–3 mm) could be comparable to that of an armour-piercing bullet!

Dr Manfred Wittig of MEW-Aerospace UG[7] estimates that the kinetic energy of a 1 kg Cubesat travelling at 7 km/s is equivalent to 24.5 MJ or 6 kg of TNT (4.184 MJ *per* tonne) which is more than enough to ensure its complete fragmentation.

Failure to restrict or reduce the amount of orbital debris threatens the sustainability of long-term use of space. The United Nation's International Committee on the Peaceful Uses of Outer Space (COPUOS) sets guidelines and makes recommendations to national organisations. Normally they meet annually and the 2019 meeting made investigation into the challenges of satellite constellations a high priority with a number of delegates expressing concern over the significantly heightened space debris risk. At that meeting they made recommendations that all spacecraft should be able to de-orbit after at most 25 years – something that was already a part of NASA's end-of-mission de-orbiting policy. Unfortunately, the 17–26th June 2020 meeting, its 63rd session, to be held in Vienna, Austria, when more substantive reports and discussions regarding constellations would have been presented, has had to be postponed (probably until late-August 2020) due to the COVID-19 threat.

SpaceX has a collaboration with the US-led multinational Combined Space Operations Center (CSpOC) organisation which, before 18th July 2018, was known as the Joint Space Operations Center, JSpOC. It's responsible for US coordination with its allies, commercial and other civilian space organisations and, in this case, it provides space tracking data to the Starlink satellites so that they, *in principle*, have the ability to autonomously modify their path to avoid a collision. SpaceX also have links to NASA and the US Air Force Center for Space Situational Awareness.

However, having the ability to avoid other satellites doesn't guarantee that SpaceX will make the manoeuvre to do so. On 2nd September 2019 ESA were advised by US military sources that the probability of a collision between the Starlink 44 satellite and their Aeolus weather observation satellite was greater than 1-in-1,000 which is about ten times riskier than that for which ESA consider an avoidance manoeuvre necessary. Due to a failure in the way that SpaceX handled communications from ESA, it meant that ESA were forced to slightly alter Aeolus's orbit to reduce the risk of collision to an acceptable level.

On that occasion it was for a manual change to an orbit but Starlink satellites are designed to autonomously avoid collisions; this has an immediate safety benefit but only if any change in orbit is promptly and accurately communicated to other spacecraft operators. This autonomous change in orbit also makes it harder for ground-based astronomers to plan telescope observations around the timing and position of the satellites in the sky.

SpaceX have estimated they'll need to perform collision avoidance no more than about once *per* year but this is very likely to be a underestimate by a factor of 5 or more.

De-orbiting

With concerns for the growth and persistence of space debris in Earth orbit and the consequent increased risk of collisions, SpaceX were required to provide the FCC with details[8] of how they planned to remove defunct satellites from orbit once their mission life was complete (after the designed useful lifetime of 5 to 7 years) or if they failed in-service.

There were already plans to de-orbit non-working satellites from the interim 290 km altitude but the FCC needed to know what would happen to those already in their operational orbit and, in particular, for those at higher altitudes.

In Casey Handmer's Blog[9] on space debris he makes the following comment:

> "Roughly speaking, for each additional 100 km in altitude, orbital debris lasts for 10 times as long before being eaten by the atmosphere. This process concatenates, so that a piece of debris may spend 1000 years falling from 700 km to 600 km, 100 years falling from 600 km to 500 km, 10 years falling from 500 km to 400 km, 1 year falling from 400 km to 300 km, and only a few weeks falling from there to burning up."

This comment highlights the approximately inverse-exponential nature of the drag *versus* altitude relationship but the actual time-scale also depends on the *cross-sectional-area*-to-*mass* ratio of the object in orbit with high cross-section, low-mass objects being more effectively slowed by drag forces than small cross-section, high-mass objects.

SpaceX have said that a 'dead' Starlink satellite in a 550 km orbit will de-orbit solely due to drag forces within 5 years and, notwithstanding the strict implication of the numbers in Casey Handmer's quote above, those satellites in higher orbits could take somewhere between '*many* decades' and 'thousands of years' to re-enter if left entirely to atmospheric drag – clearly active de-orbiting is required.

The end-of-mission de-orbiting plan submitted to the FCC[10] consists of:

1. Using all remaining fuel to lower the orbital perigee to at most 300 km but maintaining an apogee of 550 km. SpaceX have said that this will take "several weeks" and will retain enough fuel to allow it to continue to manoeuvre to avoid other satellites such as the ISS.
2. Reorienting the satellite to maximise the cross-sectional area in the direction of orbit so that the effects of atmospheric drag are maximised.
3. De-spinning reaction wheels, draining batteries and powering down.
4. In a matter of weeks or a few months the satellite will re-enter the atmosphere and be destroyed.

In this manner, SpaceX are confident that satellites still functioning at the end of their useful mission can be de-orbited within one year.

However, none of the above answers the problem of how they do that with a satellite that has become unresponsive. It's a requirement that all satellites are sufficiently protected against micrometeoroid or small debris impacts to prevent the systems required to complete a de-orbit from failing but such precautions aren't perfect.

There is also the consideration of how to manage manoeuvring to avoid other satellites during the de-orbiting phase and, especially, once the fuel has been depleted. For example, the ISS orbits at between 408–410 km altitude with an orbital inclination of 51.64° and, once the perigee altitude of a de-orbiting Starlink satellite falls below the ISS' altitude range, the regular orbit-crossing could pose a potential threat to the ISS and its crew. The ISS' orbital inclination is close to the proposed Starlink orbital inclination of 53° for the 1,584 satellites at 550 km altitude and 53.8° for the 1,600 satellites at 1,100 km altitude; this has the potential for a large number of near-parallel convergences of path and a heightened risk of collision.

The Hubble Space Telescope (HST) orbits at altitudes between 537.0 km and 540.9 km with an inclination of 28.47°. Since the proposed 550 km Starlink orbits lie only 9.1 to 13 km outside this altitude range they may represent a risk to the HST and the satellites could potentially interfere with some of the HST's imaging. Also, if there were a space debris impact event causing fragmentation of a Starlink satellite, this could scatter debris into the path of the HST.

Replacement Satellites

The mission lifetime of a Starlink satellite is designed to be about 5 to 7 years. With current plans for about 12,000 Starlink satellites in orbit that means approximately 150–200 of them will reach the end of their mission every month. If the total number eventually rises to 42,000 that will mean approximately 500–700 of them will need to be replaced every month.

The number of satellites re-entering each month and the number of launches to just maintain the number of satellites has a serious impact:

- Pollution from the one or two Starship launch vehicles *every* month (more if the Falcon 9 continues to be used)
- Squandered natural resources such as the rare-earth metals commonly used in electronics
- Pollution from the re-entering satellites
- Starlink satellites that start in the interim 290 km check-out orbit take up to 45 days to transfer to a higher orbit during which time they are significantly brighter than when in-service. If there are 200 new satellites being launched each month that means up to 400 fairly bright satellites in the sky with the potential to affect astronomical observations even *if* those in their target orbits do not.
- Following the end of their useful mission Starlink satellites will transfer to a low orbit prior to re-entry. During this time of transition, and depending on the time to transfer to the lower orbit, there will be 200 or more satellites brighter than those at their target orbit.
- SpaceX have said that, during the service time of the satellites, they will endeavour to orient the solar panels for minimum interference with ground-based observations. However, during the de-orbit phase the solar panels will be aligned to maximise atmospheric drag and this may not be optimal for reducing reflections.
- If 200 Starlink satellites will be re-entering the Earth's atmosphere each month the bright streaks they leave across the sky will similarly have the potential to affect astronomical observations.

