

Ballooning satellite populations in low Earth orbit portend changes for science and society

Technological advances and business incentives far outpace space regulations.

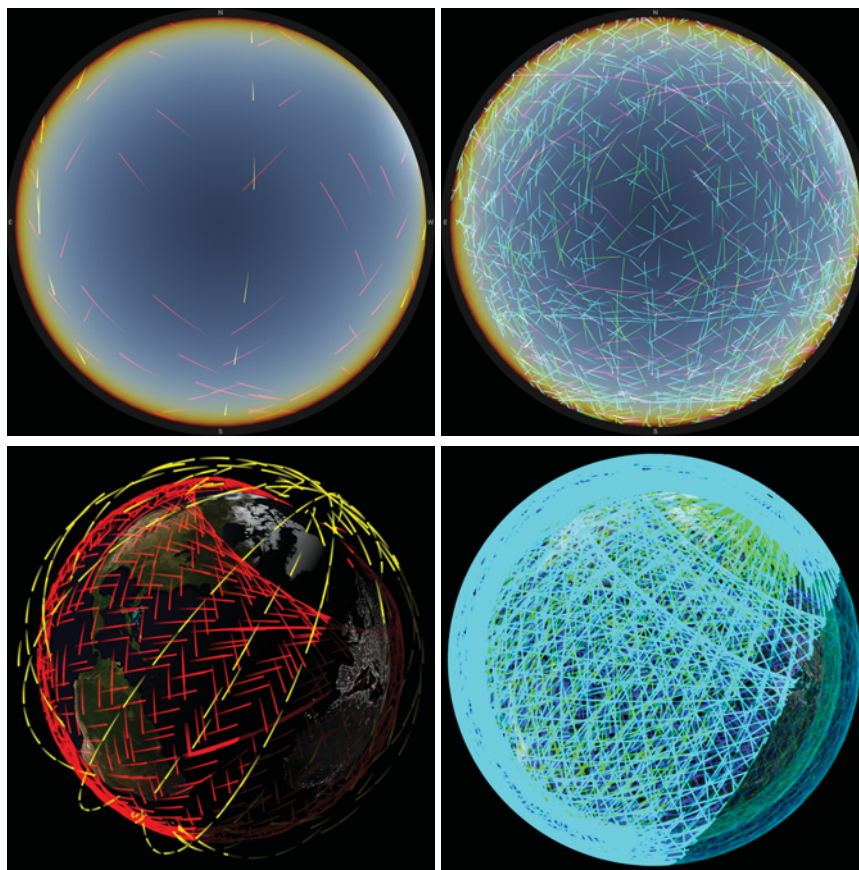
Several hundred thousand satellites could circle the globe in low Earth orbit by 2027, according to estimates based on license applications to national and international communications regulators. That's up from around 6300 active and defunct satellites today and 3300 in 2019.

As companies around the world rush to launch vast numbers of satellites into low Earth orbit, astronomers and others ponder the implications: How many satellites can space accommodate? What happens if that limit is exceeded? What are the effects of increasing launches, burn-up, and space debris on Earth's surface and atmospheric environments? How will celestial appreciation and discovery be affected? What can astronomers, satellite companies, and other stakeholders do to mitigate any ill effects?

Aaron Boley is a planetary astronomer at the University of British Columbia in Vancouver, Canada, who is interested in the sustainable use and exploration of space. Humanity increasingly depends on activities in space, he notes. Global positioning for navigation, time synchronization for banking and other purposes, monitoring activities for global security and disaster relief and recovery, understanding climate change, and providing internet access are examples.

"We want to use space because it can dramatically improve life on Earth," says Boley. But pointing to the depletion of the stratospheric ozone layer, accumulation of plastic in the oceans, and climate change, he cautions that "we humans have amazing capacity to underestimate our own influence on the environment" and that the wanton use of space has the "possibility of degrading the potential for its future use."

At the forefront among companies that plan to put up satellite swarms is Elon Musk's SpaceX. Around 2000 satellites in its Starlink program are currently in orbit, with the full system envisioned to have around 40 000. When SpaceX and



HOW MANY SATELLITE SWARMS can low Earth orbit accommodate? The top images show a view of space from a latitude of 30° S—where the Vera C. Rubin Observatory will see first light in 2025—in stereographic projection at around sunset. The top left image includes existing satellites, and the top right incorporates the full systems of Starlink, OneWeb, and Project Kuiper. The two lower images show Earth from space with satellites buzzing around—again with existing numbers on the left and with the three planned megaconstellations on the right. The images were made with the freely available Mega Constellations app created by Hanno Rein of the University of Toronto Scarborough.

others have put 65 000 satellites in orbit, "one out of every 15 points of light you see in the night sky will be a moving satellite," says Samantha Lawler, who studies the Kuiper belt at the University of Regina in Saskatchewan, Canada. OneWeb has launched 358 of a planned constellation of 6372 satellites—down from earlier plans for 48 000. Amazon's Project Kuiper is preparing to launch 7774 satellites. Other planned constellations include ones from China, with 12 992 satellites; Rwanda, with more than 327 000; and the Canadian company Kepler Communications, which has

launched a few satellites and plans to create—or sell spots in—a constellation of 115 000.

