VERA C. RUBIN OBSERVATORY

Satellite Constellation Challenges for LSST Science

Tony Tyson
University of California, Davis

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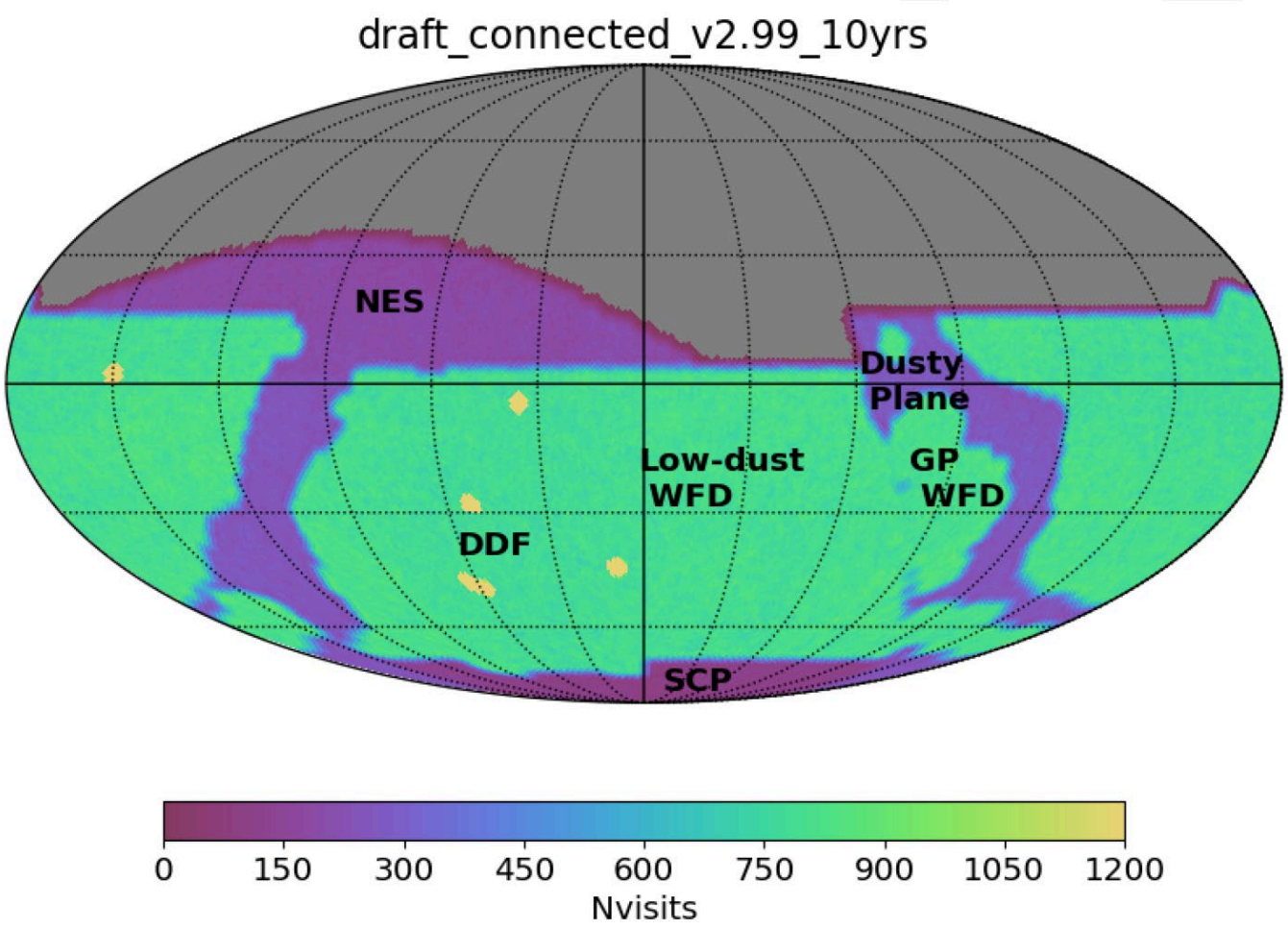
NSF AURA U.S. DEPARTMENT OF ENERGY SLAC CHARLES AND LISA SIMONYI FUND FOR ARTS AND SCIENCES LSST CORPORATION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750
900
1050
1200
Nvisits

