@merrdiff

@mrawls

arxiv.org/abs/2006.12417

Comparing SpaceX's DarkSat to brighter Starlink siblings in *g*-band with DECam

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UNIVERSITY of WASHINGTON

DiRAC

Rubin Observatory

LSST Legacy Survey of Space and Time

SATCON1 • June 29, 2020

NSF

AURA

U.S. DEPARTMENT OF ENERGY | Office of Science

SLAC

Why observe low-earth-orbit satellites?

Rubin Observatory

- Tens of thousands will be launched in the next ~decade
- Even with mitigations, they will land in our data

Nov 18, 2019
DECam DELVE Survey/ CTIO/AURA/NSF

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- Predict their impact on astronomy now
  - Wide-field ground-based optical surveys in particular
  - Rubin Observatory's LSST (Legacy Survey of Space and Time) ~2023

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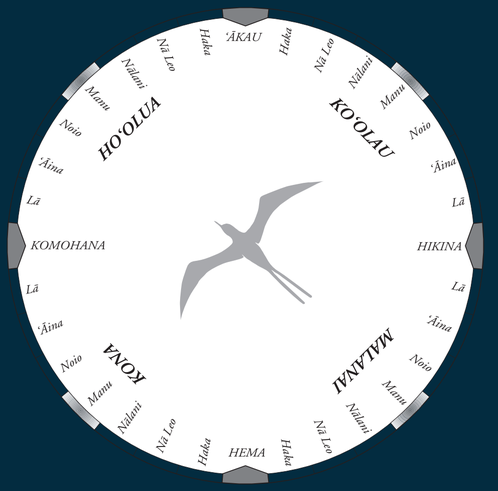
- Quantify ways to minimize satellite impacts
- Mitigate their impacts beyond science, too



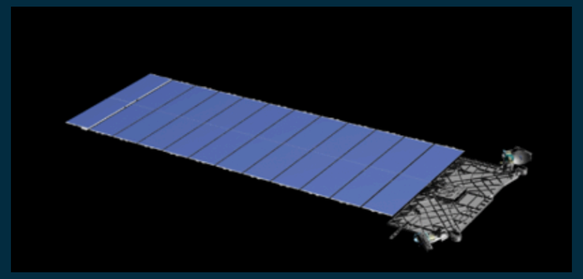
Polynesian Wayfinding Star Compass
hokulea.com / Charles Nainoa Thompson

Low-earth-orbit satellite life cycle 101

For my astronomy colleagues who are learning this for the first time

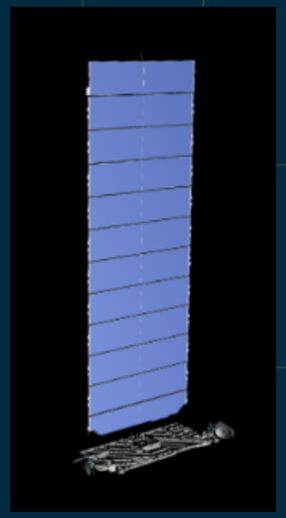
- SpaceX's Starlink is the first example of a megaconstellation
- Satellite life cycles should be ~similar for other operators

Orbit Raise (months)



SpaceX images

On Station (~550 km, years)



Not shown:
Launch, insertion, parking orbit, de-orbit

Data from wide-field ground-based optical surveys (like Rubin Observatory's LSST)

Rubin Observatory

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Rubin Observatory

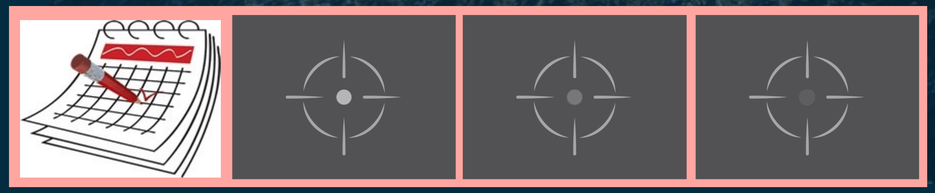
Prompt

60s

Real-time alerts

24h

Prompt products database with forced photometry



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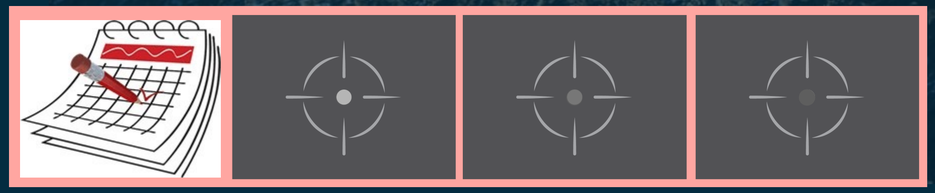

