Impacts of Satellite Constellations on Observational Science

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Rationale

Vera Rubin Observatory and 30-meter telescopes coming online in the next decade will address fundamental questions and substantially enhance humankind’s understanding of the cosmos.

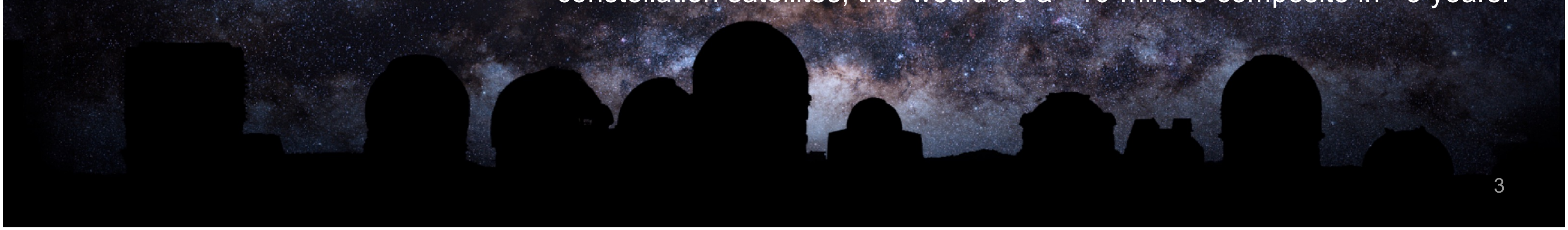
For reasons of expense, maintenance, and instrumentation, such facilities cannot be launched into, or operated from, space. Ground-based astronomy is, and will remain, vital and relevant.

Ground-based observatories require dark night skies!

No combination of mitigations will eliminate the impact of satellite constellations on optical-infrared astronomy.

Meeting the proposed limits in apparent brightness is the minimum step to preclude substantial scientific loss and minimize visual impact.

2-hour composite image from Pinnacles in Western Australia. (Joshua Rozells, NASA APOD – 14 June, 2022.) With planned numbers of constellation satellites, this would be a <10-minute composite in ~5 years.



Ground-based Observatories Remain the Engines of Cutting-Edge Scientific Discovery

- The Vera Rubin Observatory, being constructed in Chile, will provide the shapes for billions of faint galaxies, yielding the distribution and amount of Dark Matter.
- Tracing the filamentary cosmic web of matter requires many thousands of blue-green spectra from instruments in Arizona and Chile.
- The Dark Energy Spectroscopic Instrument on Kitt Peak in AZ has 5000 fibers at the focus of the Mayall 4-m telescope.
- These are key programs for the mission of the US Department of Energy, in partnership with the National Science Foundation.

