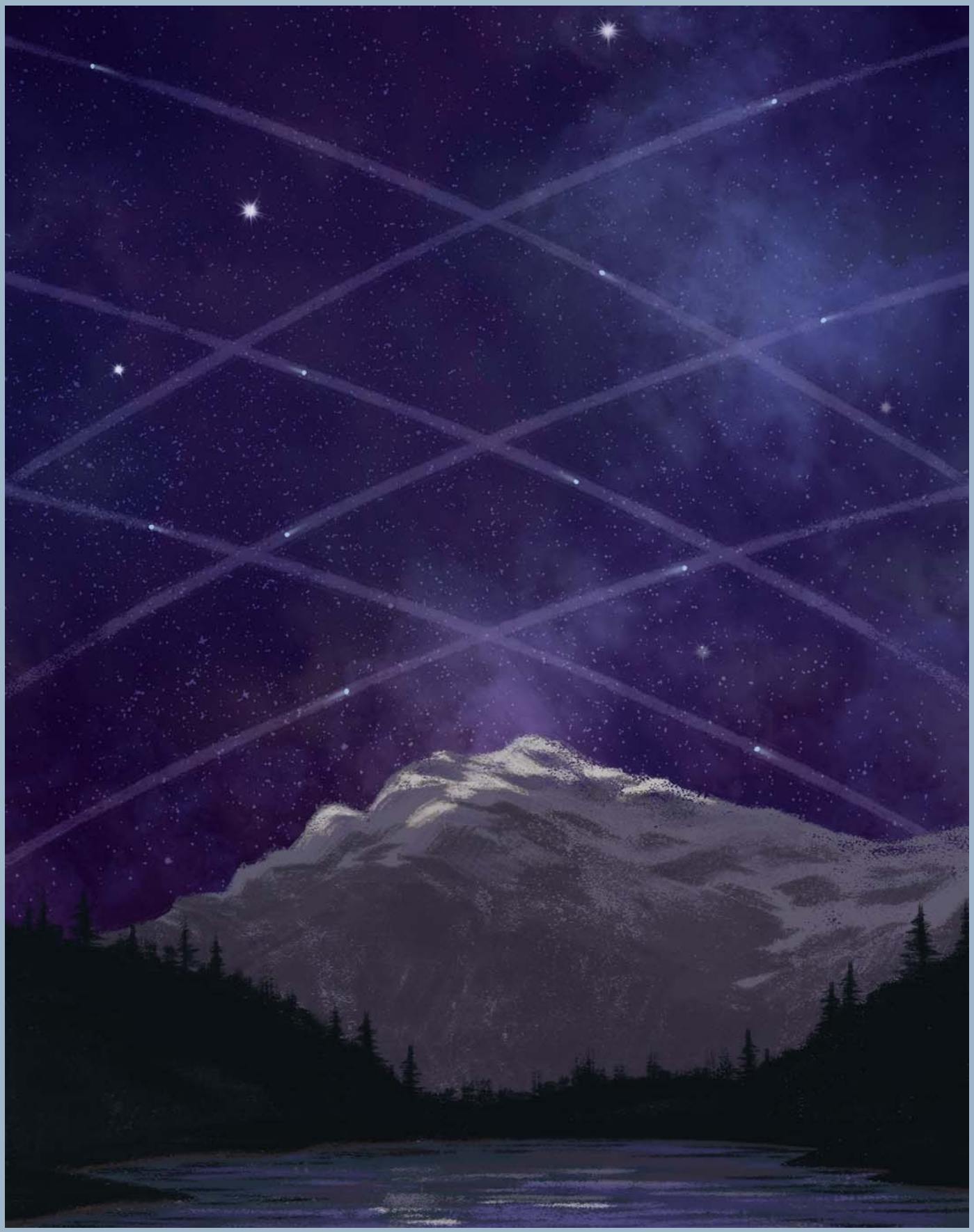
SATELLITES VS. STARS by Monica Young



The *New* Space Race

Multiple companies are launching, or planning to launch, a throng of satellites into low-Earth orbit. The effects on everyone from backyard stargazers to professional astronomers could be profound.

On May 23, 2019, SpaceX launched a packet of sixty 227-kilogram (500-pound) satellites, deploying them to an initial orbit of 440 kilometers (273 miles). These satellites represented the initial phase of SpaceX's Starlink *megaconstellation*, a giant network of satellites buzzing around Earth. Starlink has a lofty goal: to provide worldwide broadband internet access from low-Earth orbit. But it also heralds unintended consequences for astronomy.