"We are changing the sky," says Meredith Rawls, a University of Washington astronomer who works on data pipelines for the Vera C. Rubin Observatory under construction in north-central Chile. "We are at a turning point." Brighter skies from the sheer number of objects floating around reduce the number of stars anyone can see. And satellites and space debris complicate telescope observations. (For more on space debris and space environmentalism, see the

interview with Moriba Jah at <https://physicstoday.org/jah>.)

Bright satellites

Satellites are visible when they reflect sunlight. The brightness depends on such factors as the materials, size, shape, position, orientation, and altitude of the satellite; the latitude, season, and time of night on the ground; the observing angle above the horizon; and the diameter of the telescope mirror. For an observer at 30° S—the latitude of the Rubin telescope—satellites at 600 km reflect sunlight for a few twilight hours at dusk and dawn.

So what's the harm of a satellite flying through the field of view of a telescope? Astronomers don't have the full answer yet. There are too many unknowns to accurately predict, says Jonathan McDowell of the Center for Astrophysics | Harvard & Smithsonian. How many satellites will actually be launched into low Earth orbit? How reflective will they be? What mitigation measures will be implemented?

Still, some satellite impacts are clear: For optical wavelengths, telescopes with a wide field of view and long exposure times will suffer most. Satellites are most visible at twilight, which will make it more difficult to detect near-Earth asteroids, and some could be missed. Transient events, such as supernovae explosions, could be obscured. And, says McDowell, "Faint things you don't know are there could be missed."

"You are hosed"

In May 2019, when SpaceX launched the first 60 Starlink satellites, the Rubin Observatory chief scientist, Anthony Tyson, began investigating their effect on astronomical observations. In lab experiments at the University of California, Davis, with the same CCD chips that the Rubin Observatory will use, he and colleagues discovered that satellite streaks are accompanied by parallel streaks caused by nonlinear cross talk in the electronics. Their calculations suggest that if the satellites are no brighter than seventh magnitude (coincidentally also the limit of what the naked eye can see in a dark, clear sky), the "ghost streaks" can be removed computationally.

"With 100,000 satellites, every Rubin exposure will have at least one satellite streak across the focal plane," says Tyson. Even if ghosts are suppressed, he says, "the main streaks will still need to be

masked out, at the cost of lost survey area." (See "Dark-sky advocates confront threats from above and below," PHYSICS TODAY online, 9 February 2022.)

The European Southern Observatory's 40-meter Extremely Large Telescope under construction in Chile and other behemoths—the Giant Magellan Telescope and the Thirty Meter Telescope, which are not as far along—have smaller fields of view but will still be affected because of their typically long exposure times.

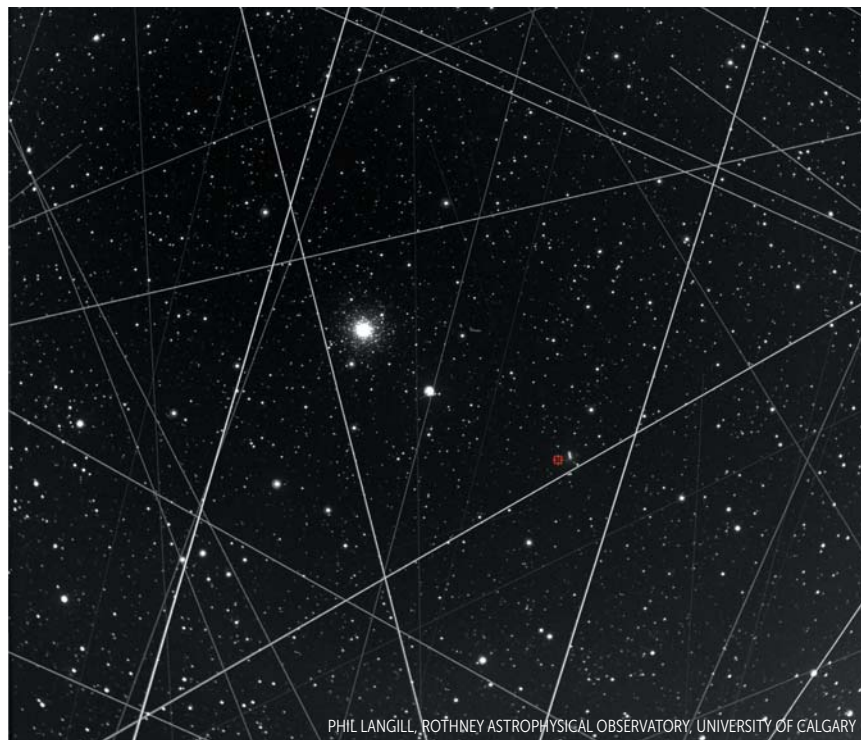
Multiobject spectroscopy is also vulnerable. Individual optical fibers positioned by small motors collect light from selected targets. "Some poor astronomer will have to figure out which fiber has been polluted by light reflected from a passing satellite," says Tyson. In terms of identifying interference, he adds, "their job is harder than ours at Rubin. We know immediately if we have a streak."

