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The impact of satellite constellations on astronomy

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12 February 2025

CPS IAU NOIRLab SKAO

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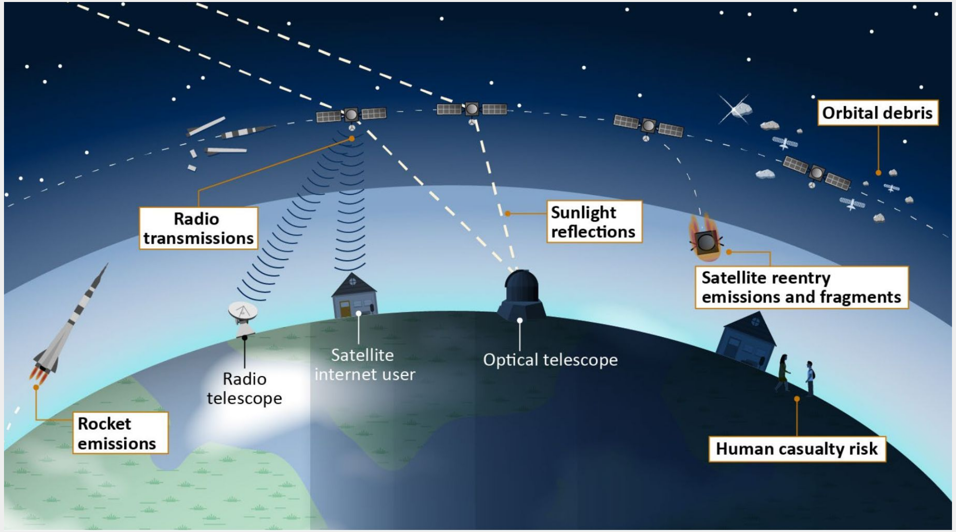
Overview

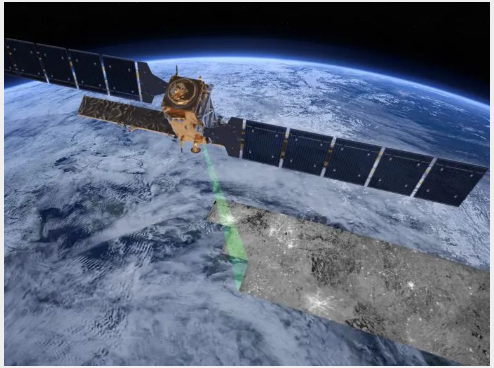
1. Introduction to satellites
2. Optical impact
3. Radio impact
4. Mitigations
5. IAU CPS
6. Policy
7. Conclusions



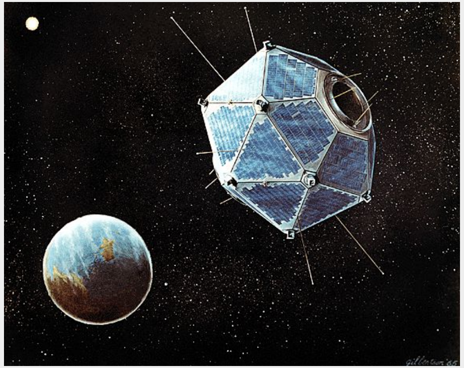
Introduction to satellites

Reasons for launching satellites

Telecommunications

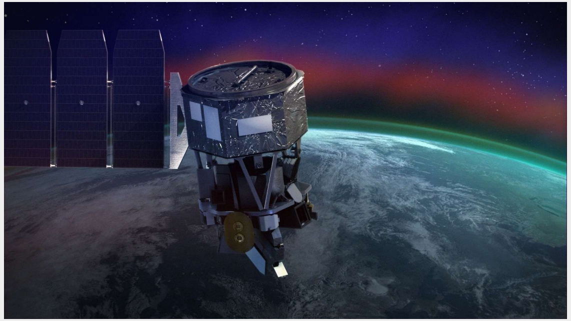


Earth observation



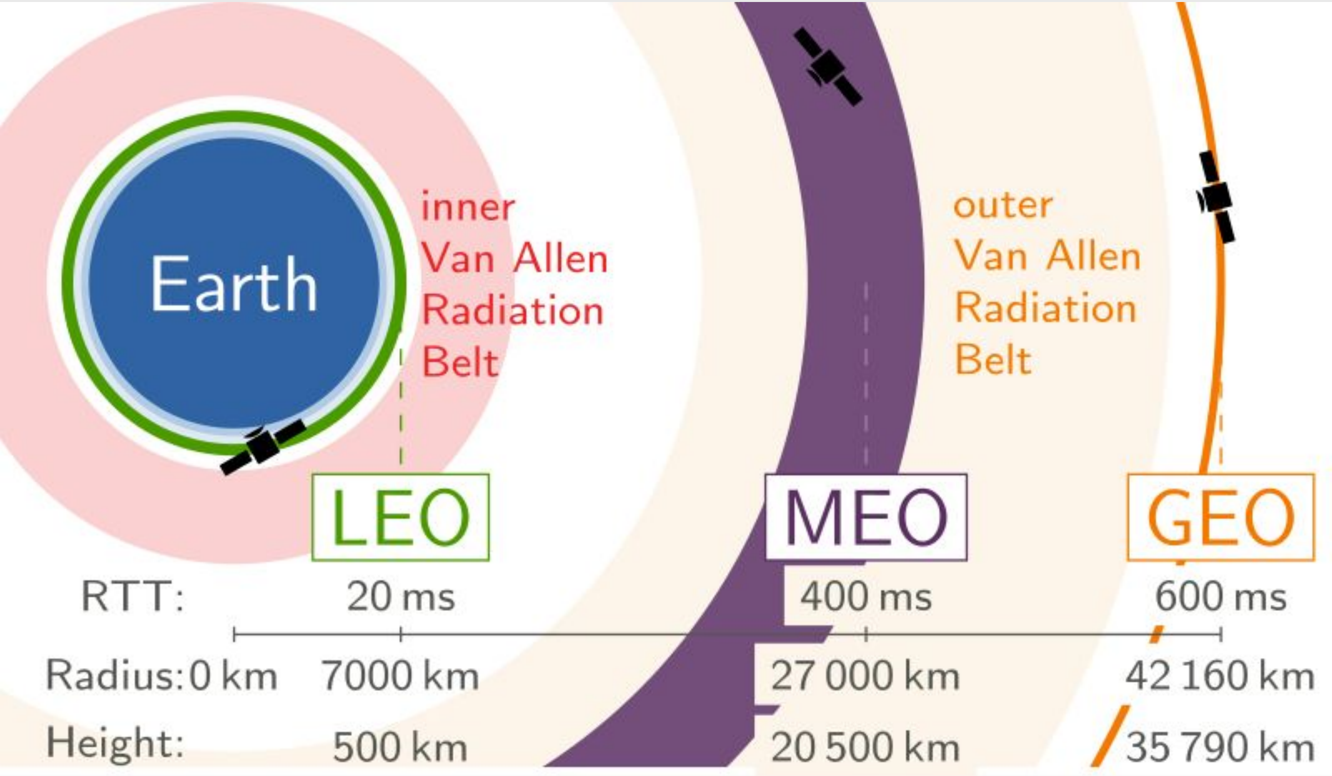
Military applications

Weather forecasting



Space science

Different orbits



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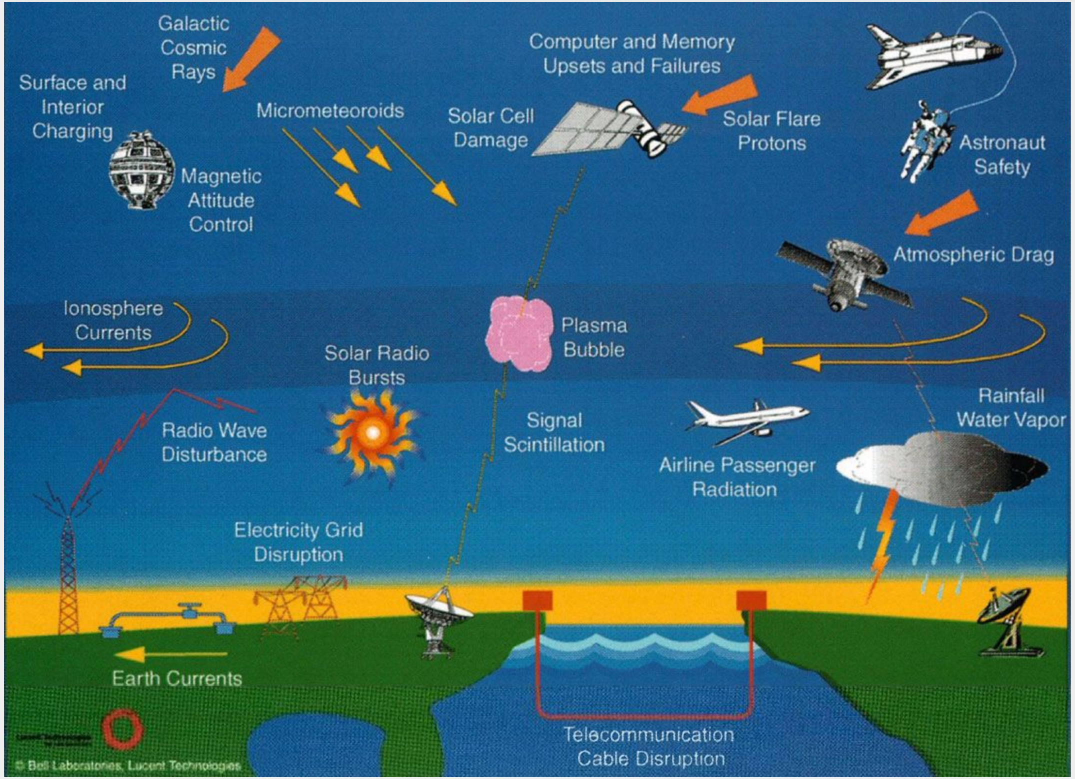
The space environment