Kessler Syndrome

In 1978 Donald J. Kessler and Burton G. Cour-Palais published a, perhaps prescient, research paper[11] that considered the potential fate of near-Earth space if the problems of space debris weren't addressed. This fate, termed the 'Kessler Syndrome', was given wider public exposure in the popular 2013 film, *Gravity*, when a Russian missile destroyed a defunct satellite and the cascade of fragments generated by that explosion catastrophically destroyed both a Space Shuttle and the ISS.

In their paper Kessler and Cour-Palais, informed by Kessler's earlier work on fragmentation in the asteroid belt, considered the ultimate result if collisions or explosions produced enough hypervelocity fragments (~10 km/s) that the probability of successive collisions was heightened enough for the process to become exponentially out of control in a 'chain-reaction' effect. As well as components breaking up due to collision they also considered the ejection of molten particles from the high-energy impacts which would then solidify and contribute to the particles in Earth-orbit; the analysis included whether these particles would either collide with other objects and increase the flux of particles or whether atmospheric drag, forcing re-entry, would decrease their number before they became a problem.

Their conclusions were that the growth in the number of satellites at that time may cause a self-perpetuating growth in space debris by the year 2000. This didn't happen but the *very* much larger number of satellites in constellations now being proposed makes this a resurrected threat. They predicted that, once collisional breakup started and even without new satellites being added, the debris flux near Earth would grow and potentially result in a "ring system, similar to those around Saturn or Uranus". They suggested that mitigation of this effect required a reduction in the number of large, non-operational satellites as well as satellite designs that reduced the risk of break-up or explosion.

To a large extent the risk of runaway space debris from VLEO satellites is diminished by atmospheric drag causing that debris to re-enter. However, this assumes that the rate at which new debris is created in those orbits (due to, for example, explosions, collisions, failures or meteoroid impacts) is small in comparison with the rate at which debris re-enters. Even if that were to be the case, a collision or other fragmentation event that caused a large 'spike' in the amount of LEO debris, particularly above 1,000 km, could cause significant damage for decades before eventual re-entry of the debris quenched the risk.

In an extreme case of the Kessler Syndrome the grimly ironic situation could be reached where it would be impossible to launch replacement satellites fast enough to compensate for the rate of failure due to collisions with space debris. Such a scenario would also prevent or, at least, severely restrict all human endeavours in space for decades because it would become increasingly difficult to find a safe and reliable launch window. The risk to astronauts' lives would increase and the insurance premiums on both those lives and hardware could become a major factor in the cost of using space.

Radio bands to be used

Even if you have satellite manufacturing and launcher capabilities of your own it isn't as simple as just 'build it and launch it'. Every satellite placed in orbit around Earth has to be communicated with and so needs to be allocated one or more frequency bands by the International Telecommunications Union (ITU) – a specialist branch of the UN, formed as the International Telegraph Union in 1865 and now the oldest global international organisation. Other issues within the ITU's remit are regulation of radio interference, standardisation (formerly as CCITT) and development of new methods and technologies.

The ITU works on behalf of national governments and their agencies (such as the Federal Communications Commission (FCC) in the United States) to coordinate the allocation of communication frequencies; such allocations may be to Primary or Secondary services. The high-priority Primary services must be protected against radio interference *from* Secondary services and Secondary services have no claim against interference *by* Primary services.

Radio astronomy is considered to be a high-priority scientific venture and the most significant molecular frequencies, such as H_2O and OH, are reserved with primary status. However, there are many bands commonly used in radio astronomy that aren't exclusively reserved (secondary status) and the usual solution is to create Radio-Quiet Zones (RQZs) around radio telescopes (*e.g.* the SKA) to mitigate the effects of ground-based interference. Options for satellites passing over RQZs are to temporarily stop transmitting or, for satellites with beam-steering technology (such as Starlink), for the beam to be diverted away from the RQZ.

Even with the above options for mitigating the problem of radio interference, existing telecommunication satellites in geostationary orbits and passing aircraft already represent a significant problem for radio-astronomical observations.

Starlink has been allocated the V (40–75 GHz), K_u (12–18 GHz) and K_a (27–40 GHz) bands which are very close to those commonly used in radio astronomy. In particular, there are concerns that SpaceX should not use the lower 250 MHz of the allocated 10.7 to 12.75 GHz band for downlinks as out-of-band emissions could interfere with the adjacent 10.6 to 10.7 GHz band used for radio astronomy.

Transmissions from satellites passing through the high-gain beam of a radio telescope may, in some circumstances, be powerful enough to damage the extremely sensitive radio receiver system used to amplify the received signal.

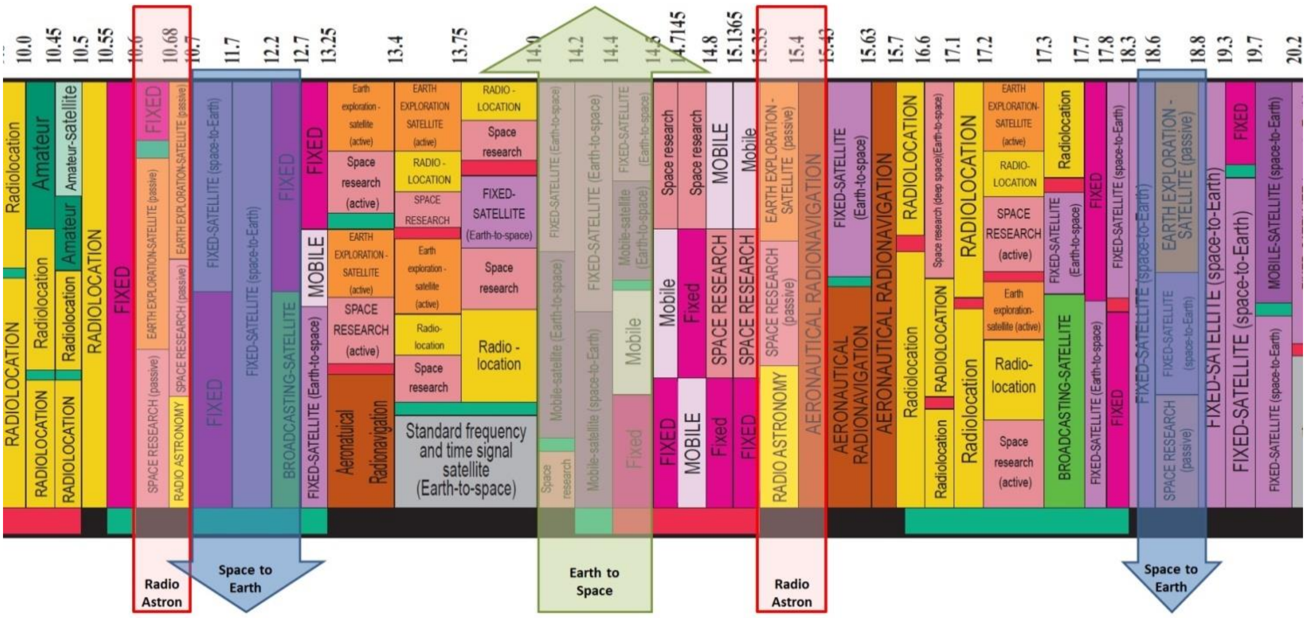

Figure 2 Starlink allocated frequencies versus Radio astronomy frequencies

The *intended* transmissions from Starlink satellites clearly could present a problem to radio astronomy but there are also concerns about possible *unintended* transmissions from satellites in the L-band produced simply by the digital noise generated by the satellite's own electronics. Normally these emissions are rigorously controlled to EMC military standards but some radio astronomy antennae have such high gains (65–80 dBi) that a satellite passing through the beam of that antenna could produce a detectable signal sufficient to be considered radio interference. At the moment these sources of interference can be avoided by accounting in advance for the overhead passage of known satellites. However, with the very large number of fast-moving Starlink and other LEO constellation satellites occupying the sky, the opportunities for such avoidance become almost vanishingly small.