During the commissioning phase, while the Starlinks were still flying together, archaeologist and satellite-tracker Marco Langbroek set his sights on spotting them. The satellites' orbital elements weren't available yet, so Langbroek made his own calculation to narrow down which part of the sky to search. And he got 'em. When a flock of some 56 satellites entered his field of view, Langbroek recounted in his blog, "I could not help shouting, 'OAAAAAH!!!!'"

The video in Langbroek's blog soon went viral. The satellites shone at magnitude 2, as bright as Polaris. News outlets and voices on social media warned of a night sky disrupted, and various astronomy agencies, including the International Astronomical Union (IAU) and the American Astronomical Society (AAS), scrambled to issue statements.

Technically, the Starlink launch wasn't a surprise. SpaceX had filed plans years ago, first with the International Telecommunication Union (ITU), which is responsible for assigning frequency space to satellites from countries worldwide, and then with the Federal Communications Commission (FCC), which enforces a modified version of ITU standards in the U.S. Those filings ultimately make space for 11,927 Starlink satellites at various altitudes.

SpaceX is not alone in this venture. When Starlink made the news, an internet company known as OneWeb had already launched its first six broadband satellites with relatively little fanfare. The company plans to launch more — up to 32 at a time — starting in January 2020, in order to fill out an initial network of 648 satellites by the end of 2020. Amazon has likewise filed paperwork for its planned Project Kuiper constellation.

These companies are competing for access to a $1 trillion market, aiming to serve billions of people worldwide who are currently without reliable internet access. Even a small percentage of this global market promises billions in revenue.

Yet, even though plans have been in the works for years, the brightness of the Starlink satellites came as a shock to astronomers. "The ground-based optical and infrared observatories were really taken by surprise with the first launch," says Kelsie Krafton, a public policy fellow at the AAS.

After all, megaconstellations have no precedent. Perhaps the closest thing is Iridium's 66-piece network, which enables the global operation of satellite phones and pagers, but Starlink would outnumber Iridium almost 200:1. As the issues at stake are ones of scale, there's really no comparison.

In response to concerns about the future of the night sky, we have asked experts to provide hard numbers in the face of media hype, quantifying how worried we should be about everything from visual astronomy and astrophotography to astronomical science and space debris. Their answers show the threat to astronomy is real, but also that the future isn't a foregone conclusion: Astronomers are actively connecting with aerospace companies and talking over potential solutions. Nevertheless, the situation is in flux and how everything works out remains to be seen.

▲ **10, 9, 8 . . .** Sixty Starlink satellites launched on May 23, 2019, aboard a Falcon 9 rocket. Another packet of 60 launched on November 11th, shown here. The May launch deployed to an altitude of 440 km and the November launch to 280 km, but both sets of satellites will operate from 550 km.

ILLUSTRATION: LEAH TISCIONE / *S&T*; STARLINK SATELLITES: SPACEX / CC BY-NC 2.0

The Backyard View

Alarming as Langbroek's viral video was, a few reasoned voices in the astronomy community urged caution in the face of the (social) media whirlwind that followed last May's Starlink launch. Within days the satellites' brightness had already begun to fade, as their solar panels turned toward the Sun and their krypton-powered thrusters took them to an operational altitude around 550 km.

Enter SeeSat-L, a somewhat anarchistic group of satellite observers who trade information via a mailing list. Langbroek is a member of this group; so is Cees Bassa, a Dutch radio astronomer at the Netherlands Institute for Radio Astronomy (ASTRON). Bassa and others contributed observations in July and August, compiling at least one magnitude measurement for more than a dozen of the satellites. The observing campaign revealed that the satellites' visual brightness at their operational altitude ranges from magnitudes 4 to 7. Most measured magnitudes cluster around magnitude 6.

That means that for the average citizen living in an urban or suburban area, these satellites will be nearly invisible. But they'll have a noticeable effect on the night sky in rural areas. "From a really dark site, they all are in the range of objects that you can still see with your naked eye," says Langbroek.