Adapted from Lanzerotti et al. 1999

Re-entry risks...

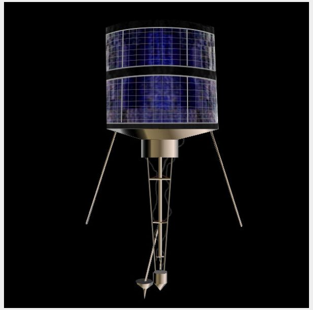
Ko Maung Myo/Myanmar Times

ESA/NASA

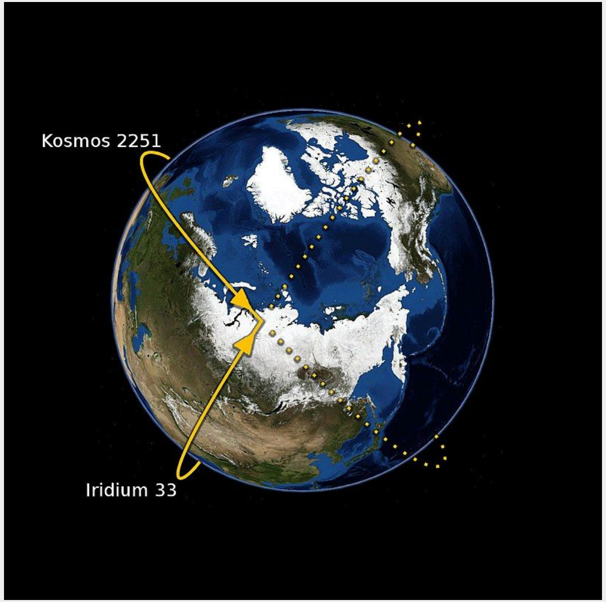
Orbital collisions

Iridium 33

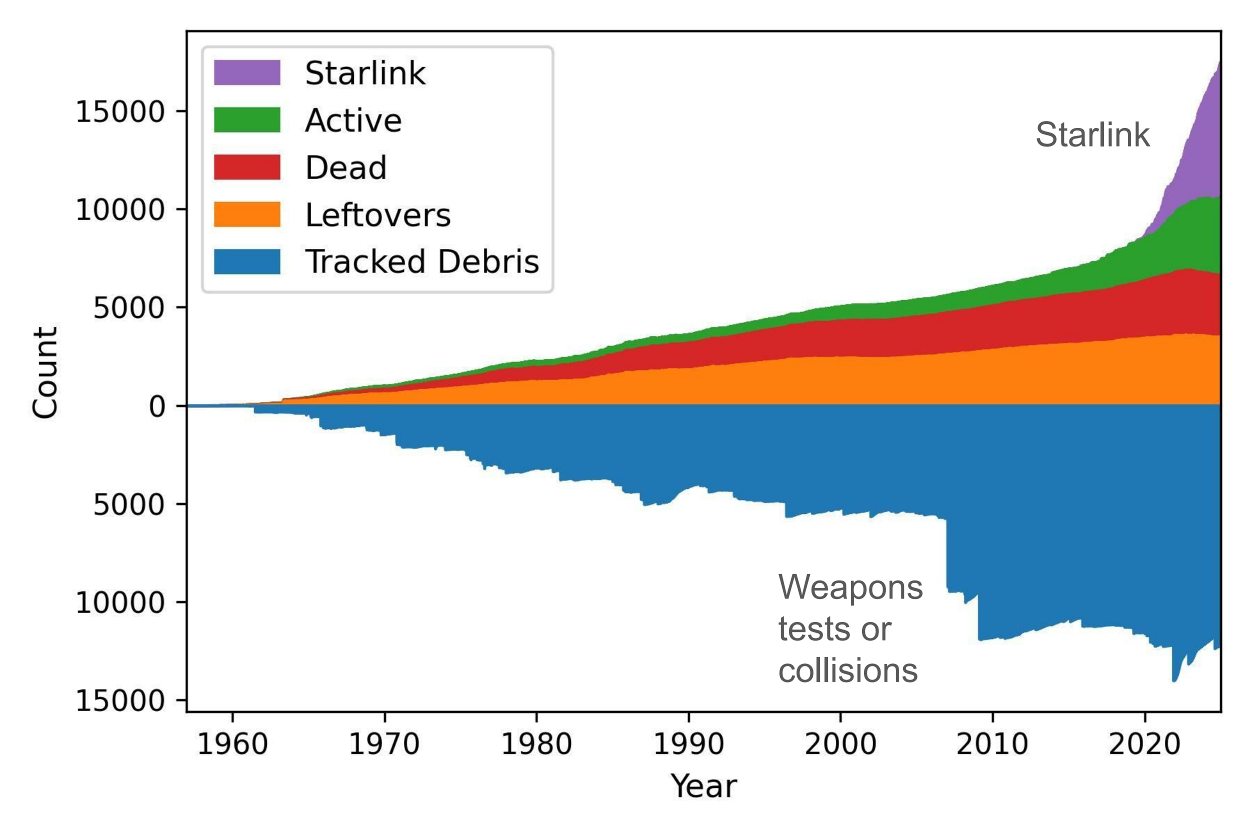
Kosmos 2251



10 February 2009 direct collision



Increasing numbers of satellites



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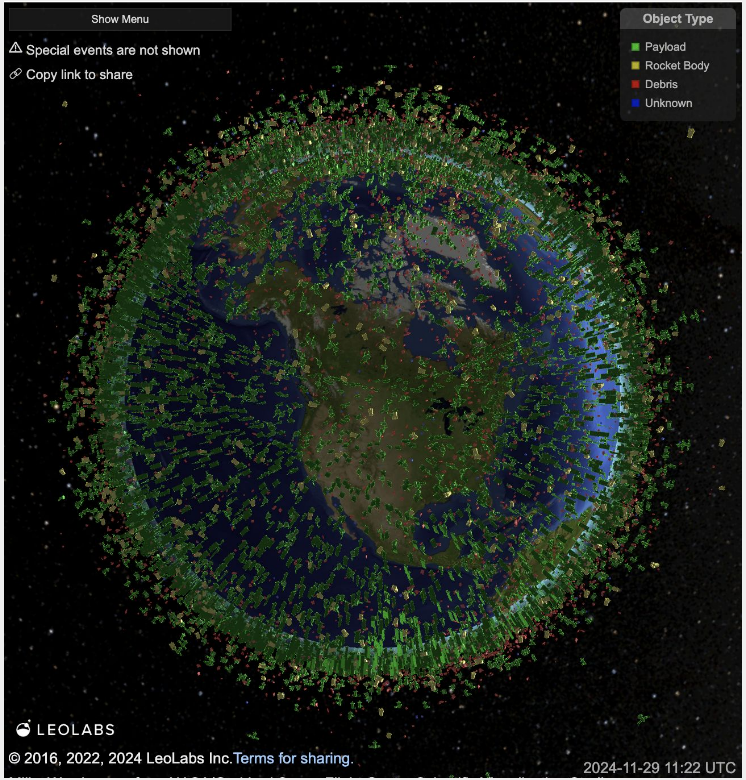
Space is changing rapidly

- 8500+ satellites in Low Earth Orbit
- Plans for > 1,000,000 satellites by 2030s
- Major concerns:
    - Effects on optical astronomy
    - Effects on radio astronomy
    - Effects on the night sky
    - Space traffic management
    - Space debris



Many different satellite constellations

- Starlink (US, ~7,000 satellites, ~35k more expected)
- OneWeb (UK/EU, ~650 satellites, Gen 1 completed, Gen 2 coming...)
- Amazon Kuiper (US, 2 test satellites launched, many more coming)
- AST SpaceMobile (US, 6 so far, ~200 expected)
- Qianfan (China, ~70, many more coming)
- Guowang (China, ~20, many more coming)
- ...