Shadow geometry

In an attempt to quantify the potential problem for optical astronomers both Hainaut & Williams[12] and Galozzi *et al* [13] have considered the Sun-Earth-Observer-Satellite geometry.

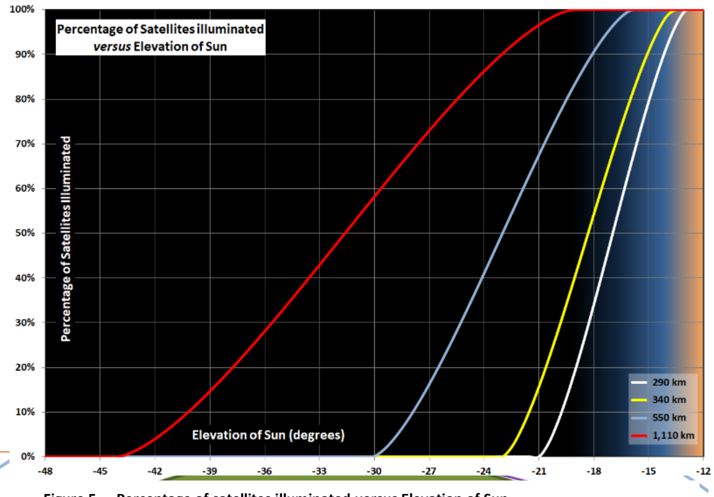

Figure 5 Percentage of satellites illuminated *versus* Elevation of Sun

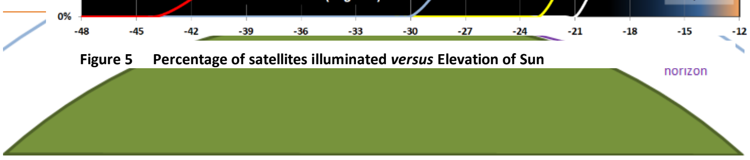

Figure 3 Problem satellites at 1,000 km altitude: Sun 15° below horizon

Figure 3 is drawn approximately to scale and shows satellites at an orbital altitude of 1,000 km and the Sun at 15° below the horizon (chosen as a typical time for astronomical observations to start). During dusk the eastern sky is shadowed, no satellites there will be illuminated and so will be unable to reflect sunlight to an observer.

During *early* dusk, when the Sun is *only just* below the western horizon, any illuminated, low-elevation satellites in the East are further away and also dimmed by the thickness of the atmosphere. The same dimming *would* be true for satellites low in the western or north-western sky (in the northern hemisphere) for some time after sunset *except for* the fact that satellites there are much more likely to have glancing reflections off their flat surfaces ('glinting') and be significantly brighter. The discussion above is also true for dawn with East/eastern and West/western swapped over.

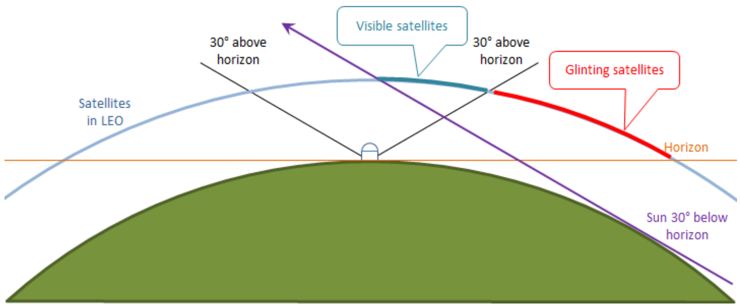

Figure 4 Problem satellites at 1,000 km altitude: Sun 30° below horizon

It's assumed that observations are only being made above altitudes of 30° or more (*i.e.* within 60° of the zenith) so that the cone bounded by those lines encloses a sky area of about 10,313 deg^2. That direction was chosen as the air-mass, the amount of atmosphere along that line, is 2 which is the upper limit for most professional astronomical observations. Adopting a conservative satellite density value of 0.5 satellites *per* hundred deg^2 from Figure 1 this corresponds to approximately 52 satellites present within the cone. Note that, in Figure 3, all of the satellites in between the 30° boundaries are illuminated.

In Figure 4 the Sun is now shown at 30° below the horizon. The shadowed part of the sky is now much larger and about half of the satellite orbits between the 30° lines are now shadowed. Note that, if the altitude of the satellite orbits were lower, fewer of them would be illuminated and at the 550 km altitude almost none of them would be illuminated once the Sun was more than 30° below the horizon.

Altitude	Elevation
290 km	-33.9°
340 km	-36.6°
550 km	-46.0°
1,100 km	-63.0°

Table 7 Solar elevation below which no satellites of the given altitude that are above the horizon are illuminated.

Figure 5 shows the percentage of satellites within the cone above 30° elevation for 290, 340, 550 & 1,000 km altitude orbits that are illuminated *versus* the elevation of the Sun. The graph then has to be interpreted along with the observer's latitude when considering the potential number of illuminated satellites in Summer and Winter.

Figure 6 shows a cross-section of the celestial sphere with the horizon shaded green, the observer in Birmingham (latitude 52.5°N) at *O* and projections of the Tropics of Cancer and Capricorn (red-dashed and blue-dashed lines respectively) onto the celestial sphere. These tropics mark the extreme North and South declination (±23.4°) of the Sun on the celestial sphere at the solstices; the calculations on the right-hand side (colour-coded to match the arrows) show that, at midnight on the Summer solstice, the Sun is only 14.1° below the northern horizon and, on the Winter solstice, 60.9° below the northern horizon.

From the graph in Figure 5 these elevations correspond, for a 340 km orbit, to 90% of satellites being illuminated at midnight in midsummer and no satellites being illuminated at midnight in midwinter.

So far we've considered the orbits and the proportion of satellites that may be illuminated as a function of observer latitude and the Sun's elevation. However, this doesn't say anything about how *visible* the satellites are even when illuminated.

Visibility

Hainaut & Williams[12] recognised that some parts of the satellite's body diffuse incident light but other parts (such as the solar panel array) are complex, multi-faceted components, with varying reflectance from different facets. The attitude of the satellite relative to the Sun and observer therefore determines whether the observer sees a mirrored flash of sunlight or just a dull reflection. They simplified their approach to modelling the apparent brightness of the satellites by assuming them to be simple spheres with a single albedo and reflecting light according to a basic Lambertian reflection model that takes only the geometric cross-section, albedo (reflectivity) and solar phase angle into account.