Data Release

Annual reprocessing with stacked images

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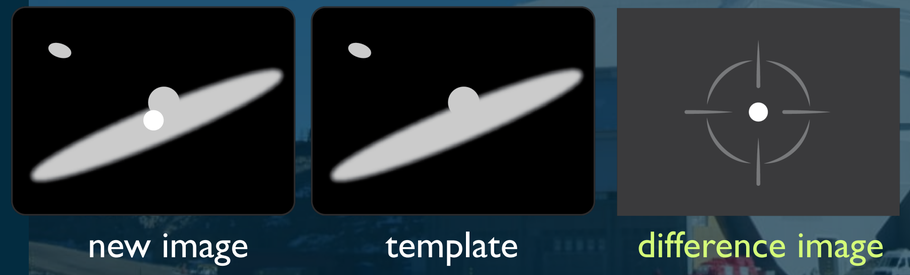
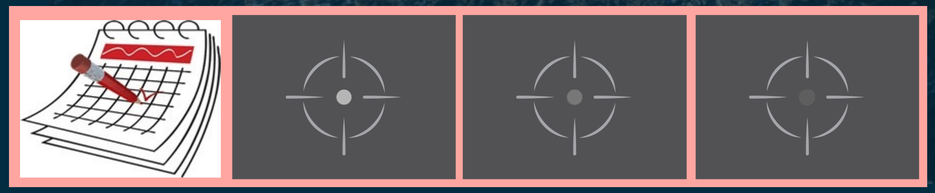




Data Release

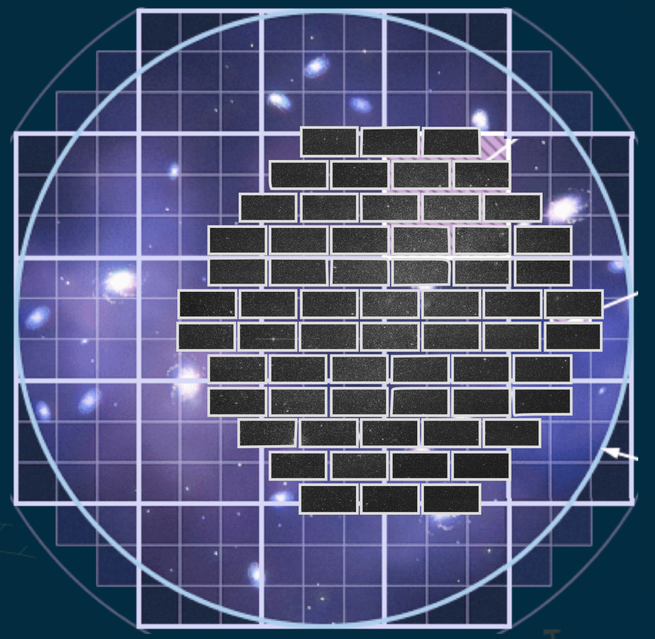
Annual reprocessing with stacked images

User Generated

DIY scripts

Processing raw telescope images

- Many steps before data products are ready for science
- LSST Science Pipelines: open source software for this (and much more!)
  - pipelines.lsst.io
  - Bosch et al. 2019 arxiv.org/abs/1812.03248
- Blanco 4-m DECam (Dark Energy Camera) is a precursor to Rubin Observatory 8.4-m LSSTCam