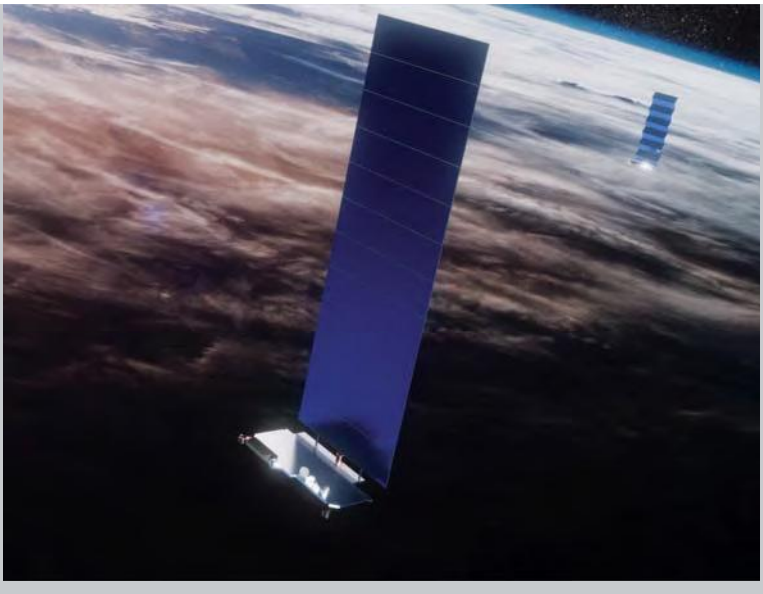
Nevertheless, it's still far from obvious what effect mega-constellations might have on backyard astronomy. For one, the view depends on where you look. The initial Starlink network, for example, will consist of 1,584 satellites in 24 orbital planes, with 66 satellites in each ring. (SpaceX is still waiting for approval of a September 2019 filing to the FCC asking to spread the same number of satellites over 72 rings instead.) So, Bassa explains, if you happen to look into one of these planes, you'll see one satellite, then two minutes later the next, then two minutes later the next — like the recurring noise of overhead jets if you live near a major airport. Given the large number of orbital planes planned for several competing companies, it won't necessarily be obvious which regions of sky to avoid.

The satellites' visibility also depends on the time of year, observing latitude, and satellite altitude. Satellites are only visible when they reflect sunlight. So, while lower-altitude satellites are brighter (because they are closer to Earth), they are also visible for shorter fractions of the night. According to Bassa's calculations, the initial 1,584 Starlink satellites would be visible from the equator only during twilight. But the

▲ **WAGON TRAIN** On May 24th Marco Langbroek captured a spectacular video of the 2nd-magnitude satellite train. "I was dancing behind the camera," Langbroek says. "After that, of course, the concern came."

VIRAL VIDEO STILL: MARCO LANGBROEK; STARLINK PACKED AND UNFOLDED SATELLITES: SPACEX (2)

▲ **LOCKED AND LOADED** Sixty Starlink satellites are packed like sardines within the nosecone of a SpaceX Falcon 9 rocket.



▲ **UNFURLING** Starlink satellites, still flying as a flock post-launch, deploy their singular solar arrays in this artist's concept.

situation is markedly different for higher latitudes during the summertime: Starlinks would be visible for most of the night.

Higher-altitude orbits help in some respects. OneWeb's satellites (which are also smaller than Starlinks) fly at 1,200 km and should be at least two to three magnitudes fainter, according to an estimate by Jonathan McDowell (Center for Astrophysics, Harvard & Smithsonian). Moreover, the higher altitude means the company will need fewer satellites overall. However, the satellites will be reflecting sunlight for a larger fraction of the night from all latitudes, and even if they're out of naked-eye range, they'll still be an issue for photographers and professional astronomers.

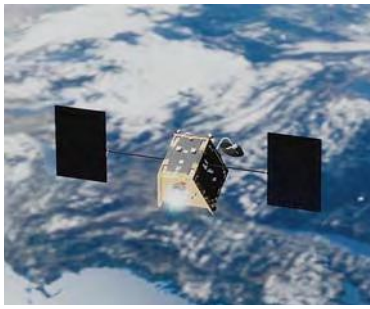
Making (and Removing) Tracks

"For even modest astronomical instruments, these are quite bright objects," Langbroek says. Once the constellations have been assembled, astrophotos are virtually guaranteed to record satellite trails.

In some cases, the problem is easy to deal with. Even now, deep-sky photographers often capture satellite trails, not to mention the trails left by airplanes passing overhead, explains astrophotographer Richard S. Wright, Jr. The techniques for dealing with these kinds of trails are not only well established but also easy to apply.

Astrophotographers don't typically take single exposures of deep-sky objects; they more often take many shorter exposures and stack them together into a single image via image-processing software. Photographers can reject unwanted signals during this process. Although the name and details of the process may vary depending on the software, the basics remain the same: The software looks at the values of a single pixel across multiple frames, then rejects any pixels that are significantly brighter (or fainter) than the others.

However, single-shot and nightscape photographers don't have those same processing options. *S&T* Contributing Photographer Babak Tafreshi notes that a typical 10- to 20-second nightscape exposure would easily pick up the satellites, as would wide-angle images. The only option for removing the trails would be to go through images pixel by pixel.



▲ **ONEWEB** In this artist's concept, a OneWeb satellite fires its thruster. OneWeb had launched six satellites at press time.

