STARLINK AND OTHER SATELLITE CONSTELLATIONS:

KNOW THEM - AVOID THEM

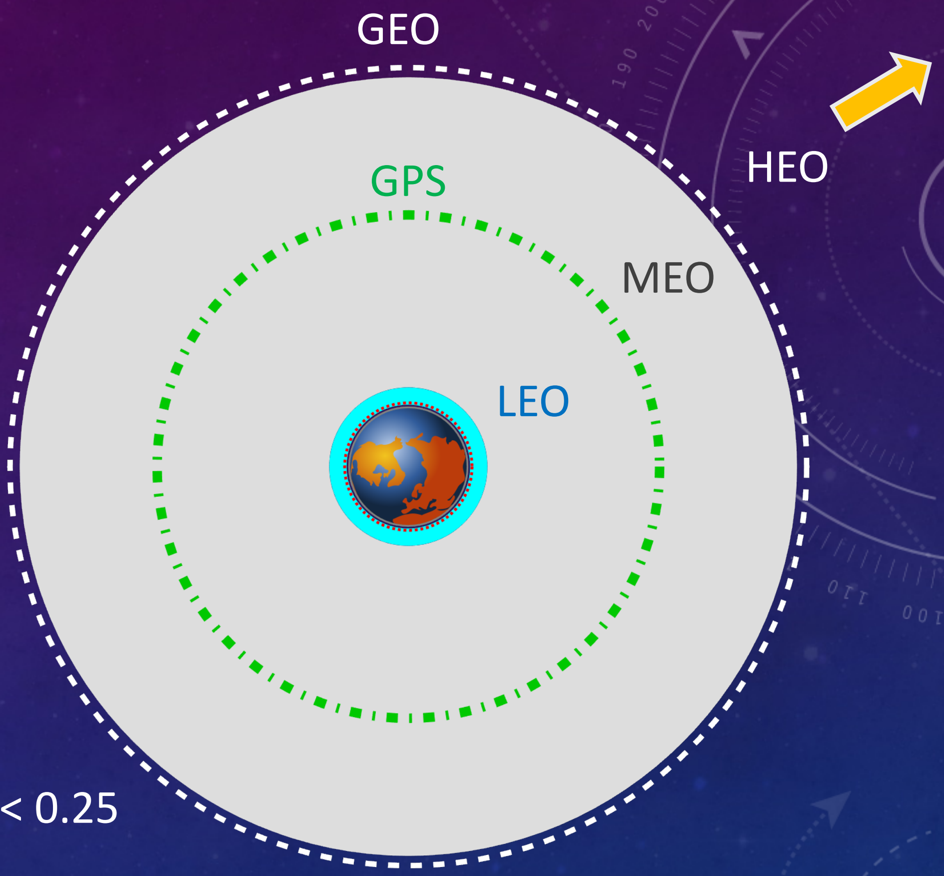
Luciano Nicastro, INAF – OAS Bologna

Satellites orbits

- LEO: <~ 2,000 km
- MEO: 2,000 – 30,000 km (GPS: ~ 20,200 km)
- GEO: 35,786 km
- HEO: >~ 36,000 km

But also:

- LEO: Period <~ 128 minutes and Eccentricity < 0.25
- MEO: 600 minutes <~ Period <~ 800 minutes and Eccentricity < 0.25
- GEO: 23.76 <~ Period <~ 24.24 hours and Eccentricity < 0.01
- HEO: Eccentricity > 0.25



https://en.wikipedia.org/wiki/List_of_orbits
https://en.wikipedia.org/wiki/Geocentric_orbit
https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg

Satellites orbits – 2

https://en.wikipedia.org/wiki/High_Earth_orbit

Situation (pre-Starlink and current)

Objects with orbits determined with good approximation before Starlink

- LEO: ~ 14,000 (3,250)
- MEO: ~ 500 (200)
- Others: ~ 50 (35)

Total: ~ 14,550

Operational

In **Space-Track.org** now

21,619 in orbit

- payloads: **6,212**
- rocket parts: **2,248**
- debris: **13,018**

46,758 total tracked

https://www.space-track.org/
https://celestrak.com/

See also: https://github.com/shashwatak/satellite-js/wiki/Sites-using-satellite.js

