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 by Anthony Mallama & Monica Young

BEYOND STARLINK: The Satellite Saga Continues

SpaceX has engaged astronomers and made improvements, but with other companies set to launch their own satellite fleets, goodwill is not enough.

The first launch of 60 Starlink satellites aboard a SpaceX Falcon 9 rocket alarmed many, from amateur and professional astronomers to dark-sky advocates and space debris experts (*S&T:* Mar. 2020, p. 14). And for good reason: That batch was only the first volley. SpaceX has now lofted more than 1,100 satellites into low-Earth orbit with the aim of providing high-speed broadband internet to hard-to-reach places around the world. Initial plans call for a "constellation" of 1,584 Starlinks, but ultimately the company intends to fill out a network of as many as 42,000 spacecraft.

SpaceX is the leader of a growing pack when it comes to large satellite constellations. UK's OneWeb, which has launched 74 satellites so far, has approval for 6,372 satellites in all. Amazon's Project Kuiper has likewise filed and received approval for 6,236 satellites. Other companies and countries are getting in the game, too. China, for example, recently inues

GOING GLOBAL A train of Starlink satellites still raising their orbits flies over the town hall in Tübingen, Germany.

filed with the International Telecommunication Union to fly 12,992 satellites.

Even as SpaceX has led the charge into this new industry, the company has also led the way in engaging with astronomers and voluntarily reducing its impact on astronomy. At the virtual 237th meeting of the American Astronomical Society (AAS) in January, SpaceX representative Patricia Cooper presented improvements to the original Starlink design, using a radio-transparent shade to prevent much of the incident sunlight from reflecting to observers on the ground.

The first so-called VisorSat launched on June 4, 2020, and it follows an earlier attempt at mitigation that painted parts of a Starlink satellite black. (This "DarkSat" resulted in thermal issues and was discontinued.) Since August 7, 2020, all Starlink satellites have been VisorSats. SpaceX also altered the relative orientation of the satellite bodies and their solar arrays with respect to the Sun, in order to further diminish their reflectivity. The software changes enacting these adjustments were uploaded to all operational satellites.

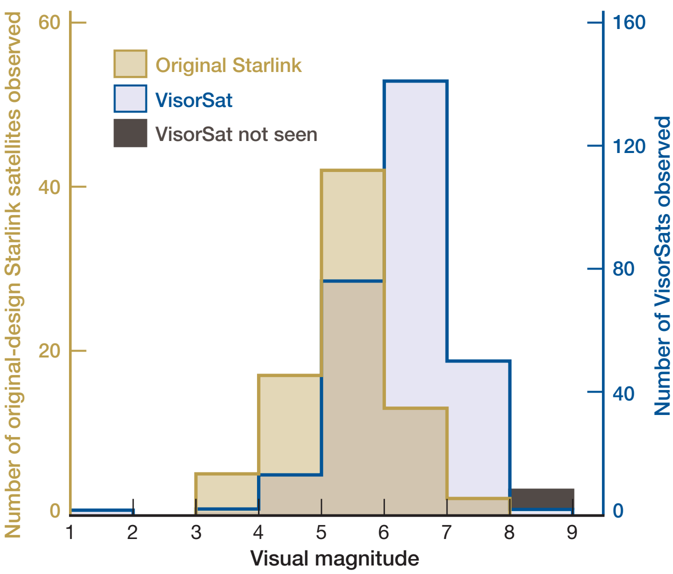
Despite these recent developments, though, the growing number of satellites still deeply troubles astronomers. First, while the mitigations resulted in significant improvement, even the VisorSat design isn't completely unobtrusive to stargazers. And even if SpaceX continues to iterate on that design, there's no legal reason for other companies to follow suit.

VisorSat Is Dimmer . . . But Is It Enough?

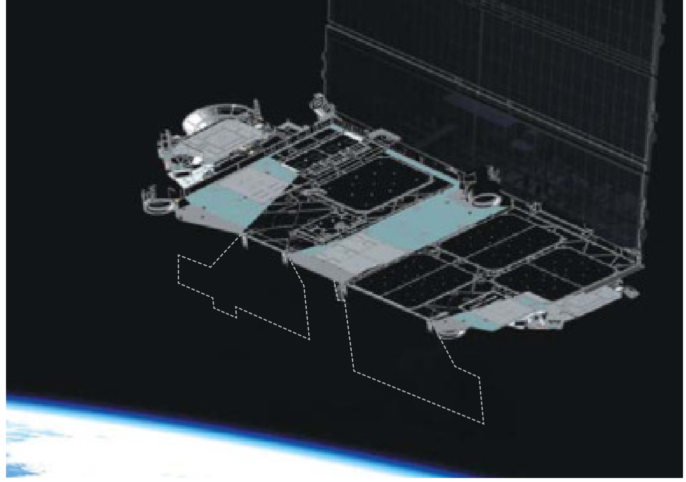
One of us (Anthony Mallama) has studied more than 1,000 observations of original-design and VisorSat satellites in order to compare their brightness at operational altitude (550 kilometers, or 340 miles). The data include visual estimates by Anthony and Jay Respler, both members of the SeeSat-L group of observers, who compared passing satellites to nearby reference stars of known magnitudes. Photometric measurements from a robotic observatory in Russia called Mini-MegaTORTORA (MMT) provide a close match to the eyeball estimates.