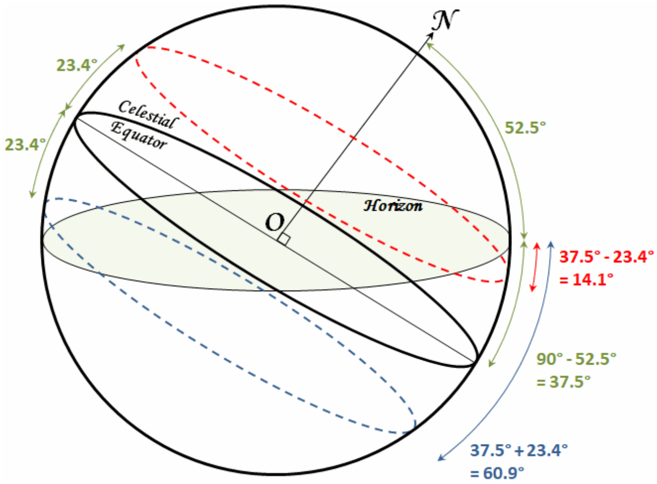

Figure 6 Calculation for 52.5°N to show the angle of the Sun below the northern horizon at midnight at the solstices

The Starlink satellites don't have a regular shape and their albedo is unknown so, for their model, they used a representative size of 1 m radius and the same albedo, 0.25, as attributed to NOAA satellites. This produced visual magnitudes in the range 4.2 to 5.9 mag for satellites at 550 km (those in lower orbits would be brighter, those higher would be fainter). They concluded that only the Starlink satellites illuminated in the lowest orbits would be visible to the naked eye with those in higher orbits estimated to be as faint as ~8 mag.

An analysis of the brightness due to the irregular shape of the satellites, and including the reflections from the solar panels, has also been carried out by Anthony Mallama[14] who found an *absolute* visual magnitude (magnitude at 1,000 km distance) for the satellites to be 4.1 ± 0.1 mag and whose model concluded that, though the orientation and geometry of the satellites has led to them often being unusually bright compared with other satellites, there are some circumstances where solar illumination only on the upward side renders them invisible from the ground.

In his paper, Jonathan McDowell[15] noted that amateur and professional astronomers, seeing the interim orbit 'string of pearls' of just-deployed satellites, reported visual magnitudes of 1 to 3 mag *per* satellite. Once the solar panel array had been re-oriented they dimmed by 'several mag' and then faded a further 0.5 mag as the satellites were raised to their 550 km target orbit. At that altitude they were still visible (~5 mag) to the naked eye (magnitude 6 or brighter) from dark sky sites.

SpaceX have experimented with a dark coating on one satellite, Starlink-1130 (commonly referred to as DarkSat). Analysis by Tregloan-Reed *et al* [16] measured Starlink-1130 and Starlink-1113's brightnesses against comparison stars: the measured brightness of Starlink-1130 (DarkSat) was found to be 6.21 ± 0.04 mag and that of Starlink-1113 5.33 ± 0.05 mag. The result of the dark coating appears to have only dimmed the satellite's reflected light to about 55% ± 4.8% of that from uncoated satellites (*i.e.* 0.88 ± 0.05 mag fainter).

One of the consequences of darkening the satellites to absorb more light is that their operating temperature will be higher, possibly with consequences for the satellite's longevity or reliability, and they will radiate more in the infra-red (IR). Possibly as a consequence of this heating, SpaceX have advised that the dark coating approach to reducing the brightness of the satellites is to be abandoned in favour of dynamically adjusting the attitude of the satellite solar panel array to reduce the chance that glinting from them will affect astronomical observations and also fitting an adjustable black 'visor' to reduce the light incident on the satellite body[17]. Neither approach is likely to be adequate to completely render the satellites invisible for astronomical purposes. Any visor, if dark coated to avoid reflections, will warm in sunlight and may become an IR source. One satellite with a visor (*aka* VisorSat) was launched on 3rd June 2020 and SpaceX have said that, if effective, all satellites launched after that date will have a visor.

Transits and Astrophotography

Mostly it will be the satellites as points of light against a dark sky that will be of concern but there are also occasions when a satellite will transit another astronomical object under observation. Table 8 shows the distance, angular diameter and angular velocity of satellites for a range of orbit altitudes and elevations above the horizon; it's assumed the satellite has a diameter of 9 m which is the approximate size of a Starlink satellite's solar panel array.

From Table 8 we can see that the disk of the Sun at an elevation of 50° would be transited in about one second by a satellite at 550 km altitude (30.9 arcmin/s) so that, with typical photographic exposure times being just 1/30 to 1/500 second, it's unlikely (but not impossible) that a satellite could be caught in the image. The diameter of a solar convection cell (a granule) is approximately 1,500 km which, seen from Earth, subtends an angle of approximately 2" so the satellite, at 2.7" diameter, would appear slightly larger than a typical granule.

	Distance (km)				Angular Diameter (arcsec)				Angular Velocity (arcmin/s)[1]			
Altitude (km)	290	340	550	1,100	290	340	550	1,100	290	340	550	1,100
Elevation (°)												
0	1,944.0	2,109.0	2,703.8	3,902.1	1.0	0.9	0.7	0.5	4.0–13.7	3.9–12.6	3.8–9.7	3.4–6.4
10	1,130.5	1,275.2	1,815.1	2,949.6	1.6	1.5	1.0	0.6	8.0–23.5	7.5–20.8	6.2–14.4	4.8–8.5
20	741.2	853.5	1,293.6	2,290.2	2.5	2.2	1.4	0.8	16.1–35.9	14.4–31.0	10.5–20.2	6.9–11.0
30	546.3	634.9	992.8	1,851.7	3.4	2.9	1.9	1.0	28.0–48.7	24.5–41.7	16.5–26.3	9.7–13.6
40	438.0	511.2	812.1	1,561.4	4.2	3.6	2.3	1.2	42.2–60.7	36.5–51.8	23.6–32.1	12.9–16.1
50	372.9	436.2	698.9	1,368.1	5.0	4.3	2.7	1.4	57.2–71.3	49.0–60.8	30.9–37.3	16.0–18.4
60	332.5	389.3	626.9	1,240.4	5.6	4.8	3.0	1.5	71.0–80.0	60.6–68.1	37.6–41.6	18.8–20.2
70	307.7	360.6	582.2	1,159.4	6.0	5.1	3.2	1.6	82.1–86.4	69.9–73.5	42.9–44.8	21.0–21.7
80	294.3	345.0	557.8	1,114.4	6.3	5.4	3.3	1.7	89.2–90.4	75.9–76.8	46.3–46.8	22.4–22.5
90	290.0	340.0	550.0	1,100.0	6.4	5.5	3.4	1.7	91.7	77.9	47.4	22.8

Table 8 Distance, angular diameter and angular velocity of a 9 m diameter satellite at various altitudes and elevations above the horizon.

1 The first number in the angular velocity range is for the satellite moving along the meridian (the line joining the southern compass point on the horizon to the zenith) at the elevation in the left-hand column. The second number in the range is for when the satellite is moving perpendicularly to the meridian at that elevation. At 90° elevation (the zenith) the observer is in the satellite's orbital plane so both have the same value.