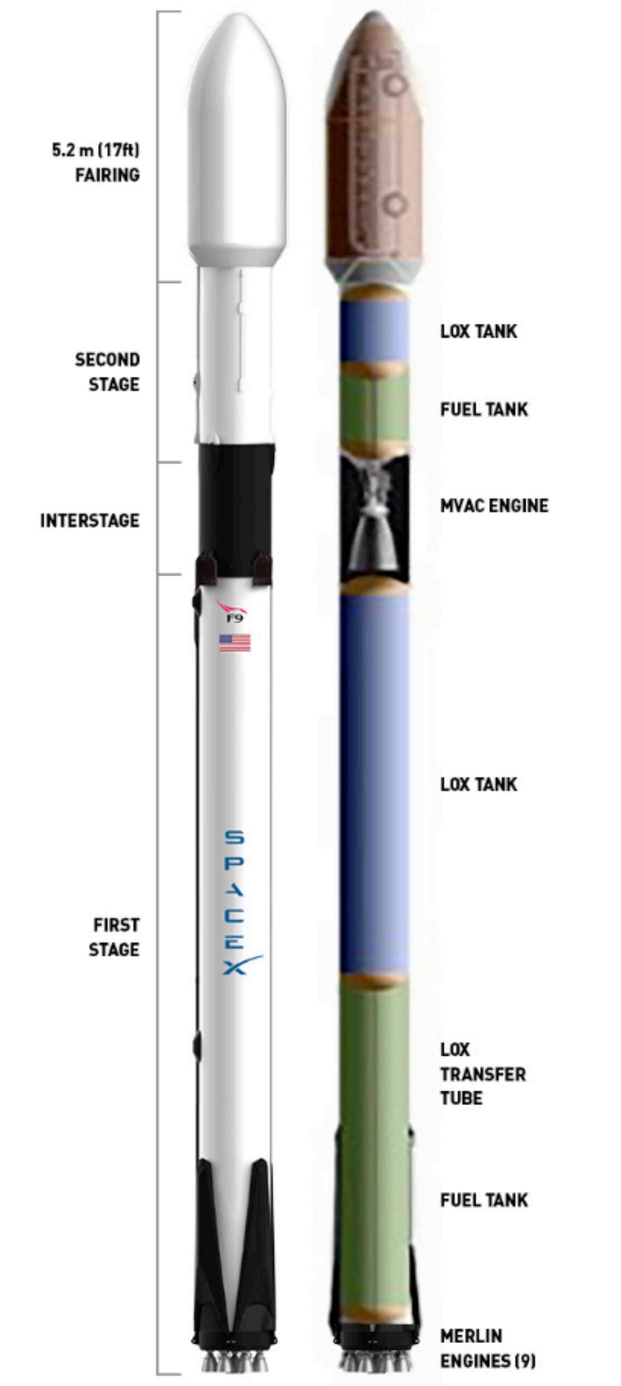


Figure 2-1: Falcon 9 overview


STARLINK

The constellations era: Starlink et al.

18 constellations in development:

SpaceX, Amazon, OneWeb, Samsung, Facebook (?), et al.

Starlink

- ~ 42,000 within 2025 (1,584 within end 2020)

Amazon

- ~ 30,000 (project Kuiper 3,236)

OneWeb

- ~ 48,000 (at 1200 km !)

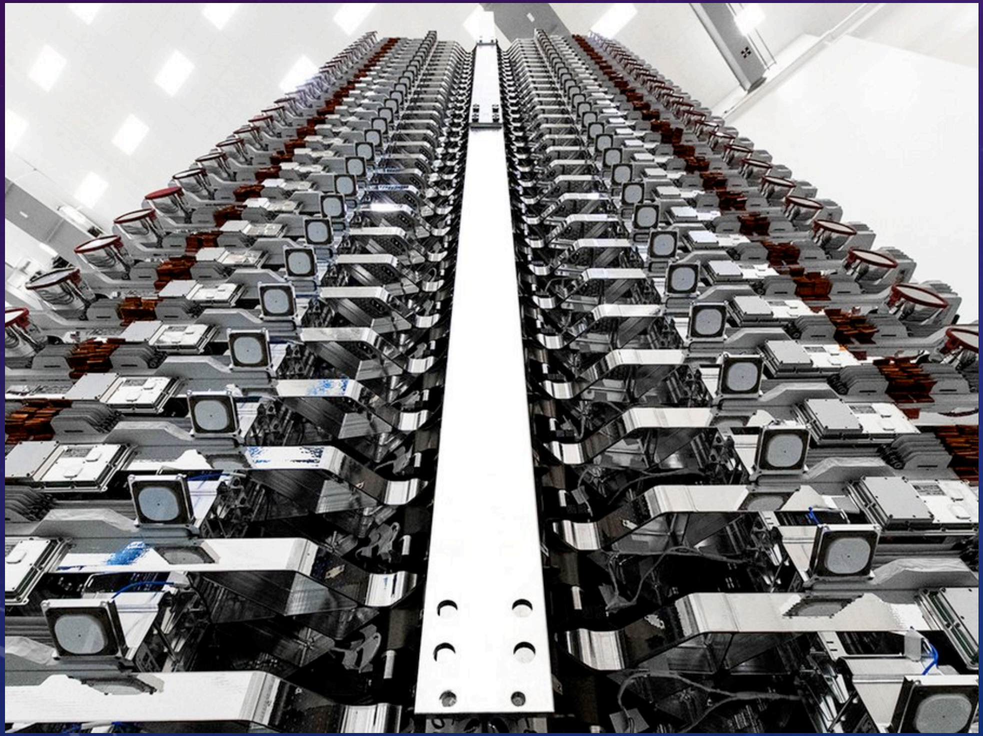
Samsung

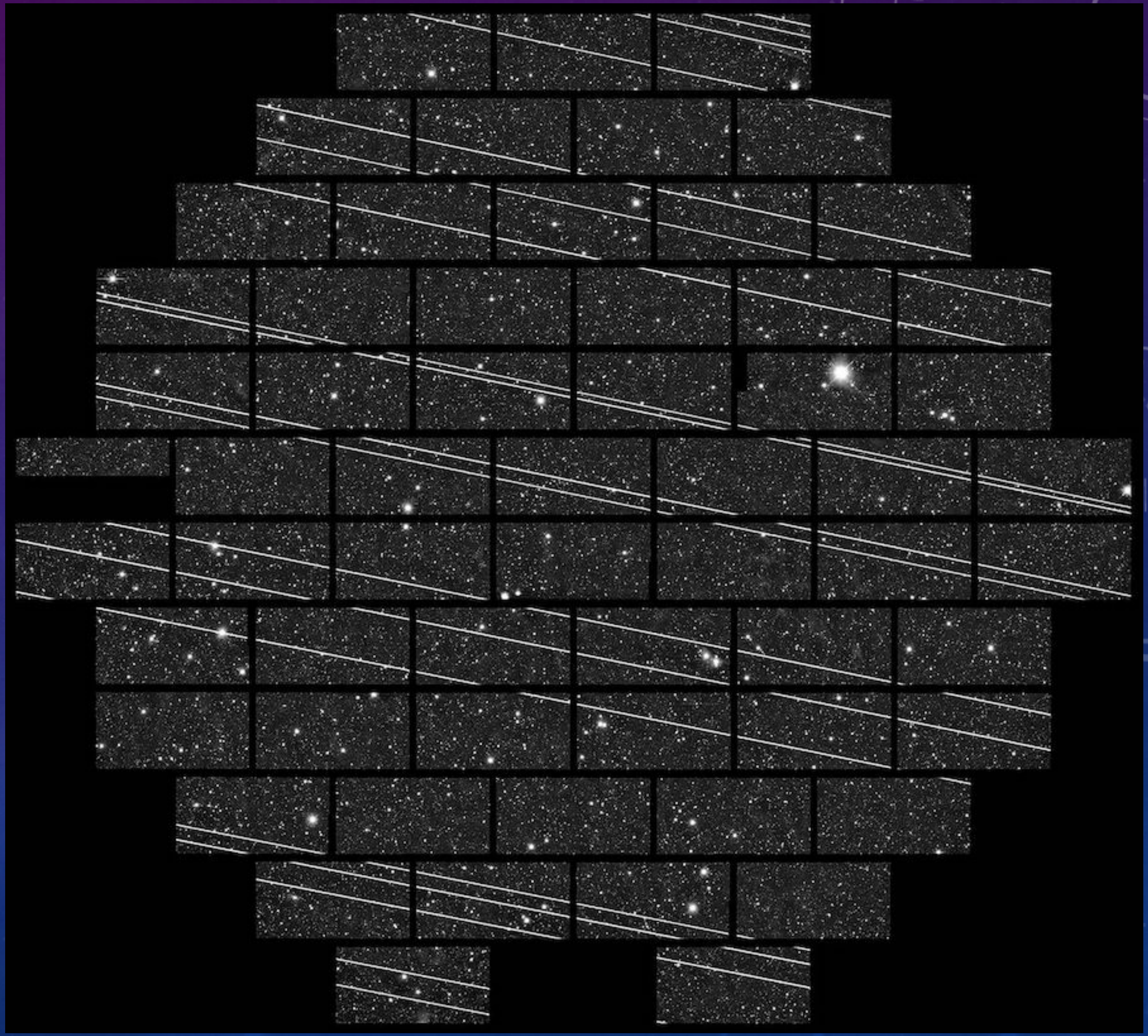
- ~ 5,000 (at 2000 km !)

