Opinion

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Satellite mega-constellations pose threat to ground-based astronomy

Soon the number of artificial light sources visible across out night skies could outnumber natural stars, a disturbing scenario that would become a reality if ambitious current projects to build mega-constellations of artificial satellites for worldwide Internet access are completed. As David Galadí-Enríquez explains, the intensive use of low Earth orbit by these new satellite networks is already proving detrimental - whether from an aesthetic, cultural or scientific point of view - to our view of the night sky.

■ LSST at sunset, taken from behind the nearby Gemini telescope at the Cerro Pachón ridge in Chile.

LSST Project/NSF/AURA

▲ Typical smallsats in a mega constellation.

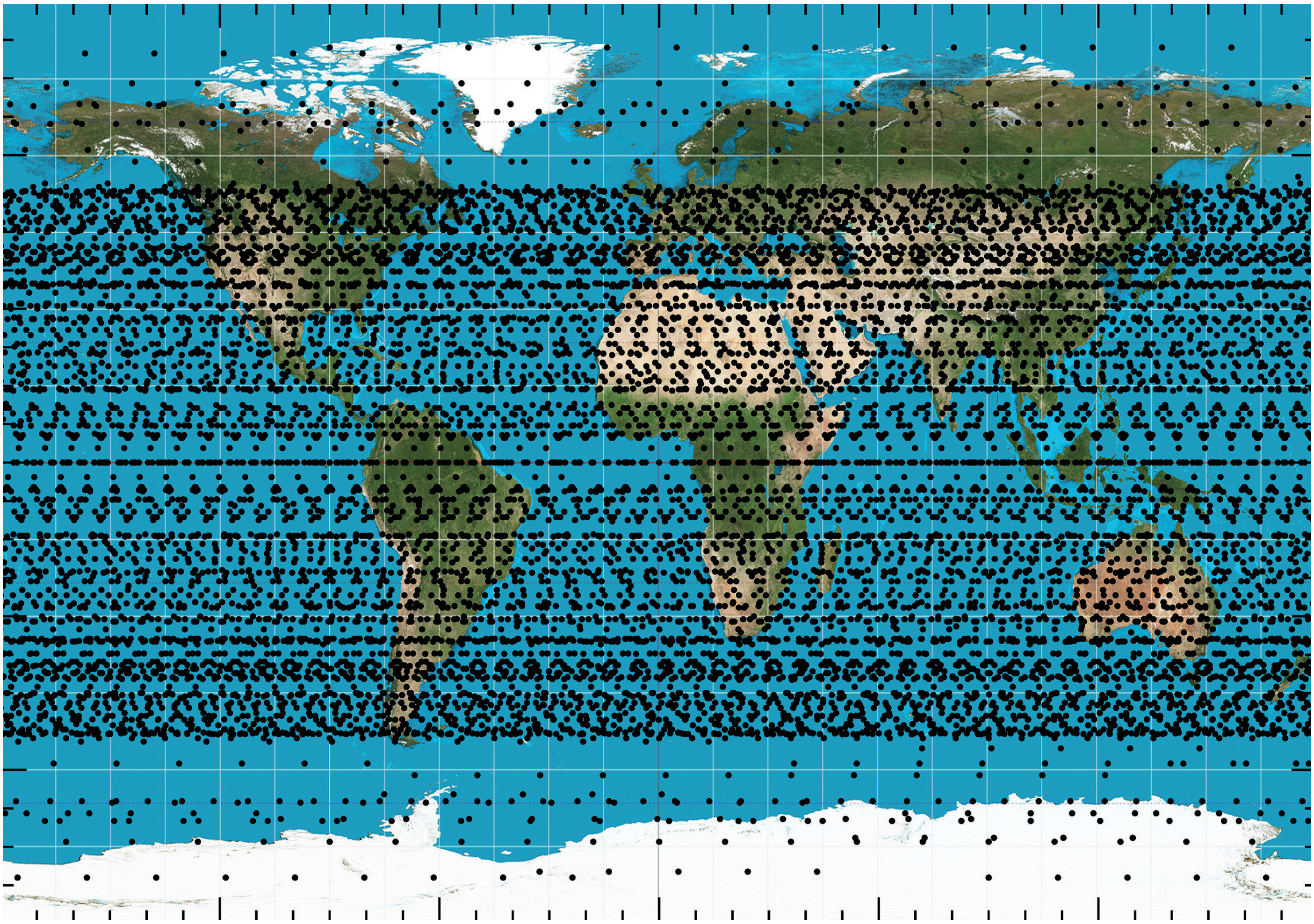
Artificial satellites have been a part of the night sky since the dawn of the Space Age in 1957, and a good number of spacecraft can be observed with the naked eye on any night, after sunset and before sunrise, when the sky is dark but direct sunlight still illuminates the satellites. This naked-eye observation of satellites reveals objects in low Earth orbit (LEO), and the spacecraft observable from any location on Earth can be predicted by means of online tools such as Heavens-Above (www.heavens-above.com). Moreover, any amateur telescope reveals fainter objects, allowing even the observation of geostationary satellites.