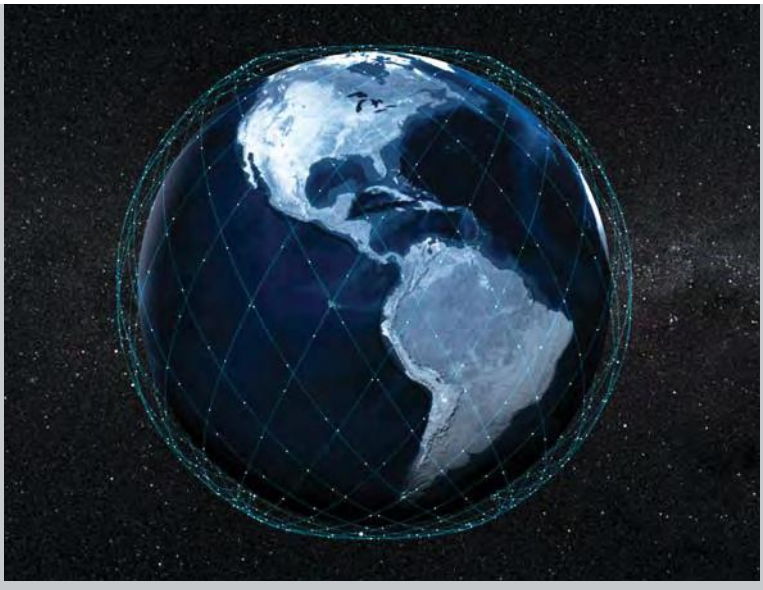
A Limiting Case

The situation may be even more dire for some professional telescopes. Anthony Tyson (University of California, Davis) argues that megaconstellations will most profoundly affect a telescope that hasn't been built yet: the Large Synoptic Survey Telescope (LSST).

The LSST will have an 8.4-meter mirror, an almost 10 square degree field of view, and a 3.2-gigapixel camera. It will record the entire sky visible from Cerro Pachón, Chile, every

NO ACCESS

21.3 million Americans lack broadband internet, according to a 2019 FCC report.



▲ **GLOBAL PRESENCE** This image shows the initial phase of the Starlink constellation: 1,584 satellites in 24 orbital planes at 550 km. (SpaceX has applied to the FCC for a change to this configuration, spreading the same number of satellites across 72 planes.)

▲ **BEAMING BROADBAND** The Starlink network will use specific radio frequencies to provide broadband internet connectivity. SpaceX intends to begin offering coverage to the northern U.S. and parts of Canada in 2020, expanding to near-global coverage by 2021.

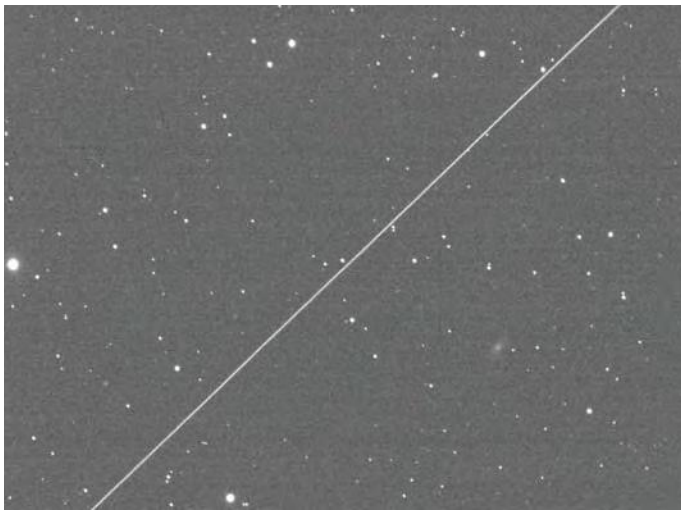
STARLINK WEB AND BROADBAND DELIVERY: SPACEX (2); ONEWEB SATELLITE: ONEWEB SATELLITES

three nights over the course of a decade (*S&T:* Sept. 2016, p. 14). Other professional telescopes may have comparable sensitivity, but LSST's "wide, fast, deep" approach means that it represents what Tyson calls a "limiting case." The average person might simply call it a worst-case scenario. But in some ways, LSST also represents the future of astronomy, as wide- and deep surveys have become the new normal in the field.

To calculate how bright a satellite would be to LSST, Tyson first looked at a series of images taken by one of the Las Cumbres Observatory's 40-centimeter telescopes at Haleakalā, Hawai'i. If that telescope had been tracking the satellite, it would have recorded visual magnitudes ranging from 5.8 to 7.6. However, a satellite crosses multiple CCD pixels over the course of a typical exposure and, without tracking, the satellite trail appears fainter in any given pixel. Correcting for LSST's different instrumentation, seeing, and other factors, Tyson calculated that the telescope would see the same satellite as having a surface brightness of 12 magnitudes per square arcsecond.