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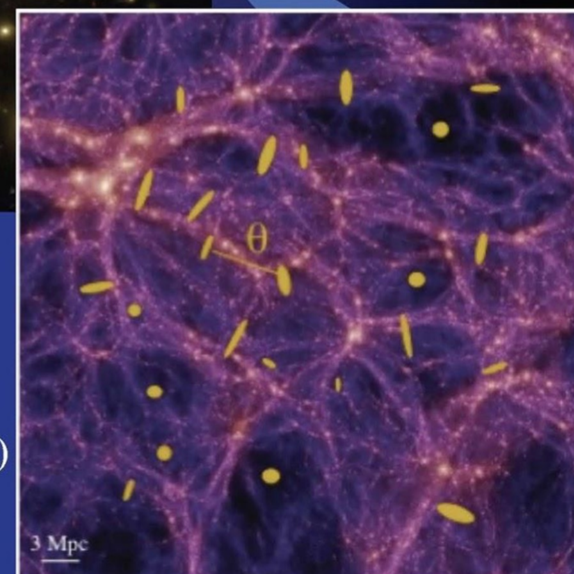
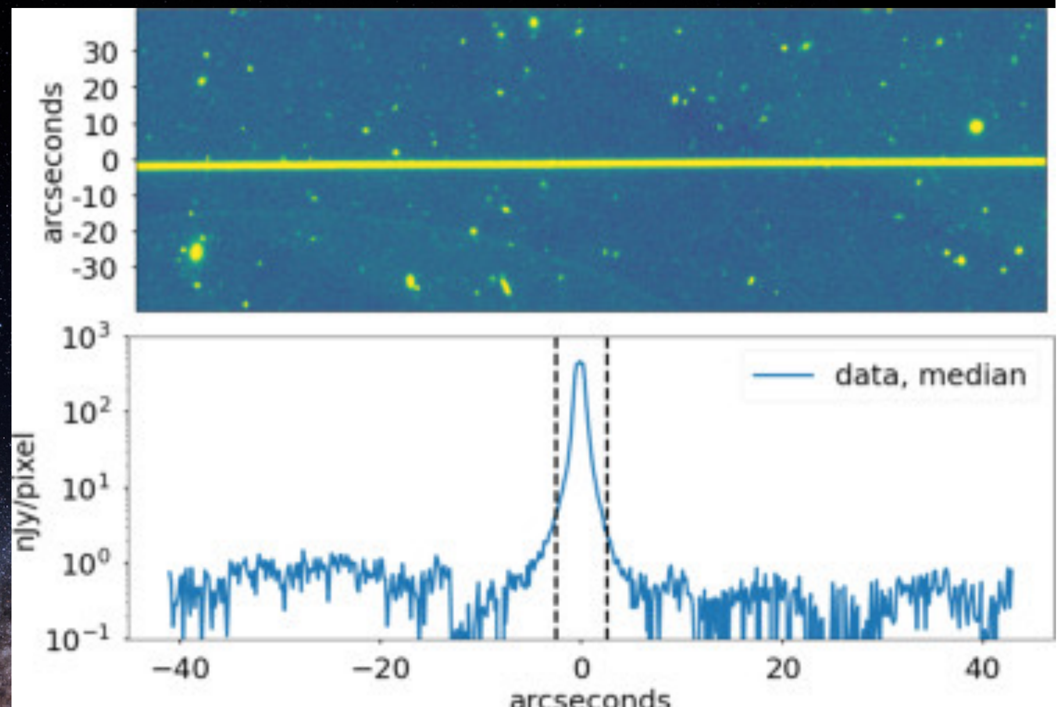
- Einstein's Theory of General Relativity holds that gravity bends the trajectory of light.
- Dark matter concentrations elongate the shapes of distant galaxies projected behind them.
- The LSST "gold sample" will contain ~2.6 billion galaxies with $g<27^{\text{th}}$ magnitude for strong statistical determination of the dark matter distribution as a function of cosmic time, key to tracing the history of the Universe.

Strong lensing in galaxy cluster Abell 2218 above stretches background galaxy images into long arcs.
The matter in the 'Cosmic Web' (right) creates slight elongations as modeled.



Satellite Streaks Impact Data Quality

- A galaxy with g~27 provides ~1% of the detected photons compared to the natural skyglow from a one arcsecond square patch of dark sky.
- To avoid excess noise from the tail of a satellite streak brightness profile, the area parallel to the peak will need to be masked out of the data, probably out to ~10".
- Extensive supercomputer simulations will be required to understand the systematics of long masked areas at arbitrary angles in an image on the shape analysis algorithms detecting the patterns of elongations of faint galaxies.

