BRIGHTNESS MITIGATION BEST PRACTICES FOR SATELLITE OPERATORS

Space exploration is fundamental to SpaceX's core mission. SpaceX has therefore taken unprecedented steps to work with the astronomy community to better understand how SpaceX--and all satellite operators--can mitigate the effect that the Sun's reflection off of satellites can have on astronomical observations.

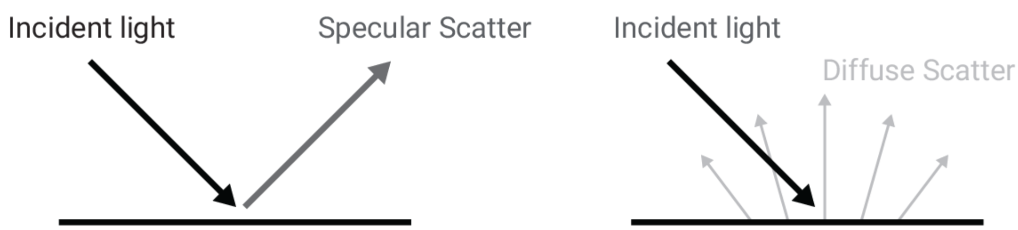
As a result of this deep, collaborative work, SpaceX has implemented innovative technological solutions and techniques to minimize its satellites' effect on the night sky. In fact, SpaceX has invested more than any other satellite owner/operator to develop and deploy such technologies and techniques. Below is an update on SpaceX efforts, which we have previously shared here, and their beneficial impacts.

Brightness Mitigations

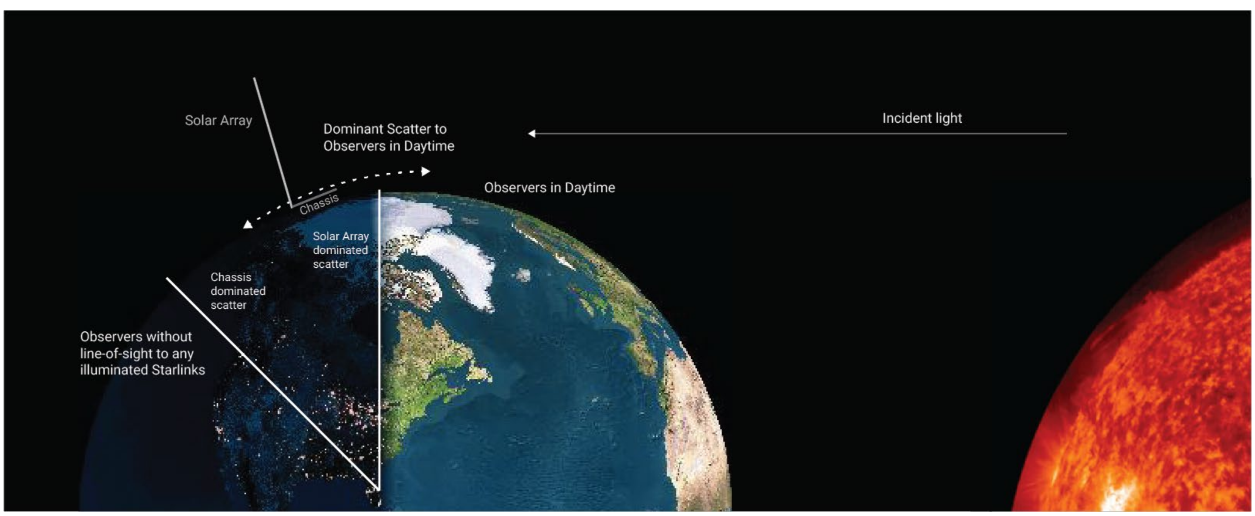
Through its collaboration with the astronomy community, SpaceX has identified and mitigated the main sources of satellite brightness and has sought to make its satellites invisible to the naked eye when at their standard operational altitude.
Any satellite can be visible from Earth at night if it is illuminated by the Sun and scatters light to Earth observers. Satellites typically are visible when they are just over the dark side of the terminator (the day/night boundary on Earth), corresponding to the first several hours into night and before dawn. Several factors determine a satellite's visibility from the ground. Satellites at higher altitudes are illuminated deeper into night; whereas, satellites at lower altitude will have incident sunlight blocked by Earth shortly after sunset or sunrise. For instance, satellites at 1200km are visible at midnight to observatories like the Vera Rubin Observatory (the top-ranked large ground-based project in the 2010 Astrophysics Decadal Survey). SpaceX satellites will be invisible to the Vera Rubin Observatory at midnight as they won't be illuminated.