That may sound faint, but LSST's CCDs saturate at 16th magnitude in a 30-second exposure. Of course, many stars have magnitudes greater than 16, which is why LSST reads out images in segments. Every image is recorded by 189 CCDs, each of which is 4,000 pixels on a side. Every CCD is separated into 16 segments. "The whole thing gets read out at the same time, in parallel — 3.2 gigapixels in two seconds," Tyson explains. Bright stars, appearing as saturated points, are effectively segmented out by the readout process.

However, because a satellite appears as a streak rather than a point, crosstalk effects between segments as they're read out create copies of the trail throughout the CCD. So, while a single Starlink trail would only pass through a small number of pixels as it passes across a series of CCDs, copies of the trail would impact the entire CCD, not just the individual pixels. These residual effects are hard to completely remove. Based on FCC filings, Tyson estimates that by the mid-2020s, nearly every exposure within two hours of sunrise or sunset would have a streak from a megaconstellation satellite, significantly impacting the science the telescope can do, including the hunt for near-Earth asteroids.



▲ **LAS CUMBRES CAPTURE** This 120-second exposure using a 40-centimeter telescope on Haleakalā, Hawai'i, shows a Starlink trail 75 minutes after sunset. If the telescope had been tracking the satellite, it would have had a visual magnitude of 6.5. Three additional exposures gave magnitudes ranging from 5.8 to 7.6. Scientists working with the Large Synoptic Survey Telescope used images like this one to help gauge the Starlink constellation's cumulative effects.

TODD BOROSON / LAS CUMBRES OBSERVATORY

The more crowded the sky, the less possible avoidance becomes. "At tens of thousands of satellites, it becomes a wild goose chase trying to find an opening."

If even lower-altitude Starlinks launch — and SpaceX plans to launch more than 7,500 to an altitude of only 340 km — they'll likely be a full magnitude brighter. "What that does is it actually 'blooms' across the entire CCD, from one side to the other," Tyson says. "You basically lose the exposure."

Rather than remove satellite trails, Tyson had originally hoped to avoid them altogether. But the more crowded the sky, the less possible avoidance becomes. "At tens of thousands of low-Earth orbit satellites, it becomes a wild goose chase trying to find an opening," Tyson says.

Another option is to paint the parts that would reflect sunlight at observers black. "The Department of Defense paints many of its birds black," Tyson notes. In fact, many countries have been using these low-tech invisibility cloaks for decades, and he has calculated that black paint could reduce the satellites' brightness by 3.5 magnitudes.

Tyson and other professional astronomers have been passing such recommendations along to SpaceX and OneWeb. SpaceX has responded by announcing plans to make the base of its Starlinks black. The next launch, planned for December as of press time, will have one satellite test such a coating.

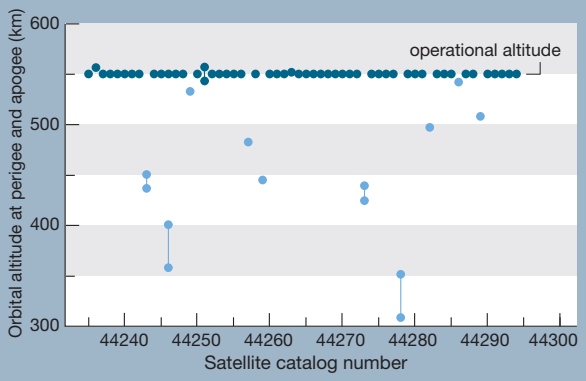
Frequency Protection

Conversations between aerospace companies and astronomers have been most prolific — and perhaps the most optimistic — from the side of radio astronomy, due largely to national and international regulation of radio frequencies.

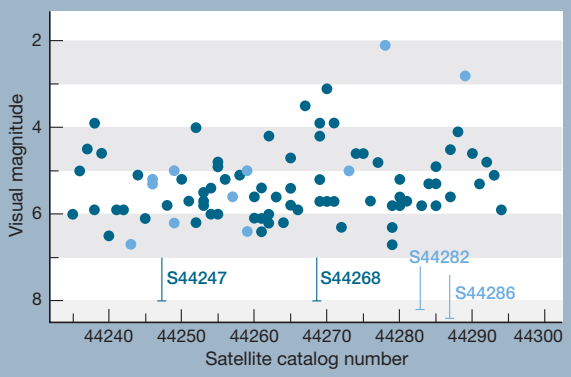
However, the ITU only carves out a few specific frequencies for astronomers. These protected bands, such as the one at 1400 to 1427 MHz used for observing neutral hydrogen in the nearby universe, have regulations in place to prevent interference from other sources. But radio astronomers also observe almost continuously from 1 to 50 GHz, notes Arecibo program director Ashley Zauderer (NSF), even in bands that are not set aside specifically for them. That's because radio astronomy, unlike most uses of radio frequencies, is passive.