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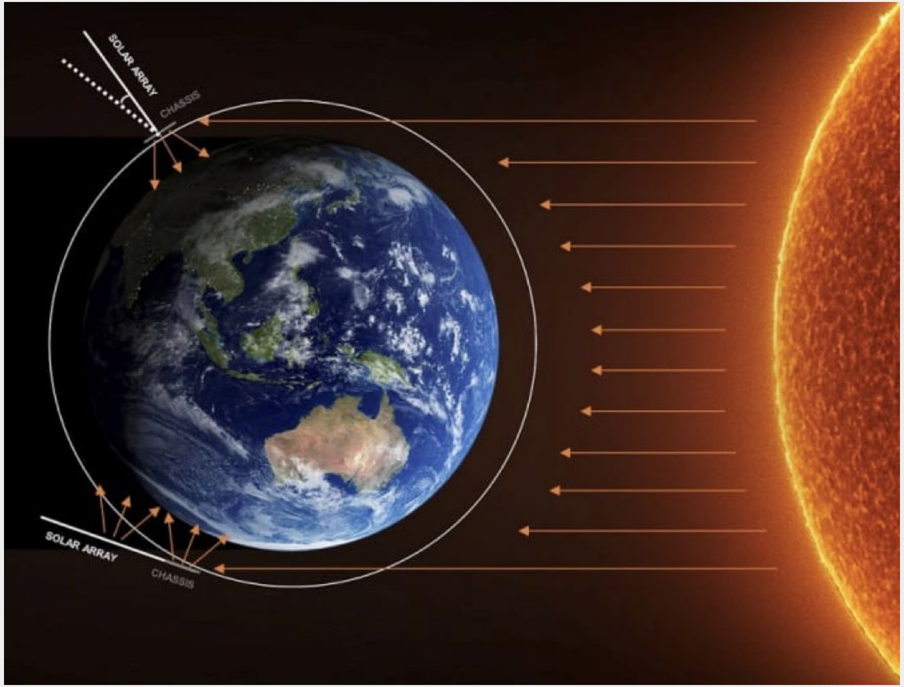
Optical impact

Impact on the night sky

Pentre Ifan burial chamber, Pembrokeshire, Wales - Max Alexander "Our Fragile Space"

Satellites during twilight

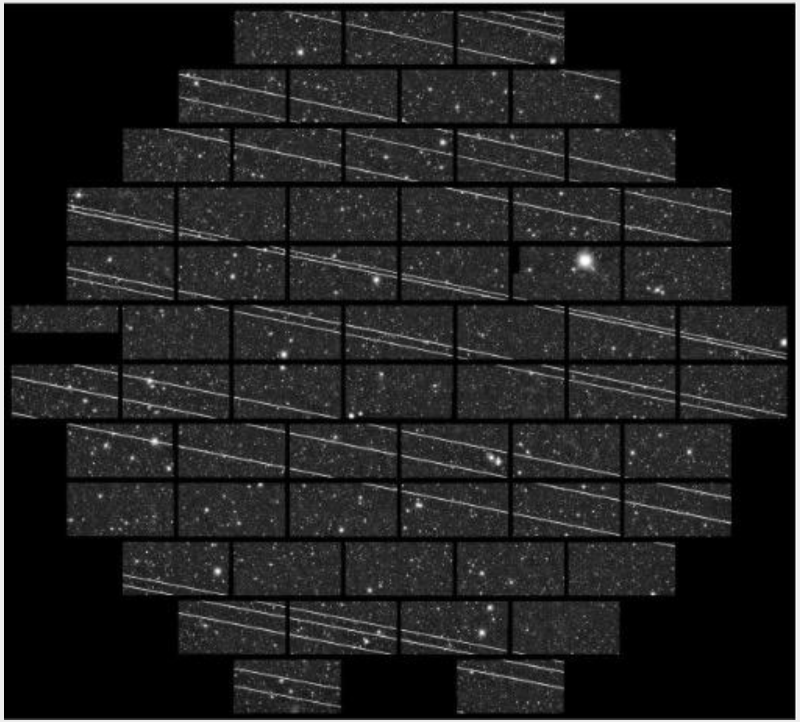
- Sunlight can be reflected by satellites' bodies in a diffuse way
- Depends on: area, materials, altitude, attitude, …
- Brighter than magnitude 7 is visible with the naked eye
- Brightest during early evening and early morning



Credit: SpaceX

Effects on optical astronomy

- Satellite streaks can cause unusable data
- Impacts to science include:
  - Asteroids: best time to spot them is during twilight
  - Variable stars: lost time series
  - Dark Matter weak lensing: subtle distortions to the shapes of galaxies
  - Spectroscopy: contamination by reflected sunlight
  - Extreme brightness can cause damage to optics



Credit: CTIO/NOIRLab/NSF/AURA/Decam DELVE Survey

Impact on optical observatories

- Narrow field
  - Gemini, Keck, ESO's VLT, ELT
  - ~10% of frames at the end of astronomical twilight
- Wide-field
  - Blanco, VST
  - 50% of frames during twilight
- Super-Wide-field:
  - Rubin Observatory
  - ~ all image frames during twilight
  - Many frames - during whole nights

Credit: NOIRLab

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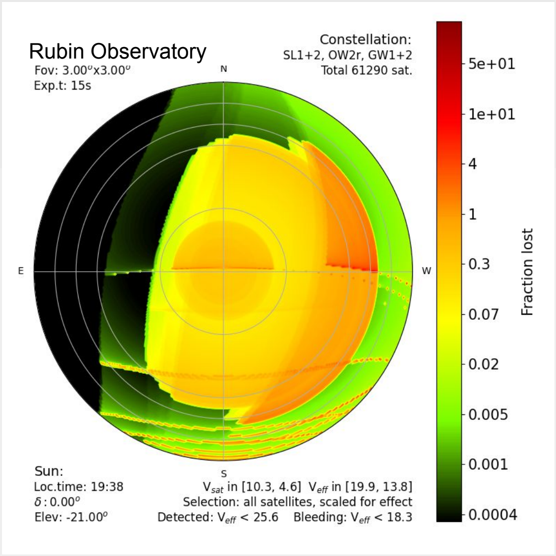
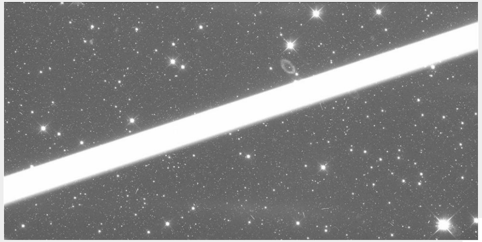
Accidental optical light



Up to V=3 in parking orbits. **Need 7th magnitude** or better (higher magnitudes are fainter).

Significant effect on future optical telescope surveys like LSST with Vera C. Rubin Observatory. Even seen with Hubble...

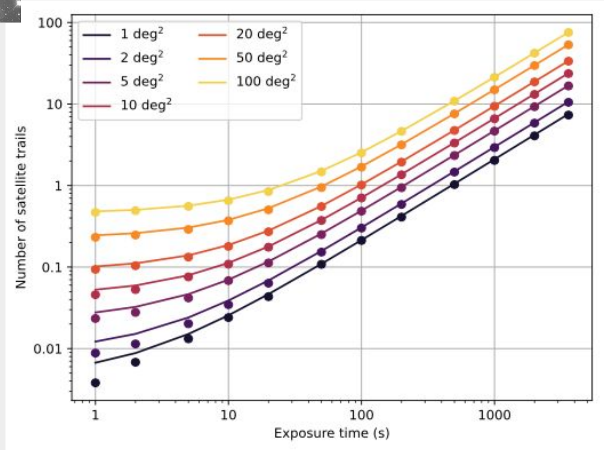


Starlink satellite size has been limited by Falcon 9 rocket, but Starship will enable them to launch more, bigger ones soon - hopefully with improved mitigations...