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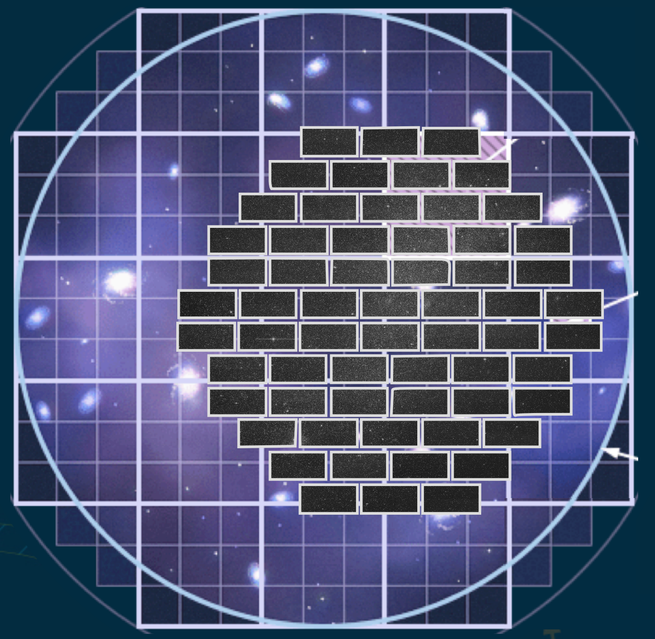
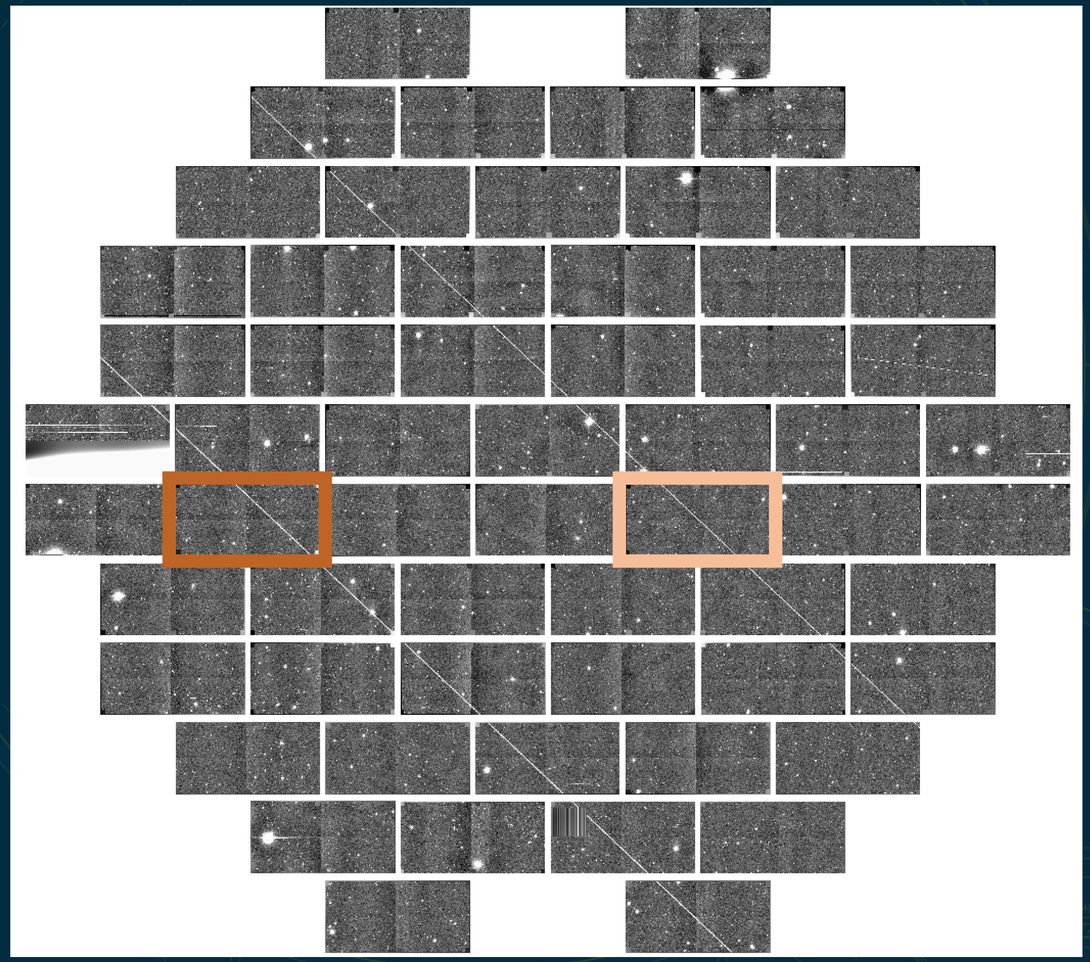


PSF = Point Spread Function

Two Starlinks in 1 of 4 DECam visits

Rubin Observatory



Observations courtesy of DELVE (Alex Drlica-Wagner)