"The concern from the radio astronomy perspective is that, up until this decade, above 10 GHz has generally been free of interference," Zauderer says. Most constellation satel-

Starlink by the Numbers: Brightness and Visibility



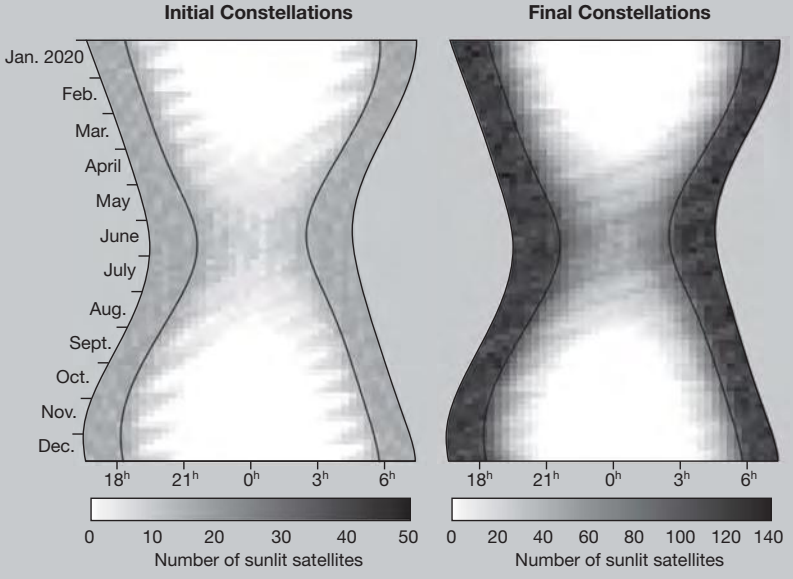
▲ **HOW HIGH?** Observations from the SeeSat-L group contributed to this plot of the altitudes of the Starlink satellites, current as of press time. Fifty Starlink satellites are at an operational altitude of 550 km (dark blue). The ten satellites lower than 550 km are marked light blue. Two of these are intentionally deorbiting, and three more stopped communicating with ground stations and will deorbit naturally.



▲ **HOW BRIGHT?** SeeSat-L contributors Jay Respler, Brad Young, Bram Dorreman, and Ron Lee observed Starlink satellites in July and August 2019, when the majority of the first batch of Starlink satellites had reached 550 km. Those at lower altitudes are marked light blue; satellites with no measurements are marked with vertical lines. Most measurements cluster around magnitude 6, the limiting magnitude for a rural site, and well within range of naked-eye viewing at a truly dark-sky site.

PLOTS: LEAH TISCIONE / S&T; SOURCE: JONATHAN MCDOWELL (2); STARLINK TRAILS: DELVE SURVEY, CTIO / AURA / NSF; SATELLITE VISIBILITY: GREGG DINDERMAN / S&T; SOURCE: CEES BASSA

▲ **STARLINKED** On the morning of November 18th, newly launched Starlink satellites flying at 280 km crossed over the Dark Energy Camera, which is mounted on the 4-meter Blanco Telescope at the Cerro Tololo Inter-American Observatory in Chile. The six-minute exposure of the outskirts of the Large Magellanic Cloud was designed to look for new dwarf galaxies in the Milky Way's vicinity but instead recorded the passage of the Starlink train. These satellites will spread out and fade somewhat in a matter of weeks — but they will still affect professional exposures.



▲ **HOW VISIBLE?** The numbers of megaconstellation satellites visible in the night sky are plotted for an observer at latitude 40°N, with darker squares representing more satellites. The charts show satellite density for a given time of day (horizontal axis) and time of year (vertical axis). *Left:* Here's what could be in store by the end of 2020, assuming initial constellations of 1,584 Starlink satellites and 648 OneWeb satellites. *Right:* Future satellite visibility is based on FCC filings, with 11,927 Starlinks, 1,980 OneWeb satellites, and 3,236 Kuiper satellites. The edge of the plot marks sunset and sunrise, while the interior black line marks astronomical twilight.

lites, though, will use portions of the K_a (26.5–40 GHz) and K_u (12 to 18 GHz) bands for communication, and growing megaconstellations mean this frequency space will increasingly have interference.

To deal with this encroachment, astronomers will have to pursue a combination of technology development and coordination. Right now, for example, most receivers saturate when they come within tens of degrees of a radio-emitting satellite. So National Radio Astronomy Observatory (NRAO) scientists are working to build new receivers that are more resistant to interference.