To compare the two designs, Anthony first corrected the magnitudes for where the satellite is in the sky. Starlink satellites are nearest, and thus brightest, when passing directly overhead, while those observed toward the horizon are farther away and correspondingly fainter. Anthony adjusted all observed magnitudes to the apparent brightness that would be measured at zenith.

The average magnitude of the original Starlinks is 4.63, making them visible under even moderately light-polluted skies. Conversely, the average VisorSat magnitude is a third of that brightness, at magnitude 5.92 — significantly fainter but still visible from dark, rural skies.



▲ **DIMMING THE LIGHTS** The distribution of visual magnitudes for VisorSats is shown in blue. These satellites are generally fainter than original-design Starlinks, indicated by the beige bars, though the brightness varies due to the spacecrafts' complex reflectivity. A few satellites were too faint to be seen (dark gray) and were assigned magnitude 8.5.



▲ **STARLINK SUNSHADE** This artist's concept of the VisorSat design shows the deployable visor that shades the antennas from sunlight. The visor is transparent to radio frequencies.

There's some variation, though. The brightness of a Starlink satellite can range from roughly 5th magnitude to 7th, likely due to the complicated reflecting properties of these satellites' many surfaces. Thus, an observer under dark skies will see some VisorSats while others will pass by unnoticed.

Based solely on the MMT data, astronomer Patrick Seitzer (University of Michigan, Ann Arbor) estimates that SpaceX's mitigations have dimmed the VisorSats a bit more, to about a quarter of the original design's brightness. But even this result is still brighter than the 7th-magnitude limit recommended by the AAS. That limit is designed in part to put all satellites out of range of unaided eyes.

"The 7th-magnitude brightness target is enormously helpful," Cooper said at January's AAS meeting. "Now we have something to drive toward." At the same time, though, she suggested there might be a limit to what the company can do. "We're going to come to a point of — not the end of creative brainstorming, but some lead prospects that we want to put more effort and emphasis on," she added.

Even if satellite operators meet that limit, though, it won't solve the problem for professional astronomers. The Vera C. Rubin Observatory's chief scientist, J. Anthony Tyson (University of California, Davis), pointed out in the same AAS session that a 7th-magnitude Starlink streaking across the observatory's wide-field camera would still be 40 million times brighter than a typical galaxy in the image.

In a single exposure, astronomers can't apply simple rejection algorithms, such as those that suffice to clean stacked astrophotos. And at that level of sensitivity, a bright-enough satellite creates electronic "ghosts" throughout the image, he explained. While astronomers can remove the ghosts if the satellite streak is fainter than magnitude 7, they can't excise the trail itself. "There's an impact there that's difficult to mitigate," Tyson said.

Beyond Starlink

The 7th-magnitude recommendation came as part of the Satellite Constellations 1 workshop, which took place virtually from June 29 to July 2, 2020. Besides SpaceX, other participants included OneWeb and Amazon's Project Kuiper

VISORSAT: SPACEX; MAGNITUDE COMPARISON: ANTHONY MALLAMA as well as professional and amateur astronomers and dark-sky advocates. They worked together to assemble guidelines for both satellite and telescope operators to mitigate the threat that numerous, bright satellites pose to astronomy, wide-field astrophotography, and stargazers.

In addition to the blanket 7th-magnitude limit, the group also proposed an altitude-dependent brightness limit (starting with 7th magnitude for satellites at 550 km) and recommended that satellites fly no higher than 600 km.

OneWeb's satellites are above that limit, at 1,200 km. They're correspondingly fainter than Starlinks at first glance, with a median magnitude of 7.9. But due to their greater distance, OneWeb satellites travel at slower speeds and therefore appear more in focus to telescopes. According to Tyson, the surface brightness of a 7.9-magnitude, 1,200-km OneWeb satellite streaking across an image is actually the same as a 7th-magnitude Starlink satellite at 500 km.

What's more, OneWeb's higher altitude means a significant fraction of these satellites will remain visible throughout the entire night during summer months. Lower altitudes are therefore actually beneficial to professional astronomy, as they guarantee at least some unobstructed hours.

Despite the recommendation, OneWeb is unlikely to change altitude: It already has approval from the Federal Communications Commission to fly there. The company did, however, significantly reduce the total number of satellites it plans to launch, in part due to new ownership under the UK government following a Chapter 11 reorganization.

