SATCON1 Metrics Working Group Draft Report

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On behalf of the Metrics WG

30 June, 2020

Committee with Relevant Experience

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Takeaway Messages

- Vera Rubin Observatory has determined a level of reflected sunlight from LEOSats below which loss of sky-limited image area is confined to the illuminated satellite track.
- Collaborative discussion among SpaceX, Vera Rubin Observatory and the AAS has prompted engineering solutions for Starlink units that shows promise for meeting that brightness limit.
- Precision, publicly available ephemerides, combined with a widely accessible (observatory) user app can aid mitigations such as pointing avoidance or mid-exposure shuttering.
- Limiting reflected light during post-launch parking stage requires additional spacecraft attitude control considerations.

Takeaway Messages

- Obtaining sufficiently accurate ephemerides for avoidance during mission phases with frequent thruster firings or de-orbiting is highly desirable, but could be challenging.
- An assumption is that conditions that satisfy the facility with the greatest etendue (effective area x field of view) should satisfy most others, however, different telescope focal lengths and detector dynamic ranges can change the situation.
- Some programs/instruments cannot accommodate mid-exposure shuttering or streaks anywhere in the critical image area. More detailed simulation studies are required to refine understanding of the impact and to identify any lower reflectivity threshold that preserves a significant number of programs.

Takeaway Messages

- The Starlink constellation, with its 550 km altitude, has primary visibility from sunset until astronomical twilight. Major scientific areas affected include searches for potentially hazardous asteroids (a national priority), and multi-messenger astronomy source identification.
- Should tens of thousands of LEOSats be launched into 1200 km orbits as requested, they will be visible all night, and no combination of mitigations can avoid the impact of those trails on astronomical observations.

Charge to the Metrics WG

1. Define a limit on reflected sunlight in the optical/infrared by any unit of a satellite constellation in operational orbit for any time after nautical twilight as determined by the most sensitive ground-based wide-field telescopes to be a tolerable amount of non-celestial interference.
2. Define the required accuracy of TLEs (data precision and frequency of update) for operational units to allow for pointing avoidance in specific target fields.

Charge to the Metrics WG

3. Assess the impact on the programs, as reported by a variety of ground-based observatories, that could not be mitigated to tolerable levels by the metrics from 1) and 2). From that assessment,
4. Identify further mitigations of the remaining impacts though
   a) defining possible additional metrics and achievable target values,
   b) operational software tools that could be developed and distributed to the astronomy community, and/or
   c) deeper understanding through a recommended program of more detailed simulations.

Proposed Metrics – Operational Orbit

- Reflected sunlight to be limited to illumination level that avoids uncalibratable cross-talk in Vera Rubin Observatory CCD detectors, V=7 mag.
- Out-of-focus image creates wide trail with surface brightness dependence canceling image concentration with orbital height; only dependence is 'dwell time' per pixel.
- *Requirement for operational orbit: Reflected sunlight slowly varying with orbital phase as recorded by high etendue (effective area × field of view), large-aperture ground-based telescopes to be fainter than [7.0] V mag +2.5*log(r_orbit / 550 km), equivalent to [44]*(550 km / r_orbit) Watts/steradian.*
- Note that a satellite at 1200 km needs to have ~2.2x lower reflectivity than V=7 to meet the condition.

Mitigations for Reflected Sunlight

- Operators: Surface darkening, sun shielding, and possible attitude control consistent with power constraints to reduce effective reflectance. SpaceX Visorsat is the latest experiment to reach the needed limit, employing all three mitigation approaches.
- Observatories immediate options:
  - Image post-processing to identify and mask affected pixels in track with additional noise > threshold over sky noise.
  - When possible, optimize clocking waveforms to reduce cross-talk for high signal levels.
  - With precise ephemerides of entire constellation suites, close shutters for the seconds around predicted passage. Option available to those instruments and programs for which shutter close and open does not compromise image quality or cause unacceptable delays for target/guide star reacquisition.