The visibility of a satellite also depends on the materials used for its surfaces. Unlike objects like street lights that create light pollution, a satellite typically does not emit its own light. Instead, brightness results from natural sunlight scattering off the satellite's surfaces and reflecting back to Earth. This light can scatter off the satellite in two ways: specular or diffuse. Specular light is reflected at a single angle like a mirror. In contrast, diffuse light comes off the surface at all angles, and while giving off a matte appearance when looking at a satellite, the reflected light is viewable from more directions. While counterintuitive, satellite flat nadir pointing surfaces that reflect more like a mirror actually have less impact on astronomy because a perfect reflection would never intersect Earth. Diffuse reflected light, conversely, spreads across – and can therefore be seen from – multiple angles. As described below, SpaceX has therefore invested in specular surfaces.

But not all materials are highly reflective; some materials can be "absorptive," meaning that the light reflected by the surface is much less bright than the incident sunlight that it is reflecting. Absorptive materials can be specular or diffuse. But no materials are perfectly specular, diffuse, or absorptive. Rather, all materials have varying degrees of reflectivity and a varying amount of specular and diffuse content. SpaceX invests in absorptive materials for surfaces that are not flat nadir pointing.



SpaceX satellites have two primary drivers of visibility from the ground: sunlight scattering off of the main body (or “chassis”) of the satellite, and sunlight scattering from the solar arrays. SpaceX has adopted mitigations for both issues on its current, first-generation satellites. But because SpaceX now has a better understanding of brightness, it plans even better mitigations on its second-generation satellites.