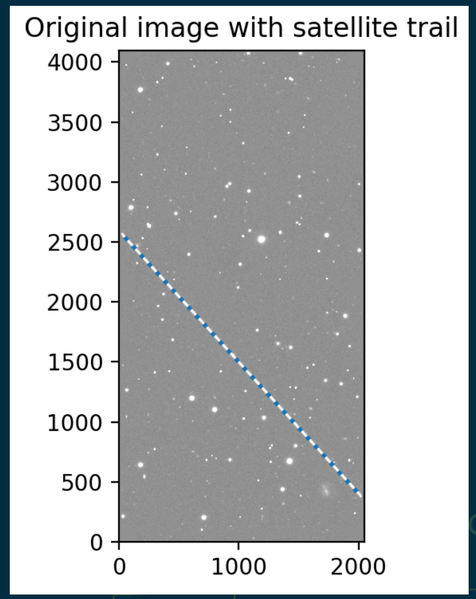
Blanco 4-m
David Walker

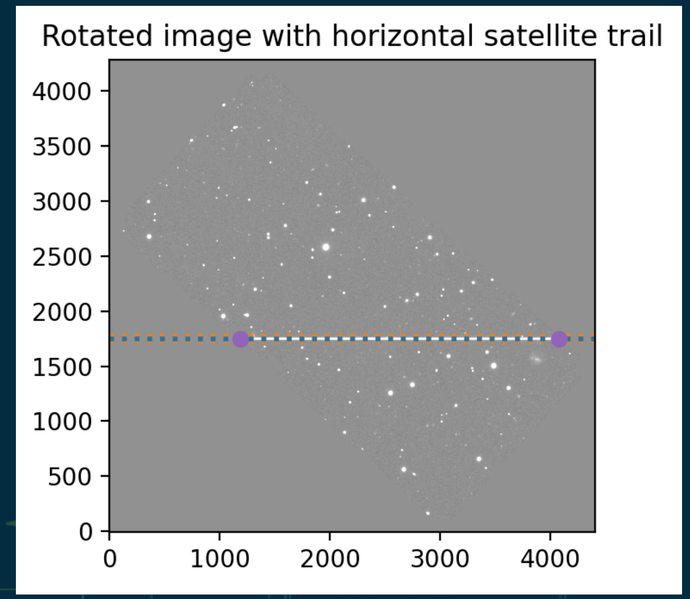
Full analysis: Tyson et al. 2020
arxiv.org/abs/2006.12417

Analyzing processed DECam images with python

Rubin Observatory

- Load processed image data
- Get Sun location and phase angle
- Rotate image so trail is horizontal
- Measure trail brightness
- Account for exposure time
- Account for satellite speed
- Estimate distance to satellite
- Estimate satellite size