Total (2025 – 2030 ?): ~ **100,000**

The constellations era: Starlink

- Latest launch (15°): 24 October 2020
- N (**8** ?) more launches in 2020
- Total in orbit: **895** (1,584)





Credits: CTIO/NOIRLab/NSF/AURA/DECam DELVE Survey

The constellations era: the study

Olivier R. Hainaut and Andrew P. Williams, A&A 636, A121 (2020)

Some data

- considered 26,750 satellites from 18 constellations
- uniformly distributed
- 2 orbital zones: < 600 km and between 1000 – 2000 km
- luminosity derived from observational data

Twilight

- civil: –6°
- nautical: –12°
- astronomical: –18°

Relevant zenithal distances: 90°, 80°, 70°, 60°

Infrared emission calculated assumed

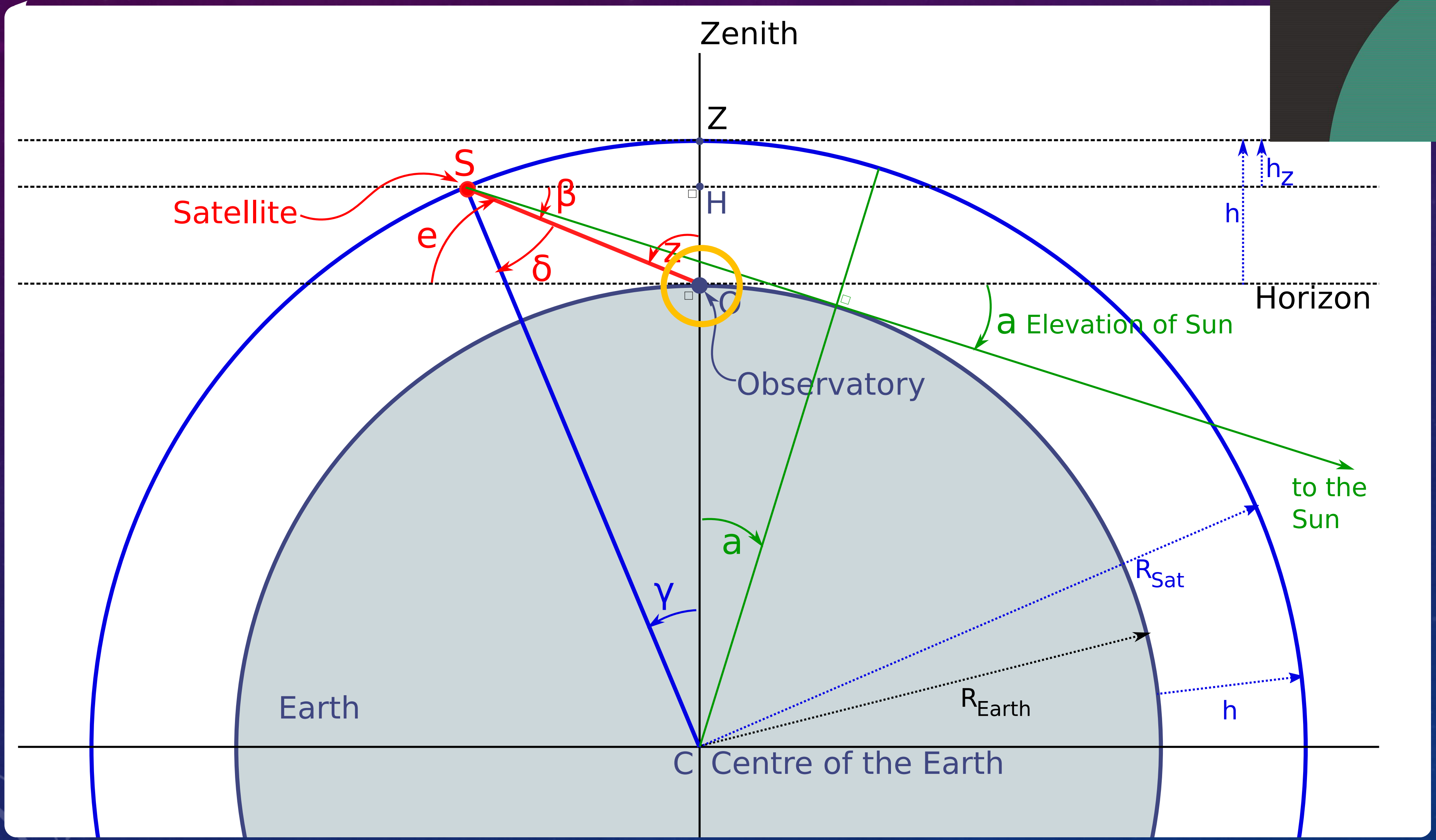
- sphere of 1 m
- albedo of 0.25
- temperature of 300 K
- constant flux of 100 Jy in N-band (8 – 13 μm) and 50 Jy in M-band (5 μm) and Q-band (18 – 20 μm)