The disk of the Full Moon is about the same diameter as the Sun's so the time taken for a satellite to transit will be about the same. Exposure times of, typically, 1/125 second also mean that it's unlikely a transit will be caught. However, if caught, the angular size of the satellite is comparable to that of craters ~5.0 km in diameter at the lunar distance and is also about the same apparent size as the central peak of craters like Copernicus or Tycho.

The Sun and Moon are the main celestial objects with a surface brightness significantly greater than might be expected for a satellite to show as a silhouette. However, it's possible that transits of other objects could occur when the satellite is in the Earth's shadow. Given that the angular diameter of Jupiter is between about 30" and 47" we can see that, in the unlikely event that a satellite did transit the disk of Jupiter, it would cover about 6–9% of the diameter but the transit time would only be ~20 milliseconds.

Long imaging exposures are more of an issue than transits. A simple formula can be used to estimate the number of satellites that could pass through the field of view in a given time:

$$N = \rho_{sat} \times FOV \times t_{exposure} \times \frac{\theta}{60}$$

Instrument	FOV (deg^2)	N
Typical 10x50 binoculars	8.0	12.0
Typical amateur telescope	1.0	1.5
Hale 200", Large Format Camera	0.16	0.24
Pan-STARRS	7.0	10.5
Vera Rubin Telescope (LSST)	9.62	14.43

Table 9 Some instrument FOVs in square degrees (see text for an explanation of N)

Where N is the number of satellites passing through the field of view, ρ_{sat} is the density of satellites in the sky in satellites *per* deg^2, FOV is the instrument's field of view in deg^2, $t_{exposure}$ is the duration of the exposure in seconds and θ is the angular velocity in arcmin/s. It's also assumed that all satellites making up the ρ_{sat} value are illuminated in the part of the sky under observation.

As an example, Table 9 contains some instruments and their FOVs (in deg^2), assumes a typical ρ_{sat} (from Figure 1) of 0.5 satellites *per* hundred deg^2 and uses a typical angular velocity for the satellites of 30 arcmin/s for a 10 minute exposure to calculate the listed value of N.

Exposure times for the Vera Rubin Telescope are more typically about 15 s[18][19] each so, in practise, N falls to 0.36 (about one satellite *per* three exposures) though, with the wide range of possible values for ρ_{sat} and θ depending on observer latitude and observing direction, N could be anywhere between about 0.1 and 5.

Who's affected? Everyone!

The discussions in the preceding part of this article introduced the principle problems posed by the megaconstellations to astronomy and the future use of space and, in particular, the SpaceX Starlink constellation which has already become the dominant threat.

If the OneWeb megaconstellation is eventually completed with the proposed 47,844 satellites[2] as well as those being considered by Amazon, Samsung, Facebook and others then, depending on the orbits chosen, the possible pollution could be 2–3 times greater than that from Starlink alone and the space debris risk from multiple, independently-operated megaconstellations multiplicatively greater unless an effective international space-traffic management authority is created (none is currently planned).

In this section I discuss how the Starlink satellites will impact professional and amateur astronomers and the stargazing public.

Professional Astronomy

Professional astronomical observations usually involve larger, more complex, more expensive, more sensitive and more varied observing equipment than that used by amateurs and, if the research being conducted is to have any integrity, particular attention must be paid throughout to *quantitative* analytical detail using robust, thoroughly-tested algorithms working on the best data available.

Optical Astronomy

The work by Hainaut & Williams[12] analysed the impact of Starlink's initial ~12,000 satellites (Phase 1 & 2) on the work of the ESO observatories and found that it's generally low to moderate for the older or smaller instruments with traditionally small fields of view. However, the wide-field camera telescopes such as the Vera C. Rubin Telescope (VRT, formerly known as the Large Synoptic Survey Telescope or LSST) and Pan-STARRS telescope, will be seriously compromised.

The VRT[20] has an 8.4 m diameter primary mirror and images onto the world's largest camera which contains a highly-sensitive, 3.2 gigapixel CCD sensor giving the telescope a potential limiting magnitude of 24th mag. Due for operational use from late 2022, it's been designed to take a pair of images of the same part of the sky every 15 s and complete a survey of the sky in 3 days before starting a new survey scan all over again. After its nominal 10 years of operation every part of the sky will have had 800 images taken of it. The 20,000 GB of data *per* day streaming from the telescope will be analysed in real-time and, if any change is found, an automatic alert will be broadcast within 60 s. The VRT is considered to be especially relevant for the detection of new near-Earth asteroids and comets, follow-up observation of reported transient events such as Gamma Ray Bursts and Fast Radio Bursts, Exoplanet transits and optical verification following a gravitational wave event detected by LIGO or VIRGO.

The VRT's CCD sensor is *very* sensitive and any bright satellites caught on an exposure will saturate the sensor's pixels along its track. In addition to this, and inherent in the design and physics of CCD sensors, any very bright light source will not only saturate the pixels in that part of the image and for several pixels either side but, due to cross-talk within the sensor, will also generate faint 'ghost' artefacts elsewhere in the image. In extreme cases a bright source may be severe enough that, even when the sensor is reset and cleared ready for the next image, a temporary afterimage may remain where it was previously saturated.

Astronomers at the Vera Rubin Observatory (VRO) have concluded that complex post-processing of the images may be able to remove the artefacts but, in some cases, it may only be possible to remove the effects of the satellite track by comparing each pair of images; in some cases this will not be a practical solution. Their calculations suggest that, if the satellites can be dimmed to be fainter than 7th mag, saturation will not occur and post-processing may be more effective.

In an interview with Business Insider on 9th March 2020, Elon Musk said[21] "I'm confident that we will not cause any impact whatsoever in astronomical discoveries, zero. That's my prediction. We'll take corrective action if it's above zero.". Further, when addressing the National Academy of Sciences Astro2020 decadal survey hearing on 27th April 2020, Musk said[22] "Our objectives, generally, are to make the satellites invisible to the naked eye within a week, and to minimize the impact on astronomy, especially so that we do not saturate observatory detectors and inhibit discoveries". As evidence of Musk's stated commitment to avoid damaging ground-based astronomy, SpaceX have been working closely with the VRO to try and work out ways to mitigate the effects of the satellite tracks and dimming the satellites to satisfy the needs of the VRT is considered by them to be the high-bar they must clear.

Currently (before any evaluation of VisorSat) attempts to dim the satellites sufficiently have failed and the VRO have said[19] that about 30% of the images are likely to contain at least one satellite. Hopefully the addition of visors to the satellite and adopting an optimal attitude in orbit will bring the brightness down below 7th mag.

Another proposed mitigation for professional observatories is the publication and frequent updating of satellite ephemerides so that observatories can avoid observing in parts of the sky that will have a satellite passing through them during the exposure. Again, this may be a solution for short exposures that can 'dodge' the satellites or the smaller FOV instruments but is hardly workable for long exposures or wide-field camera telescopes.

Starlink may not be the only problem: if not properly darkened, the proposed 47,844 OneWeb satellites launched to an altitude of 1,200 km would remain in sunlight for far longer and may represent a greater level of pollution for the VRT and similar telescopes.