Coordination with satellite companies will likely play an important role as well. So-called *dynamic sharing*, in which satellites stop transmitting a particular frequency when passing over ground-based radio telescopes, could enable radio astronomers to access parts of the spectrum that might otherwise be unavailable. "I think the technology that we're seeing in these new satellite systems provides a lot of opportunities to not only protect radio astronomy but also expand access to the spectrum," Zauderer muses. "Lots of potential for win-win for everybody here."

It's worth noting, though, that the technology — and therefore the opportunities — vary between satellite constellations. OneWeb, for example, cannot dynamically share radio frequencies because its satellites' beams are both fixed and, due to its satellites' higher orbits, necessarily much larger than Starlink's steerable beams.

The Space Debris Problem

Megaconstellations' potential impact on astronomy is outweighed by their potential to contribute to the growing space debris problem (*S&T:* July 2018, p. 34). Only about 1,950 active satellites were orbiting Earth in early 2019, but SpaceX alone aims to increase that number by 80% by the end of 2020, and by a factor of seven within the decade. These satellites, as well as their accompanying deployment structures, are virtually guaranteed to leave debris behind.

They would challenge a tracking system that's already stretched thin. The U.S. Air Force 18th Space Control Squadron uses radar to track more than 20,000 pieces larger than 10 cm, large enough to shatter satellites and contaminate the space environment. Based on this number, statistical models run by the European Space Agency (ESA) indicate that there are 900,000 pieces between 1 cm and 10 cm. Even one of these smaller but speedy pieces could end a mission. "The energy equivalent of a collision with a 1-cm object is the explosion of a hand grenade," says Holger Krag, head of the ESA's Space Debris Office.

Dead megaconstellation satellites would only add to the current menagerie. With its first launch of 60 satellites, SpaceX reported that three had lost communication with ground stations before they reached operational altitude and were deorbiting naturally. Reentry is expected within a year, in accordance with NASA's guidelines. SpaceX says two additional satellites are being intentionally de-orbited.

However, that doesn't seem to be the full story. "When you look at the reality, the objects' current altitude, there are a number of objects that behave oddly," Langbroek notes. Observations by the SeeSat-L group show that 10 of the satellites had not reached operational altitude by the end of October, and SpaceX has not commented on the five unaccounted-for satellites that have not reached their station.

Even a small percentage of failure is too much, Krag says. "The sheer number, even with good behavior on individual satellites, causes worry."

Another concern is coordination between satellites. Starlink satellites are equipped with autonomous collision avoidance, a feature SpaceX argues puts it on the leading edge of on-orbit debris mitigation. Krag says that ESA's operators perform about one debris avoidance maneuver per year per satellite. Meanwhile, the Starlink satellites had already performed more than a dozen automatic maneuvers within a couple months after launch.

But that works best when facing something inert; encounters between active satellites will require coordination between satellite operators. "Today, there is not even a phone number that I can call," Krag says. "This traffic is not organized at all." That lack of direct communication caused the ESA to redirect its Aeolus wind-monitoring satellite in

◀ **SPACE DEBRIS** This artist's impression of objects in low-Earth orbit is based on actual density data, but the size of the objects has been exaggerated to make them visible at the scale shown.

ESA

September 2019. Calculations had put it on a possible impact trajectory with a de-orbiting Starlink satellite, but the Starlink wasn't moving, so Aeolus had to.

Ultimately, Krag says, data-sharing will be crucial to deciding who should maneuver and how big the maneuver should be. SpaceX is open to working on these solutions with ESA, he adds.

But sometimes, what makes for good space stewardship can have unintended consequences for astronomy. Before the first launch, SpaceX had filed to lower the orbits of its first Starlink satellites from more than 1,150 km to 550 km, so that if one of them did fail, it would de-orbit more quickly. It's these lower orbits that make the objects so bright when seen from the ground.

And professional observatories such as LSST can work to avoid megaconstellation satellites only if the satellites follow their set orbits and don't swerve to avoid a crash. "These guys are moving around! All by themselves!" Tyson exclaims. SpaceX will have to share these autonomous movements promptly if astronomers are to adapt.

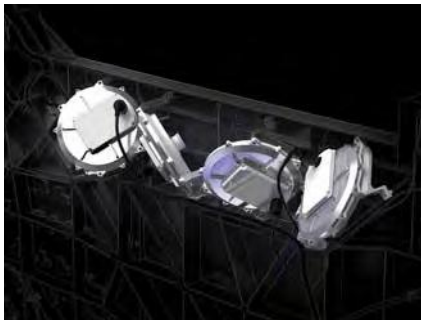
Other companies are working to address the space debris issue in different ways. OneWeb, for example, has rolled out a Responsible Space initiative that focuses less on altitude and more on responsible design.