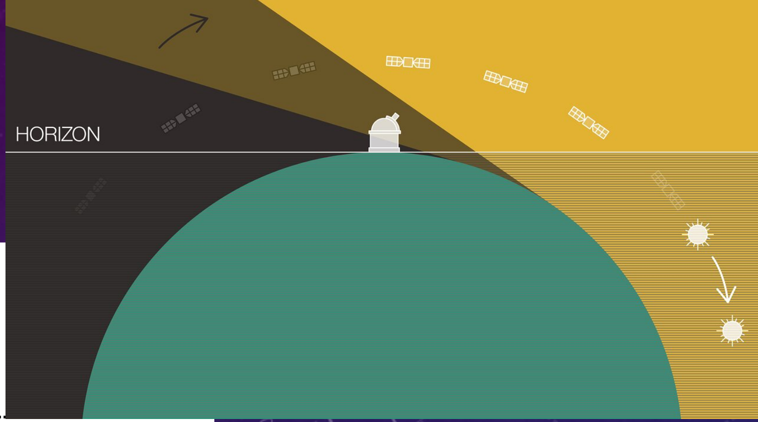
Instrument field of view (FOV)

- narrow: FOV < 0.5° squared
- medium: 0.5° < FOV < 1° squared
- wide: 1° < FOV < 10° squared
- ultra-wide: FOV > 10° squared

References: https://www.eso.org/public/italy/news/eso2004/, https://www.eso.org/public/italy/announcements/ann20022/