Automated discovery and data exploration

DISCOVERING THE UNEXPECTED

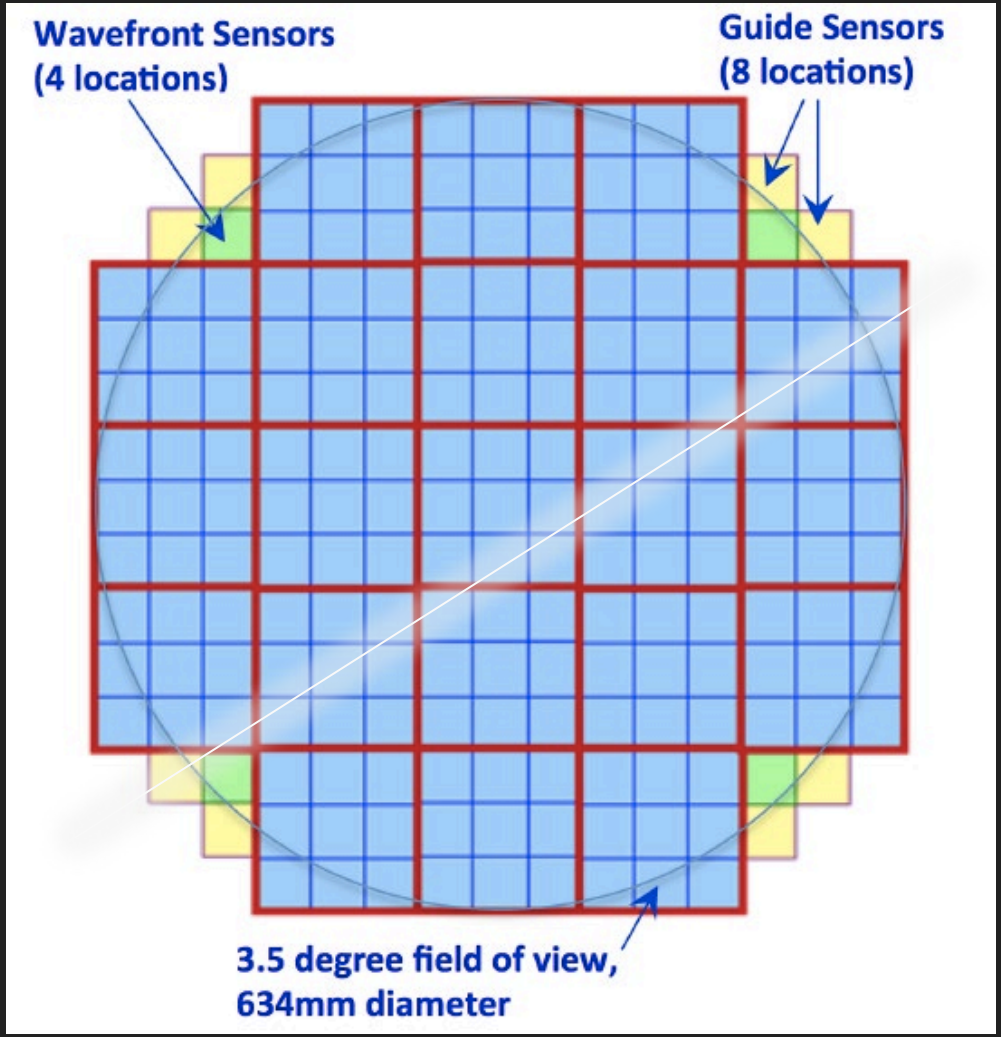
Rubin's potential for discovery is also its vulnerability to Low Earth Orbiting satellites

LSST Mitigation Challenges

- Streaks
  - CCD non-linear crosstalk
  - Streak masking residuals
- Variability & Glints
- Bogus events
- Science impact simulations
- Brightness mitigations by industry

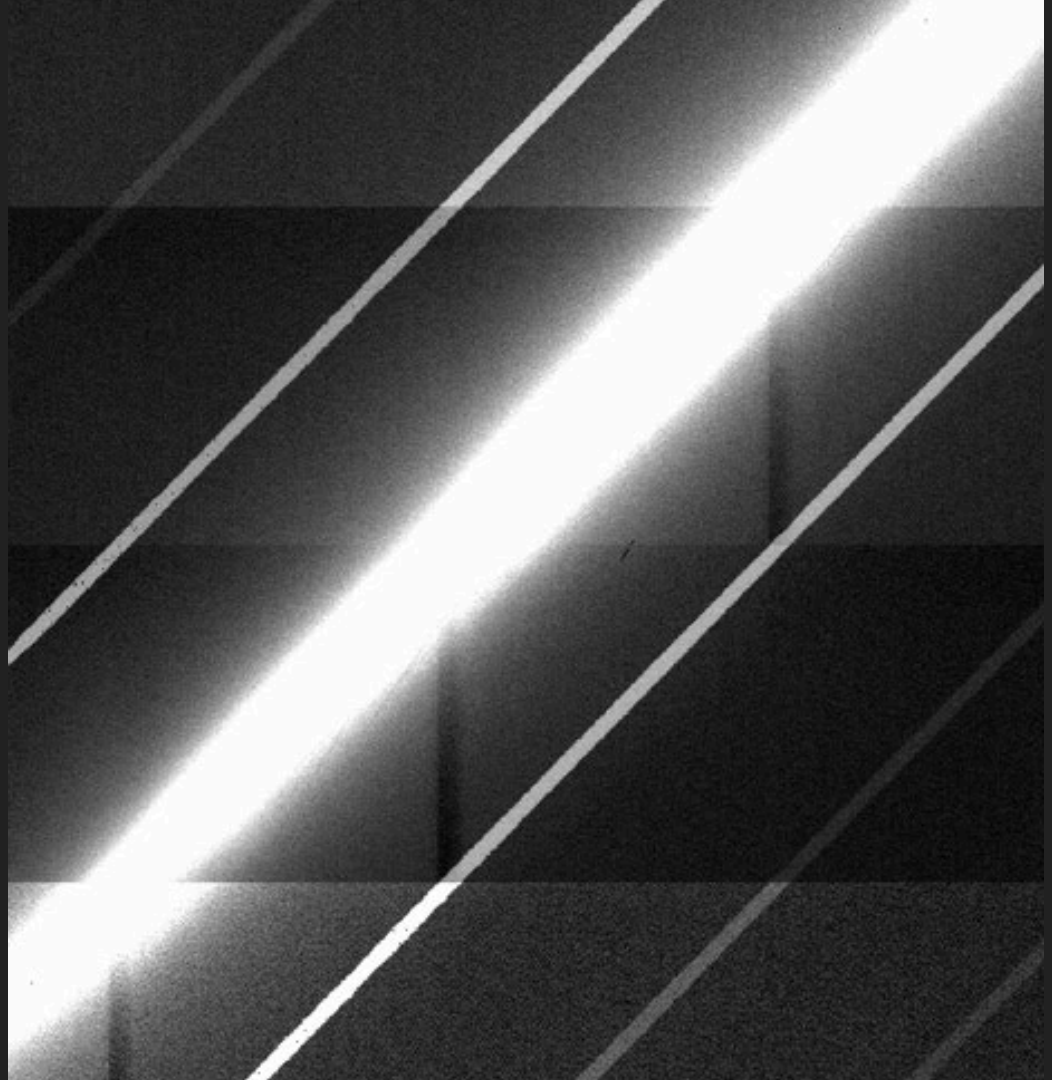
Simulating Satellite Streaks in the Rubin Camera