"We're not launching something with a high chance of failure in orbit," Mike Lindsay, then head of OneWeb's advanced mission design, said at a July 2019 conference. "Once it fails in orbit, it becomes everybody else's problem, and we don't view that as acceptable." By aiming for reliable design rather than quick re-entry times, OneWeb is able to place its satellites at 1,200 km, where the company says there is a lower density of objects.

Taming the Wild West

As this issue goes to press, SpaceX has launched another 60 Starlinks on November 11th, with another three launches in the works. Likewise, OneWeb has a single launch of at least 30 satellites set for January and two more marked for early 2020. SpaceX has also filed paperwork with the ITU for an additional 30,000 satellites. Even though the ITU's approval may take years, the request indicates that megaconstellations are a reality that astronomers won't be able to avoid.

A complicating factor is that space remains largely untamed, legally speaking. The Federal Aviation Administration regulates commercial launches, and the ITU and national agencies regulate frequencies (and to some extent satellite orbits). But there isn't anything that protects the night sky from satellites in low-Earth orbit except for a single federal law against "obtrusive space advertising."

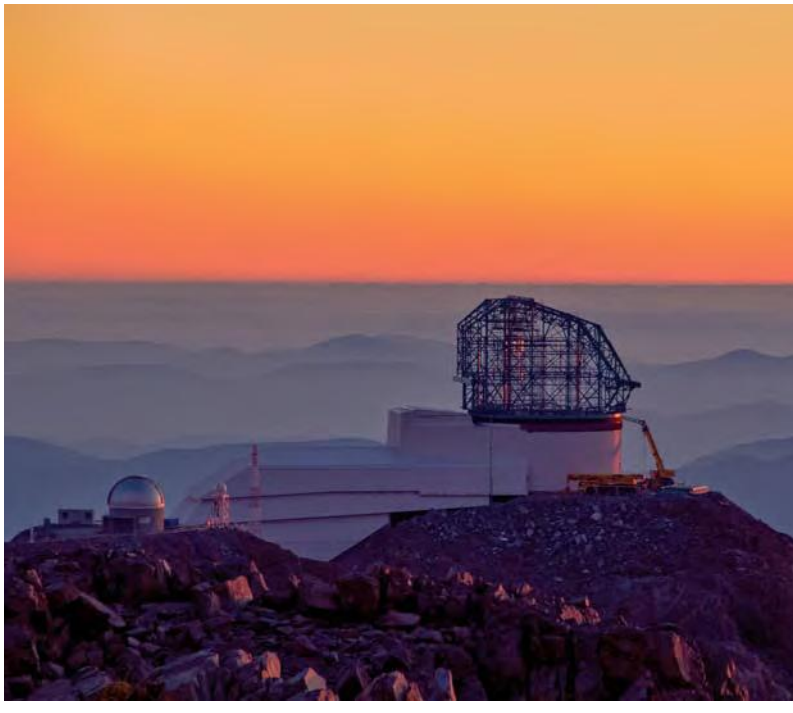


◀ **AUTONOMOUS AVOIDANCE** This figure shows the Starlink satellites' autonomous collision avoidance system. It uses inputs from the Department of Defense's debris-tracking system to maneuver around inert objects.

Until space law catches up, communication will be key. It helps that the space industry has a certain affinity for the stars. "We've found that pretty much every company we've talked to is very enthusiastic about astronomy," says Jonathan Williams (NSF), but he adds, "They don't always know how to put that into practice." For example, following the hubbub around the May 2019 Starlink launch, SpaceX began working with leading astronomy groups from around the world, including the AAS and the IAU, to lessen their satellites' impact on our view of the universe. The recent decision to paint the base of future Starlink satellites black is just one result of these ongoing conversations.

However, as a sea change occurs in low-Earth orbit over the next few years, we cannot rely on companies' goodwill alone. At least one astronomer involved in these conversations expressed skepticism that companies will come through on their promises. Given the rapid change in rhetoric from the SpaceX CEO's initial Twitter dismissals of astronomers' concerns, skepticism is understandable. Policies protecting sky and space will have to be enacted if we are to ensure our access to the universe.

■ *S&T* News Editor **MONICA YOUNG** usually likes shiny things . . . but sometimes she prefers them to be matte black.



▶ **NEW EYE ON THE SKY** The Large Synoptic Survey Telescope (LSST) is still under construction atop Cerro Pachón, Chile. It's expected to begin full science operations in 2023 — when the night sky may look significantly different than it does now.

COLLISION AVOIDANCE SYSTEM: SPACEX; IMAGE OF LSST: LSST PROJECT / NSF / AURA