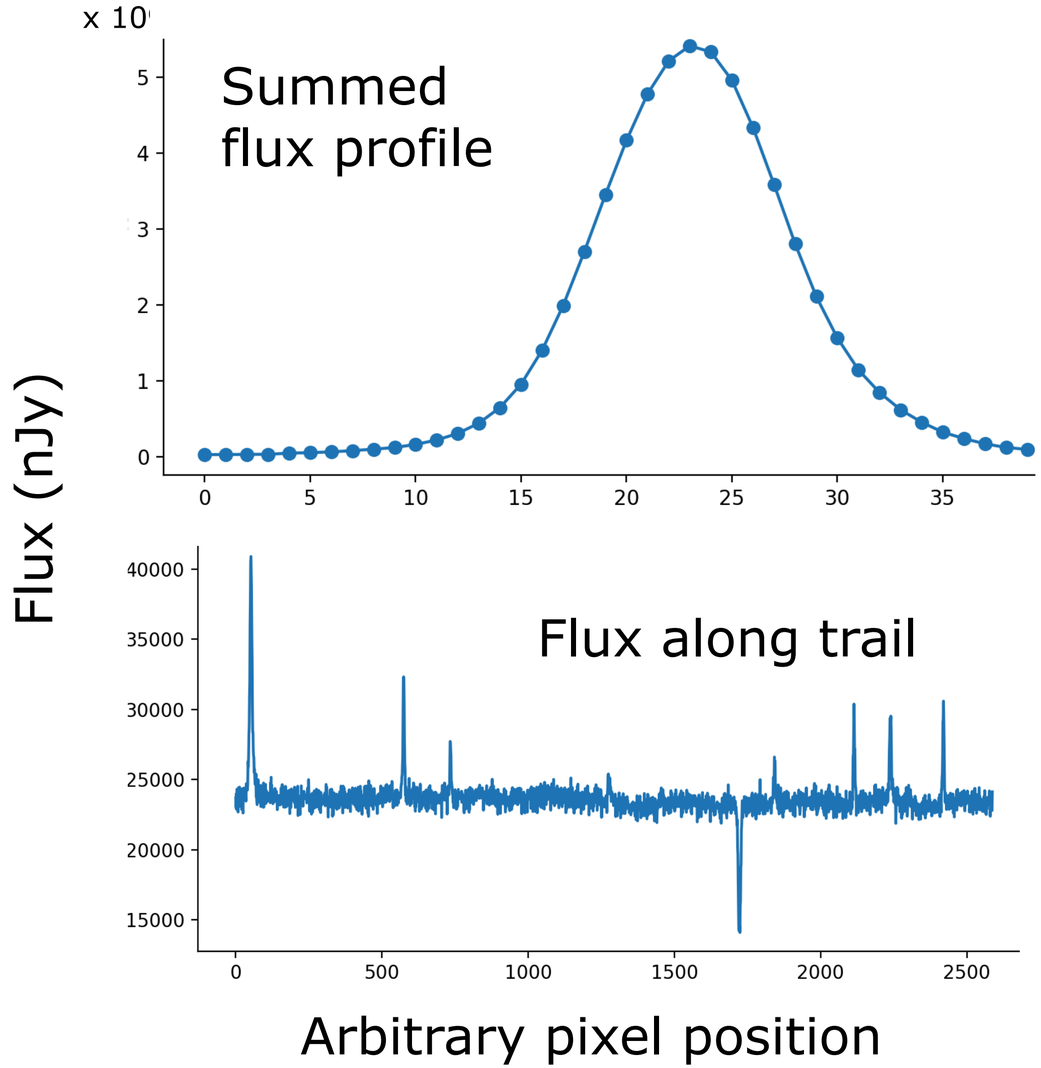


LSST Science Pipelines

astropy-powered
astropy.org

- All publicly available: https://github.com/dirac-institute/starlink

Measuring satellite trail brightness



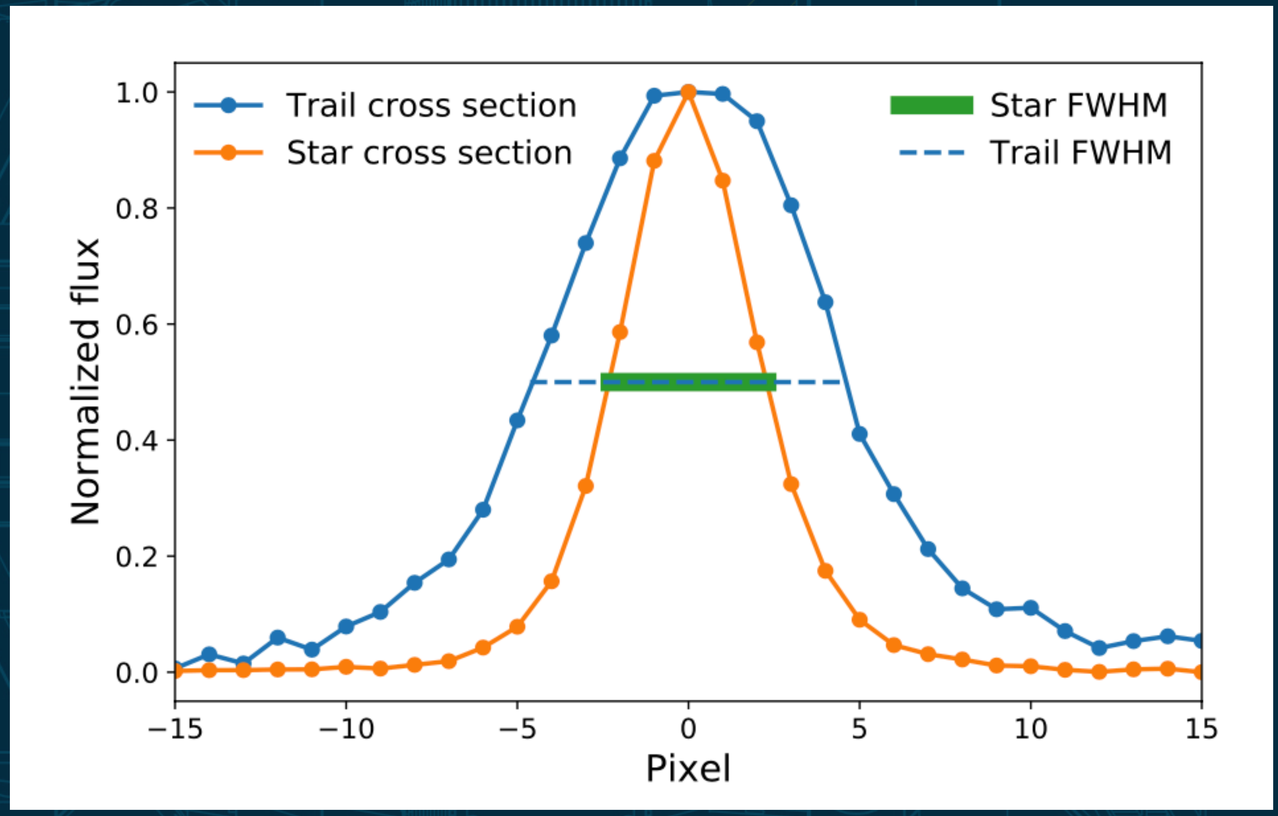


Fig. 9, Tyson et al. 2020 arxiv.org/abs/2006.12417

- Images are background-subtracted
- Pixel values are calibrated (nJy)
- Trail width is a function of telescope size