The American Astronomical Society (AAS) have also been in close discussion with SpaceX and, at the Press Conference of their 236th meeting[23] on 3rd June 2020, presentations were given by Patrick Seitzer and James Lowenthal on the progress with SpaceX. Lowenthal reported the results[24] of a seven-question survey of professional observatories around the world. Notably, when asked whether a solution that satisfied the VRT would also resolve potential problems for their observatory, 6 of the 15 that replied to the question said "No"; SpaceX cannot, therefore, assume that the VRT high-bar is the *only* bar to be cleared. Also, most of the survey questions were based on the effects of the initial 1,584 Phase 1 satellites to be placed at 550 km altitude but, when asked how a constellation that was 10x larger would impact them, 12 of the 16 that replied said that would represent 'critical failure' for their observatory ranging from 10% or more loss of data, instruments becoming obsolete or the observatory being completely unable to function. If this is the case then one might conclude that multiple megaconstellations, launched by different operators and totalling up to 100,000 satellites, will be the end of most ground-based optical astronomy unless action is taken to restrict their number – even with all the careful post-processing available, there is a limit to what can be achieved when the burden of multiple mitigations grows to asphyxiate access to our skies.

Radio Astronomy

Much of the work done for the optical community has considered the brightness of the illuminated satellites and, apart from transits, has been able to discount those in the Earth's shadow. This is not the case for radio astronomy as the satellites are broadcasting downwards to ground stations and user terminals as well as emitting weaker signals from their own electronic circuitry regardless of whether they're in sunlight or not. It has been estimated that, in the radio astronomy context, the intensity of the signal from a Starlink satellite downlink is 14x greater than the glint from a specularly reflecting satellite to an optical observer.

Radio transmitters would ideally broadcast at a single, well-defined frequency and, for point-to-point communications, into a single, narrow beam. This would concentrate all of the energy of the transmissions into the frequency being monitored by the receivers and only in the direction towards the intended receiver. Usually, however, the transmissions leak out into *sidebands*, adjacent frequencies, and *sidelobes*, weaker mini-beams close to the main central beam – this is a design limitation of all antennae.

Clearly, to provide an internet service Starlink satellites have to broadcast to several points on the ground below and so have a number of steerable beams for the downlink. SpaceX have said that they will avoid beams being directed into RQZs (Radio Quiet Zones) that surround some radio astronomy installations (such as the SKA sites) but not all such sites are protected by an RQZ.

Radio astronomy has a few protected frequencies, the hydrogen emission lines for example, but many of the molecular line frequencies (*e.g.* the methanol maser line at rest frequency 12.178 GHz) are <u>not</u> protected by the ITU. In addition, a receding object being observed may have a sufficiently high redshift that lines may be shifted from a protected part of the spectrum into an unprotected part of the spectrum or *vice versa*. One frequency band of concern is the radio astronomy protected 10.6–10.7 GHz band with the assigned Starlink downlink frequency in the adjacent 10.7–12.75 GHz band. SpaceX have recognised the need for strong attenuation of the signal in the sidebands as well as agreeing to constrain their use to 10.95–12.75 GHz and so leaving a 250 MHz margin between their band and the radio astronomy band. On top of the concerns for the downlink transmissions is the possible Radio Frequency Interference (RFI) from ground stations and user-terminals.

Amateur Astronomy

Amateur astronomical observations are mostly limited to binocular or small-to-moderate aperture instruments and, in a few rare cases, more exotic tools such as spectrographs. Although some amateurs have professional-quality CCD cameras the majority of those who image use standard off-the-shelf cameras with their high-quality, but less-sensitive, CMOS sensors. Generally amateurs don't observe with the goal of producing research papers and so the requirement for quantitative rigour is low: they observe the sky for the joy of it and images are processed to achieve qualitative visual impact rather than as a source for scientific analysis.

However, while there are a few thousand professional astronomers around the world there are hundreds of thousands of amateurs. The contribution that amateur astronomers make to astronomy is also significant; partly because of the sheer number of 'eyes on the sky' (unconstrained by observing budgets and telescope schedules) but also because amateurs, with their passion for general observing, frequently have a more intimate knowledge of the sky. Amateurs have often been the ones spotting a new comet or supernova and bringing it to public attention or simply doing the 'grunt work' observing meteors or long lists of variable stars and feeding a steady stream of observations into centralised databases operated by, for example, the UK's British Astronomical Association (BAA).

Optical Astronomy

The most common wide-field instruments used by amateurs are binoculars but, though it's possible to point a camera through a binocular's eyepiece with the right clamp for the camera, binoculars are not usually used for imaging. A visual observing session through binoculars might see the dot of an occasional constellation satellite taking a few seconds to pass through the FOV but the interruption would be just fleetingly irritating.

Most off-the-shelf cameras used by astroimagers, such as those from Canon, Nikon and Olympus, use a CMOS sensor. CMOS is cheaper and produces a slightly noisier image but doesn't suffer from the kind of cross-talk that causes ghost artefacts in CCD sensors and saturated pixels do not bloom to affect nearby pixels to the same extent. The use of specialist CMOS cameras is also growing; uncooled 16 megapixel cameras are available for a few hundred pounds and those using a Peltier effect device to cool the sensor to about 40–45 °C below ambient temperature to reduce noise sell for one to three thousand pounds.

Visual observations through most telescopes, with their typically 1° FOV, will be less affected than binoculars. However, long-exposure deep sky images might typically encounter one satellite trail for every five minutes or so of exposure. Amateur astronomers have long been used to the process of 'stacking' a set of selected good-quality images to reduce noise and it's likely that this technique (or a reasonably ingenious extension of it) will also serve to remove the unwanted satellite trails and, perhaps, more effectively than professional images due to the more common use of CMOS.

Radio Astronomy

Compared with amateur optical astronomers there are relatively few amateur radio astronomers.

Andrew Lutley of the UK Radio Astronomy Association put the author in touch with John Cook, Director of the UK's BAA Radio Section whose own work is with the VLF detection of solar flares as sudden ionospheric disturbances which is an area that he says won't be affected by Starlink.

John sought comments from their section members and there was a reply from some who are involved with the observation of meteors *via* the Fireball Recovery and InterPlanetary Observation Network (FRIPON). FRIPON uses the GRAVES VHF radar located near Broye-lès-Pesmes, France, as a source and they report echoes from some of the new Starlink satellites still in low orbits. With careful processing the echoes are clearly distinguishable from those of meteors so the impact on their observations is also minimal.

The Public

Anyone who simply admires the night sky and its twinkling array or who has, perhaps, a small telescope or pair of binoculars and turns them on the heavens every month or so is a potential astronomer. Youngsters are inspired by the vastness of space, the Moon and the planets. So, how is the casual observer going to be affected?

The Starlink satellites launched into in the interim 290 km orbit are the brightest, reaching magnitudes between 2 and 4. These will fade to be between about 4th mag and limiting visual magnitude for the unaided eye but will still be visible in a pair of binoculars or a small telescope. Currently there are 478 satellites in orbit and there are already very many reports from the public of the bright strings of satellites. SpaceX are aiming to have launched over 1,000 by the end of this year and already have permission to launch a total of nearly 12,000 so the satellites are likely to continue to be noticed.

The 45 days or so it takes for the satellites to transit to their higher target orbit and the several weeks it takes for them to return to low orbit prior to end-of-mission re-entry will probably be the time when the satellites are at their brightest. Once the full complement of 42,000 satellites is in place their 5-year lifetime means a replacement rate of about 500 satellites *per* month or more. For at least some of this time (Musk said one week[22]) the satellites will be visible to the naked eye so, counting those ascending and fading and also those descending and brightening, there could be 250 satellites or more with naked eye brightness (though not all visible at the same time). In addition, 500 or so satellite re-entries *per* month somewhere around the globe will leave bright re-entry trails across the sky.