Reflected Sunlight

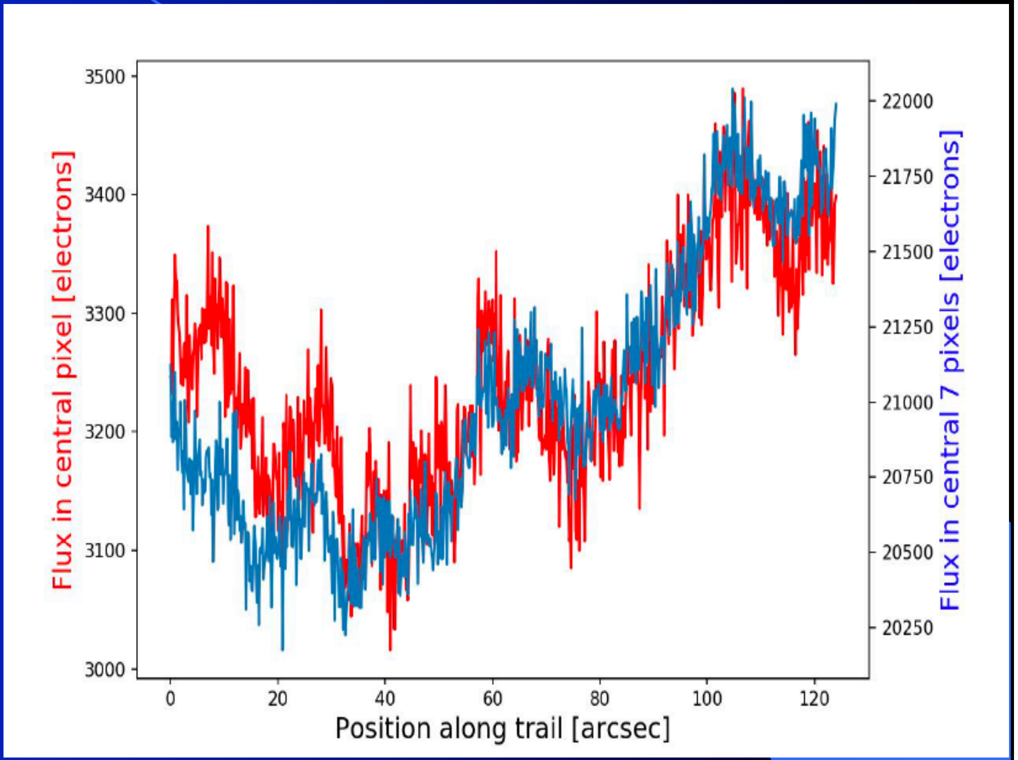
- Observatories longer-term mitigation options:
  - New instruments designed for mid-exposure shuttering.
  - Exploration of CMOS detectors for pixel shuttering.
- *Recommendation: Support for development of an application available to the general astronomy community to identify and mask satellite trails in images on the basis of user-supplied parameters.*
- *Recommendation: New LEOsat operators undertake a suite of laboratory BRDF measurements as part of their satellite design and development phase. This would be particularly effective if paired with a reflectance simulation analysis.*

FLARES

- Flares are specular reflections from designed facets of the spacecraft.
- They can be many times brighter than the surface brightness limit above, leading to uncalibratable cross-talk or saturation.
- A usable astronomical exposure is incompatible with flare illumination.
- The expectation is that flares will be rare events.
- Mitigations:
  - Operators: Potential to adjust attitude to avoid flares projecting along the ground track.
  - Collaboration: Sufficiently accurate ephemerides of the flares themselves for pointing avoidance.

Glints

- Any fine texture on the reflecting surface of the satellite, such as multi-layer insulation, will provide rapidly varying reflectivity, possibly on msec timescales. Tumbling during de-orbit or end of active control will exacerbate the effect.
- The noise produced in a track by glints will greatly exceed the photon statistical noise.
- Although it might be possible to recover some measurable area along the low-intensity skirts of the (out-of-focus) point spread function under such a track, it would be more computationally expensive than a mask, essentially the equivalent of removing the background in a dispersed spectrum.



Variations along the track of the FUSE satellite from Mitigations WG report.