DarkSat is 1.1 mag darker than its siblings in *g*-band

Rubin Observatory

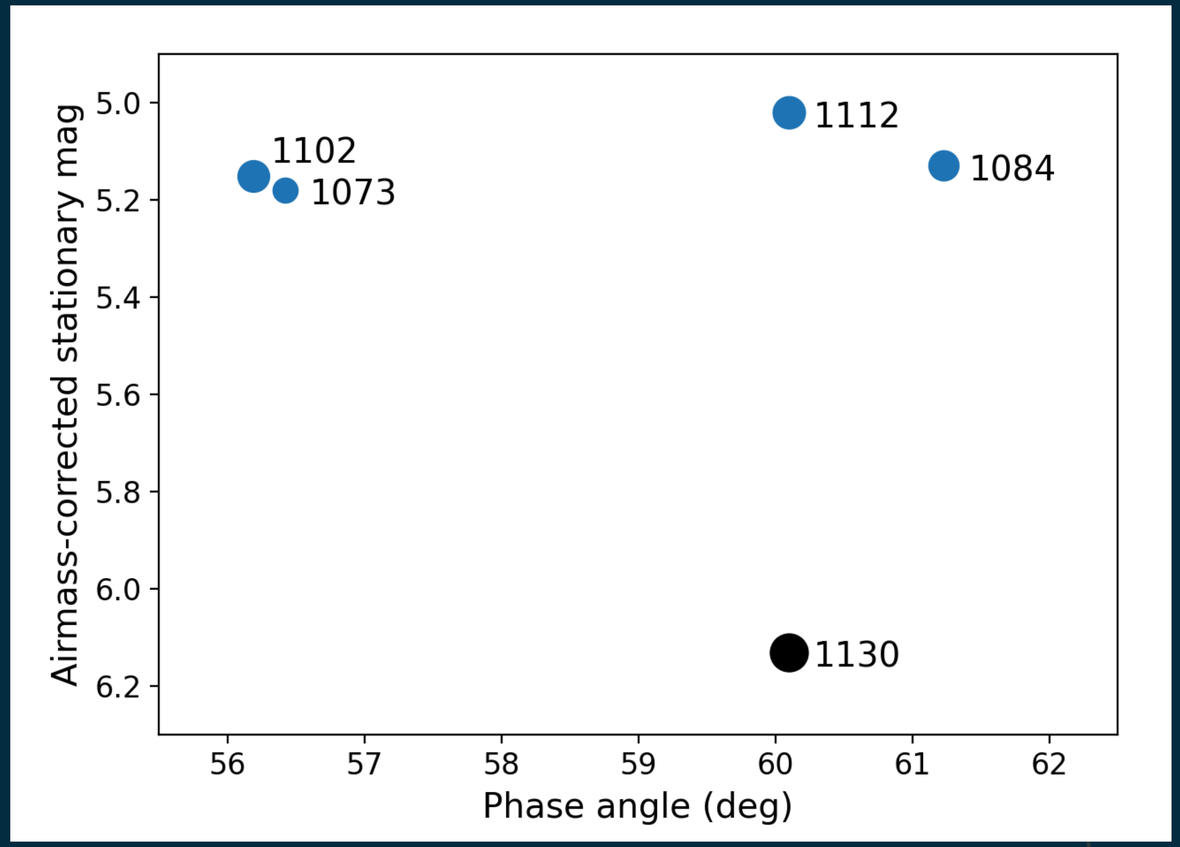
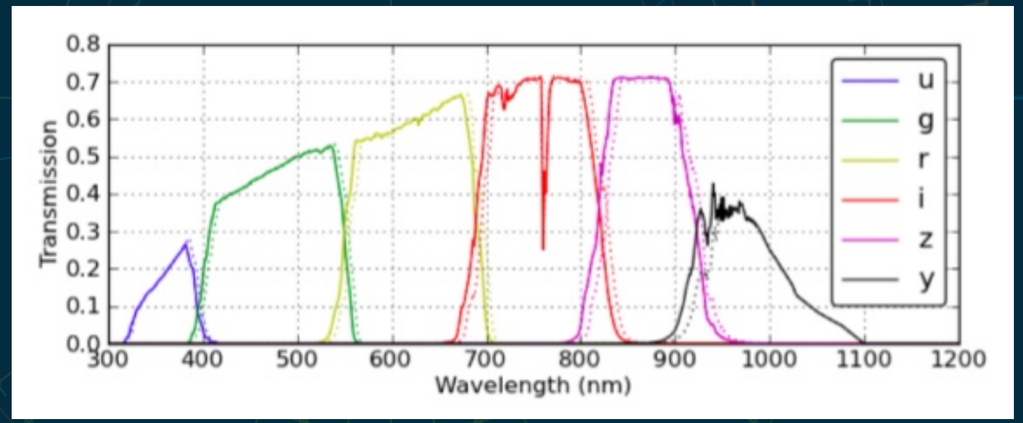