Andrew Bradshaw, Tony Tyson, Aaron Roodman, Adam Snyder, Dan Polin, Yousuke Utsumi, Homer Neal, Craig Lage, Stuart Marshall, Claire Juramy, and the Rubin Camera team


Wavefront Sensors
(4 locations)
Guide Sensors
(8 locations)
3.5 degree field of view,
634mm diameter

Bright satellite trail in the Rubin Observatory camera induces image artifacts

Electronic crosstalk between output amplifiers on 16 segments

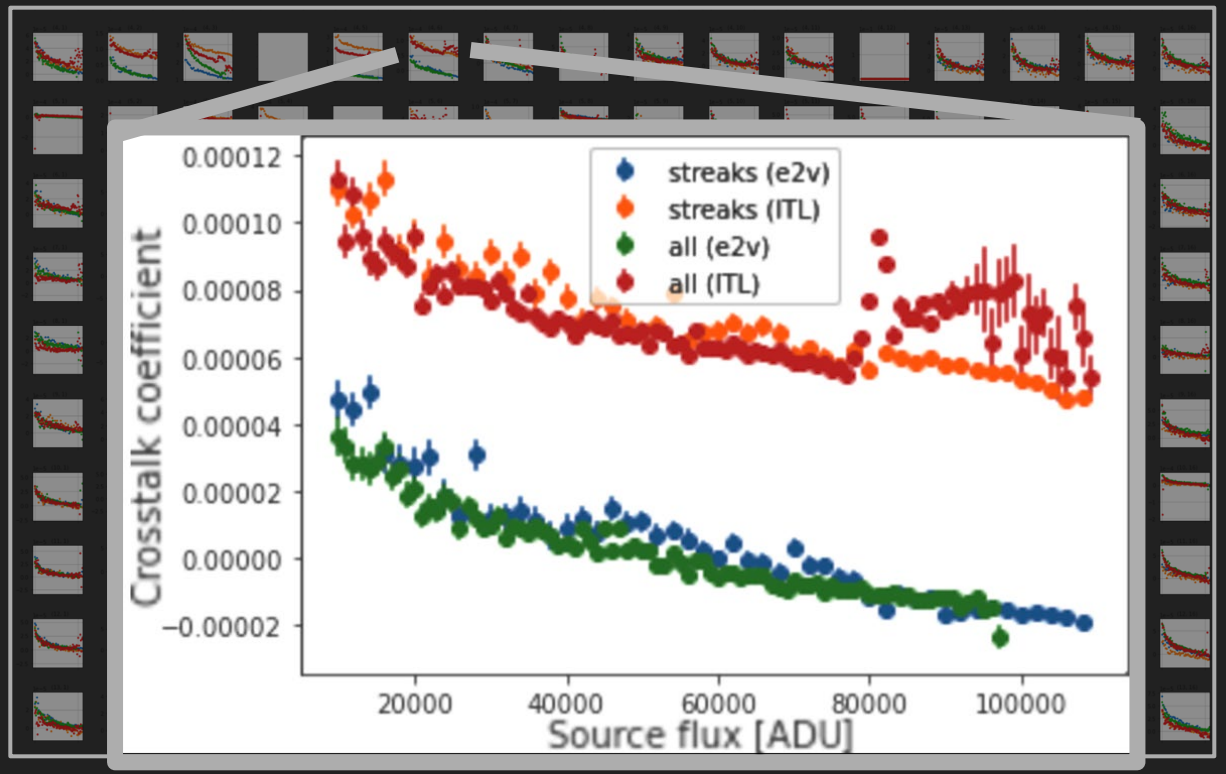


Non-linear crosstalk difficult to fully calibrate: 1 of 256 (x189)

Significant variation seen in amplifier crosstalk vs flux.

Different for ITL/e2v CCDs.

Each pixel on each CCD may need a unique flux-dependent correction coefficient.



Correctability vs Flux

A non-linear crosstalk algorithm must correct to several electrons precision in 100 frame co-add.

At 6.5 *g* mag, a 10% error on any crosstalk coefficient could create a false faint galaxy image in a co-add.

