**Satellite megaconstellations – managing a challenging future for astronomy?**

**The Earth exosphere is set to become more and more crowded, with tens of thousands of commercial telecommunication satellites planned to be launched in the next few years. Their impact on scientific facilities and in general on the dark sky is a concern for professional and amateur astronomers. Close collaboration with the industry is paramount to ensure that technological and socio-economic advancements will not imperil scientific progress or humanity's ability to have access to dark skies.**

In the 63 years since the launch of Sputnik 1, astronomers and space scientists have come to rely on artificial satellites for much of our work. Without orbiting space telescopes, study of the universe in X-rays and gamma rays would be almost impossible, and there would have been no Hubble images on the front pages of national newspapers (and on their websites).

But as long ago as 1961, radio astronomers warned of the threat the exploitation of space might pose to our science, when Project West Ford (NASA History SP-4217, Beyond the Ionosphere) attempted to create an artificial ionosphere to enhance communications by deploying 480 million copper needles in orbit.

Radio astronomers now separately benefit from spectrum protection dating from the same period, covering transmissions from the ground and space. However, only very small slices of the spectrum are reserved for (passive) scientific use, and as our demand for broadcast and mobile communications has accelerated, there is huge pressure on the use of spectrum. The natural tension between scientific and commercial use was noted in the late 1990s at an International Astronomical Union symposium (Sullivan, 2000).

Optical astronomers were in contrast relatively sanguine about the slowly growing number of satellites visible in telescopes, despite the nearly 2,000 deployed in Low Earth Orbit (up to 2,000 kilometres above the surface of the Earth) alone.

That changed last July. SpaceX, well known as a pioneering private space company led by its CEO Elon Musk, began a series of launches to build its Starlink 'megaconstellation'. This system, with a licence to eventually place up to 42,000 satellites in orbit, is designed to deliver high speed broadband to terrestrial users, particularly those in remote areas where internet connection is often non-existent.

The UK-licensed OneWeb made its first launches soon after (before filing for bankruptcy protection) and there are at least 12 other organisations with plans for their own constellations. Together these could increase the number of spacecraft in LEO by a factor of 50 or more.

It is fair to say that the scale of this change took at least optical astronomers by surprise. At radio wavelengths, researchers are used to monitoring company filings to the Federal Communications Commission (FCC), the US body affiliated to the International

Telecommunications Union (ITU), responsible for approving and regulating the deployment of new satellites.

At the moment, being a good corporate citizen and meeting FCC standards (or those of other national regulators) primarily depends on having a commitment to remove defunct satellites from orbit, observing protocols about space debris and collision avoidance, and in the radio spectrum, not transmitting in the bands protected for astronomy.

When a satellite reflecting sunlight passes through the field of view of a telescope, then it leaves a characteristic streak of light in images. Software tools to some extent mitigate this, smoothing out the data to make a cosmetic improvement to the final result. The data behind the streak is though simply lost, at least in a single frame, although astronomers can stack a succession of images to compensate for that. Later in the night there are rather fewer satellites visible, as they will be in the terrestrial shadow when above an observer's horizon.

The challenge for optical astronomers is to cope with this on a potentially far larger scale. After the first launch  the larger astronomical organisations including the American Astronomical Society (AAS), the International Astronomical Union (IAU) and the Royal Astronomical Society (RAS) all put out statements of concern, and called for a dialogue between astronomers and satellite operators. (In a salutary lesson about social media both SpaceX and OneWeb contacted one of the authors after he tweeted asking whether Elon Musk was at all concerned about astronomy.)

So far two teams (Hainault and Williams, 2020, and McDowell, 2020) have made assessments of the impact of the new satellites on professional observatories. The first considered the effect on telescopes comprising the European Southern Observatory (both are ESO staffers) and the second specifically considered Starlink.

The news from these studies is mixed, as is more recent work. Starlink satellites are deployed 550 kilometres up, and as originally configured were easily visible to the naked eye in late evening twilight and early morning before dawn. OneWeb satellites are fainter, as the existing spacecraft operate at an altitude of 1200 kilometres, but are in sunlight for far longer in each orbit, and in summer are visible all night.

Despite this, most ESO telescopes, for example, will have fewer than 1% of image frames badly affected over the course of a night. Widefield telescopes, like the Vera Rubin Observatory (VRO) now under construction, will find it harder. These instruments by definition study a large part of the sky at any one time, so are much more likely to have a satellite crossing their field of view while obtaining imagery. In  twilight nearly 50% of frames could be contaminated.