Fig. 8, Tyson et al. 2020 arxiv.org/abs/2006.12417

- Magnitudes are corrected for satellite speed and airmass
- Marker size indicates derived satellite size and ~mag error
- Brightness not measured for phase angles far from 60°



Measurements of 5 Starlinks launched in Jan 2020

Rubin Observatory

Starlink	Time	Phase angle	Airmass	PSF FWHM	Background	Trail FWHM
	UTC	deg		arcsec	mag arcsec^{-2}	arcsec
1102	00:05	56.2	1.03	1.35	19.0	2.43
1073	00:15	56.4	1.15	1.35	19.2	2.04
1130	00:30	60.1	1.55	1.20	18.9	2.12
1112	00:30	60.1	1.55	1.18	19.0	1.87
1084	00:35	61.2	1.71	1.33	18.8	1.82

Starlink	Raw trail	Corrected trail	Speed	Stationary	Zenith	d	Size
	mag arcsec^{-2}	mag arcsec^{-2}	deg s^{-1}	mag	mag	km	m
1102	19.98	14.78	0.77	5.21	5.15	565	3.84
1073	19.96	14.76	0.70	5.49	5.18	625	2.34
1130	21.31	16.11	0.54	7.08	6.13	810	5.58
1112	20.06	14.86	0.54	5.97	5.02	810	4.02
1084	20.27	15.07	0.50	6.29	5.13	878	3.47

- Night of March 5-6, 2020
- ~1 hour after sunset
- Four visits within 30 min
- All exposures 120 sec

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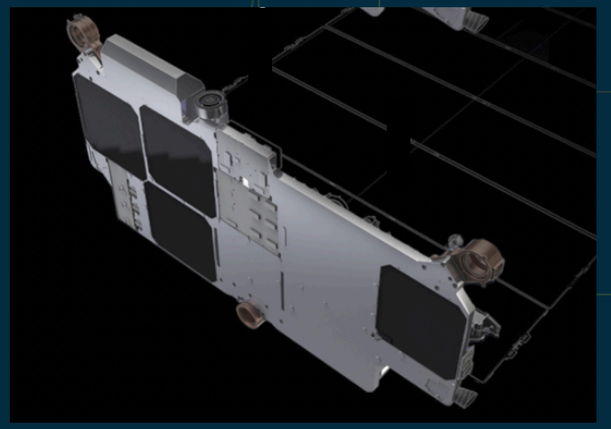
- *d* is derived distance from observer to satellite
- Size is derived satellite size from trail width, stellar PSF, and mirror

Read all about it: arxiv.org/abs/2006.12417

DarkSat is ~6th mag, but we really need ~7th mag

Rubin Observatory

- Would enable image artifact correction for Rubin Obs/LSST
- Trails that remain will likely impact science in other ways



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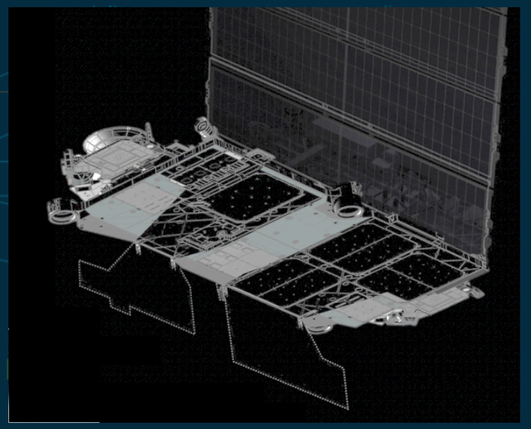

VisorSat (SpaceX)

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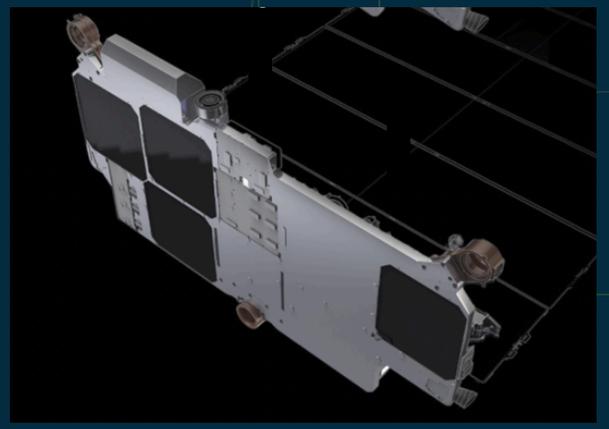