Clearly, fainter satellites are needed

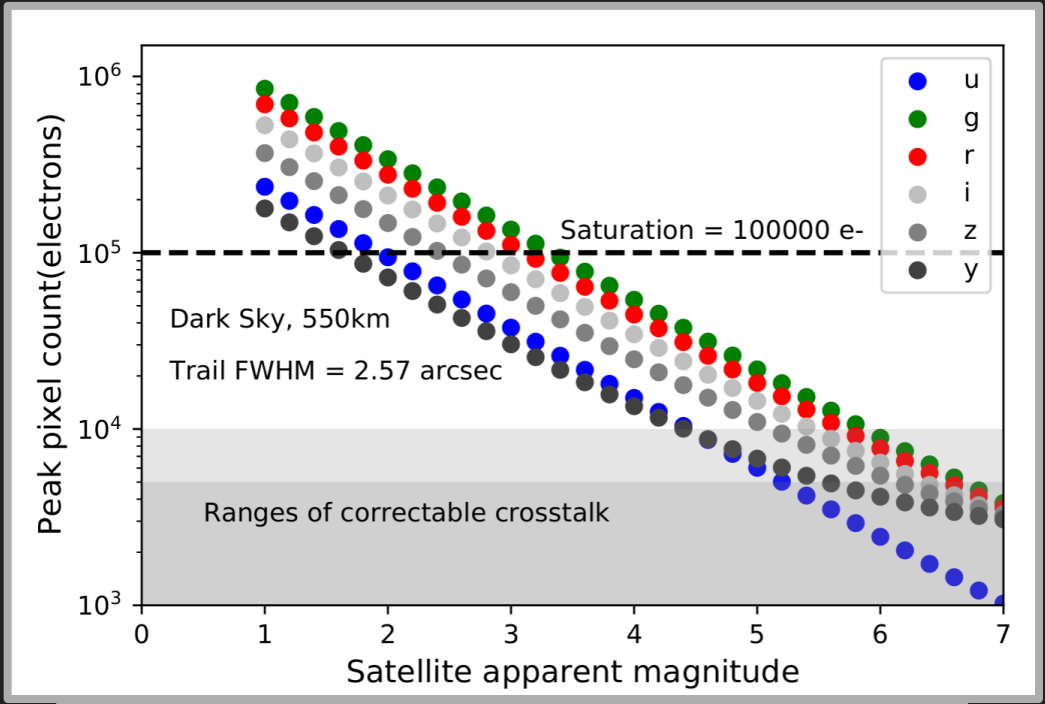
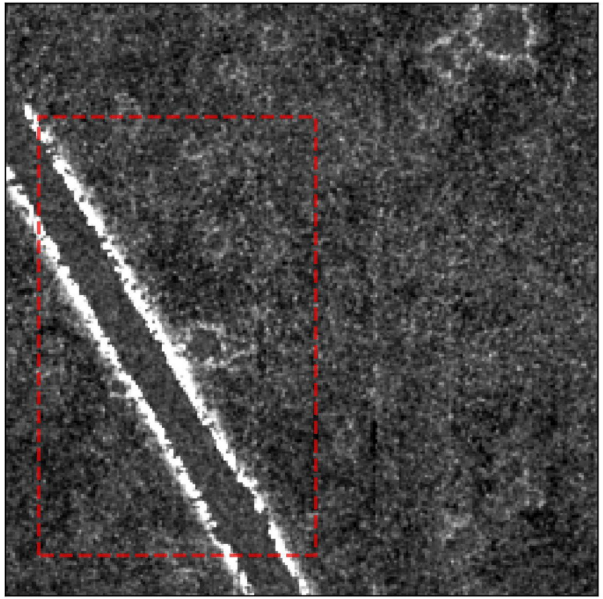


Figure 5. The peak trail brightness in e^- per pixel for a Starlink satellite at 550 km as a function of apparent AB mag as seen by Rubin Observatory. Colors correspond to the six different LSSTCam filter bands. The approximate saturation level of an LSSTCam CCD is indicated. The approximate dynamic ranges over which camera crosstalk artifacts can be corrected down to below the noise level, using our current algorithm, are shown in the shaded regions (see Section 7).

Masking Satellite Trails

Incomplete masking of satellite trails can cause systematic effects:

- Residual spill-over light.
- Lines of “bogus galaxy detections”.



Satellite trail in a coadd image masked using a 40-arcsecond wide mask.

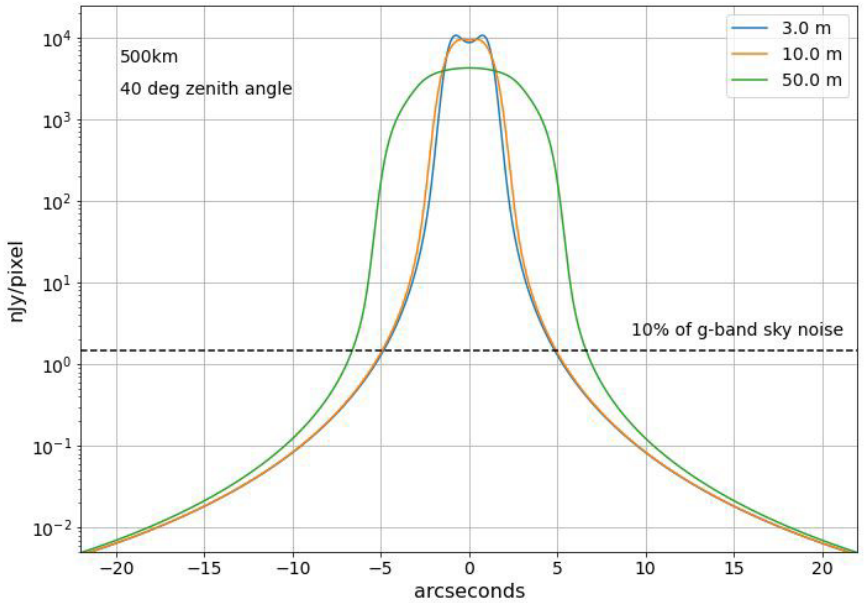
Hasan et al (2022)

Satellite Streak Profile Examples

Each satellite trail requires a unique mask

Depends on:

- Apparent brightness
- Size of satellite reflective elements
- Telescope primary mirror size
- Orbital height
- Seeing



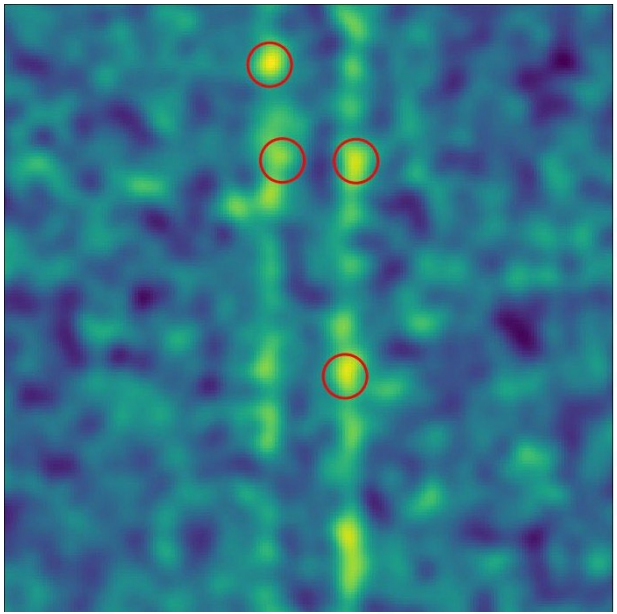
Simulated satellite trail profiles for 3 differently sized satellites as observed by the Rubin Observatory.
Nourbakhsh et al (in prep)

Bogus Galaxy Detections

It is challenging to prevent the occurence of bogus detections in all cases.