Besides OneWeb and Project Kuiper, which together with SpaceX could launch a combined tally of 54,000 satellites, smaller companies are also looking to edge in on the market. "We have dealt primarily with the big three constellations," Seitzer said. "But sliding under the telescope cover, so to speak, there are many smaller constellations of 30 to 50 satellites. My concern is that we will get blindsided by them as their numbers grow and grow and grow."

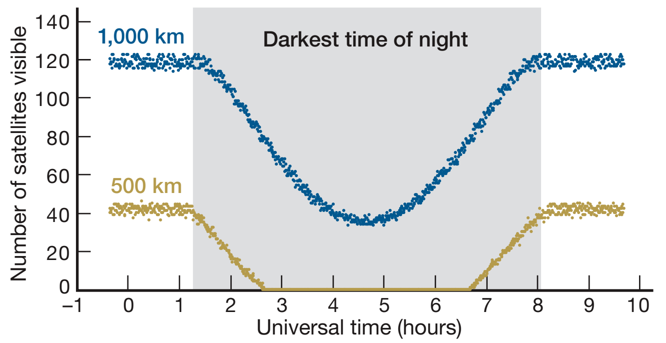
Astronomers and even satellite operators agree that depending on the goodwill of individual companies will not suffice in the long term. International regulations will be key, in part to prevent companies from moving operations to countries with more lax restrictions.

To that end, Connie Walker (NSF's NOIRLab) and colleagues have recently written up a report to be submitted to the United Nations Committee on the Peaceful Uses of Outer Space, outlining recommendations to protect dark skies and including guidelines for satellite operators. The UN is not a regulatory body, so if the plan is ultimately approved, it would then go to member nations for policy and enforcement.

While academia, federal agencies, and international bodies move along at an "Entish" pace, as panel participant Aparna Venkatesan (University of San Francisco) put it for Tolkien fans, the satellite-constellation industry continues to develop at a fast clip. SpaceX aims to provide near-global coverage by the end of the year, and OneWeb plans to have its first-generation network of 648 satellites aloft by mid-2022.

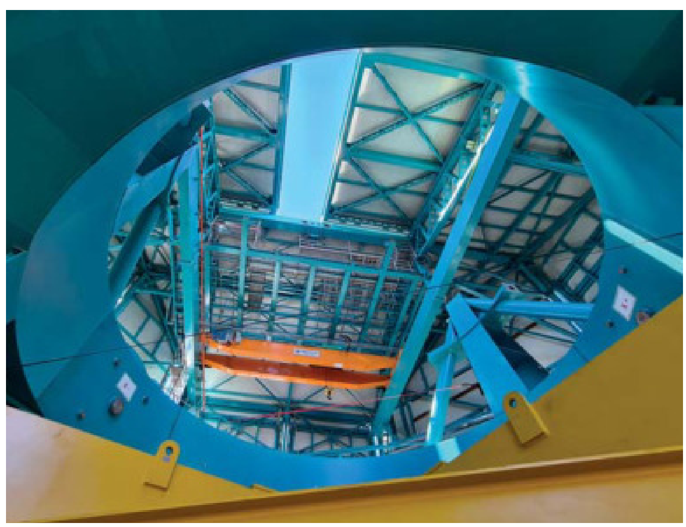
Also in 2022, the Rubin Observatory is due to start full operations, beginning the observations intended to generate a decade-long movie of the night sky. But it will have to do so while dealing with satellites too numerous to dodge and as yet too bright to completely remove from observations.

At the AAS session, Tyson took umbrage at the idea that observatories can take actions now to protect themselves in the future as near-Earth space becomes more crowded. "This notion of future-proofing is a charming idea," he said. "But very frankly, we did a lot of simulations and found that there is no combination of mitigations that we know of that can correct for the lost science — particularly the discovery of the unexpected."



▲ **NIGHTTIME VISIBILITY** This illustrative plot shows satellites' visibility throughout a summer night at 30° latitude depending on their distance above Earth's surface. At each altitude, the calculations divide 10,000 satellites amongst 100 orbital planes with orbital inclinations of 53°. Observed altitudes are assumed greater than 30°. The gray area marks when the night is darkest, between the hours of astronomical twilight.

■ **ANTHONY MALLAMA** is a retired astronomer working with the American Astronomical Society to measure satellite brightness. **MONICA YOUNG** is *Sky & Telescope*'s news editor.



▶ **UNDER CONSTRUCTION** The Telescope Mount Assembly has been assembled inside the Vera Rubin Observatory in Cerro Pachón, Chile. A sliver of blue sky peeks through the dome above.

VISIBILITY COMPARISON: PATRICK SEITZER (UNIVERSITY OF MICHIGAN, ANN ARBOR); VERA RUBIN OBSERVATORY: RUBIN OBSERVATORY / NSF / AURA