There is no doubt that the linear tracks of these artificial satellites produced by long-exposure imaging techniques are detrimental to professional wide-field astro-photography. However, to date, many amateur astronomers have enjoyed tracking the satellites and the International Space Station (ISS), and registering the impressive flashes caused by the older Iridium satellites.

The European Space Agency's Space Debris Office estimates there are currently some 22,000 artificial objects of considerable size (several tens of centimetres or larger) orbiting around Earth, only 2300 of which are functioning satellites. The remainder constitute the population normally known as space debris or space junk, a swarm of objects comprising anything from abandoned satellites and rocket upper stages to fragments from explosions and collisions, and even tools unintentionally released by astronauts.

The number of pieces of space junk increases exponentially if we consider even smaller sizes, tiny pieces that are difficult to follow but may cause considerable damage to operational satellites and crewed spacecraft should they collide. Many institutions are worried by the uncontrolled proliferation of space junk, but the current situation may worsen drastically if several companies execute their plans to fill LEO with overwhelming quantities of communications satellites. If these plans are fulfilled, the current number of artificial objects purposely placed in

Several Starlink satellites are already out of control, which raises concerns about space safety and the growth of the space debris population.



orbit may more than double. The implications of these projects are potentially huge, and they deserve close and detailed consideration.

▲ Figure 1. The Starlink constellation derived from the profile provided in Table 1 (see page 74). A total of 11,832 satellites cover the Earth in eight shells with different altitudes and inclinations. Each dot represents one satellite.

Constellations

Satellite constellations are groups of spacecraft of the same design, distributed among a series of orbits in order to cover the planet in a close to optimum way; their applications include Earth observation, global positioning and one or two-way communication services. Several such constellations already exist, the best known of which are the GPS, Glonass and Galileo systems. But they all comprise a small number of satellites, in each case well below a hundred.

Now, several companies have announced their intentions to build satellite constellations orders of magnitude larger than existing constellations, to provide two-way communication links for Internet access worldwide. The information available on these projects is incomplete, perhaps because the companies do not want to reveal their intentions to competitors but also because the details may be decided 'on the fly', depending on the prospects for commercial success.

Among the dozen or so projects for Internet-related satellite constellations, we find those of Boeing and OneWeb, and a similar initiative being prepared by the Chinese Aerospace Science and Technology Corporation. However, everything indicates that the most advanced project is Starlink, driven by Elon Musk's SpaceX company, which plans to launch at least 12,000 satellites. The construction of this network is underway, with several hundred satellites already in orbit and launch dates for many others already scheduled.

Even though it is stated that these satellites should de-orbit by themselves at the end of their useful life, failures that will restrict this are bound to occur. In fact, several Starlink satellites are