Due to variability of:

- Satellite streak profile
- Coadd and detection parameters:
  - Width of the satellite trail mask
  - Filter (ugrizy)
  - Number of individual visit exposures used
  - Detection threshold (e.g. 5-sigma)

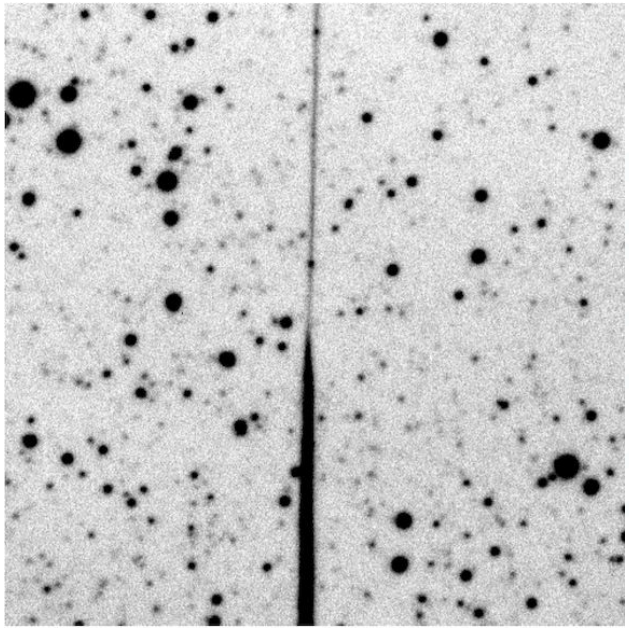


Simulated coadd image (smoothed by the PSF) and example bogus detections caused by a satellite trail.

Satellite Masking Challenges

- Identification of satellites in individual visit exposures
- Determination of an appropriate mask width
- Prevention of bogus galaxy detections in all cases

Further complicated by variation of surface brightness profile along the trail.



Asatellite trail whose surface brightness profiles varies along the direction of the trail.
Paillassa et al (2020)

Next Generation Starlink Constellation

Majority of 2nd generation Starlink constellation to operate at 360km or below.

These sats will be illuminated more briefly near dusk/dawn.

1st Generation Starlink Constellation

Altitude (km)	Inclination (deg)	Total Planes	Sats per Plane	Total Sats
550	53	72	22	1584
540	53.2	72	22	1584
570	70	36	20	720
560	97.6	6	58	348
560	97.6	4	43	172
			Total	4408

2nd Generation Starlink Constellation

Altitude (km)	Inclination (deg)	Total Planes	Sats per Plane	Total Sats
340	53	48	110	5280
345	46	48	110	5280
350	38	48	110	5280
360	96.9	30	120	3600
525	53	28	120	3360
530	43	28	120	3360
535	33	28	120	3360
604	148	12	12	144
614	115.7	18	18	324
			Total	29988

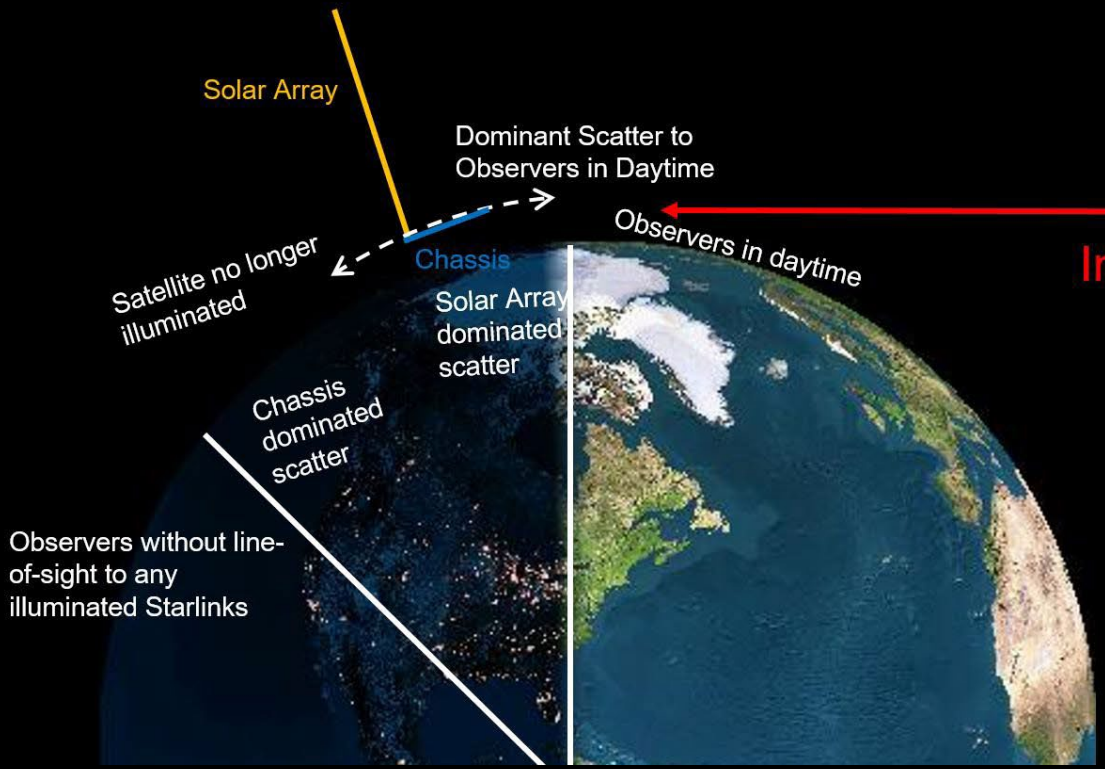
- SpaceX is working with the astronomical community to reduce the light pollution effects on optical astronomy