Space Law and Options for Legal Challenge

As with all big projects, there are supporters and detractors: those who see the megaconstellations as a good sign of progress towards humans becoming space users, the interested space/satellite community and promoters of global internet access are very much in favour of the megaconstellations and what they will bring but, with few exceptions, the astronomical community are outraged by the intrusion into their working domain and the pollution of what is seen by many as the common natural inheritance of all the people on Earth.

So, what are the options, what are the relevant international laws, which court will hear any disputed cases, who will police those laws and how could they be enforced?

Firstly, there are no *global* laws regarding the use of space – only international treaties where the specific signatories agree to be bound by international law. Seeing the potential for a clash in the use of space, the UN asked the US and Soviet Union to each submit draft treaties on the peaceful use of space. After months of negotiation to reconcile these two drafts and then endorsement of the resulting document by the UN General Assembly at the end of 1966, the treaty was opened for signatories on 27th January 1967 and, after being ratified by the US, Soviet Union, UK and sixty other countries, the non-armament *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, (1967)* (*aka* the 'The Outer Space Treaty (1967)') came into effect and is still in effect today[25].

Under the terms of the 1967 treaty (and extensions in 1968 and 1972) the signatory nations agreed:

(i) Prohibition of nuclear or other weapons of mass destruction in orbit or on the Moon or other bodies in space.
(ii) No claims for sovereignty over space, the Moon or other celestial bodies.
(iii) The exploration and use of outer space would be carried out for the benefit "of all mankind".
(iv) Nations are responsible for their own activities in space.
(v) Nations are liable for any damage caused by objects launched into space from their territory.
(vi) Nations are bound to assist astronauts in distress.
(vii) Nations' space installations and vehicles shall be reciprocally open to other countries for inspection.
(viii) That all parties agree to conduct outer-space activities openly and in accordance with international law.

Note that item (ii) doesn't prohibit or limit the exploitation of space, the Moon or other bodies as a resource but, in establishing space as a 'global commons', does prevent any nation(s) from claiming a region of space, any orbit(s) or any part of the lunar or other bodies' surface as their own. The Outer Space Treaty (1967) was formulated during the cold-war/space-race era: Sputnik was only 10 years earlier, the use of space was still a novelty being explored and launch and satellite technology were in a fledgling state. We've been in space now for 63 years applying the rules of a treaty that's nearly 53 years old and, though a valuable landmark agreement between nations back then is now starting to show its age – the treaty didn't foresee the extent to which space might be used for military purposes, didn't consider the legalities of asteroid or lunar-surface mining and didn't anticipate the rise of megaconstellations.

On 3rd December 1976 seven equatorial countries (Columbia, Republic of Congo, Ecuador, Indonesia, Kenya, Uganda and Zaire) adopted the "*Declaration of the First Meeting of Equatorial Countries*" (*aka* 'The Bogotá Declaration')[26]. Brazil signed the declaration as an observer and Gabon and Somalia joined later. The declaration attempted to claim, for each of those countries, sovereignty over the portions of the geostationary orbit above each respective country. In effect, any geostationary satellites placed in those segments of the orbit would be subject to the laws of the equatorial country below. Their principle objection was that the wealthy developed countries could eventually dominate the use of the geostationary orbit and, by the time any poorer developing countries could afford to place their own satellite in geosynchronous orbit, there would be no 'slots' in that orbit above their own country or, even worse, no slots available at all. The Bogotá Declaration was a direct challenge to Article II of the Outer Space Treaty (1967) (item (ii) above) and, because it was only relevant for a few uninfluential states, it was almost universally ignored. The signatory countries have tried several times since then to get the declaration internationally recognised but without success.

In 1979 the "*Agreement Governing the Activities of States on the Moon and Other Celestial Bodies*" (*aka* 'The Moon Treaty/Agreement (1979)') attempted to reserve jurisdiction over all celestial bodies and orbits around them to the signatories of the treaty under the auspices of the UN so that all activities would be bound by international law. However, none of the significant space-faring nations (US, ESA, Russia, China or Japan) agreed to sign up to the treaty and so, with their refusal to be bound by its terms, the treaty is effectively useless. One problem was that, though the treaty attempted to update the Outer Space Treaty (1967), many of its terms were ambiguously worded – a common problem when legal clauses try to satisfy the agendas of all the parties trying to define them!

In 2015, during US President Obama's time in office, the *US Commercial Space Launch Competitiveness Act* (CSLCA or HR 2262) was signed into US law[27]. This made it legal for US companies and citizens to own and sell resources extracted from the Moon, Asteroids and other bodies.

On 6th April 2020, US President Donald Trump called the Moon Agreement (1979) "a failed attempt at constraining free-enterprise" and signed an executive order, "*Executive Order on Encouraging International Support for the Recovery and Use of Space Resources*", recognising that, as a right, private companies could claim and recover resources (including water and minerals) in space[28]. Perhaps more worryingly, it also stated "Outer space is a legally and physically unique domain of human activity, and the United States does not view it as a global commons.".

Ramon J. Ryan, a second-year law student at Vanderbilt University, has prepared a paper to be published this Summer in the *Vanderbilt Journal of Entertainment and Technology Law* [29] (and reported in Scientific American[30]), in which he concludes that the US FCC failed in their obligation to check the applications made by SpaceX against the National Environmental Policy Act (1970) (NEPA). Under the terms of NEPA, all US Federal Agencies are required to carry out an environmental impact assessment before they can grant someone a license to proceed with a project – this applies to projects being proposed by an agency (*e.g.* NASA) as well as private commercial companies (*e.g.* SpaceX or Amazon). The necessary environmental reviews can take many months or years, adding to the timescale, cost and paperwork produced.

Some agencies are granted a 'categorical exclusion' from having to obey the legal requirements of NEPA for some or all of their activities but only if they can show that those activities wouldn't impact the environment and a review would be unnecessary. Unusually, the FCC has been granted a very broad categorical exclusion on almost all of its activities, including giving its approval for space projects, whereas agencies such as NASA are required to carry out full NEPA assessments. The FCC's argument is that granting approval for use of certain radio bands and satellite orbits doesn't affect the human environment but, argues Ryan in his paper, though this may have been true in the past when relatively few satellites were involved in any one space project, it isn't appropriate in this era of megaconstellations with thousands of satellites and hundreds of launches. The FCC, he argues, in *not* carrying out such an assessment, has violated the law. He says, "The FCC has never performed a study showing why commercial satellites deserved to be classified as categorically excluded from review, and the evidence shows that these satellites are having an environmental impact. If the FCC were sued over its noncompliance with NEPA, it would likely lose.".

If a lawsuit were to be brought against the FCC for NEPA non-compliance the legal wrangles would probably take several years and, during that time, an injunction could be sought to suspend the launch of further Starlink, or other megaconstellation, satellites. If the FCC lost the case then the situation is unclear: would the FCC need to review all existing licenses against NEPA or just have to apply NEPA for future applications?

Ryan's proposal is that the FCC, in order to avoid future legal challenges, should carry out environmental assessments using the same model as that adopted by NASA and so help to establish more firmly a consistent industry standard on the assessment of satellite projects for environmental impact.