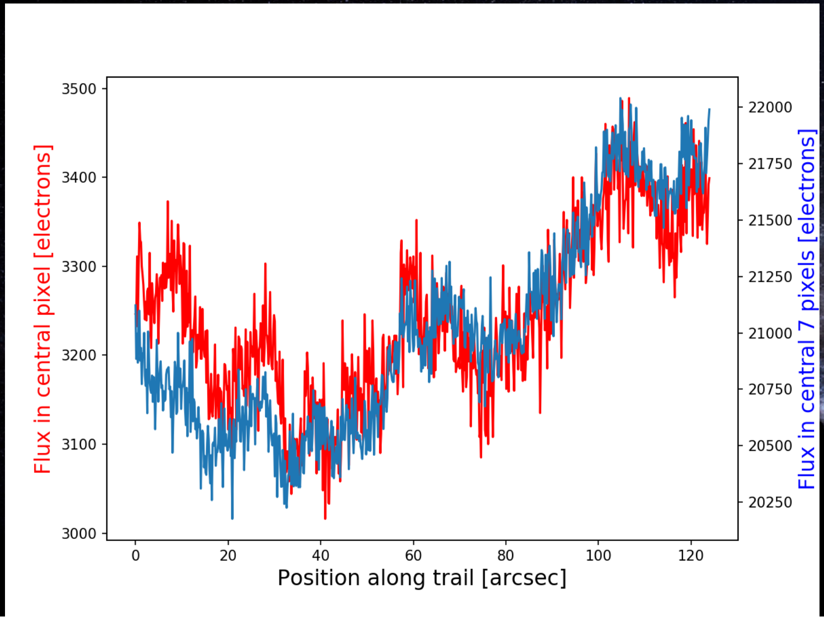


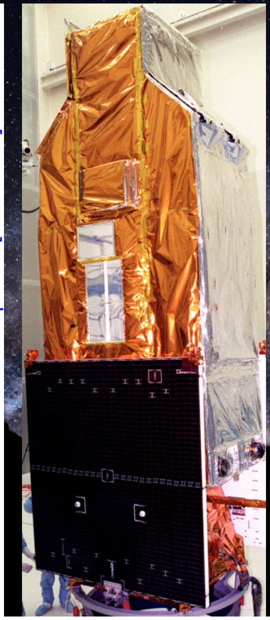
Upper: satellite streak recorded in data from Subaru Telescope Hyper-Suprime Camera, processed with LSST pipeline. Lower: surface brightness profile coadded along the streak. Hasan+ 2022, A&C, 39.

Further Impacts

Structure in the satellite trail can confuse algorithms that detect individual objects, creating artifacts in stacked images with variable noise just outside the masked trail.

Even more challenging is the subtle injection of a sunlight spectrum from a satellite trail into fibers or slits of massively multiplexed spectrographs, doing the next phase of survey identification. Without highly accurate ephemerides, such instruments will require parallel simultaneous imaging, just for the purpose of eliminating contaminated spectra post hoc.





Trail flux variation from the FUSE satellite: (*left*) shows the flux measured along a portion of the trail in the central pixel (red) and the central seven pixels summed (blue). 10% variation in the per pixel flux is seen along this trail. Large variations can be caused by changing reflections off the MLI blanket of the spacecraft (*right*).

Origin of Brightness Limits

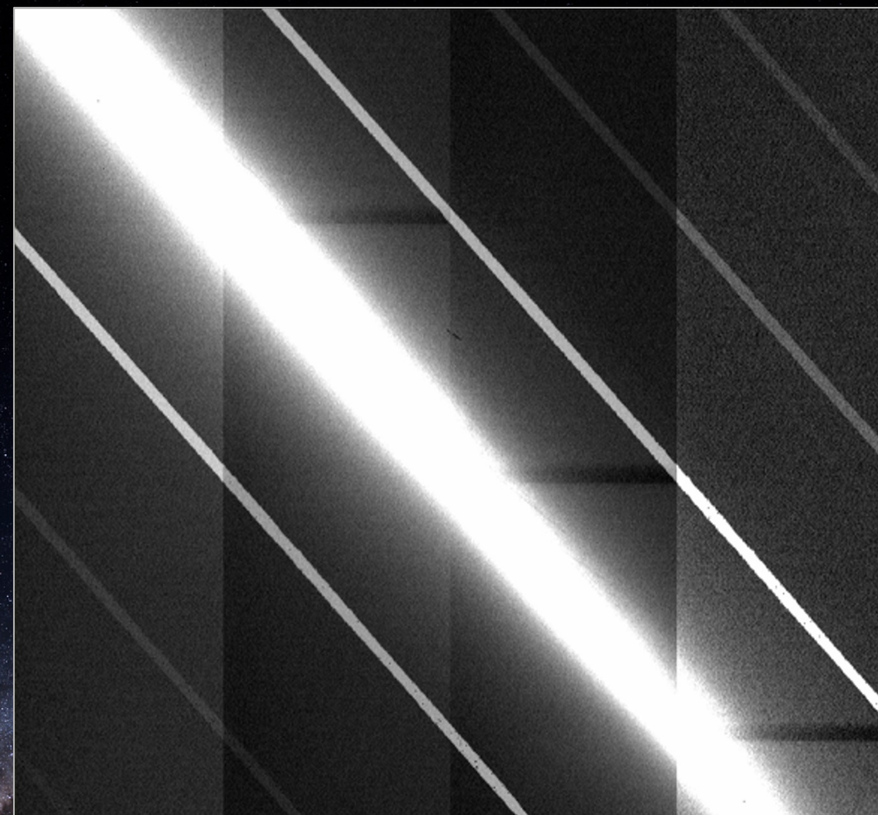
Bright satellite trail in the Rubin Observatory camera induces image artifacts from CCD amplifier cross-talk. (Lab simulation.)

If a LEOsat at 550 km is darkened to 7th mag in the green filter band (44 nW/sr @ 476 nm), special pixel processing can remove the "ghost" trails. (Scales as $1/r_{orbit}$.)