SATCON2 algorithms report

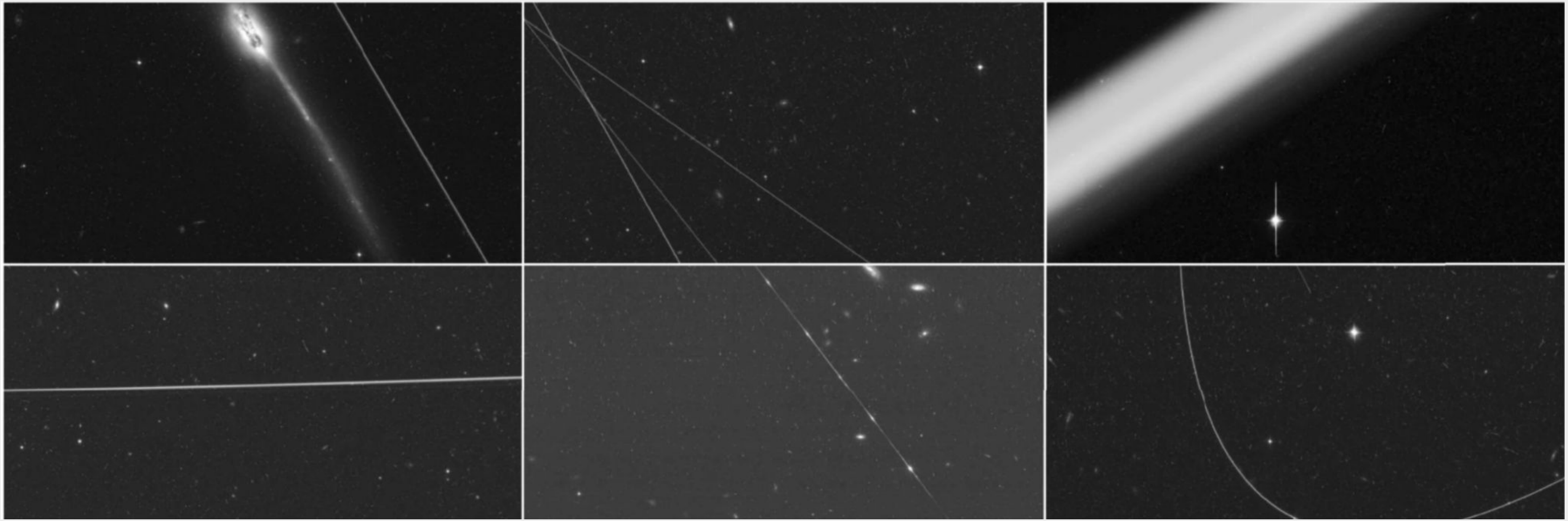
Satellite	Operational altitude [km]	Mag at op. alt.	Mag dispersion	Mag at 1000km
Starlink original	550km	4.6	0.7	5.9
		4.0	0.7	5.3
		4.2	(model)	5.5
Starlink DarkSat	550km	5.1	(single)	6.4
Starlink VisorSat	550km	6.2	0.8	7.5
		5.8	0.6	7.1
OneWeb	1200	7.6	0.7	7.2

Bassa et al.
arXiv:2108.12335



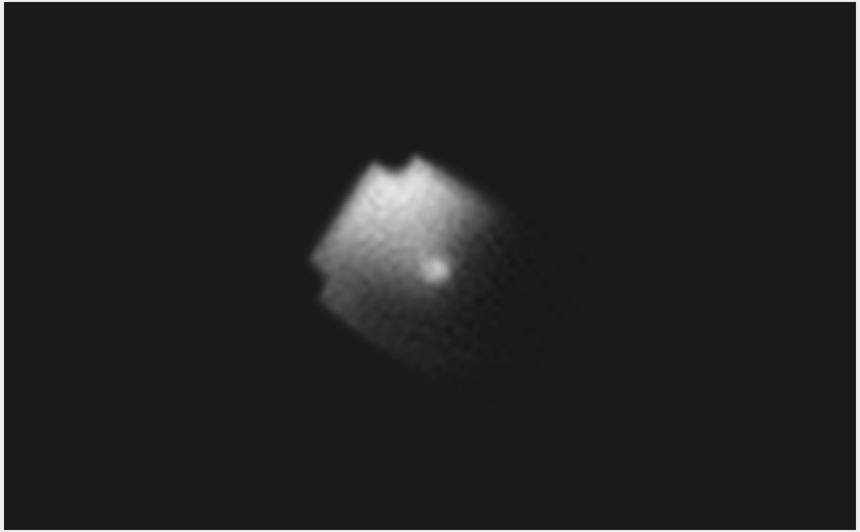
Satellites' Impact on Space-based Astronomy

Satellite trails in HST individual exposures (Kruk et al. 2023, NatAs, 7, 262)

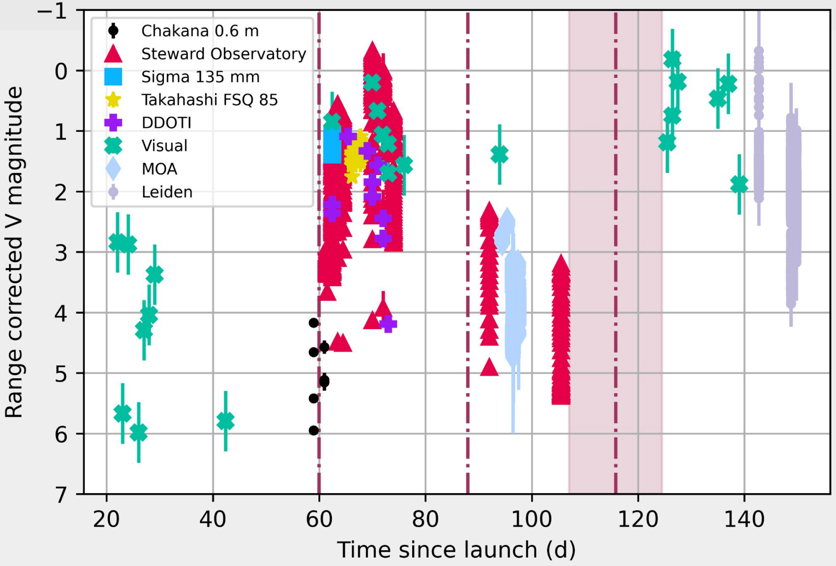


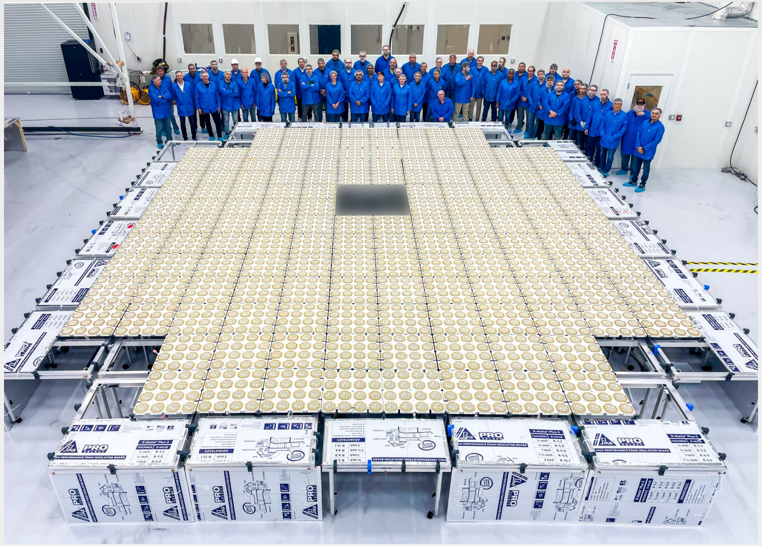
AST SpaceMobile Bluewalker 3 observations

- Launched 10 September 2022
- Observations by CPS members
- Apparent magnitude 0.4
- CPS recommendations are maximal brightness of 7
- AST SpaceMobile working to address concerns
- Extra bright due to its phased array of antennas (8x8m white platform)



BlueWalker3: optical bright, also thermally bright?





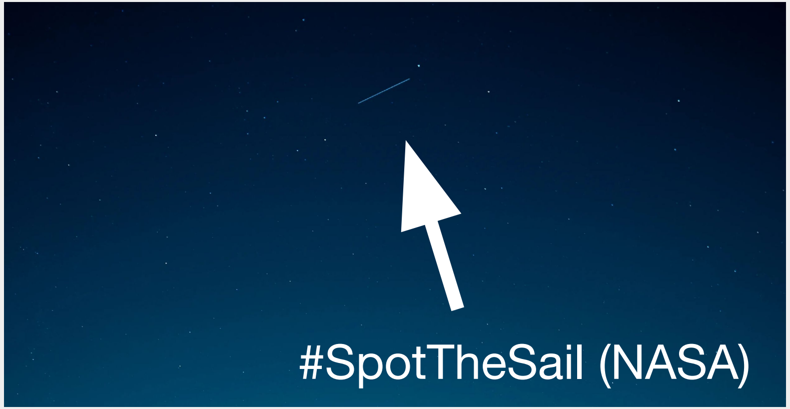
- 64m^2 phased array, prototype for mobile phone connections using standard phones + satellite
- Optical measurements show it to be brighter than all except top 10 stars (Nandakumar et al., Nature, 2023)
- (+ launch vehicle adapter bright & untracked for first few days, + position predictions degrade over time)
- Thermal brightness unknown: have SCUBA2/JCMT time to observe ISS + BW3, observations later this year

New types of satellites continually launched

- Starlink direct-to-cell, lower altitude and larger, V mag ~4–5 (5x brighter than higher smaller counterparts, despite mitigations)
- AST SpaceMobile, 5 BlueBirds launched Sep 2024, V mag ~7 pre-unfurling
- NASA solar sail demo launched Aug 2024, tumbling, V mag oscillating from ~0 to ~8 (drag devices may also be thermally bright?)