For a telescope with a wide field of view, "there is no dodging," says Rawls. But all telescopes will be affected—it's a matter of degree. If fewer than one streak per field of view is captured, corrupted images can be thrown out or cropped, says McDowell. But if a regime develops

such that there are many streaks in every image, "you are hosed."

Radio astronomy is especially vulnerable because downlinks from satellites overpower the signals from celestial sources. Some parts of the spectrum are protected by International Telecommunication Union (ITU) rules. Harvey Liszt is spectrum manager for the US National Radio Astronomy Observatory and chair of IUCAF (the international Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science). But ITU protection goes only so far, he says. Nowadays radio astronomers want to look at much more of the spectrum than decades ago when the regulations were adopted, he explains. "Because the universe is expanding, we receive redshifted signals from distant receding sources."

Moreover, special protections for radio telescopes in remote locations apply only to ground sources. "We have no protection from satellites," says Federico Di Vruno, spectrum manager at the Square Kilometre Array Observatory (SKAO), which is being built in Australia and South Africa. Radio telescopes may be able to partially adapt by recording shorter exposures to maximize their clean



SATELLITE STREAKS CRISSCROSS a two-hour sequence of observations collected in May 2021 at the Rothney Astrophysical Observatory outside of Calgary, Alberta, Canada. Near the center is a globular cluster and marked in red is a comet.

data, says Di Vruno. Interferometry also helps, he says, by “diluting the effects of signal from satellites.”

“The new constellations pose a large change in the way we see the sky,” says Di Vruno. “The difficulty is understanding how, and how to avoid both the immediate downlink and spillover noise.” Liszt notes that radio astronomy has contended with satellites for decades. “The sky is falling, just not all of it, because satellites don’t use the whole spectrum.”

Astronomers are also contemplating hardware solutions. In radio astronomy, it may be possible to modify receivers to mask satellite signals. And a small wide-angle optical telescope could be placed near a much larger telescope to identify fibers in spectroscopic studies that get blasted with a satellite reflection. “If you pour in enough money, that might work,” says Tyson. “You have to know the satellite is there, and how bright it is, to know how much solar spectrum to subtract.”

Industry and regulatory measures

“The main problem for astronomy is that there is almost zero regulation,” says Andrew Williams, who handles external relations at the European Southern Observatory. “The current regulatory landscape is not fit for these massive satellite projects.” Astronomers, satellite companies, and others are working with national and international agencies to formulate policies.

At its annual meeting in February, the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) discussed keeping skies quiet for science and society. “They added an agenda item for us for next year’s meeting,” says Connie Walker of NSF’s NOIRLab. “That is a feat.” Working at the policy level is slow and hierarchical, she says, “but eventually things get accomplished.” And because the UN operates through consensus, once resolutions are adopted, they can be influential. “We hope the UNCOPUOS endorses best-practice guidelines,” says Williams. “That would create a social norm to consider. We are also asking for recognition that astronomy is part of the space domain.”

Richard Green is assistant director for government relations at the University of Arizona’s Steward Observatory. He notes that an industry group is developing best practices for space use. Astron-

omy, he says, “will get the farthest and fastest by cooperating with the satellite companies.” Eventually, he adds, “the mitigations should become a requirement for getting licenses to launch or operate.”

Indeed, technology advances are far outpacing formation of legal frameworks, so for the short and medium term, astronomers are forced to rely on the goodwill of companies. The satellite companies “didn’t set out to ruin astronomy,” says the University of Washington’s Rawls, “but it can be a side effect.” Any mitigations by operators are voluntary, she notes. “There is nothing compelling them to take the needs of astronomy into account.”

SpaceX painted satellites dark to make them less reflective. That made them too hot. Visors work better, but they block laser signals between satellites. Other approaches to reducing reflections include adjusting satellite orientation and optimizing surface materials. A spokesperson for Amazon says the company will test mitigation methods this fall with prototype missions for its Project Kuiper.