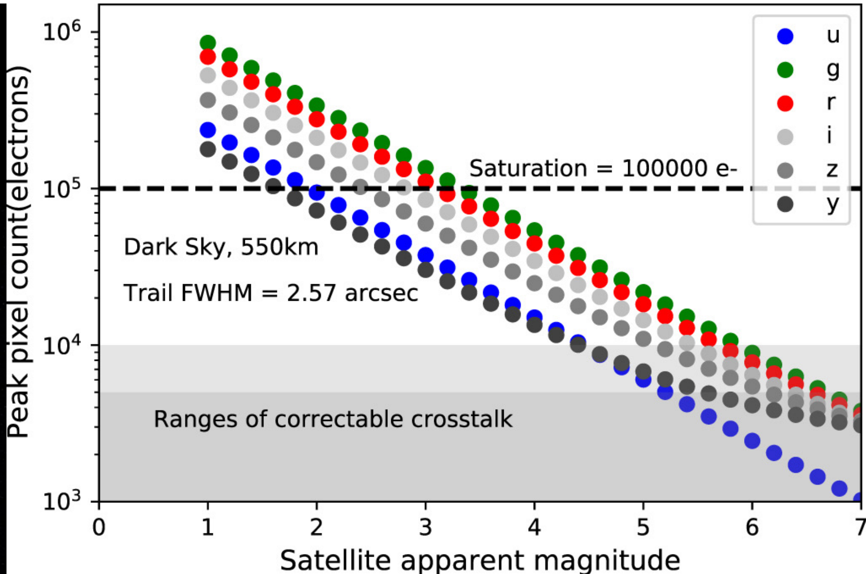
Calibrating and removing those artifacts reduces the area lost to the streak by more than 4X.

Satisfying the requirement for the telescope with the largest product of sensitivity x field of view is considered sufficient to meet the needs of most other observatories.

Meeting that visual magnitude limit also puts the reflected sunlight below the limit of human visual acuity as well, minimizing visual impact during operations phase.



Tyson+ 2020, AJ, 160, 226.



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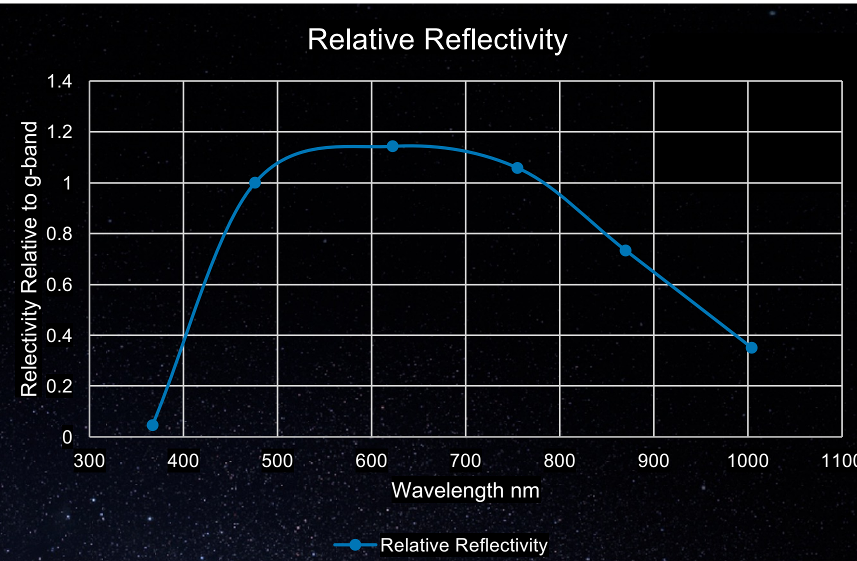
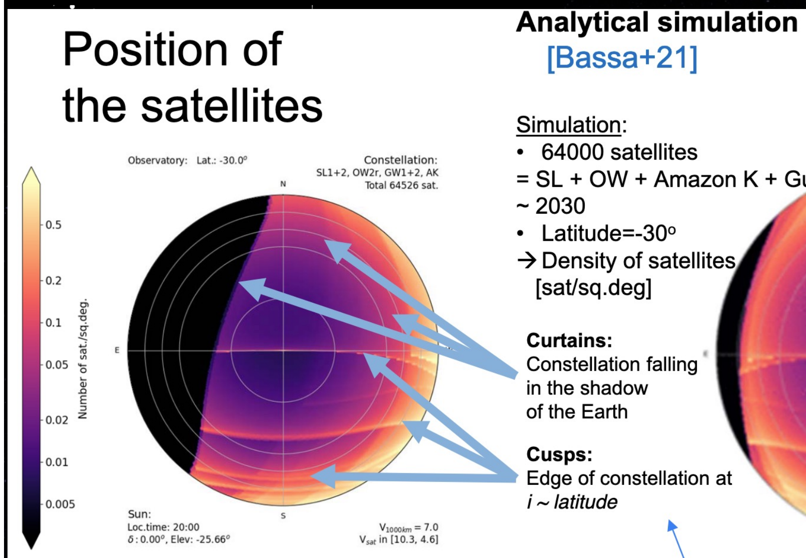
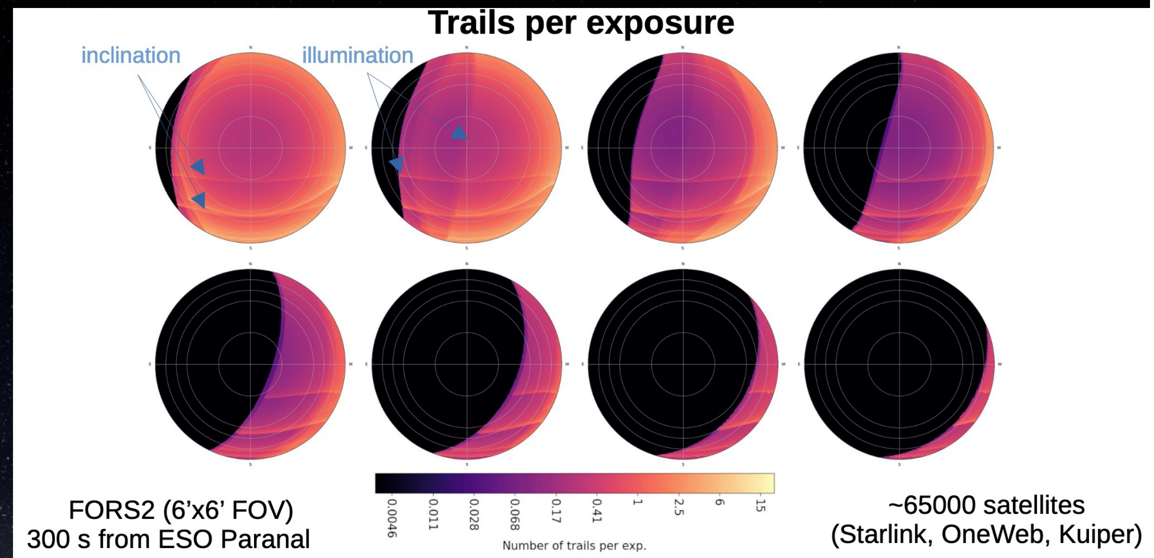