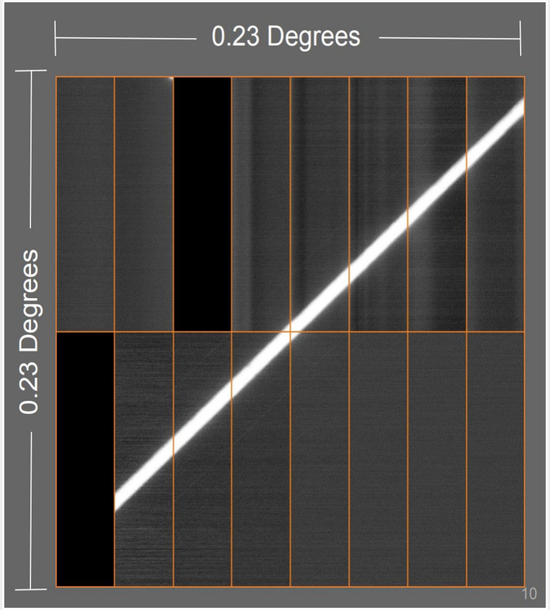
Starlink V2 mini direct-to-cell (Tom Williams)

BlueBird rendition (AST SpaceMobile)



Rubin Observatory CCDs

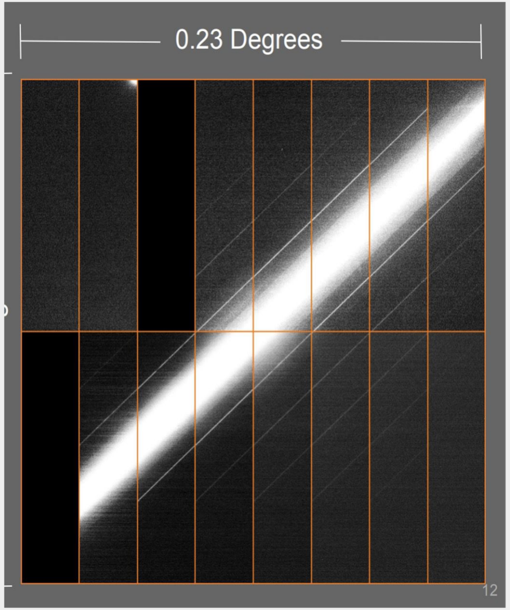
IAU CPS recommendation



Crosstalk Correctable with <10%
Error = 5,000 peak electron count
= 7-8th magnitude*

Faint brightness science affected

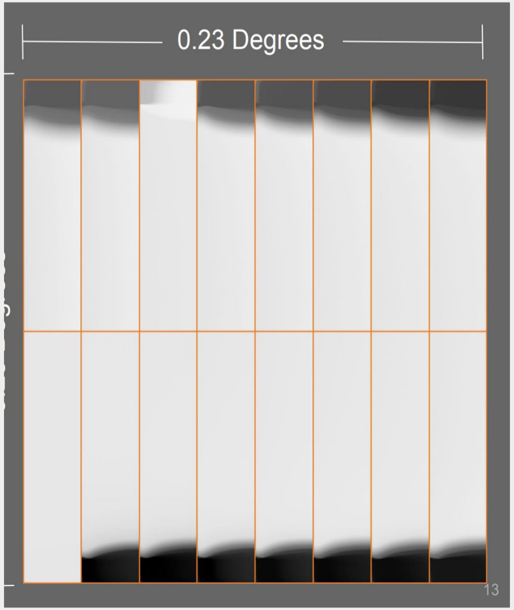
Current Starlinks



Saturation/ “Correctible” with large
Error = 100,000 electrons =
4th mag

Most science programs affected

BlueWalker 3



Blooming/ Not Correctable =
1 Million electrons = 0-1 Mag

Radio impact

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Radio spectrum is regulated and very crowded

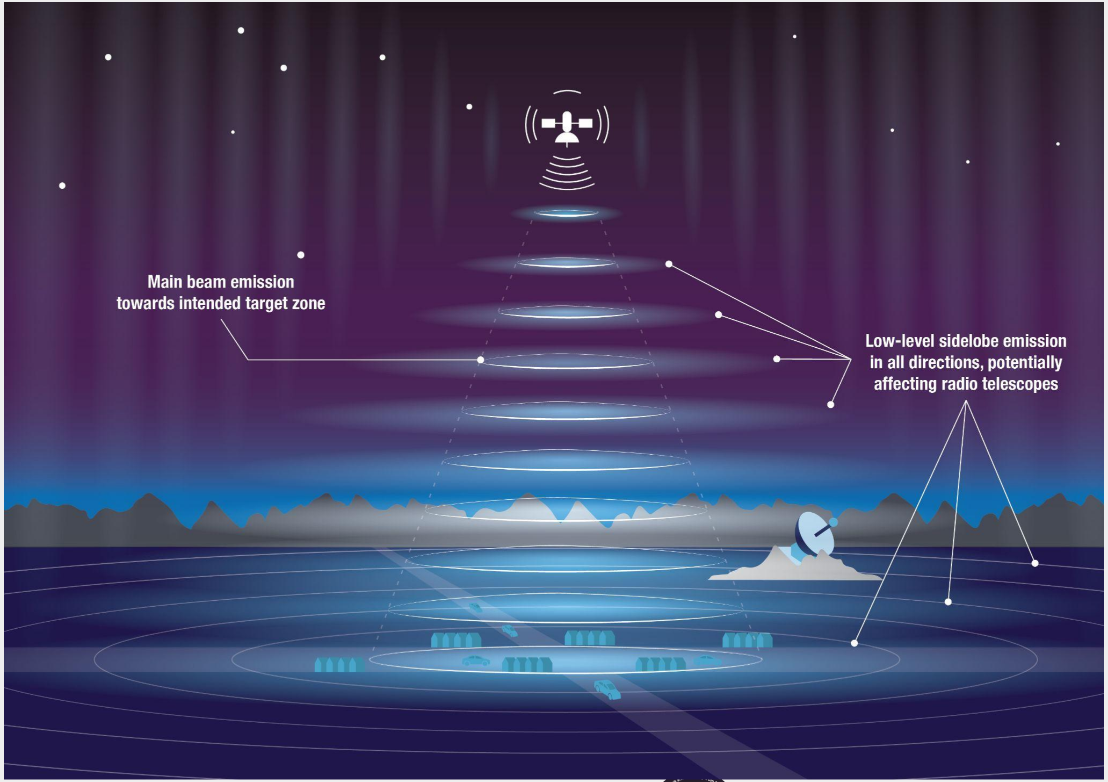
Bright yellow boxes on this chart are frequencies reserved for radio astronomy (often shared).

NTIA

Radio astronomy observes at all frequencies - has to work around active transmissions (often called 'radio frequency interference' - but not legally interference)

Effects on radio astronomy

- Intentional emissions (downlinks)
- Unintentional electromagnetic radiation (UEMR)
- Reflection of strong terrestrial radio signals signals of satellite bodies



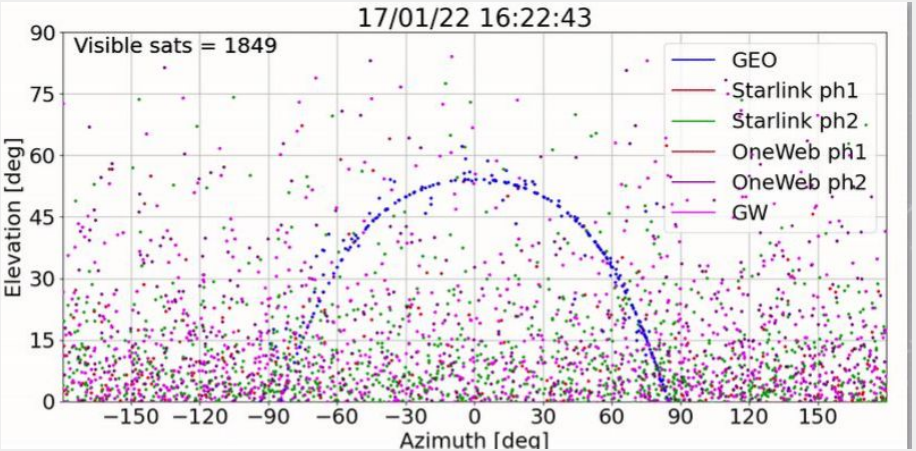
Satellite constellations

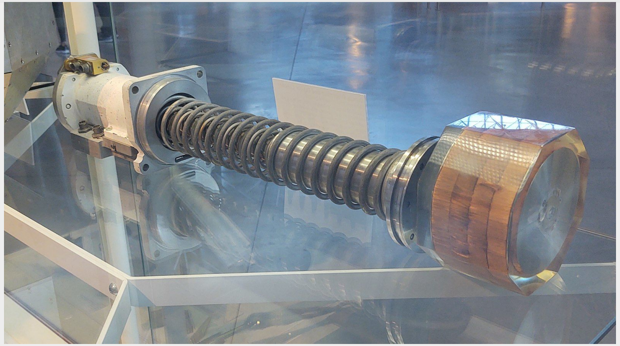
Satellites have always been an issue for radio astronomy.