Ryan's yet-to-be-published paper has generated a lot of advance interest and, on 2nd April 2020, US Senators Tammy Duckworth (Dem, Illinois) and Brian Schatz (Dem, Hawaii), in a letter to the US Government Accountability Office (GAO), asked for a review of the FCC's decision to exempt satellite constellations from NEPA. They said "Although we are enthusiastic about the increased broadband access these satellite constellations might enable, astronomers are concerned that launching thousands of bright satellites into space, as the FCC has approved doing, will interfere with their scientific research.". The senators asked the GAO to compare the FCC's stance on NEPA *versus* how NASA comply with it and to recommend whether the US Congress should, perhaps, revoke the FCC's categorical exemption.

US Lawyer Charles L. Mudd Jr., writing in *Intellectual Property* [31], the newsletter of the Illinois State Bar Association, gave a detailed legal analysis of the issues surrounding megaconstellations and the Starlink satellites in particular. In his article he states:

> "Considering SpaceX represents but *one company* from *one country* seeking to launch satellite constellations, the broader international impact and potential launch of satellite mega constellations from multiple companies and countries cries for serious policy considerations. Indeed, beyond the impact on optical and radio astronomy, the number of objects raises concerns associated with space debris and space traffic management.
>
> Given the foregoing, one reasonably could wonder how SpaceX obtained approval for Starlink from the FCC."

Mudd argues, however, for a delay in starting any action against the FCC and gives three reasons: (i) the environmental regulations don't specifically require the impact on astronomy to be considered, (ii) any party starting legal action may have insufficient legal standing and (iii) the outcome of any specific action may make it harder to change public policy (particularly if the litigation fails).

Item (ii) on legal standing refers to the strong preference for the astronomical community to have raised objections during the public comments period before the FCC granted SpaceX their license. There were no such raised comments to challenge SpaceX's assertion that there would be no environmental impact or, at least, that astronomical research could be severely affected and so any late legal action against the FCC will suffer from the lack of timely objections.

Item (iii) refers to the problem that any legal challenge of compliance on the basis of current regulations is implicitly supporting the position that those regulations are sufficient to address the astronomical community's concerns. This is patently not the case as those regulations are out-of-date as far as consideration of megaconstellations is concerned and, further, the formal legal arguments, backed up by court documents, could set a legal precedent that would make it harder to put revised regulations in place.

Mudd does, however, see a possible chink in the FCC's armour in that the US Council on Environmental Quality (CEQ) requires agencies to continually review and revise their policies and procedures with respect to NEPA as necessary and, by failing to update the relevant policies in more than thirty years, has broken the law. Again, a successful challenge on this basis might result in a lengthy suspension of all megaconstellation launches whilst the FCC revisits and revises existing licenses.

Potential Political Issues

In the quotation from Mudd's article above he refers to "*one company* from *one country*". However, that simple phrase belies the fact that the "one company's" CEO, Elon Musk, is a charismatic and often controversial man who has exploited the immense wealth generated by his successful PayPal and Tesla ventures to build SpaceX and the "one country" is (arguably) the world's most powerful nation currently being led by a US President openly exploiting rising nationalism, walking away from hard-won international treaties and actively upsetting delicate diplomatic relations in order to project a spectre of strength at the negotiating table.

Musk is an entrepreneurial 'golden boy' to the US political establishment and, despite his occasional publicity stunts (*e.g.* launching a red 2008 Tesla Roadster sports car into a heliocentric orbit in 2018) and various, highly-publicised lapses of judgement, his track-record of success led to:

- SpaceX being awarded a contract worth $297 million with the US Air Force (USAF) in February 2019. This contract was for the launch of three classified surveillance satellites during FY 2021.
- The USAF are currently developing its new Advanced Battle Management System (ABMS). This should eventually allow different battle platforms to communicate with each other and Starlink, with its global coverage, is a strong contender for helping to provide that connectivity:
  - In recent tests, Starlink satellites were used to relay data to an AC-130 gunship.
  - In the upcoming 'Global Lightning' experiment it's planned for Starlink to communicate with a KC-135 tanker aircraft[32].
- US Northern Command (USNORTHCOM) asking Congress for $130 million to explore the use of Starlink to provide missing connectivity in the Arctic arena by the end of 2020.

Clearly, the USAF are very interested in the possibilities of using the Starlink internet communications in their future ABMS and that means there will be strong political pressure *not* to cancel or delay their launches. The US DoD are also interested in supporting ailing or failing constellation providers (*e.g.* OneWeb who filed for Chapter 11 bankruptcy on 27th March 2020) as the current administration, in particular, is *very* keen to ensure that companies potentially useful to US interests aren't acquired by Chinese agents.

In a, perhaps inevitable, step, US President Trump signed an order on 20th December 2019 splitting space operations away from the USAF into a separate, fourth armed force, the US Space Force (USSF) which, according to their website[33], is "a military service that organizes, trains, and equips space forces in order to protect U.S. and allied interests in space and to provide space capabilities to the joint force. USSF responsibilities include developing military space professionals, acquiring military space systems, maturing the military doctrine for space power, and organizing space forces to present to our Combatant Commands.".

The economic value of near-Earth space is undeniable. Musk needs Starlink to provide him with funds to, amongst other projects, push for enabling human travel to Mars[34] and eventually developing a colony there; other companies similarly see the potential for large amounts of revenue. It's no wonder then that the push to dominate sectors of near-Earth space is reminiscent of the US' Land Runs of the late-19th century where settlers, on a first-come basis, could each claim land up to 160 acres even as the resident native American Indians were being forcibly re-located. The Indian fights against the foreign invaders were inevitably going to be lost given the invader's superior technology, logistics and fire-power and perhaps we, similarly, need to be wary of a military force defending burgeoning US domination of what is a natural global commons[35].

If the above seems like fanciful fear-mongering it's worth reading the detailed analysis by Nancy Gallagher and John D. Steinbruner[36] and then the United States Space Command's *Vision for 2020* document[37].

Even if there are successful legal challenges in the US courts against Starlink, the current Republican administration, perhaps even with presidential intervention, is likely to be much more interested in changing legislation to support

a) US megaconstellation(s) dominating LEO (and making it harder for rival nations to get a foothold),
b) US companies having a significant share in providing global internet cover,
c) the potential for an advanced, encrypted military communication system with global coverage and
d) military use of the USSF to enforce any attempt to obstruct or deny US interests in space

than being interested in preserving the night sky for astronomers and the public – the legal challenges may only delay what might be inevitable.

Some of the world's repressive regimes (China, Russia, Iran, Syria, UAE and others) have closed or restricted their country's digital connections to the global internet and have set up an 'internal internet' with, on the face of it, similar (but controlled and monitored) features. This is done to try and censor the information available to their people from outside and to enable monitoring of activists' digital traffic that might be considered a threat. These regimes will not take lightly their citizens' ability to access the global internet from US satellites passing overhead and it's possible they might use countermeasures to, at least, jam or otherwise deny connection *via* Starlink or even attempt to damage some of the constellation satellites at severe risk of raising the international temperature.

Whilst we should be concerned about attempts by some regimes to impose censorship on their people we should also be wary about allowing provision of significant parts of the global internet to be placed in the hands of a company (or companies) from one country. What if, at times of heightened international tension, the US decided to impose a 'digital sanction' on another country by strategically cutting them off from global connectivity?

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