- Making the spacecraft 10 times darker may remove some satellite trail artifacts in the Rubin Observatory camera

- However, *even if that works*, evidence of satellite trails will clearly be in the data – complicating data analysis, and limiting discoveries

http://ls.st/satcon

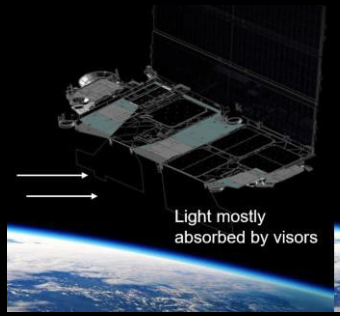
Mechanism for Satellite Brightness



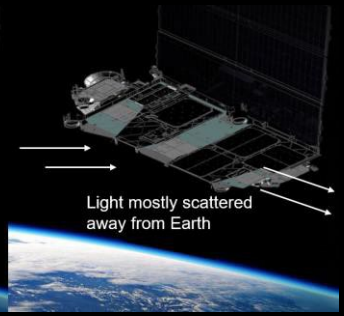
SpaceX

Dielectric Bragg Mirrors

Visors



Mirrors

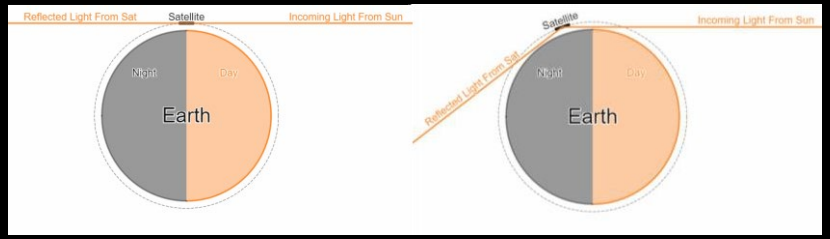


- SpaceX has switched from using visors to block light to using bragg mirrors to scatter light away from Earth.
- Brightness as observed from Earth is lowered as BRDF becomes more specular and diffuse tails decrease.
  - Intrinsic defects and surface roughness cause diffuse scatter.
- Current Starlink v1.5 satellites use the Gen1 dielectric mirrors and Gen2 dielectric mirrors are implemented for Starlink v2.