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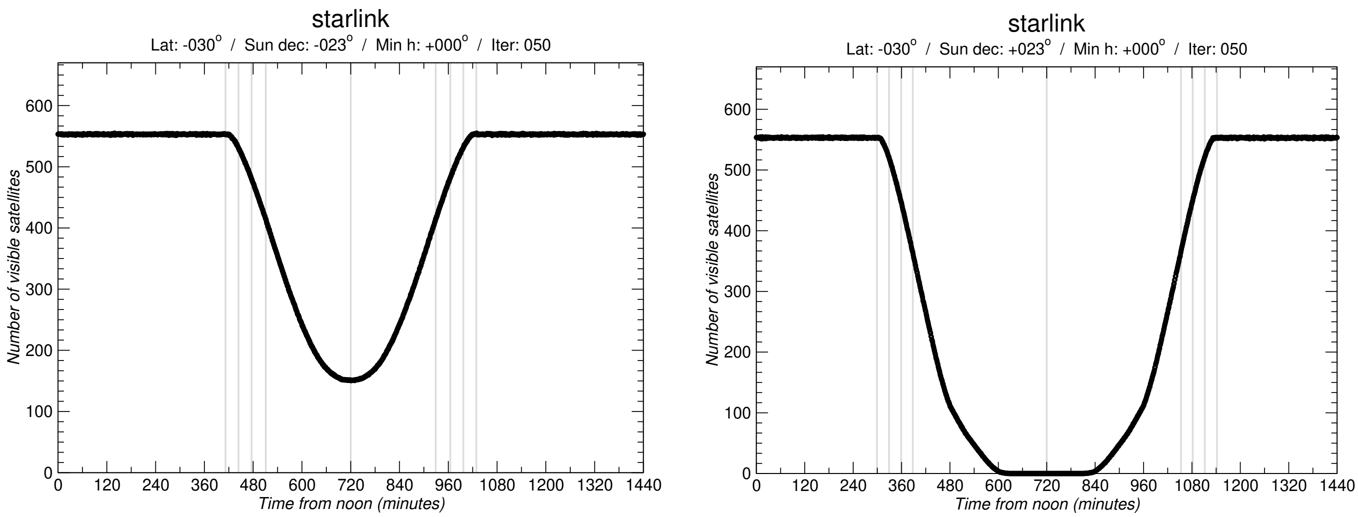

already out of control, which raises concerns about space safety and the growth of the space debris population.

Intense concerns are arising, also, among the community of radio astronomers and several institutions - the International Astronomical Union (IAU) among them - are studying the implications for the study of the universe in radio wavelengths. It is worth noting that the electromagnetic noise caused by these spacecraft is present day and night and that its intensity may not only impede radio astronomical observations in the bands affected, but may even damage the detectors which are designed to receive extremely faint natural sources of radiation.

But what first caught public attention were the potential effects of these satellite networks on the observation of the night sky in visible light. It is clear that the mega-constellations have been devised without paying enough attention to their potential effects on astronomical observations, and the first Starlink launches made this obvious to professional and amateur astronomers alike. This impact was increased by the impressive visual aspect of the 'satellite trains' just after launch, before the spacecraft slowly drifted towards their operational orbits where, luckily, their optical appearance is much less outstanding.

Impact evaluation

Several observatories and research institutions are currently evaluating the potential impact of similar projects from the optical point of view and Commission CB7 of the IAU, for the Protection of Existing and Potential Observatory Sites, is approaching the problem with different techniques. Even though many simulations,

▲ Figure 2. Graphs showing the number of satellites visible during a complete day and night interval from Cerro Pachón, northern Chile, at summer solstice (left) and winter solstice (right). Time is specified in minutes since the previous local noon. Vertical lines indicate (from left): sunset, the end of civil, nautical and astronomical twilights, and the opposite series of events on the morning side. The satellite constellation follows the profile from Table 1.

Practically all Starlink satellites visible above 30 degrees will visually pollute the night sky at places that currently preserve their natural, pristine dark conditions

computations and even observations are still being performed, it is already possible to comment on a number of outstanding results.

All current mega-constellation projects are conceived as 'Walker constellations', a concept that aims to distribute the satellites among several shells of circular orbits, each shell composed of a number of orbits with the same inclination but crossing the Earth's equator at different longitudes. The satellites are phased along these orbits to produce the most uniform possible distribution, in order to provide the best ground coverage. The science of orbital mechanics means that such satellite 'swarms' cannot be absolutely uniform, such that no satellites will overfly latitudes beyond their orbital inclination and the density of satellites tends to be higher at extreme latitudes than at the equator. But a wise combination of shells and orbits, including several polar ones, should allow a land coverage well suited to the needs of the company providing the service.

One of the constellation profiles made public for the Starlink system is shown in Table 1 and Figure 1; the figure depicts an instantaneous footprint for this constellation, where each dot represents one satellite. This description has been taken as a reference for the computations described below, which refer only to this constellation profile. However, some statements from SpaceX point to a possible final number of satellites that would more than double the number in this profile. And, of course, the possible future contribution of competing projects should also be taken into account.