West Ford (1961-63) launched 480,000,000 2cm-long dipoles to reflect 8GHz (3.5cm) signals, some still in orbit - only stopped because of a global outcry.

The Iridium satellite constellation interferes with radio astronomy observations at 1.6GHz in the protected band

Satellite constellations transmit around ~12GHz...





Project West Ford deployer.

Transmissions regulated by ITU, with protections for radio astronomy at some frequencies, but only for narrow bandwidths.

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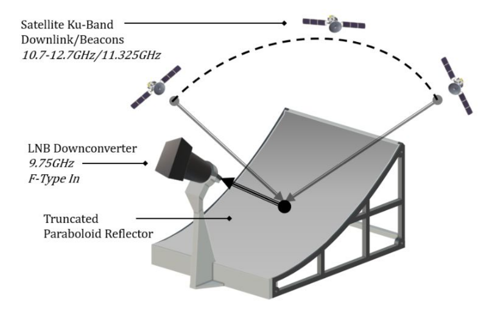
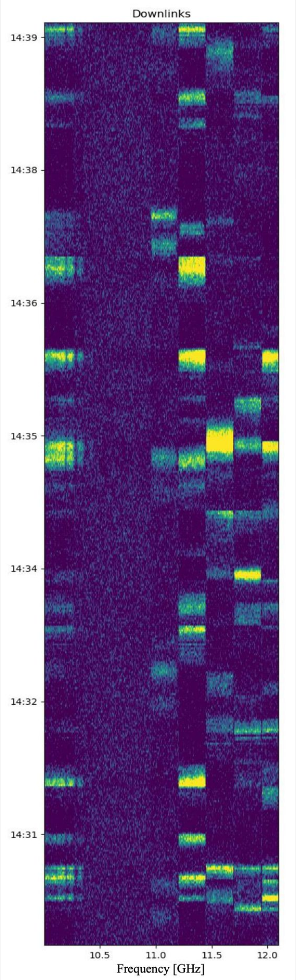
Potential impact at radio frequencies

- We don't know much yet - need observations to assess actual impact
- Active 10-20GHz transmissions - plus 40GHz soon? (and octaves!)
- (Latest Starlink filing of ~30k satellites from Tonga is 120-180GHz!)
- Sidelobe coupling also a concern, particularly for CMB experiments
- Difficult to filter out with broadband detectors, unless using FPGAs
- Highly variable - need to accurately know satellite positions, or see as transients?



Observing satellites from Blackett - Pomfret & Yasin 3rd year project, 2023



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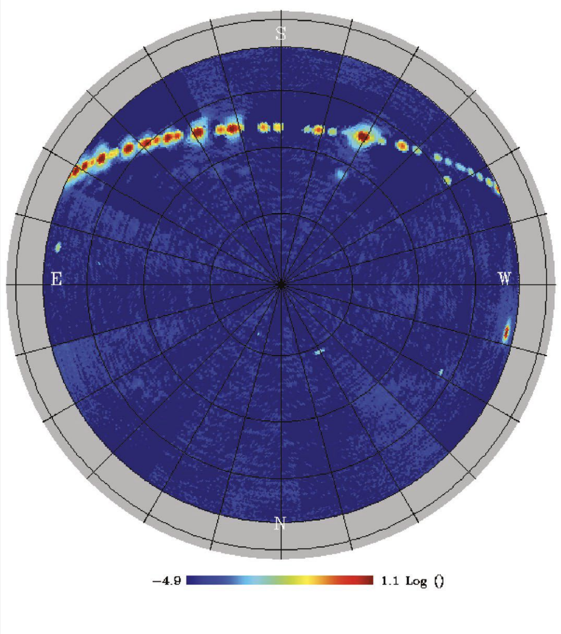
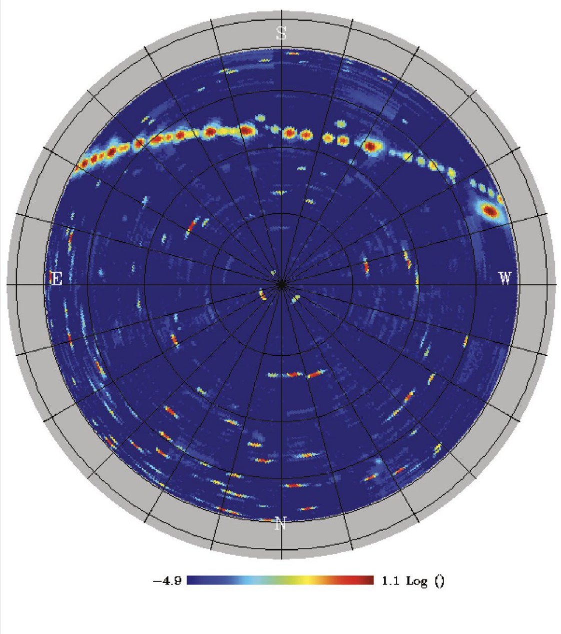
Impact on radio observations

Observations from QUIJOTE telescopes from Teide Observatory (Tenerife)



- Taken in 2014
- Shows bright band of geostationary satellites



- Taken in 2024
- Additional interference (red dots) caused by Starlink satellites

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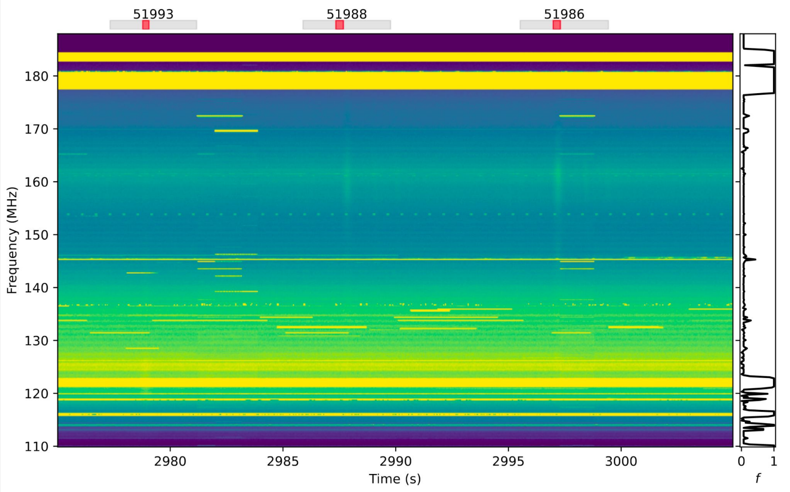
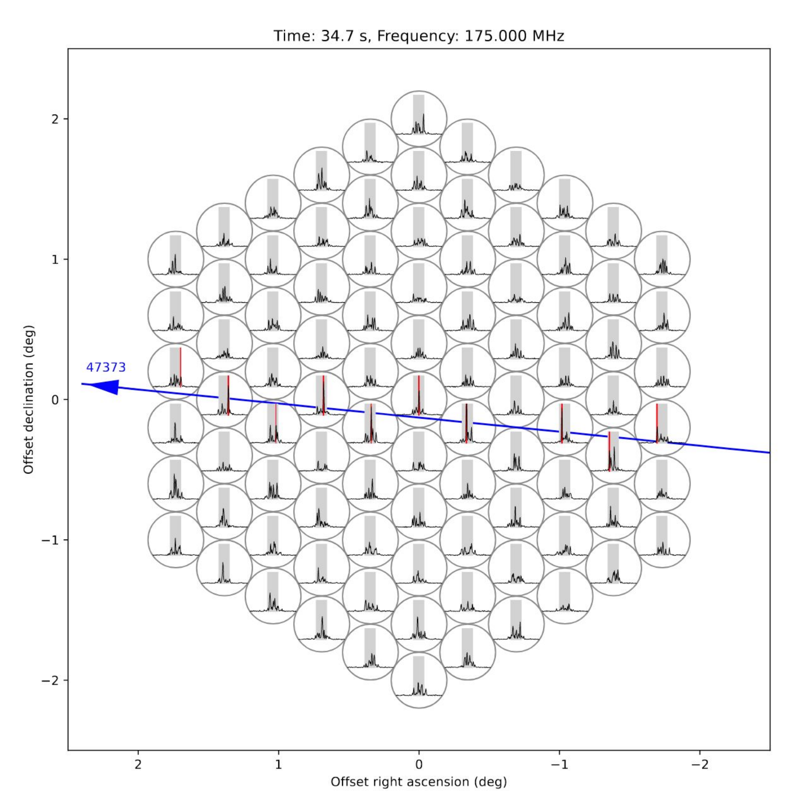
Unintended emission at low frequencies