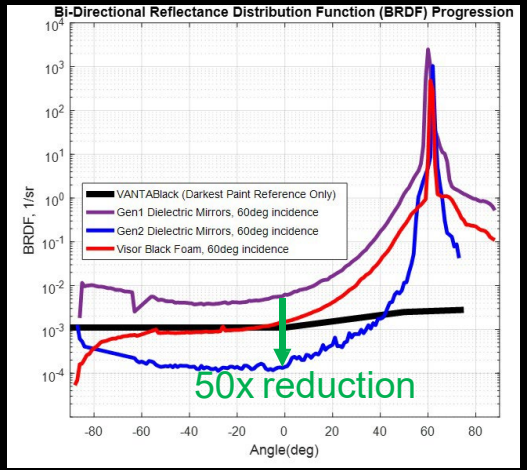
Perfect Reflection During Orbit

Sat Over Terminator

Sat Near Eclipse

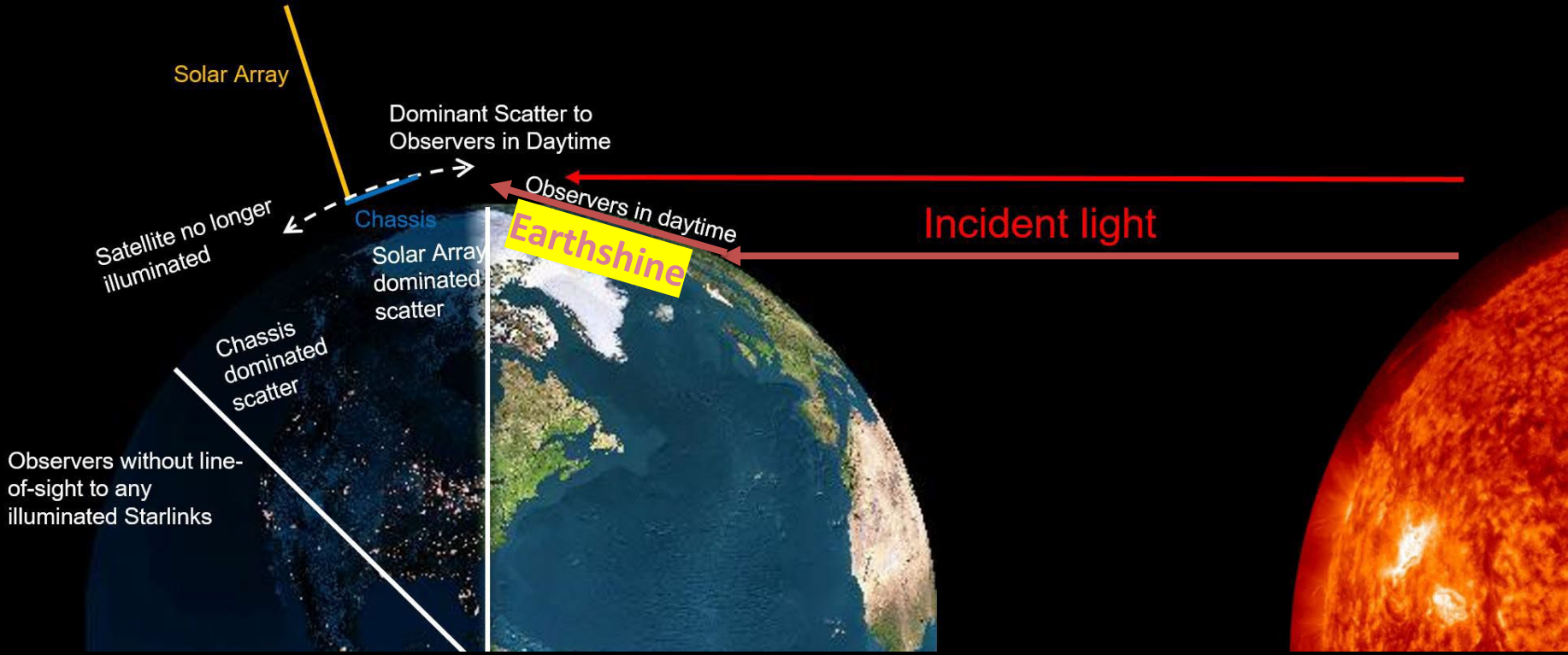


Scatter Properties



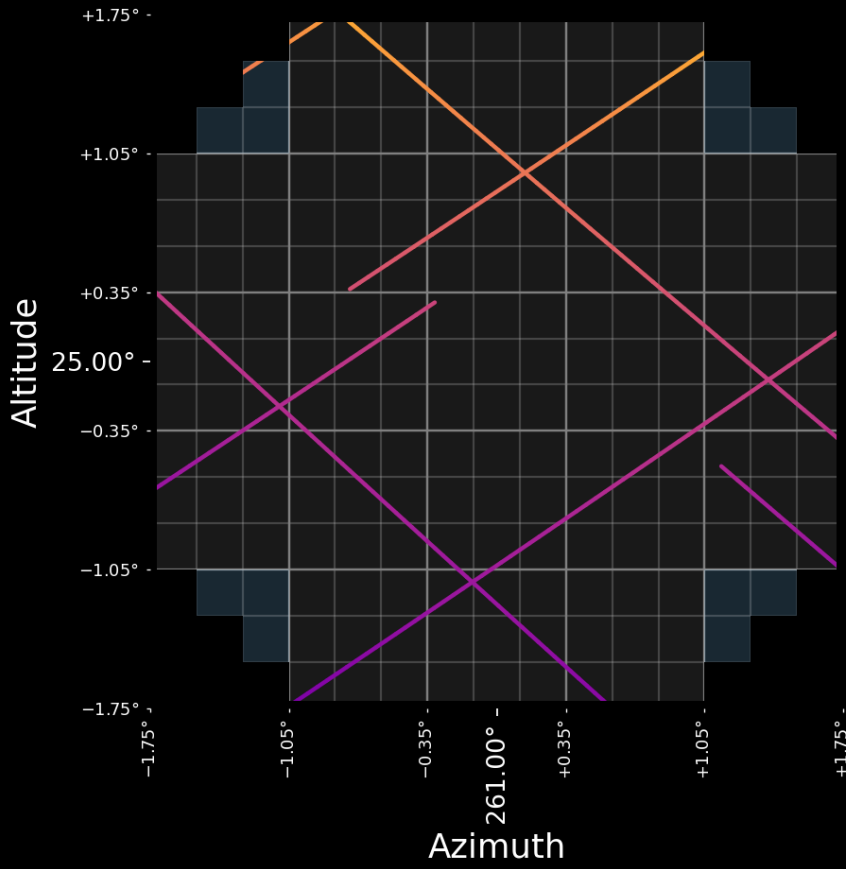
SpaceX

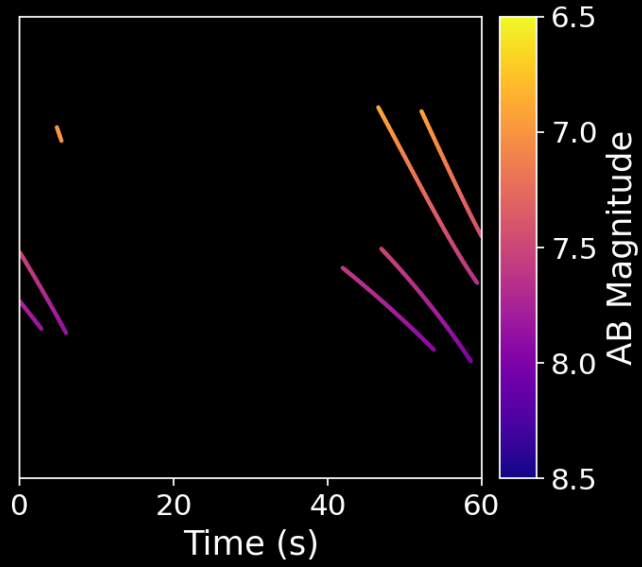
Second mechanism for satellite brightness