The constellations era: the study – 2

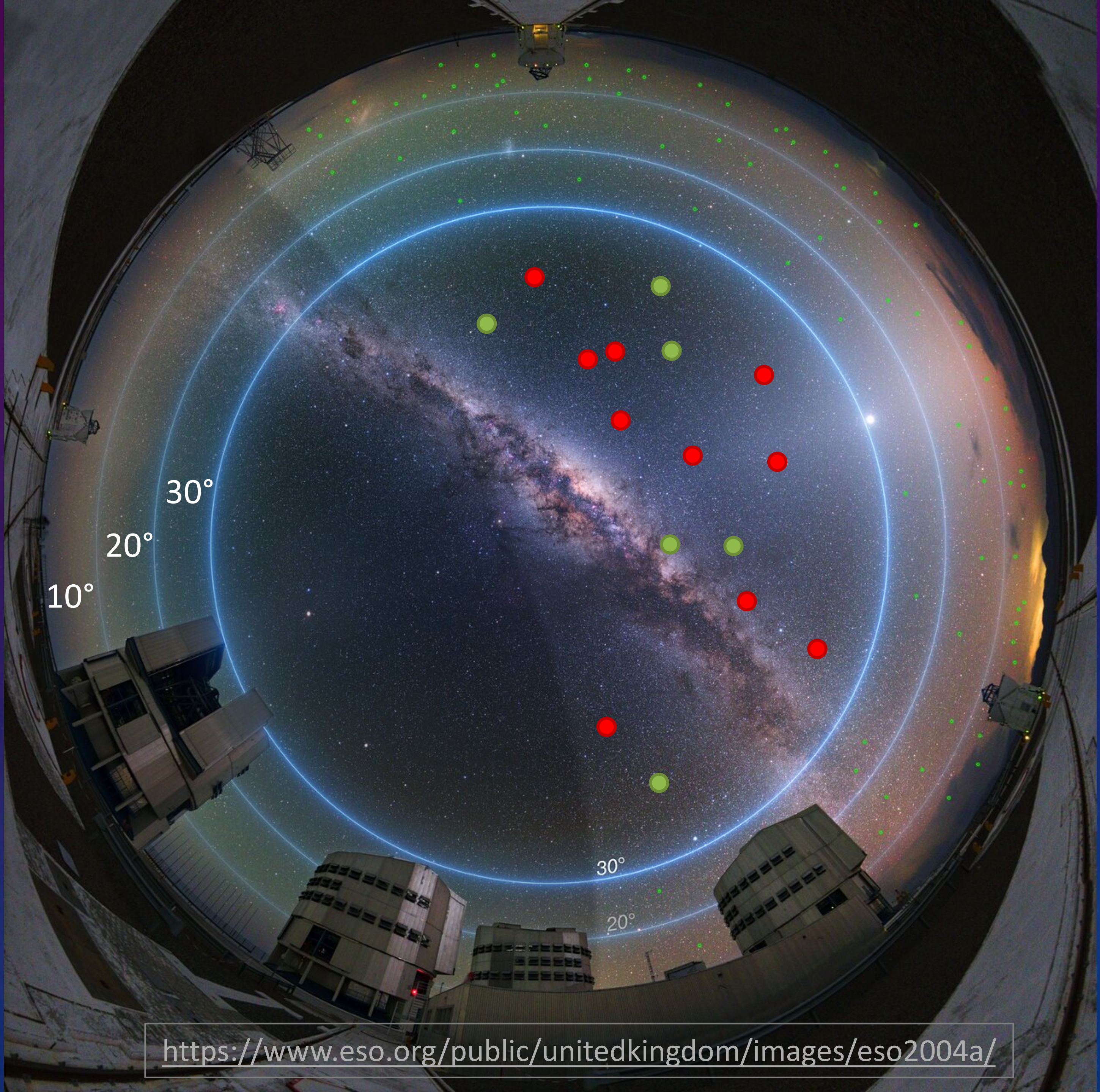




Hainaut & Williams 2020

ESO Paranal
About 90 minutes before sunrise

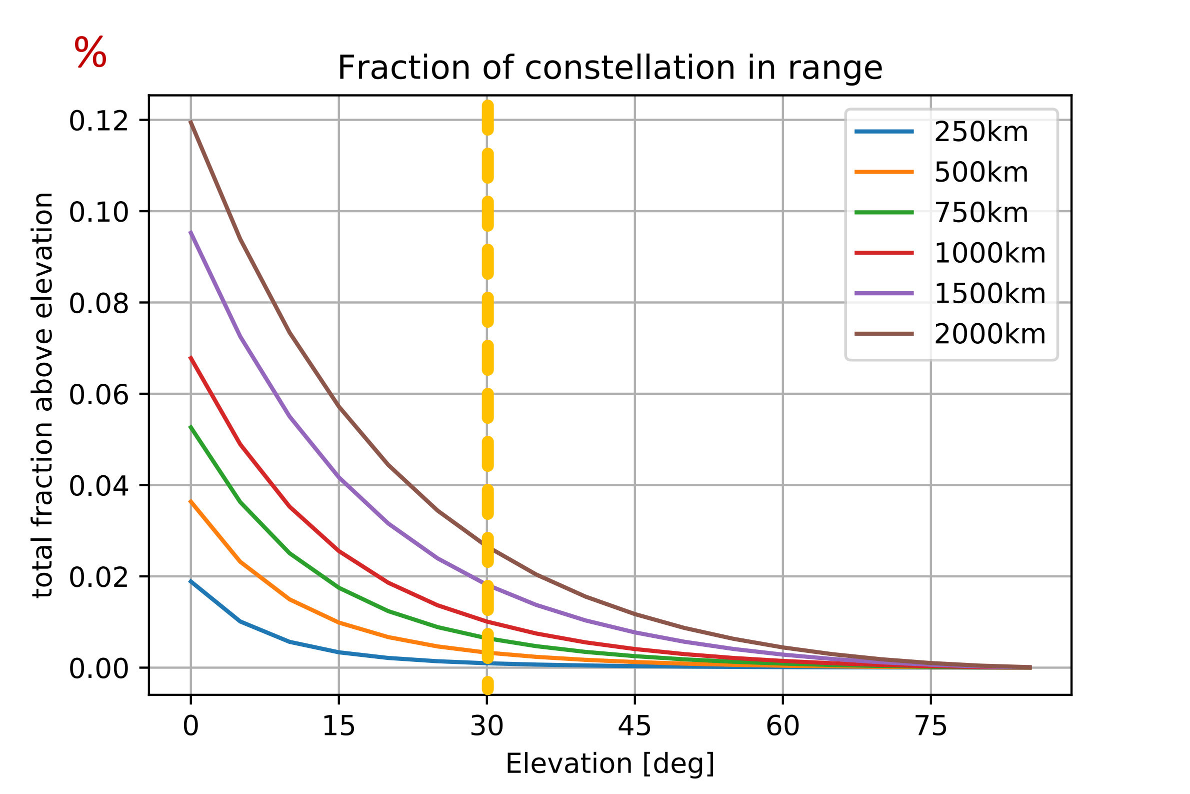
- mag ~ 5 – 6
- mag ~ 3 – 4

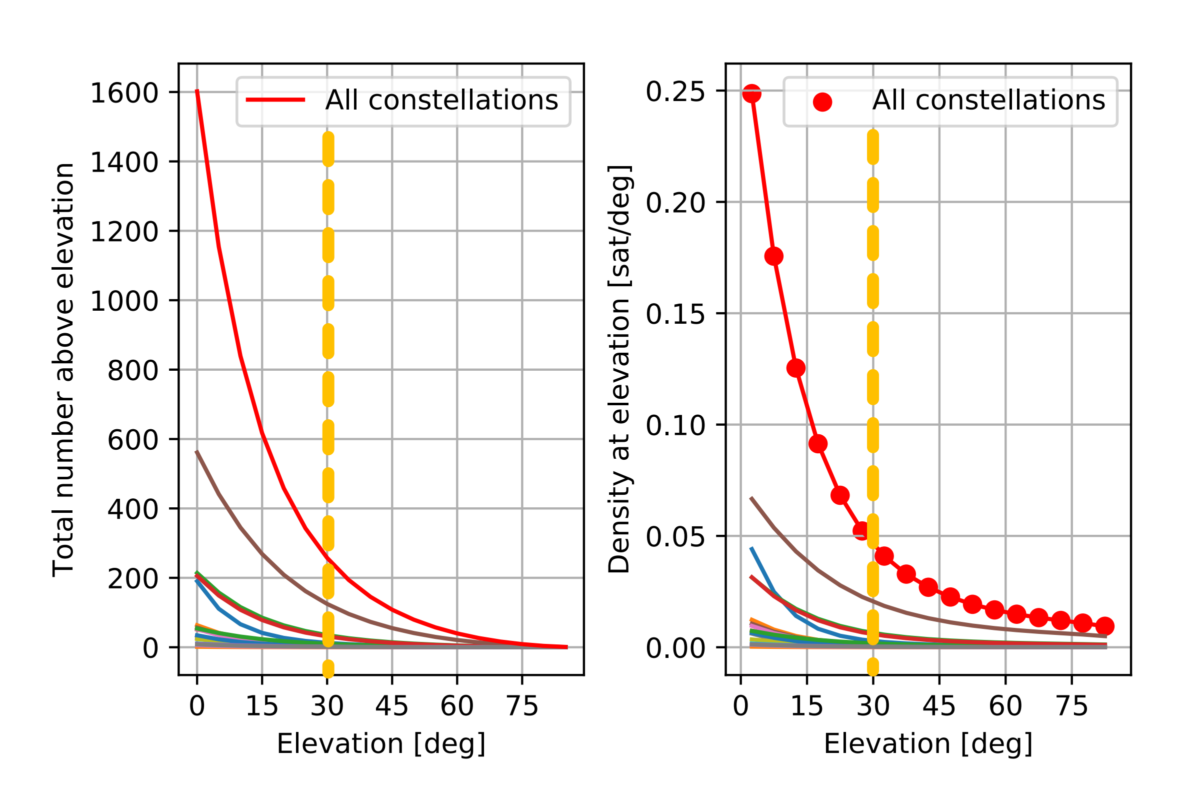


https://www.eso.org/public/unitedkingdom/images/eso2004a/

The constellations era: the study – 3

Satellites visibility as function of Elevation

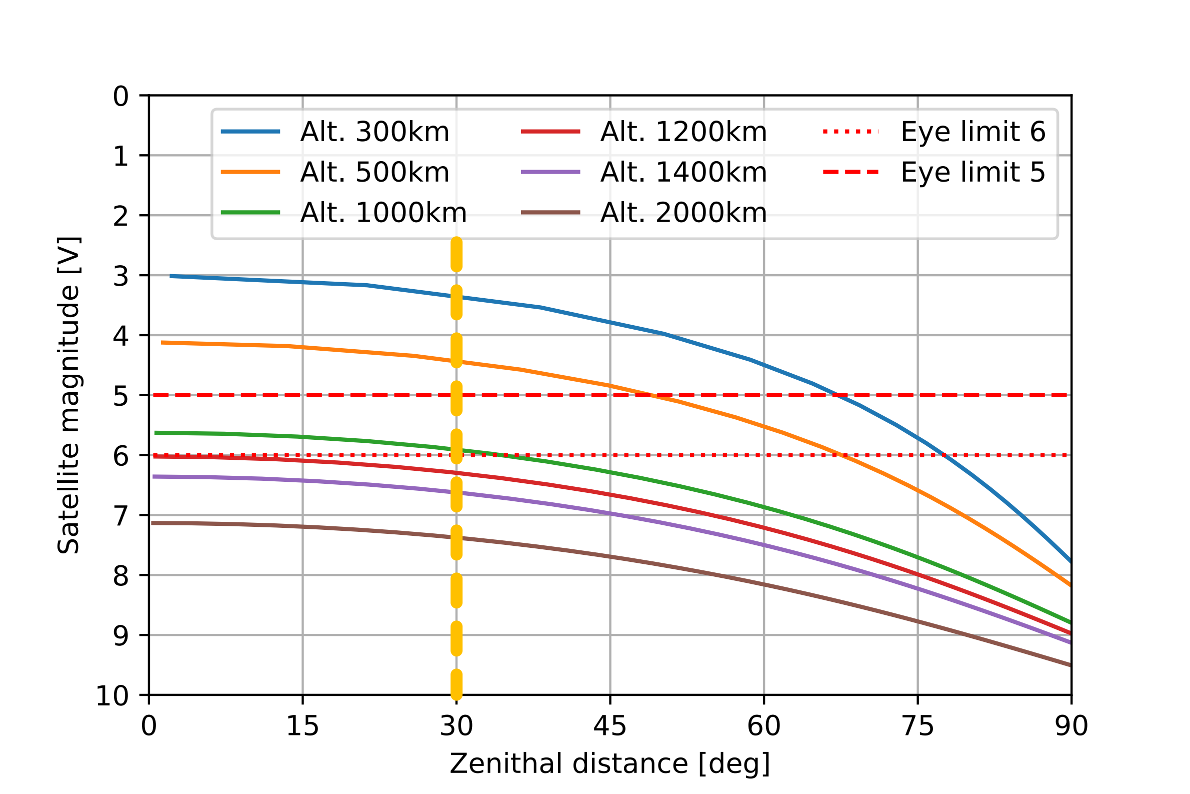




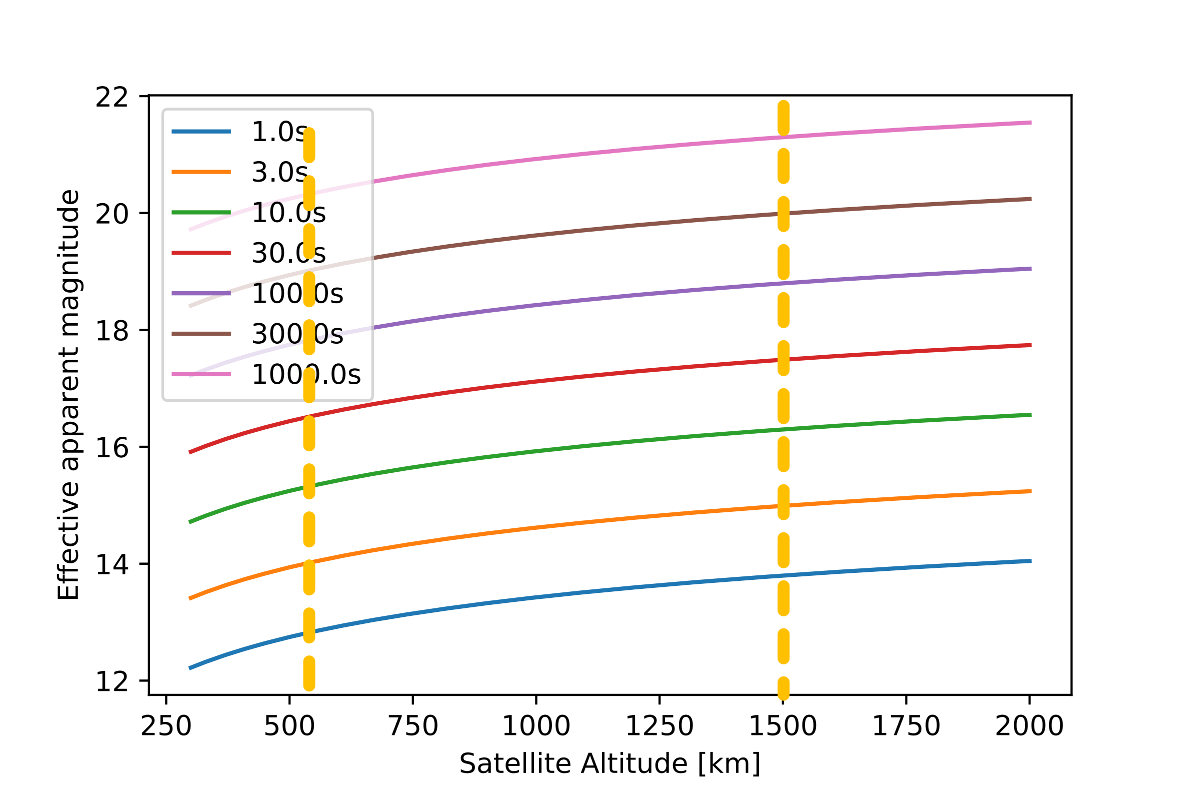
Hainaut & Williams 2020