- LOFAR sees Starlink passing overhead!
- Unintended emission from back-end electronics seen at ~150-180MHz
- Not permitted bands for transmitting...
- Di Vruno et al. (2023), A&A (published), arXiv:2307.02316
- (Also Grigg et al., 2023, 2309.15672)

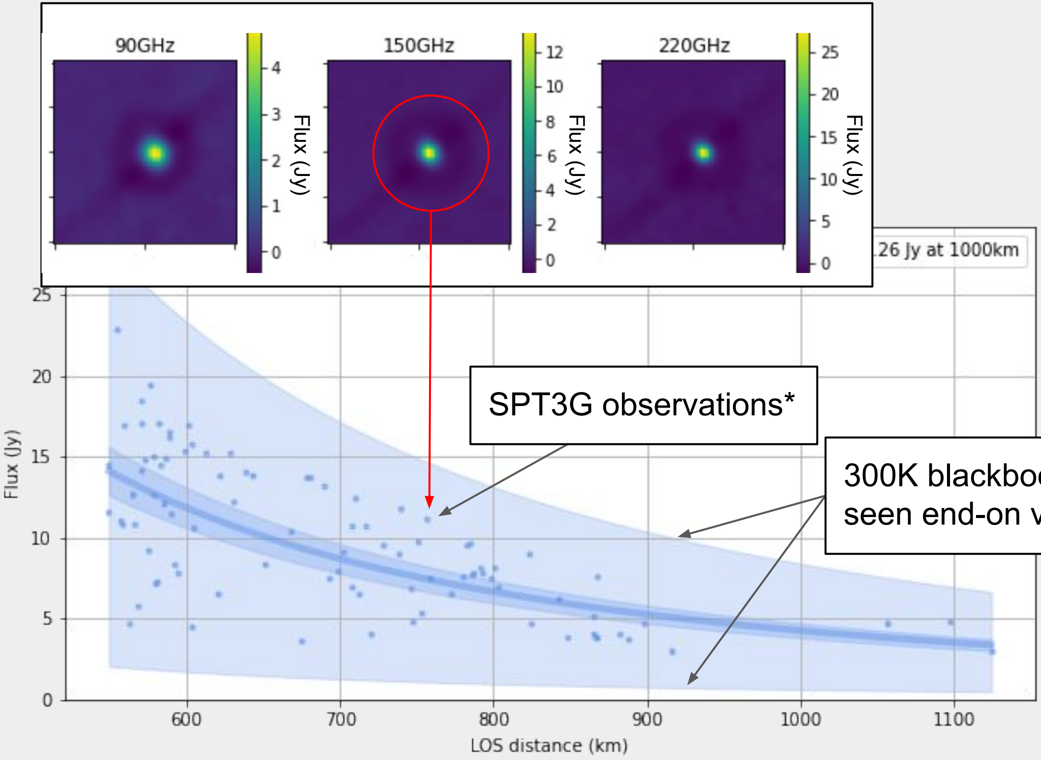




Example from SPT3G - Thermal Emission

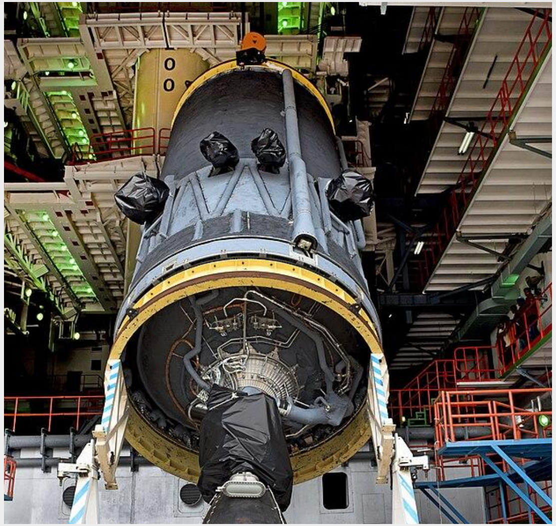
(with thanks to Allen Foster)

Even if not actively emitting RF signal, satellites can be millimeter bright!

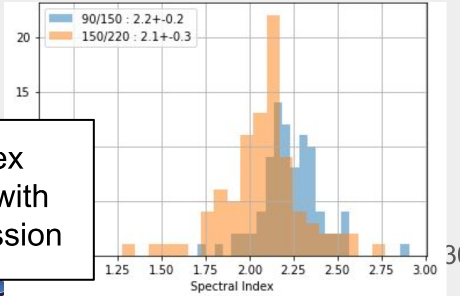


SPT3G observations*

300K blackbody LVM3 seen end-on vs side-on



LVM3 Upper stage : 4m diam. x 13.5m long



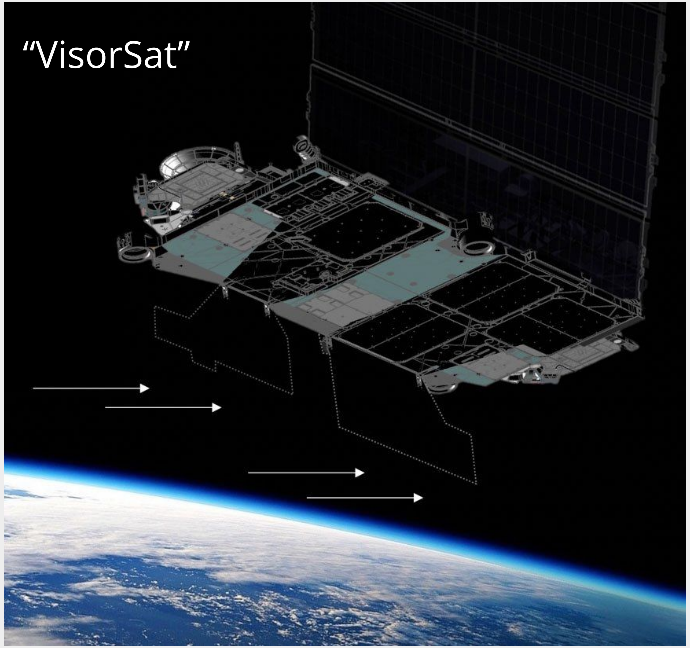
Spectral index ~consistent with thermal emission

* observed both in direct sunlight and in Earth's shadow

Mitigations

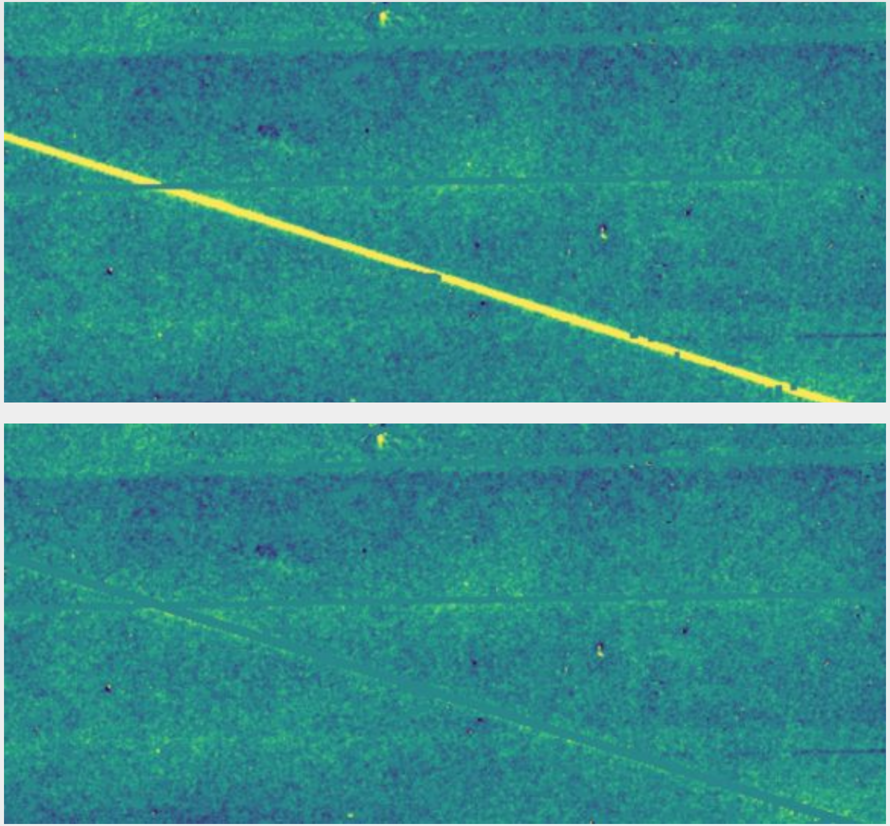
Mitigations: Satellites

- Fewer satellites
- Materials engineering: coatings (specular reflectivity)
- Attitude control (minimise reflections)
- Reflectivity simulation and testing labs (growing need)
- Steerable radio beams (enable direct illumination avoidance)
- Minimise sidelobe emission
- Control of unintended electromagnetic radiation