- The relative sensitivities of the LSST color bands (and most astronomical optical instrumentation) require different apparent brightness limits for the satellite as a function of color.
- Those sensitivities differ from the relative irradiance of the Sun, easing the reflectivity requirements in the UV and far red, while making them slightly more stringent in the yellow and red compared to the green.
- Note that these limits are considerably fainter (>10x) than those at which the detector saturates.

Simulations of Streak Frequency





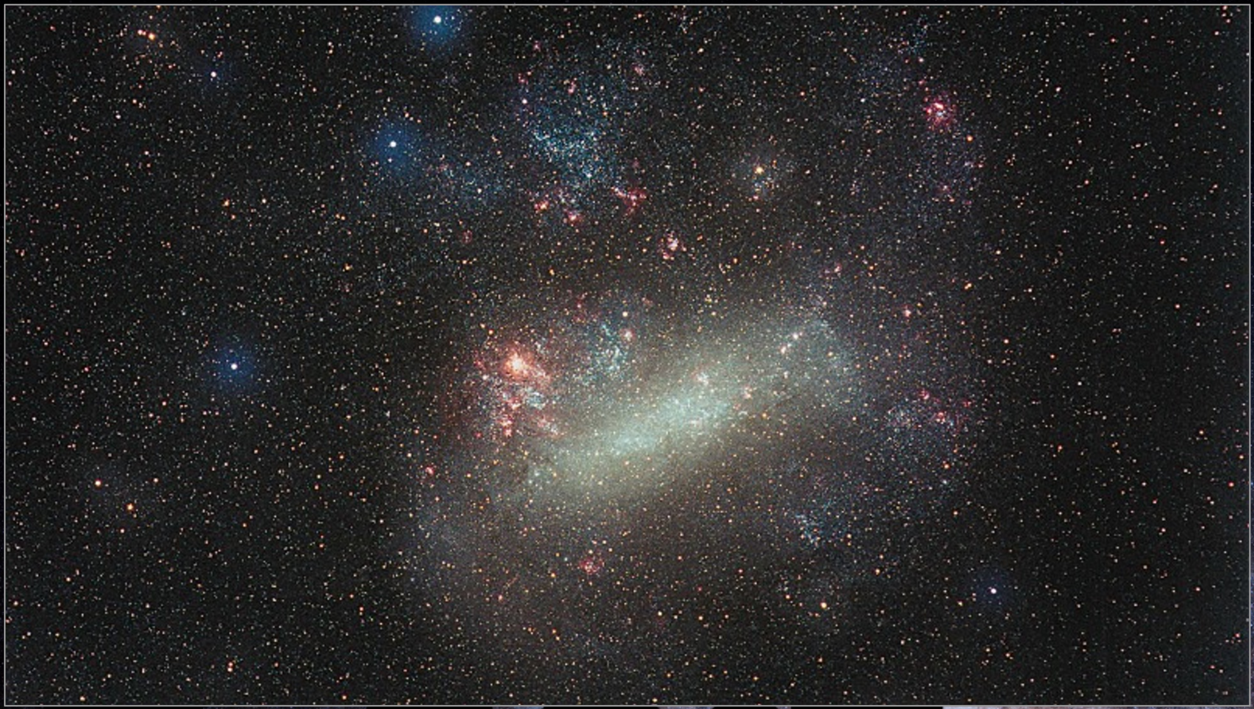
- Analytical simulations by Bassa, Hainault, Seitzer and others are based on actual filings, including orbital planes, inclinations, illumination as viewed from observatory, etc.
- The simulation shown is for the latitude of the major Chilean observatories.
- To gauge the impact on the LSST data, a typical exposure will be 15 sec rather than 300, but the field of view is 9.6 sq deg rather than 0.01 sq deg for the modeled instrument, changing the scale at 0.1 streak per exposure (purple tone) to 4.8.