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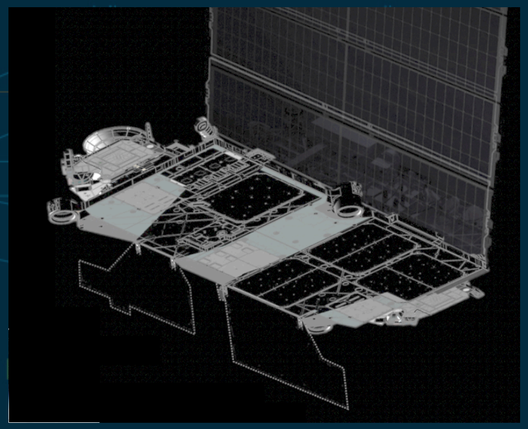

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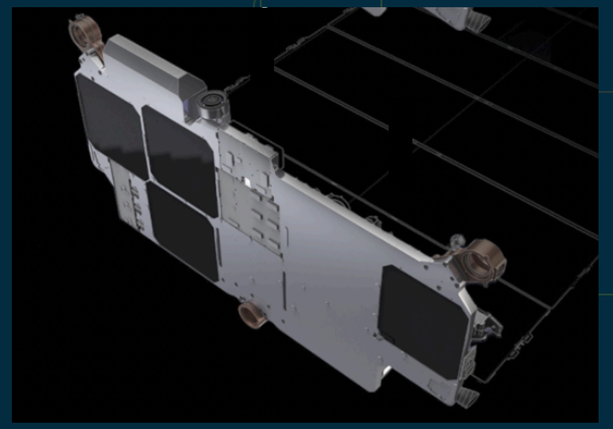
- Reaching ~7th mag requires significant operator mitigations
- Satellite phases outside of "on station" still a problem



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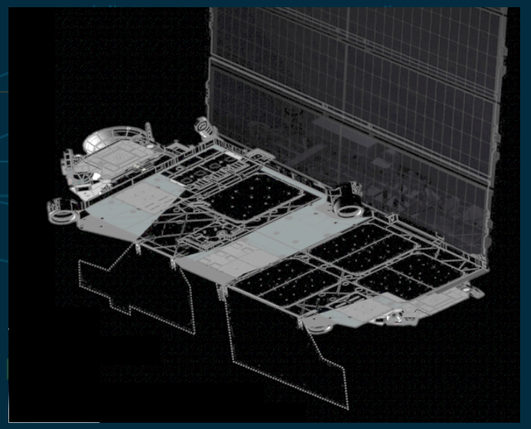

VisorSat (SpaceX)

Starlink mitigations are promising, but not everything

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- Wide-field ground-based optical imaging surveys are most impacted by many bright low-earth-orbit satellites
- Jan 2020 Starlinks are ~5th mag, DarkSat is ~6th mag
- Mitigating the worst effects is possible for ~7th mag (VisorSat?)

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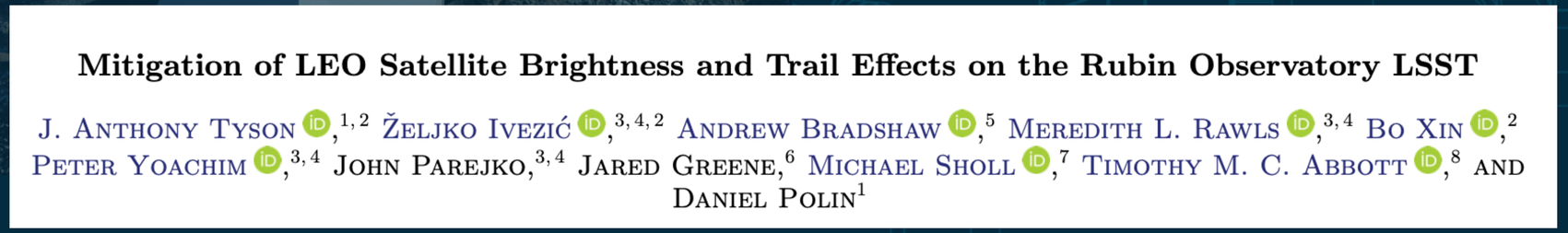
- Mitigating the worst effects is possible for ~7th mag (VisorSat?)
- Trail analysis tools: https://github.com/dirac-institute/starlink
- Unclear who will fund astronomers to do mitigation work
- Operator mitigations are voluntary, not legally required
- For more on Rubin Obs/LSST mitigations, read our paper

Tyson et al. 2020
arxiv.org/abs/2006.12417



Mitigation of LEO Satellite Brightness and Trail Effects on the Rubin Observatory LSST

J. Anthony Tyson,[1,2] Željko Ivezić,[3,4,2] Andrew Bradshaw,[5] Meredith L. Rawls,[3,4] Bo Xin,[2] Peter Yoachim,[3,4] John Parejko,[3,4] Jared Greene,[6] Michael Sholl,[7] Timothy M. C. Abbott,[8] and Daniel Polin[1]