The constellations era: the study – 4

Magnitude vs. zenithal distance



Effective magnitude vs. satellite altitude



Hainaut & Williams 2020

The constellations era: the study – 5

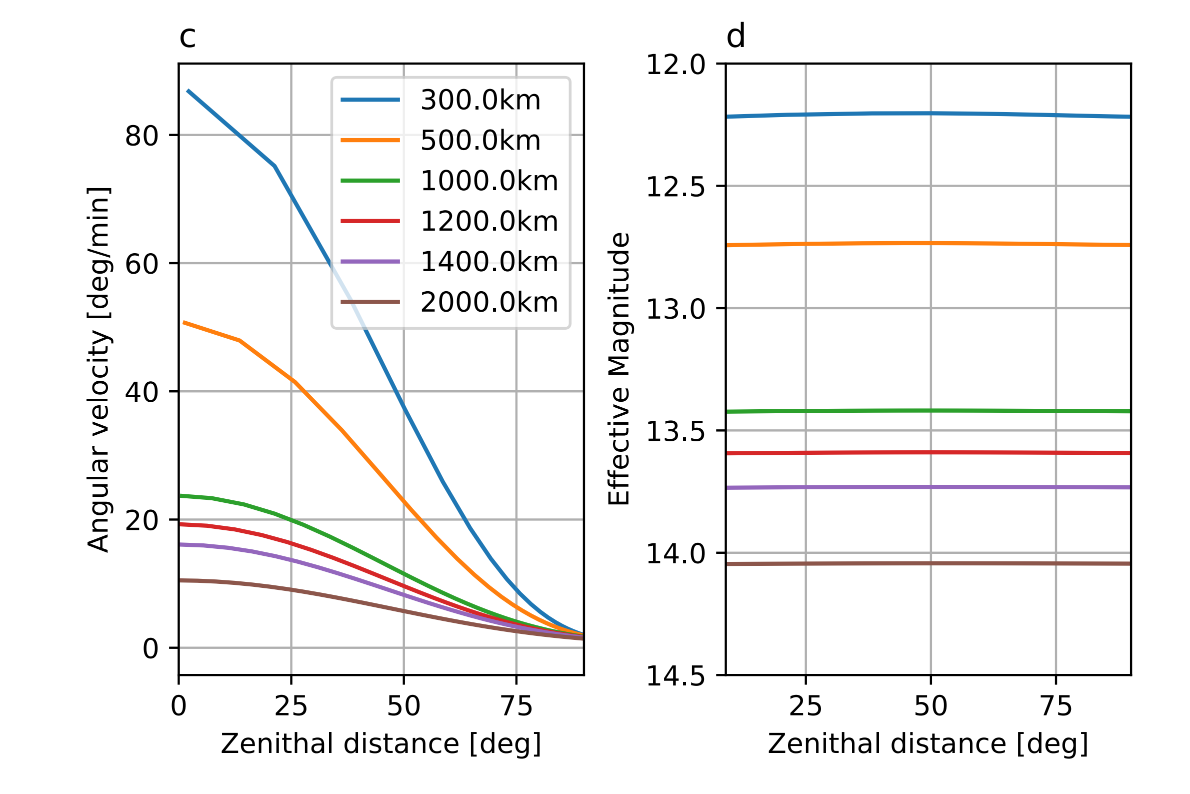
Close to the Zenith

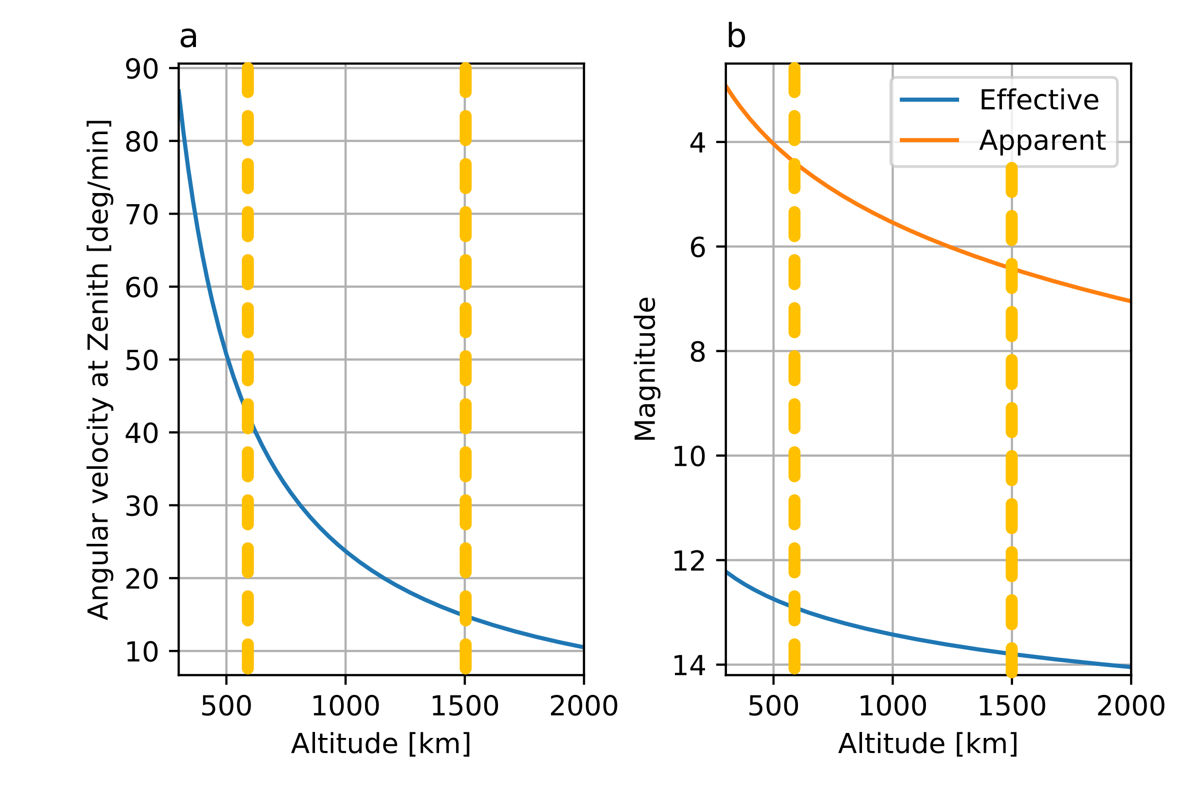
Angular velocity vs. Zenithal distance

Effective mag. vs. Zenithal distance

Angular velocity vs. altitude

Magnitude vs. altitude





Hainaut & Williams 2020

Results

Statistics

- About **1,600** satellites visible from Observatories at mid-latitudes