Radio astronomers are similarly concerned. At radio wavelengths, the downlink signal from a Starlink satellite is around 10 trillion times as bright as the weakest astronomical sources. That is a measure of the sensitivity of radio telescopes and it indicates the pressing need to protect ground-based observatories. New facilities like the Square Kilometre Array, and smaller existing telescopes around the world, have to cope with routine transmissions from the population around them, with a lesser or greater degree of site protection.

While operators including SpaceX and OneWeb are keen to demonstrate that their downlink signals will not impinge on adjacent radio astronomy bands, radio observatories do a significant amount of science outside these narrow protected bands. This is simply because greater bandwidth provides higher sensitivity, or because particular emissions fall in these bands, sometimes as a result of cosmic redshift. There is also concern that given the large numbers of satellites, there is a significant risk of poorly performing or malfunctioning satellites transmitting out of their allocated band or having unexpected directional patterns. Radio astronomy organisations are working together with satellite operators on possible mitigation strategies that could minimize the effect of these transmissions, thus maximizing the use of the radio spectrum for both commercial and radio astronomical use.

Space based facilities will also be impacted, not only for the challenges related to space debris and collision avoidance brought by an increasing population of satellites, but also for the potential effect on their operations. The Ka band, which, according to their respective FCC filings, SpaceX, OneWeb and Amazon Kuiper plan to use, is the band that will be used for control and downlinking by major planned missions, such as the NASA James Webb Space Telescope, the ESA Bepi Colombo and JUICE, raising concerns on possible disturbances in such process.

Time-sensitive scientific phenomena are likely to be most affected. Transients of exoplanets, outbursts from stars, ground-based follow of up gamma-ray bursts, and detection of near-Earth objects all depend on consistent operation of observatories. The new megaconstellations will offer services to customers and governments in different nation states, but with a global impact, as almost all astronomical facilities will have satellites passing over them.

Starlink launches take place every few weeks, and deploy around 60 satellites each time, with SpaceX now reportedly manufacturing 120 spacecraft every month. The company now has nearly 600 in orbit, enough to make commercial operations viable, initially targeting the US and Canadian markets.

Beyond professional scientists, the wider public is surely also a group with a right of access to the night sky too. Many people enjoyed the view of the ‘string of pearls’ that results each time tens of satellites are deployed together, something easier to see than the recent bright Comet C/2020 (F1) NEOWISE. In a world where a major pandemic necessarily restricts our movement, the opportunity to enjoy both artificial - and natural – space spectacles is clearly prized. The potential change to part of the natural environment may not yet be appreciated, and the public may take a different view once this is clearer.

SpaceX responded quickly to the concerns expressed and its engineers are now collaborating with astronomers around the world. The company deserves credit for making early changes to the design of their spacecraft, experimenting first of all with reducing their albedo (DarkSat) and then with a sunshade (VisorSat) that proved more effective. The latter is now deployed on all new Starlink satellites.

It would though be naïve to imagine this is sufficient. With the modifications, the Starlink satellites are at or below visibility to the naked eye when deployed, but are still bright before reaching their operational altitude, and are easily detectable by even small observatories throughout. VRO scientists still expect to spend a good deal of time on software engineering to salvage more data, and there is a concern at some point commercial considerations will likely limit mitigation through satellite redesign.

Other operators are also rather less engaged with scientists. Despite requesting bankruptcy protection in March, OneWeb filed an FCC request for 48,000 satellites in May, and in another surprise a consortium including the UK government purchased the company in July. Amazon is proceeding with its own Project Kuiper, expected to comprise more than 3,000 satellites, and operators like Samsung will follow suit.

Unsurprisingly, astronomers are increasingly aware of the risks to our science. The AAS responded speedily after the first launches, inviting SpaceX representatives to its meetings, surveying optical observatories around the world, and convening the SATCON1 workshop in July this year. In Europe, the RAS is talking to the UK government about OneWeb, and at the virtual conference of the European Astronomical Society, nearly 200 people attended our sessions on megaconstellations. This October delegates at the "Dark and Quiet Sky for Science and Society" meeting will develop recommendations to be presented to the UN next February.

There are other considerations beyond astronomy, such as the impact on the space environment, whether deploying megaconstellations is compatible with space law (the general consensus is yes, but two US senators asked their government to review the FCC licences), and whether the Outer Space Treaty dating from 1967 is still fit for purpose.

Exploitation of LEO is set to continue, and there are clearly real societal and economic benefits from enhanced communication systems, and space-based data services. This however should not come at the price of badly compromising one of the oldest sciences, and make it harder to answer the big questions about the universe we live in, an endeavour that enriches humanity as a whole.

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