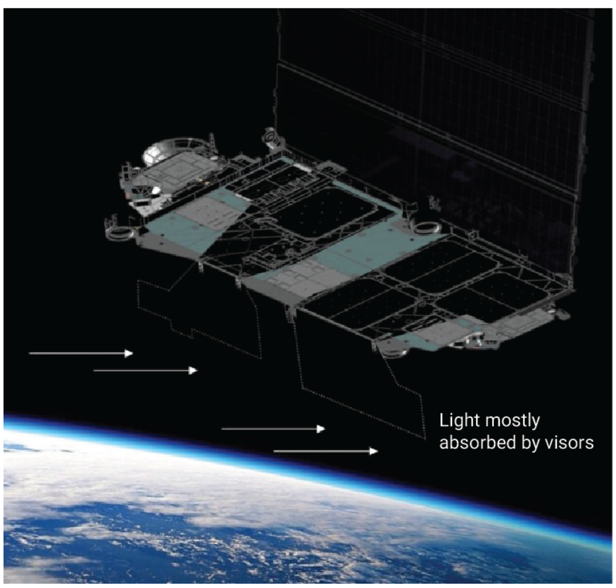


First-Generation Satellites

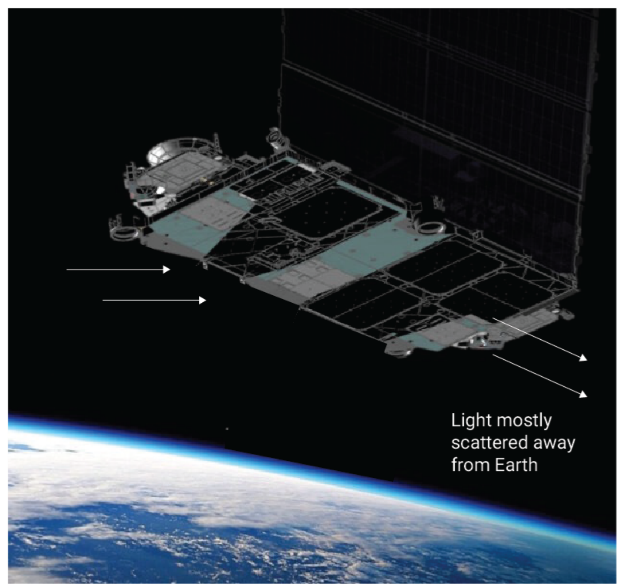
On its first-generation satellites, SpaceX developed "sun visors" that blocked sunlight from hitting the bottom side of the chassis. SpaceX successfully developed material for the visors that was "transparent" to radio frequencies and would not block the user-serving antennas of SpaceX's satellites. Unfortunately, the material did block the laser links that SpaceX needs to expand coverage to the most remote regions of the world. The visors also generated significant drag on the satellites. Because SpaceX operates at such low altitudes, this higher drag requires more thruster fuel expenditure to increase orbit altitude and station-keep once at the operational altitude. For these reasons, SpaceX ultimately determined that its sun visors were not a viable long-term solution.

As an alternative to sun visors, SpaceX started developing RF-transparent mirror films. This dielectric mirror film specularly scatters the vast majority of sunlight away from the Earth. SpaceX has been continually improving its mirror films to scatter less light back to Earth, and will be deploying a new and improved version of this film on our next-generation satellites.

Visors

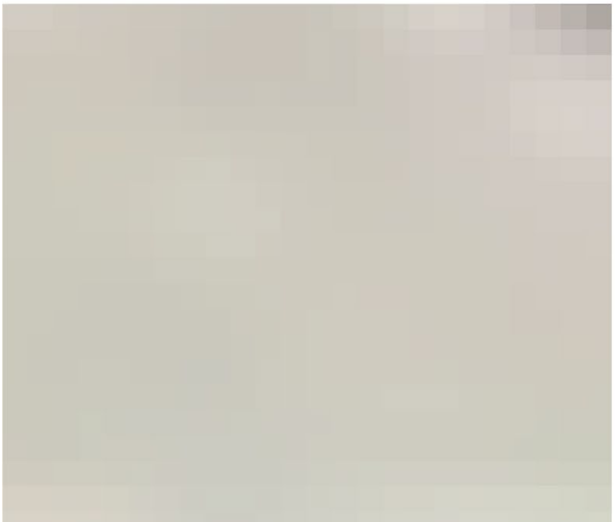


Dielectric Mirrors



Another significant brightness mitigation that SpaceX implemented on its first-generation satellites is using a darker material between the solar cells on the front of the solar array. As shown below, this inter-cell backing material was initially white, but it is now pigmented dark red, which reduces the arrays' brightness. Darkening this material increases solar array temperature, and consequently reduces performance, but SpaceX has opted to adopt many design concessions like this to reduce observed brightness.