Simulations Summary

- The fraction of satellites of each constellation that will be visible at any observatory at any one time is typically around 5%.
  - Higher altitude constellation shells will have a greater fraction visible (7-8%), lower altitude constellations a smaller fraction (<4%).
  - Most of these satellites appear at low elevation over the horizon (typically 50% below 10 degrees).
- The number of satellites visible is a function of their orbital inclination, peaking at a latitude close to the inclination.
- The constellation with the greatest impact for any observatory in terms of the number of satellites visible will be one at higher altitude and with an orbital inclination close to the latitude of the observatory.

Large Magellanic Cloud (LMC)

Largest satellite galaxy of our own Milky Way Galaxy



Eckhard Slawik via ESA

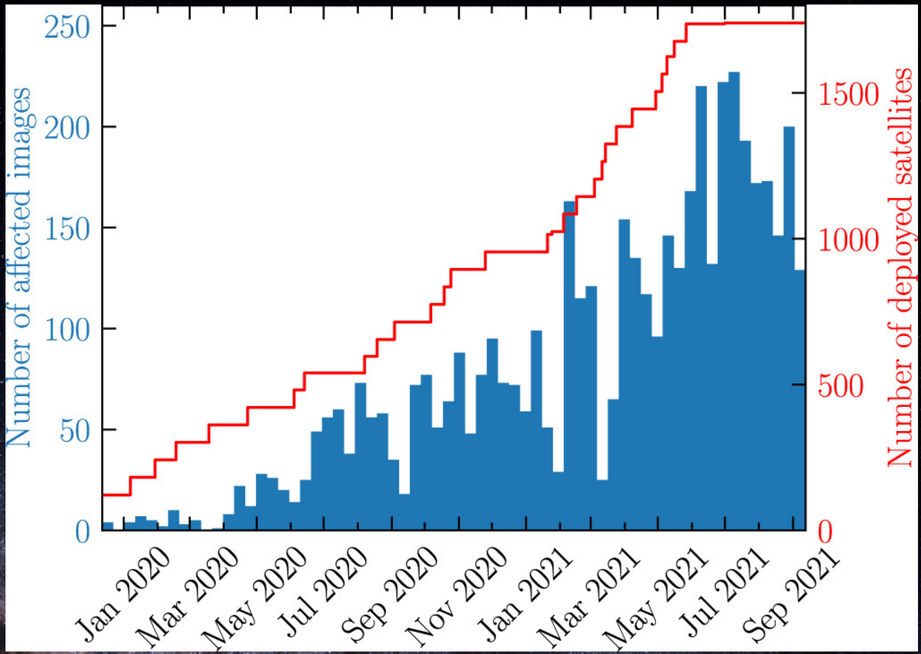
Optimal observing time: Summer in south.