Lowering the Impact

- On the basis of future simulations of impact on a range of scientific programs, it may be possible to determine a threshold for reduced upper limit on effective reflectivity that provides a significant recovery of lost imaging area, lower systematics in large samples, and/or lost total exposures.
- Initial estimates for recovering area within the track require reflectivity lower by ~10x than the 7th mag limit.
- *Goal for operational orbit: Reflected sunlight slowly varying with orbital phase as recorded by high etendue, large-aperture ground-based telescopes to be fainter than [9.5] V mag +2.5*log(r_orbit / 550 km), equivalent to [4.4]*(550 km / r_orbit) Watts/steradian.*
- Numbers in [] TBD by detailed simulations.

Post-launch Parking, Boosting, and De-Orbiting

- These mission stages can cause sunlight reflection much stronger than that in the operating orbit.
- To the extent that deorbiting a satellite is less controlled than the original orbit insertion and raising after launch, facet flares can be much more frequent.
- Even with a build-out of tens of thousands of constellation units, the number of satellites in these mission phases is expected to number in the hundreds at any given time.
- Mitigation:
  - **Observatories: Pointing avoidance when possible.**
  - **Collaboration: Ephemerides as accurate as possible, publicly available.**
  - **Operators: Best efforts for attitude control of units within power constraints to minimize effective reflectivity in direction of ground-based observatories.**

Positional Accuracy

- All impacted observational programs will rely on sufficiently high-quality information for pointing avoidance and/or identification after the fact in the recorded image.
- Pre-scheduling of observations of critical fields that can be adjusted slightly in time can use the information for planning.
- Time-critical observations, including long exposures of transient phenomena like gravitational wave sources may have the option of closing the shutter during the passage of the satellite, provided the system doesn’t lose target lock.

Positional Accuracy

- *Requirement for quasi-ballistic mission phases (parking and operations): For a given position on the sky, given start and end times for an exposure, and an instrumental field of view of [1] arcminute, the ephemerides of all units of a constellation shall be specified in a public database to sufficient accuracy that the transit of any unit across the field during the exposure interval can be predicted within [12] hours in advance of the observation to an accuracy of [1] second in time and the position of the track to [2] arcseconds in the cross-track direction and [1] arcminute in position angle.*

Positional Accuracy

- *Requirement for phases with frequent thruster firings or reduced control, such as deorbiting: For a given position on the sky, given start and end times for an exposure, and an instrumental field of view of [1] arcminute, the ephemerides of all units of a constellation shall be specified in a public database to sufficient accuracy that the transit of any unit across the field during the exposure interval can be predicted within [12] hours in advance of the observation to an accuracy of [10] seconds in time and the position of the track to [20] arcseconds in the cross-track direction and [10] arcminutes in position angle.*
- TBD numbers in [] need discussion!

Recommendation for Positional Accuracy

- *Recommendation: Support development of an application available to the general astronomy community for observation planning that predicts the time and projection of satellite transits through an image, given celestial position, time of night, exposure length, and field of view, based on the public database of ephemerides.*
- *Recommendation: An alternate standard format to TLEs be used for ephemerides in order to include covariances and other useful information. The application above should be compatible with that format and include the appropriate errors.*
- *Recommendation: Immediate post-launch configuration enables pointing avoidance most readily if the units are as tightly clumped as possible consistent with safety, affording rapid passage of the whole train through a given pointing area.*

Needs Discussion

- Coherent and compelling recommendation for support of the suite and network of observations required to characterize the lowering of effective reflectivity on test units, phase angle effects to verify BRDF models and lab measures, and what would be necessary for glint ephemerides for constellations of thousands of units.

Continuation

- Regardless of the degree to which the proposed limits and mitigations can be achieved, the new era of numerous LEOSats, particularly in higher orbits, will permanently change the relationship of humans to the night sky for professional and amateur astronomers and for the general public.
- Following talks by James Lowenthal on Impact on Astronomical Programs and by John Barentine on Impact on the Amateurs and the Community will expand on that theme.
- Jared Greene of SpaceX, our active collaborator on this WG, will conclude with a discussion about Mitigation through Collaboration.