Initial v1 Inter-Cell Material



Darkened v1 Inter-Cell Material

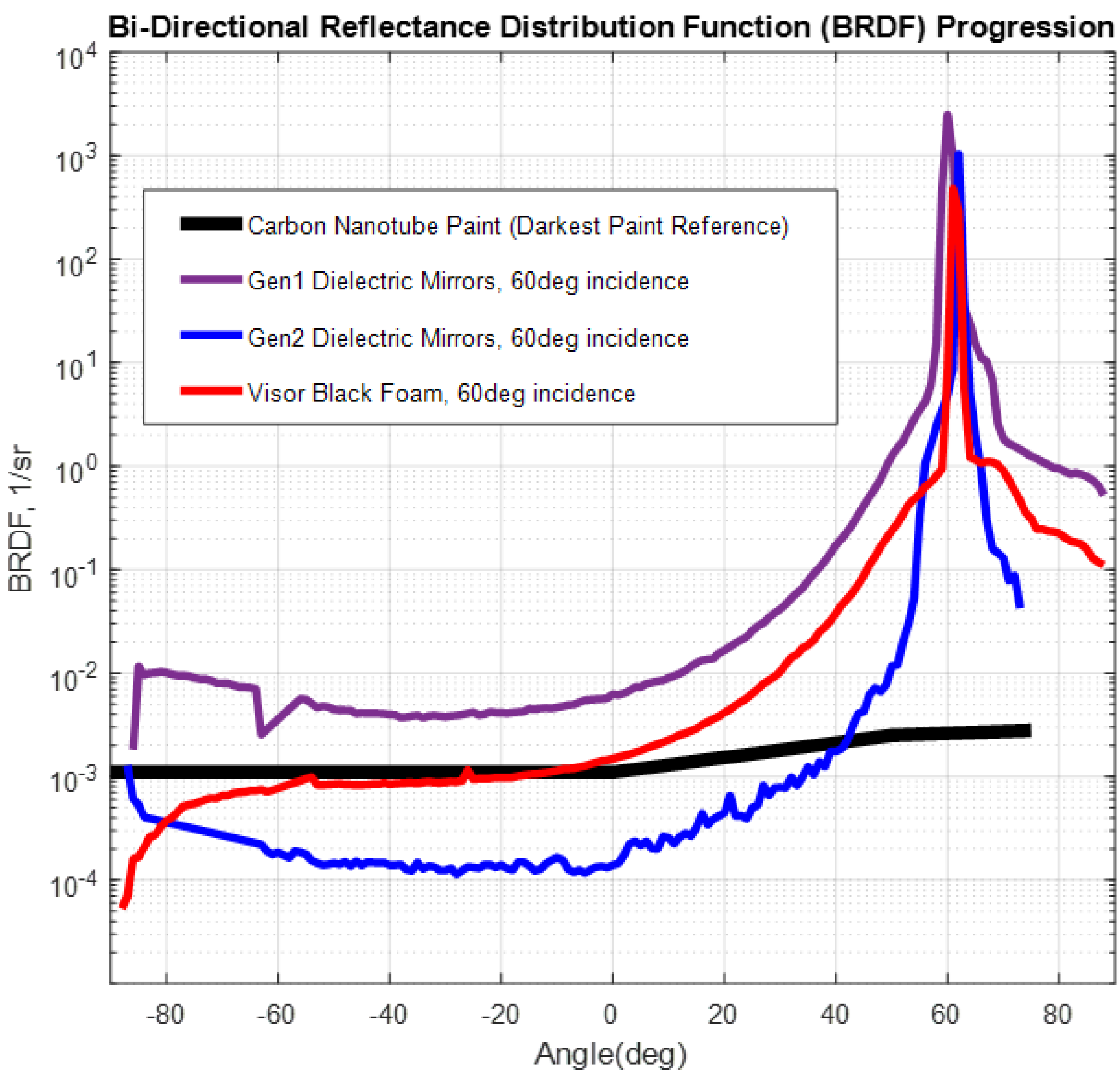
Second-Generation Satellites

SpaceX's second-generation satellite will add even more capacity to the Starlink network and connect more people in more places. All user terminals that customers already have are capable of connecting to both first- and second-generation satellites.
Even though its second-generation satellites are larger than its first-generation satellites, SpaceX still expects the second-generation satellites to be darker than the first-generation satellites due to its brightness mitigation efforts.
The second-generation satellites have a “flat sat” architecture much like the first-generation satellites, as this enables dense packaging of the satellites into Starship and provides low drag during operation. The phased array antennas that serve users are on the bottom face of the satellite, and parabolic antennas for gateway connections and laser terminals for laser links between the satellites are on the perimeter. The satellites have a greater surface area to mass ratio compared to the first-generation satellites so that they passively drag-deorbit faster in the event of a failure (you can read more here about our approach to space sustainability and safety).