If large constellations like OneWeb Phase 2 (6372 satellites at 1,200 km) launched:

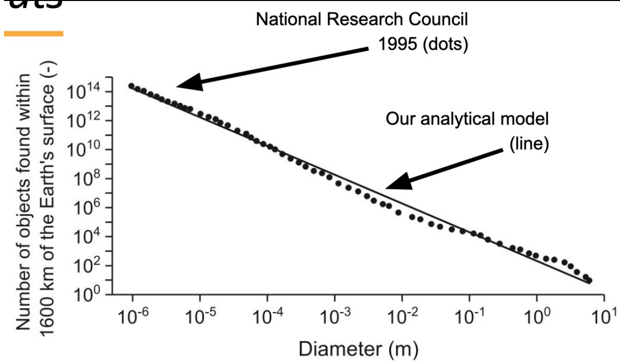
Every 4 minutes of exposure on the LMC will have at least one satellite trail / sq. deg!

What do the observations show?

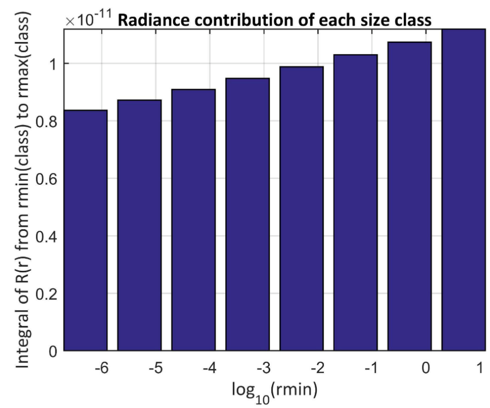
- The Zwicky Transient Facility uses the Palomar 48-inch Schmidt telescope for time-domain studies with single exposures covering 47 deg^2.
- Mroz+(2022) showed that the number of images with streaks (5301) tracked the number of deployed satellites, with 6% of the images taken in twilight in late 2020 affected, going up to 18% in late 2021.
- With 42,000 LEO satellites, every ZTF twilight image would have ~4 streaks, accounting for ~0.2% of the image pixels.
- This frequency is in reasonable agreement with the modeling predictions.
- The loss in science requires detailed simulations for the chance of missing the first detection of a Near-Earth Object or recovering key solar system objects.

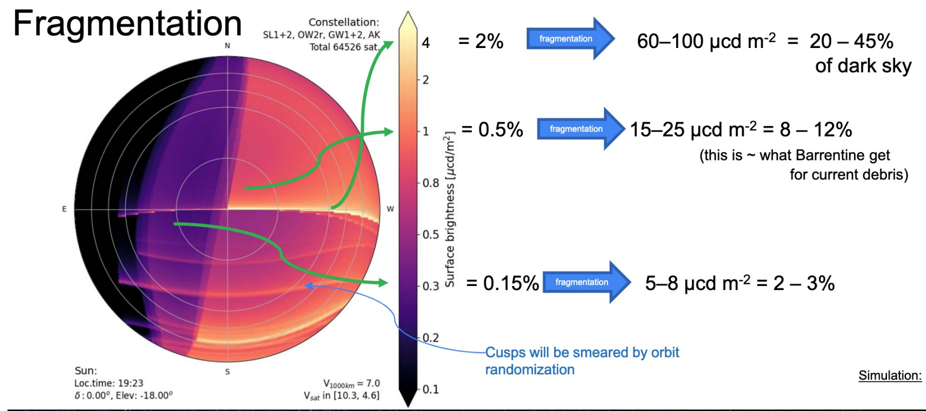


Will the Constellations Brighten the Diffuse Night Sky?



Size distribution of LEO objects





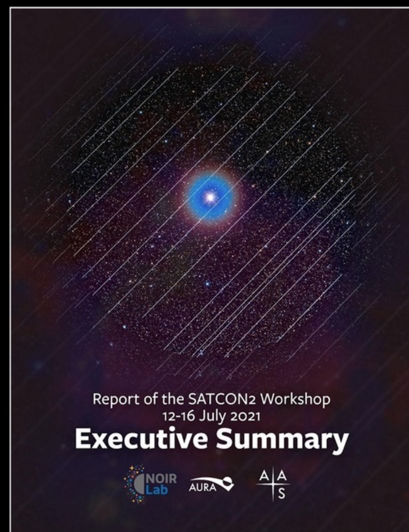
Barentine+ (2021) used this r^{-2} distribution of satellites plus debris size with almost equal contribution to radiance with size.