Mitigations: Telescopes

- Observations planning
- Software to avoid satellites
- Closing telescope shutter when satellite overhead
- More resilient receivers
- Observations to verify mitigations
- Redoing observations
- Modelling / Simulations
- Post processing of data (masking)



Hasan et al. (2022)

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IAU CPS

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CPS

- Centre for the Protection of Dark and Quiet Sky from Satellite Constellation Interference - https://cps.iau.org/
- Centre of expertise of the International Astronomical Union, hosted by the **SKAO**, an international radio astronomy observatory, and **NOIRLab**, the US national optical observatory
- International cooperation among software engineers, observers, astronomers, satellite industry folk, policy experts, space lawyers, government officials
- Our **mission**:
  coordinate efforts and unify voices across the global astronomical community to protect the dark and quiet sky from satellite constellation interference.
- Four hubs: SatHub, Policy, Community Engagement, Industry & Technology

SatHub

- Satellite observation and data analysis hub of IAU CPS
- A collaboration among pro astronomers, experienced amateurs, policymakers, industry experts, satellite operators, and more
- Open source **software development and data repositories**, with substantial contributions from NOIRLab, SKAO, and others
- Volunteer-led **observations and research projects** on satellite constellation interference and mitigation **across the electromagnetic spectrum**

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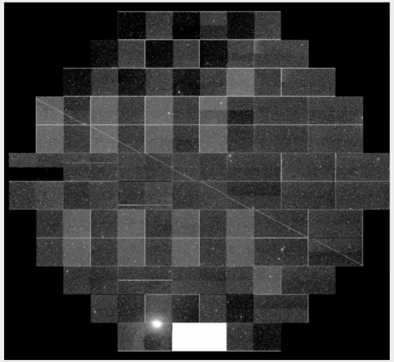
IAU CPS SatHub Aims

- **Assess constellation impact on optical and radio astronomy** via independent observation campaigns and peer reviewed publications
- **Strengthen relations** with key players:
  Privateer, The Exclosure, Slingshot Aerospace, European Centre for Space Safety, The Aerospace Corporation, AST SpaceMobile, SpaceX, Amazon Kuiper, Planet Labs, and more
- **Develop mitigation tools for astronomers**/observatories
  - SatChecker satellite position prediction service
  - Satellite Constellation Observation REpository (SCORE)
  - NSF SWIFT-Sat: Field-Of-View / active satellite avoidance service
  - Radio astronomy impact modeling (SCEPTER)
- **Coordinate mitigation efforts** with all stakeholders



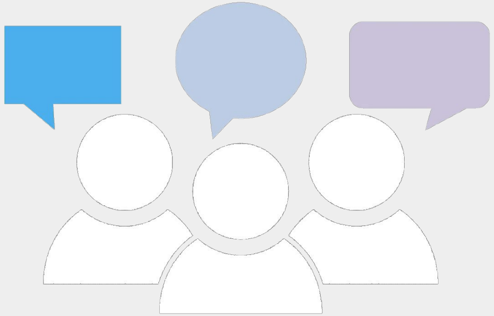
Industry and Technology Hub

- Foster collaboration between the astronomy and satellite communities
- Outreach to satellite constellation operators
- Development of tools and best practices
- Promote ongoing mitigation solutions, resources
- Membership at no cost for satellite stakeholders

Community Engagement

- Bridge between all stakeholders and communities
- Engage stakeholders to solicit their opinions
    - Community forums - for unheard voices
- Create activities for general public to understand issues
    - Developed SatCon 101 video lectures

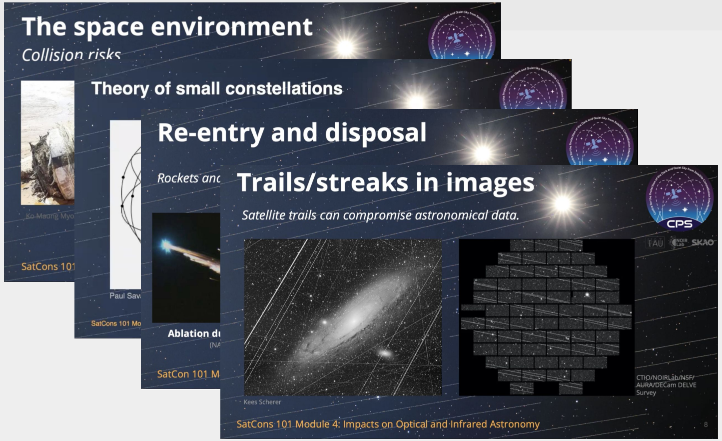
We ensures all stakeholders' voices are part of the broader discussion.



SatCons 101

- Series of 8 learning modules covering:
  - Satellite design
  - Environmental impacts
  - Effects on optical and radio astronomy
  - Cultural impacts
  - The current policy climate
  - Potential satellite mitigations

- Introduces issues of satellite constellations for astronomy to the general public



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Policy Hub

1. **Raise awareness** of astronomy requirements in space policy-making circles
2. **Coordinate policy work** conducted by national societies and observatories
3. **Foster the development of better regulation**, in coordination with national points of contact
4. **Coordinate spectrum management processes,** along with emerging optical-related issues
5. Identify **future threats**

Strategic Outcomes

- Astronomy community acts together with aligned messages
- We produce policy outputs and contribute to policy change
- Industry is aware of the issue and of the solutions
- Policy makers are aware of the issue and of the solutions

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Policy

UN Committee on the Peaceful Uses of Outer Space

- Dark and Quiet Skies agenda item in the Scientific and Technical Subcommittee (STSC)
- Group of Friends for the Dark and Quiet Skies for Science and Society, which aims to:
  - Promote awareness
  - Support/Review best practices and mitigation suggestions
  - Discuss the overall implications of the adoption of mitigating measures
  - Discuss approaches for coordination between the various stakeholders

UNITED NATIONS
Committee on the Peaceful Uses of Outer Space

International Telecommunication Union (ITU)

- WRC-27:
  - AI 1.16: to address impacts on RAS bands and Radio Quiet Zones from satellite systems
  - AI 1.18: EESS and RAS above 76 GHz
  - AI 1.15: use of radiocommunications in the cislunar space
- Report on UEMR (ongoing at WP7D)
- Resolution 219 (Bucharest 2022) and Resolution ITU-R 74: Sustainable use of spectrum and space orbits

National regulations

- United States imposes coordination with NSF to obtain licences
- Licensing conditions for operators in South Africa (ongoing discussions)
- Efforts in Space Sustainability include Dark and Quiet Skies:
  - ESA Zero Debris charter
  - UK Earth Space Sustainability Initiative
  - Switzerland Space Sustainability Rating
  - EU Space Label
  - …

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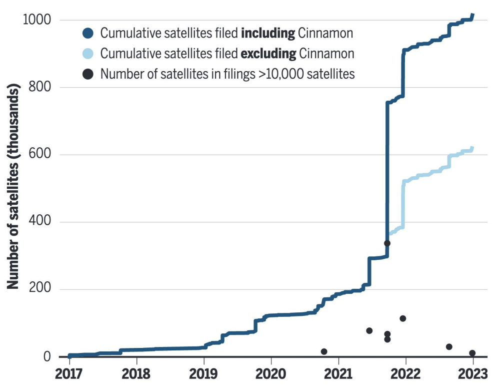
Conclusions

- Rapidly increasing numbers of satellites...
- Significant impact on optical, submm, radio astronomy
- CPS working to quantify their impact
- Policy approaches under way
- (The situation in the US is looking bleak...)
- Dave Clements and I offer 3rd and 4th year projects on satellite constellations, both optical and radio

Questions?



Falle et al. (2023), "One million (paper) satellites", Science

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