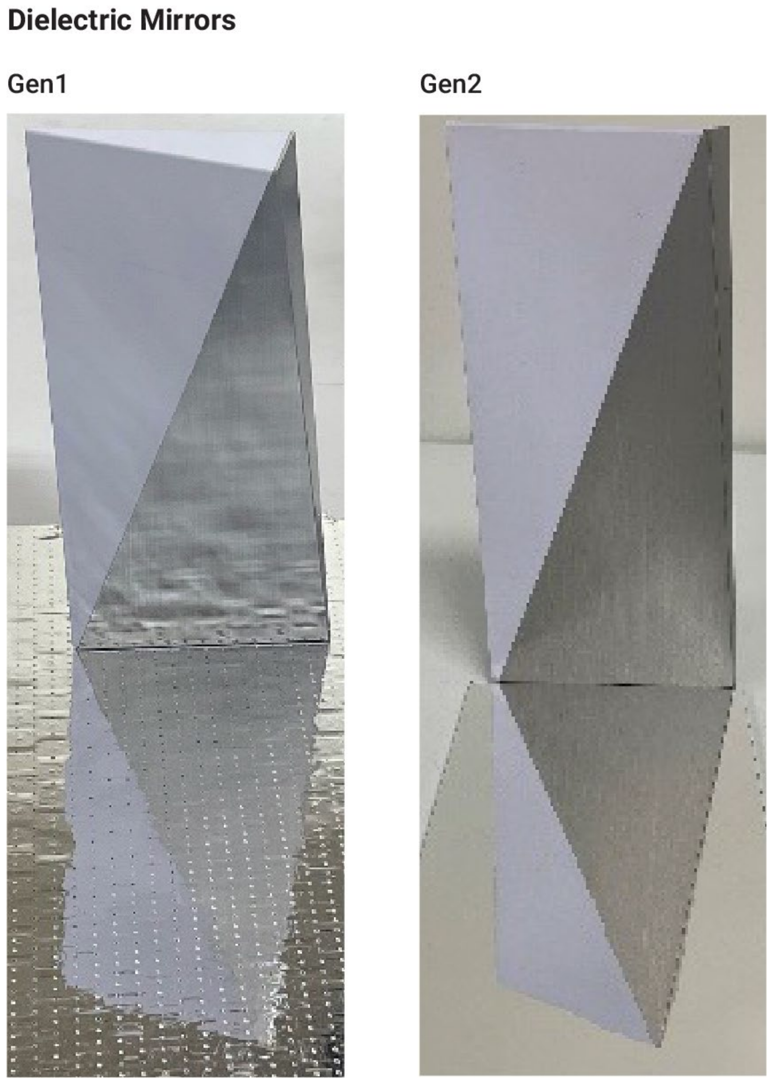
The second-generation satellites will employ three advanced brightness mitigation techniques:

Dielectric Mirror Film

SpaceX covers the bottom of its satellites with a second-generation dielectric mirror film, which is 10x better at reducing observed brightness than the first-generation film using a Bi-Directional Reflectance Distribution Function (BRDF) metric. The chart below shows the BRDF for various solutions to decrease visibility, including SpaceX's new dielectric mirror film, the older film, black foam used on the visors, and black paint. The peak in this chart corresponds to the specular reflection opposite the incident angle and the value at 0 degrees corresponds to an observer looking directly up. As you can see, while the first-generation mirrors were brighter than the black foam used for the visors, the second-generation mirrors offer an order of magnitude reduction for observers looking directly overhead (note that the y-axis is a logarithmic scale).