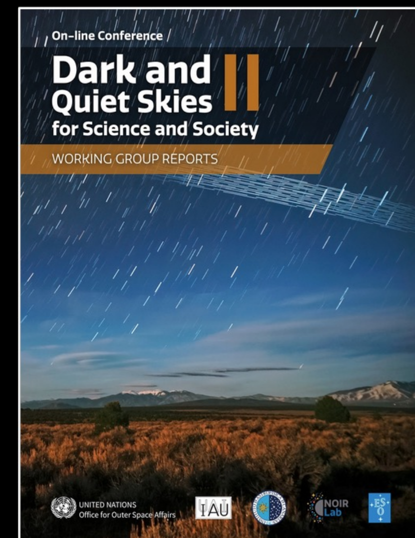
Hainault+ (2021) showed the impact of fragmentation on diffuse scattering.

- Barentine+ modeled the diffuse scattering of sunlight from the full distribution of objects in LEO.
- Small particles dominate the effect; assuming the distribution shape remains constant as the number of larger tracked objects increases, the diffuse brightness at zenith may already have increased to 16 µcd/m², compared to the dark night sky at 200 µcd/m².
- Hainault+ showed that if some of the satellites are destroyed and form debris with the same distribution, they will contribute to an increase in diffuse skyglow.
- These results depend critically on the rate of debris loss in the atmosphere and collisional production rate.

Detailed Reports Published

SATCON1, July 2020 | SATCON2, July 2021 | D&QS1, October 2020 | D&QS2, October 2021





https://aas.org/satellite-constellations-1-workshop-report

https://noirlab.edu/public/products/techdocs/techdoc031/

https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc021.pdf

https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc051.pdf

Purpose & Outcomes Driving Astronomy Community Organization

- Context: Nighttime images without the passage of a Sun-illuminated satellite will no longer be the norm.
- Technical recommendations from the meeting reports motivated the structure of institutionally supported efforts to mitigate the impact of satellite constellations.
- They fall into three general categories:
    - Astronomers will need software tools to handle data with satellite trails and provide options for dynamical scheduling for pointing avoidance and shuttering when possible.
    - Operators are strongly encouraged to design and operate to keep reflected sunlight onto telescopes below the specified limits and lower if possible.
    - Operators and astronomers will need to collaborate to improve the predictions of positions and reflections.

American Astronomical Society Committee on Light Pollution, Radio Interference & Space Debris

- Work divided into six subgroups: LP, RI, SD, Satellite Constellations, Policy, and Community Engagement.
- Some of the topics being addressed:
  - Working with the satellite industry to continue mitigation strategies for satellite darkening
  - Multi-bandpass interference: assessment and solutions
  - Assessing the debris threat
  - Expanding the advocacy and partnership globally (new IAU Center for the Protection of the Skies)
  - Legal-policy-regulatory landscape: Is space an environment? Obligations in space (e.g. mining) from existing treaties with sovereign Indigenous nations? Is space-based internet a utility?
  - Sustained engagement with communities - duty to consult and long-term relationships – humanity is the broadest constituency in space

The IAU CPS or the *International Astronomical Union Center for the Protection of the Dark & Quiet Sky from Satellite Constellation Interference*

Piero Benvenuti, Director; Connie Walker and Federico di Vruno, co-Directors.

The Centre will **coordinate global efforts** to converge on mitigation solutions

The Centre will bring together astronomers, industry, policy experts and the wider community and **act as a bridge among all stakeholders**

The Centre will **produce and disseminate open-source information and resources**
In particular, the Center will **continue research** on the satellite constellation issues to arrive at feasible and implementable solutions in the areas of:

- A hub for observations, software, etc. (SatHub)
- Policy
- Industry and Technology
- Community Engagement

The IAU CPS

- **SatHub**
  - Astronomical data repositories
  - Orbital solution portal
  - Software tools
  - Training curriculum
  - Real-time collaboration
- **Policy**
  - National Policy (through collaborators)
  - International Policy (through collaborators)
    UN COPUOS
    ITU
- **Community Engagement**
  - Education and outreach
  - Discussion Forums
  - Website and social media
  - Workshops
- **Industry and Technology**
  - Industry interactions
  - Laboratory tests and technical studies
  - Spacecraft mitigation measures
  - Telescope mitigation measures

Conclusion

Mitigation of the most damaging impacts on scientific programs is now being actively explored by the professional astronomy community worldwide. These investigations have benefited from collaboration with SpaceX and the engagement of the industry participants in the SATCON 2 and Dark & Quiet Skies 2 conferences.

If the tens of thousands of LEOsats proposed by many companies and many governments are deployed, no combination of mitigations can fully avoid the impacts of the satellite trails on the science programs of current and planned ground-based optical-NIR astronomy facilities.

This symposium is an important step in expanding the collegiality and spirit of partnership between these two communities with the aim of including more operators and observatories in a useful and productive engagement.