Satellite Streaks

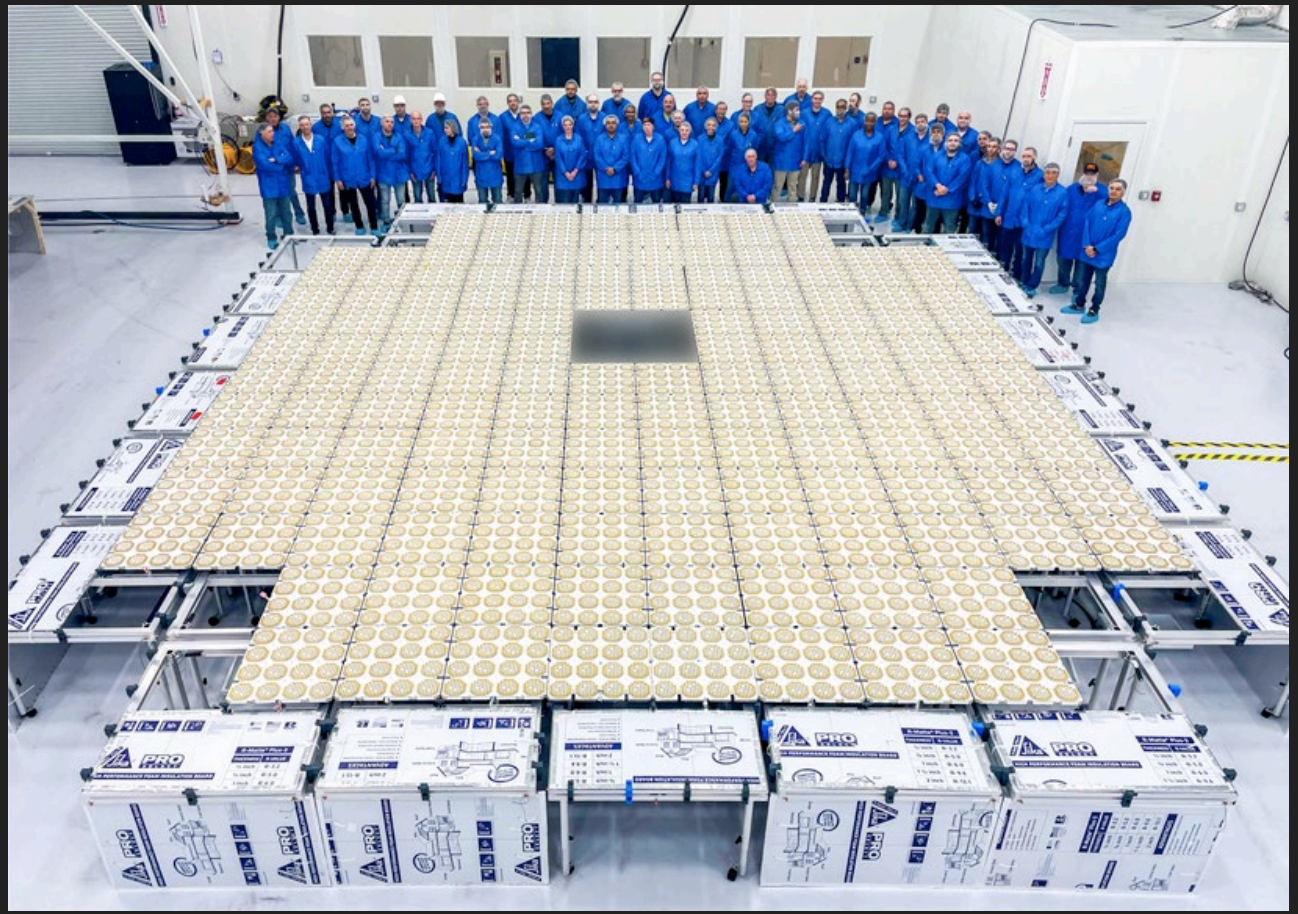
LSST NEO survey +25° Alt 261° Az





Forrest Fankhauser

AST-SpaceMobile



SpaceX also: Starlink Gen2+

Direct-to-cell is now attracting billions $ investment and strong telco support

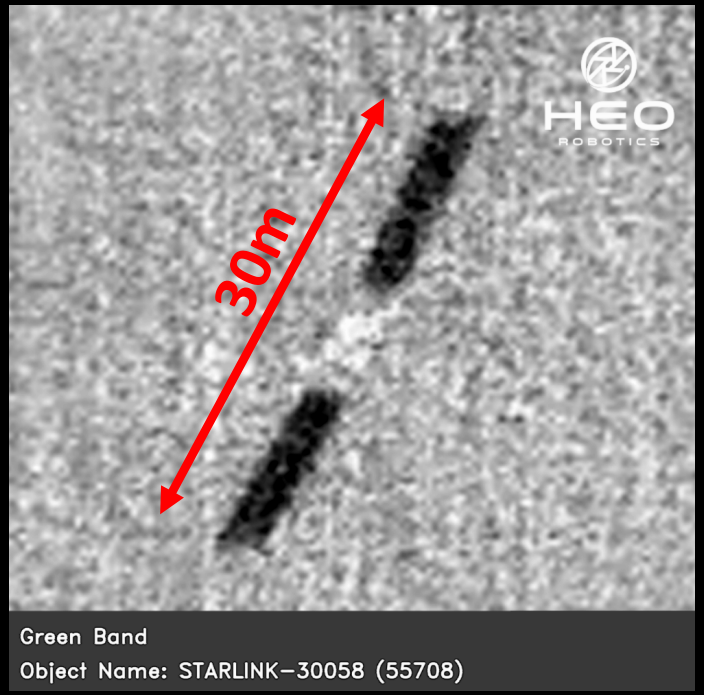
- SpaceX partnering with T-Mobile.
- Starlink Gen2+ will have deployable 25m^2 phased arrays as an add-on.
- Working with SpaceX on brightness.
  Estimate ~ 1 mag brighter.

New paradigm: Systematics limited science

- With tens of thousands of LEOsats, generally ***no combination of mitigations can completely avoid the impacts of the satellite trails*** on the Rubin Observatory LSST science programs.

- LSST is designed to probe the dark sky in new ways for dynamic events, and to unprecedented faintness. This requires fainter and fewer LEOsats to realize Rubin Observatory's scientific potential.

Starlink V2-mini



Next steps

- Work with industry to develop joint operations solutions to minimize science impact
- Develop observing strategies and new data analysis methods to partially correct for statistical and systematic effects caused by satellite trails
- Pursue international regulation of LEO space

Mitigation in analysis is complicated

Different science applications require different streak processing.

- LSST Data Brokers could supply custom streak masking.