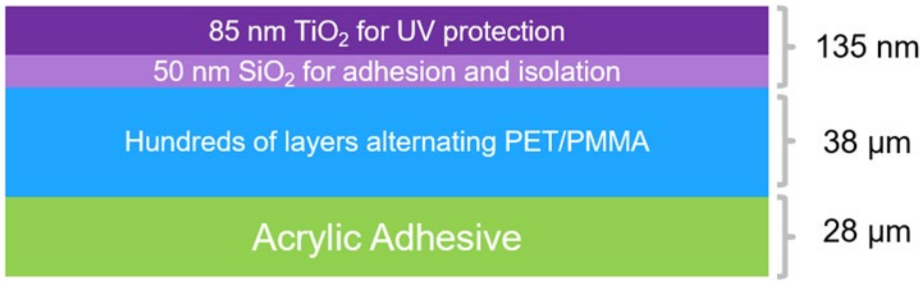


This improvement can be seen with the naked eye as demonstrated in the images below showing reflection of an older version Starlink WiFi router sitting on top of the old and new mirrors.



SpaceX has maximized the film’s specular scatter through extensive research and iteration. The core of the film is a Bragg mirror, which includes many thin layers of plastic with different refractive indices that create interference patterns internally to reflect light, but allow radio waves to pass through unimpeded. To survive the space environment (where ultraviolet degradation and atomic oxygen are problematic), protective layers of titanium dioxide (TiO_2) and silicon dioxide (SiO_2) are deposited to protect the film. These layers are thin and pure enough to not affect the film’s behavior.

But SpaceX cannot reduce the effect on space exploration alone – all satellite operators must work together. Towards that end, SpaceX will offer this film at cost as a product on the Starlink website so that all operators may use it to reduce the effect of their own constellations on astronomy and the night sky.

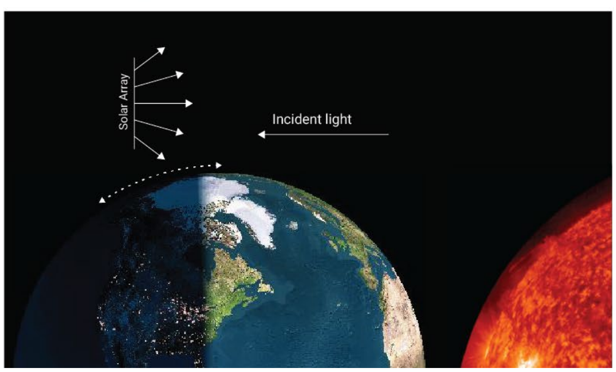


Solar Array Mitigations

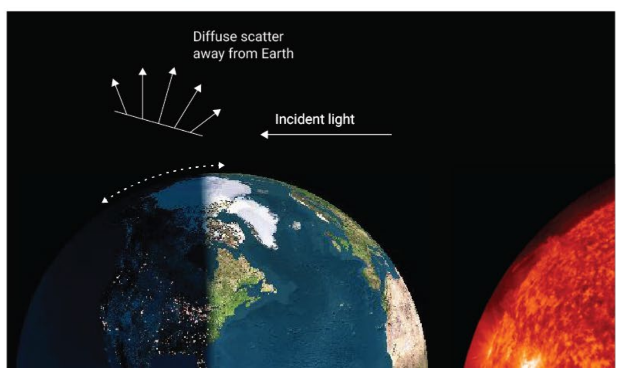
Solar arrays can also serve as a source of satellite brightness. Specifically, the front side of the solar arrays, which includes the solar cells, can scatter sunlight onto the ground, and the back side of the solar arrays can be lit up by the sun like a lampshade. SpaceX has taken steps to reduce the brightness from both of these sources on its second-generation satellites.
To mitigate the brightness from the back side of the solar arrays without overheating the solar cells, SpaceX developed an opaque pigment for the solar backsheet.