We should distinguish between satellites 'in range' and 'visible' satellites. Given a specific location on Earth (say, an observatory), if we specify

Shell altitude(km)	Satellites in orbital shell	Inclination (º)
550	1584	53
1110	1600	53.8
1130	400	74
1275	375	81
1325	450	70
335.9	2493	42
340.8	2478	48
345.6	2547	53

▲ Table 1. Starlink constellation profile used as case study. The total number of satellites in this case would be 11,832.

some minimum elevation above the horizon, we may consider that all satellites placed over that minimum elevation are 'in range'. Visible satellites will be a subset of the satellites in range, and will be those satellites that are directly lit by sunlight. For a given constellation, the average number and distribution of satellites in range depends only on the observatory latitude. However, the number and distribution of visible satellites is extremely dependent on local time and, also, on the season, because both factors define the apparent position of the Sun and, thus, the local configuration of the shadow cone of the Earth. Any satellite in shadow would be in range, but not visible.

The details change somewhat with observatory latitude, as shown in Table 2, but let us take Cerro Pachón, in Chile, as a reference case. This observatory houses the Vera Rubin Telescope (VRT), devoted to the project known as Large Synoptic Survey. There,

Latitude (º)	Example	Satellites in range	
		Above 30º	Above horizon
37	Calar Alto	68	615
30	Cerro Pachón (VRT)	54	553
29	Roque de los Muchachos (GTC)	53	543
24	Cerro Paranal (VLT)	49	491
20	Mauna Kea	47	444
00	Equator	42	386

▲ Table 2. Satellites in range for the Starlink configuration from Table 1, for different observatory latitudes and for two minimum elevations over the horizon: 30 degrees and 0 degrees. There is a smooth dependence with latitude and a very strong dependence on elevation, most satellites being concentrated towards the horizon.

the average number of satellites in range over the horizon is more than 500 on average, but 90 percent of them are concentrated within 30 degrees from the horizon. Around 50 satellites are in range, at any time, at the elevations most frequently used for professional optical astronomy, above 30 degrees.

The dependency with local time is strong, as the configuration of the Earth shadow changes. The number of visible satellites decreases as twilight advances from civil to nautical, from nautical to astronomical, and from astronomical to true night, until reaching a minimum that maintains well above 100 satellites visible over the horizon at midnight at summer solstice, one dozen of them above 30 degree elevation. In winter solstice conditions, the number of visible satellites decreases during the night until it reaches zero for some four hours centred around midnight. For latitudes more distant from the equator there may be no time free of satellites even at the winter equinox.

Visual magnitude?

We may wonder how bright these visible satellites would appear. This critically depends on size and reflectivity, and the results are still to be refined by comparison with real observations. However, research indicates that the brightness distribution of the satellites displays a structure that depends on the texture of the constellation shells and on the distance to the observatory. Distant satellites tend to be closer to the horizon and appear much fainter.

Starlink satellites visible above 30 degree elevation display a bimodal distribution peaking at visual magnitudes 4 and 6. If we remember that magnitude 6 is the faintest that can be seen with the naked eye under dark skies (and mag 4 is brighter than this), we conclude that practically all Starlink satellites visible above 30 degrees will visually pollute the night sky at places that currently preserve their natural, pristine dark conditions.

In urban or suburban areas, the levels of light pollution restrict the number of stars accessible to the naked-eye to a few hundred at most, with just a few dozen being a frequent limit for most of the population of modern cities. Under these circumstances it is not an overstatement to suggest that, from many locations worldwide, we may find many occasions on which the number of visible satellites will be comparable, or will even outnumber, the quantity of visible stars.

Visible satellites closer to the horizon tend to be significantly fainter, most of them remaining below the sensitivity threshold of the naked eye even under the darkest skies: the distribution in this case peaks at visual magnitudes 7 and 8, albeit with significant

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numbers of satellites around magnitudes 6 and 9. However, this overall faintness does not mean that they are not harmful: let us consider the impact of visible satellites on instrument-aided observations.