At higher altitudes, Earth provides less shadow, and satellites are visible for more of the night. They also move more slowly. So even though a satellite at higher altitude would be dimmer than one at lower altitude, the slower motion means more light would be collected by a given pixel in a telescope camera. “Due to the impacts on ground-based astronomy and concerns about debris generation and longevity,” the top priority recommendation in a 2020 report by the government advisory body JASON is to “eliminate or highly regulate large satellite constellations in orbits higher than 600 km.” OneWeb’s satellites are at 1200 km, but most of the other planned constellations are below 600 km.

For some observations, astronomers say, accurate information about satellite positions and trajectories would be extremely helpful—they could time data collection. But trajectories are sometimes adjusted on short notice to, for example, avoid collisions with other satellites or debris.

“If some companies set a good example,” says Rawls, “we hope others will adopt similar mitigation measures.”

Coordinating protection efforts

Considerations for how to deal with a surging satellite population are coming

under the umbrella of the new virtual Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference. Launched on 1 April by the International Astronomical Union (IAU) and cohosted by NSF’s NOIRLab and the SKAO, the center has four hubs. They focus on policy, industry and technology, community engagement, and data and software. Walker, codirector with Di Vruno, says that the center “will try to coordinate efforts among all involved parties, unify voices across the astronomy community, and work with industry.”

The center is starting with €135 000 (\$150 000) for three years from the IAU. The center’s data and software hub is tasked with creating a repository for information related to satellite interference, writing software to minimize the interference effects, and more. “Solutions won’t be one-size-fits-all,” says Walker, “but hopefully we can create tools that can be tweaked to accommodate different situations.” A major challenge is money, she adds. “So far, people have been working pro bono. They can’t do that forever. They have jobs.”

“We are pretty good at finding solutions,” says McDowell. “But we need resources. And working on this takes time away from doing science.” Regina’s Lawler agrees: Professional astronomy will lose data, she says. “And it will take more money and time to get discoveries.”

The plan for the IAU hub on community engagement is to bring together environmentalists, Indigenous communities, astrotourism interests, astrophotographers, and planetarium professionals. Everyone has a stake in the skies, says Aparna Venkatesan, an astronomer at the University of San Francisco who is involved with the IAU hub. “Right now space is a free-for-all,” she says. “The system is set up to benefit a few, and space is vulnerable to rogue action. We hope that the IAU will start an international dialog and lead to a more equitable and thoughtful use of space.”

For astronomers, as well as for amateur sky gazers and for people who care about cultural heritage, the best outcome would be to keep the numbers of satellites to a minimum. But billions of dollars are “chasing these companies to launch as soon as possible,” as Tyson puts it, “so that’s not going to happen.”

“I give SpaceX credit for stepping up

to the plate and trying to mitigate,” says Tyson. Still, he adds, at the end of the day, they may not reach the seventh-magnitude goal.

“There is a huge fear of offending the satellite industry,” says an astronomer who requested not to be identified. The concessions by industry are small, the astronomer says. The growing population of satellites “is an existential threat to astronomy.”

Traffic jams

Even if concerns for astronomy don’t lead to international regulations, orbital crowding might. “We have never operated in the environment we are about to create—congestion will be much higher than we have experienced before,” says British Columbia’s Boley. Collisions create debris, which can lead to more collisions. Such a runaway cascade could render future launches dangerous or impossible—and imperil satellites and the International Space Station. Estimates by JASON, NASA, and others show significant dangers at 1200 km with 8000 satellites. At lower altitudes, runaway cascades could also occur, but atmospheric drag slows debris.

When satellites burn up on reentry, they spew aluminum and other materials into the atmosphere. Launches also pollute. The Starlink satellites will each be operational for five years. “If you do the math,” says Lawler, “on average you deorbit 23 satellites a day. That comes to about six tons of aluminum added to the upper atmosphere.” That would be more than from naturally occurring meteorites,



BETTMANA FOOT/INTERNATIONAL DARK-SKY ASSOCIATION

FAJADA BUTTE in Chaco Culture National Historic Park, New Mexico, shown here during an astronomy festival in 2018. The site is a registered International Dark Sky Park. Views of the sky will be compromised by the ballooning population of satellites.

she notes, which deposit more mass, but are made mostly of oxygen, silicon, magnesium, and iron.

Space is getting crowded, says Venkatesan. “The different stakeholders—astronomers, the military, storytellers,

knowledge holders, cultural practitioners—all want access to space for the next few centuries, not just the next few years. That’s where I think we can unite.”

Toni Feder 

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