To scatter sunlight hitting the front side of the solar arrays, the second-generation satellites will point the solar arrays away from the Sun when crossing the terminator (the line on Earth's surface separating night and day) in a maneuver called "terminator tracking." This maneuver will point the knife edge of the solar array at the earth limb, which minimizes brightness when viewed from the ground, as shown in the image below.

Sun Tracking Ideal Power Generation



Brightness Mitigation Reduced Power Generation



Notably, this off-pointing maneuver results in a 25% reduction in available power for the satellite. Despite this cost, SpaceX has specifically designed the second-generation satellite to be able to accommodate this significant power reduction to minimize brightness as viewed from the ground.

Black Paint
Many small components on the second-generation satellite also collectively contribute to the overall brightness of the vehicle. For that reason, SpaceX assesses every component on the satellite that could be visible from the ground in any of the vehicle's flight attitudes – every antenna, every device, and every bracket, etc. SpaceX uses dielectric mirrors to minimize brightness on surfaces that are flat, while using black paint for components with complex geometries to minimize brightness and glints that occur when highly specular scatter intersects Earth. SpaceX will orient the flat satellite nadir surface so that the specular peak never intersects Earth. Unfortunately, this technique is not possible for all satellite components. For example, parabolic dishes must articulate and point at ground stations. If the dishes were specular (such as bare aluminum), then Earth observers would see glints at certain orientations. To mitigate these potential glints, SpaceX internally developed a “Low Reflectivity Black” paint, which has a five-times lower specular peak compared to the darkest available space stable paint. SpaceX also uses black paints on other components.

Flight Operations

SpaceX’s goal is to make its second-generation satellites invisible to the naked eye when they are on station serving users, covering the vast majority of each satellite’s lifetime. However, there are a few phases of flight where satellites are expected to be visible for small portions of their life.

- Immediately After Launch: During their first several orbits after dispensing from the rocket, the satellites need to stabilize and deploy antennas and solar arrays. During deployment, light is likely to reflect from the mirror film onto the ground instead of out into space.
- Orbit Raise: During orbit raise from the insertion orbit to the operational orbit, the satellites need to maximize power generation and minimize drag at low altitudes and aren't able to perform solar array off-pointing.
- Station Keeping and Collision Avoidance Burns: The satellites periodically need to perform burns on station to maintain their position in orbit and avoid collisions, and they will be brighter during such operations.
- Deorbit: Just like during orbit raise, satellites will be brighter at the end of their life while lowering their orbits until they burn up on reentry.

To address these situations, SpaceX continues to refine satellite attitude and solar array pointing techniques during orbit raising and deorbiting to mitigate brightness while still meeting mission objectives. Furthermore, SpaceX continues to work with a wide variety of astronomers, observatories, and astronomy-related groups to understand astronomer experiences, describe mitigations, and help minimize the effect of satellites on imagery. SpaceX also publishes very accurate state predictions for Starlink satellites, primarily for coordination with other satellite operators on collision avoidance, but also to enable highly sensitive ground telescopes to best schedule observations.

Summary and Future

While SpaceX has spent considerable engineering effort on mitigating satellite brightness from the ground, no engineering model is perfect. For that reason, SpaceX expects to continue to find and implement technologies and operational techniques that further reduce the brightness of its second-generation satellites. SpaceX will continue to work closely with the astronomy community to mitigate the effect of all satellite operations on their important work.
SpaceX engineers will be presenting in-person and answering questions at the Vera C. Rubin Observatory Project & Community Workshop 2022. SpaceX also participates in other astronomy conferences and workshops.

We encourage any and all questions, feedback, and discussion. SpaceX is committed to connecting as many people as possible through Starlink, improving the lives of millions of people here on Earth.

As a space exploration company, SpaceX is a strong supporter of astronomy and the scientific community. Science is at the heart of what we do every day, and the SpaceX team is passionate about our efforts to be responsible stewards of our shared space environment.