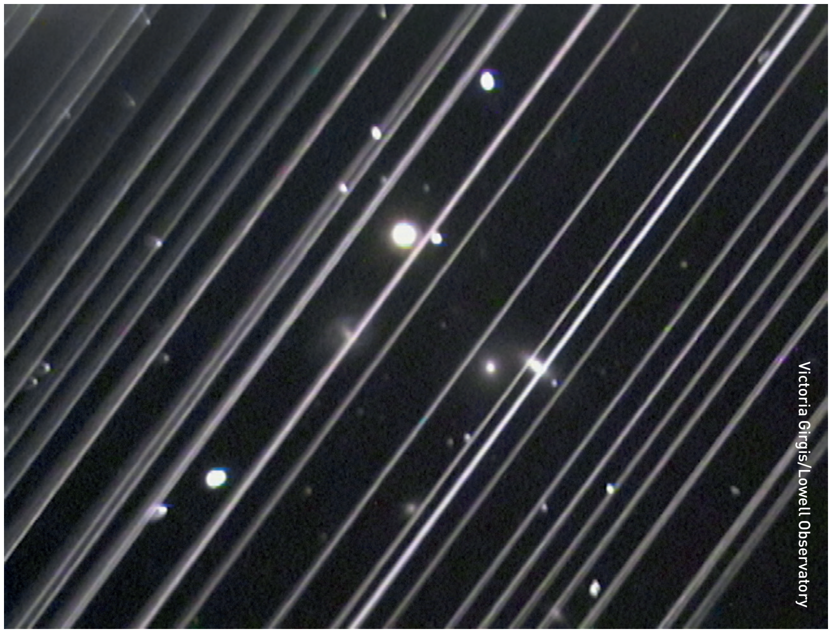
Telescope observations

The effect on instrument-based observations strongly depends on the field of view. The probability of impact on narrow-field observations is small, but it grows significantly for wide-field telescopes. Going back to our case study with the VRT, its field of view of 3.5 degrees makes it particularly vulnerable to satellite mega-constellations. Depending on the relevant variables (season, twilight phase, satellite altitude and number of satellites), between 20 and 90 percent of the observations of the VRT would be impacted.

Similar effects may be expected for the other astronomical wide-field surveys, even taking into account that these projects usually point to elevations above 30 degrees: though there are fewer satellites above this elevation, they tend to appear much brighter (because they are much closer and the light path through the atmosphere is shorter and less is absorbed), which induces saturation effects impossible to correct in any satisfactory way.

For elevations closer to the horizon the main impact will be on non-professional observations, astrophotography and nightscape imaging. Photographing and video-filming the night-time landscape will no longer be feasible, or will become difficult, requiring complex image processing, often with non-optimum results. Nightscape wide-field imaging will be altered forever, from any location on the world, once the areas closer to the horizon are permanently occupied by light streaks from the hundreds of satellites predicted. While invisible to the naked eye, they will transform any deeper, long-exposure image into a dystopic view of interweaving artificial light streaks.

The solution? Not building these satellite constellations would be the best option to avoid their impact on science, culture and the landscape. But, more realistically, if the mega-constellations are built, then reducing the reflectivity of the satellites by a significant factor may result in a helpful second option. However, this would probably complicate the thermal management of the spacecraft and, in any case, would fail to solve the problems related to radio astronomy and space debris. Either way, the satellite mega-constellations represent a threat to the astronomical status quo. ■



Victoria Girgis/Lowell Observatory

▲ An image of the NGC 5353/4 galaxy group made with a telescope at Lowell Observatory in Arizona, USA, on 25 May 2019. The diagonal lines running across the image are trails of reflected light left by more than 25 Starlink satellites as they passed through the telescope's field of view. The image was taken soon after satellite deployment and, though it serves as an illustration of the impact of reflections from satellite constellations, the density is significantly higher in the days after launch. The satellites will also diminish in brightness as they reach their final orbital altitude.

Eckhard Slawik

▶ Even before the recent increase in satellite constellations, many spacecraft were visible in the night sky on any given night. This image is composed of 300 short 13-second exposures taken within 70 minutes of each other from Waldenburg, Germany, on the night of the Perseids meteor shower 12 August 2018. The image has a field of view of 84 x62 degrees. Most of the dozens of lines are made by satellites reflecting sunlight from below the horizon.

About the author

David Galadí-Enríquez is a Spanish astrophysicist. He completed his PhD on astrometry and photometry of stellar open clusters at the University of Barcelona in 1998. He has been involved in studies and activities related to astronomical sky quality studies during the last decade and he is secretary of the commission of the International Astronomical Union (IAU) devoted to the protection of observatory sites. He is a member of the Spanish Network of Studies on Light Pollution (REECL) and currently holds a position as resident astronomer at Calar Alto Observatory, one of the main optical and infra-red facilities on European soil,