- **250** at elevations > 30°

… after the astronomical twilight (18°)

- **1,100** above the horizon
- **150** above 30°
- **260** visible with naked eye (**110** < 5° mag)

Impact

- Occultation of a source is negligible (1 every 3 nights assuming T_{exp} = 10 s and Sat_{dim} = 0.2 – 1 ″)
- Short observations (~ 1 s): *no impact*
- Medium duration observations (~ 100 s): *limited impact with ~ 0.5 % of the images contaminated during twilight*
- Long spectroscopic exposures (~ 1000 s): *from 0.3 to 3 % affected during twilight and start/end of night*
- Wide-field imaging / spectroscopy: ~ *5 % affected at start/end of night*
- Ultra-wide field exposures (*Vera C. Rubin Observatory*): ~ ***30 %** at start/end of night (~ **50 %** during twilight)*

Note: apart *Rubin* telescope, if the presence of a trail makes the full image not usable percentages rise!

NOIRLab, AURA, AAS – SATCON1 SOC report

Virtual conference: June 29th – July 2th 2020

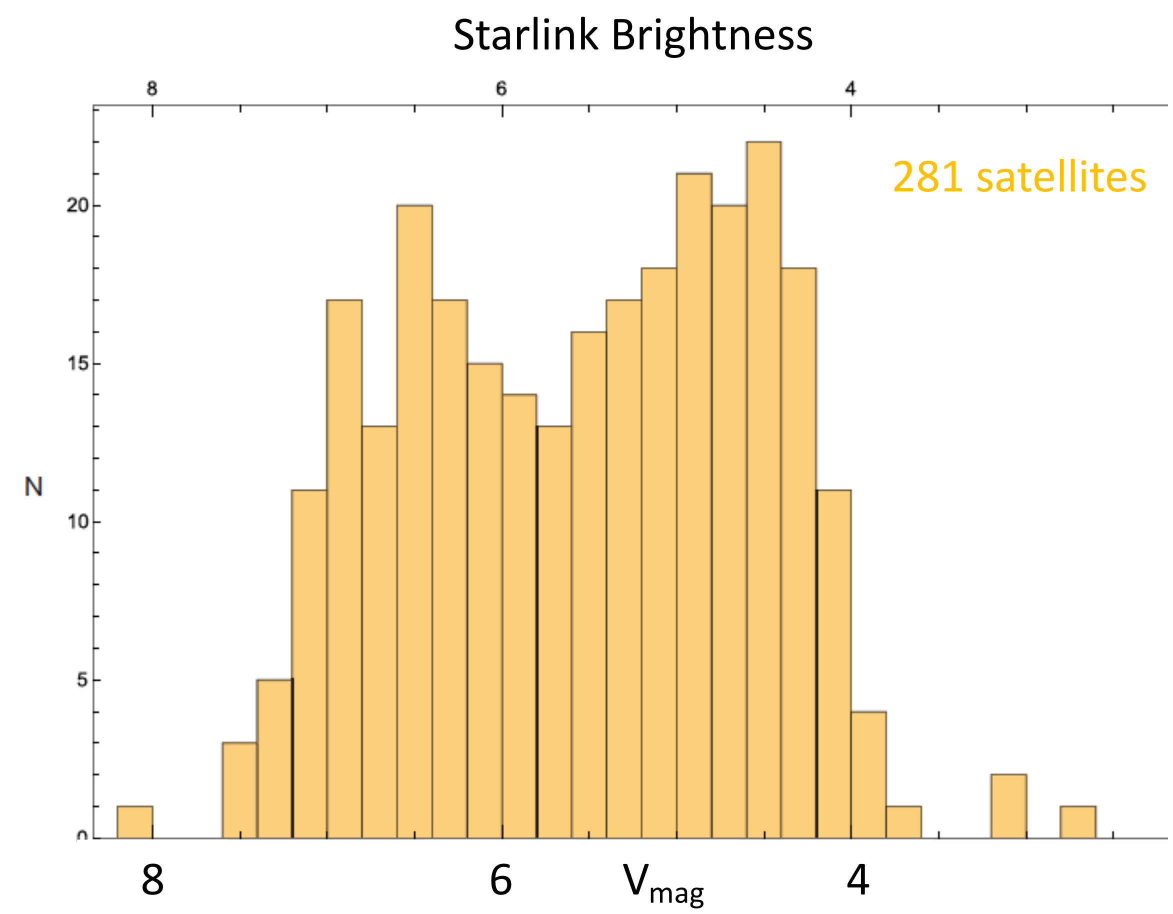
Edited by: Walker, C. (NSF's NOIRLab) and Hall, J. (Lowell Observatory)

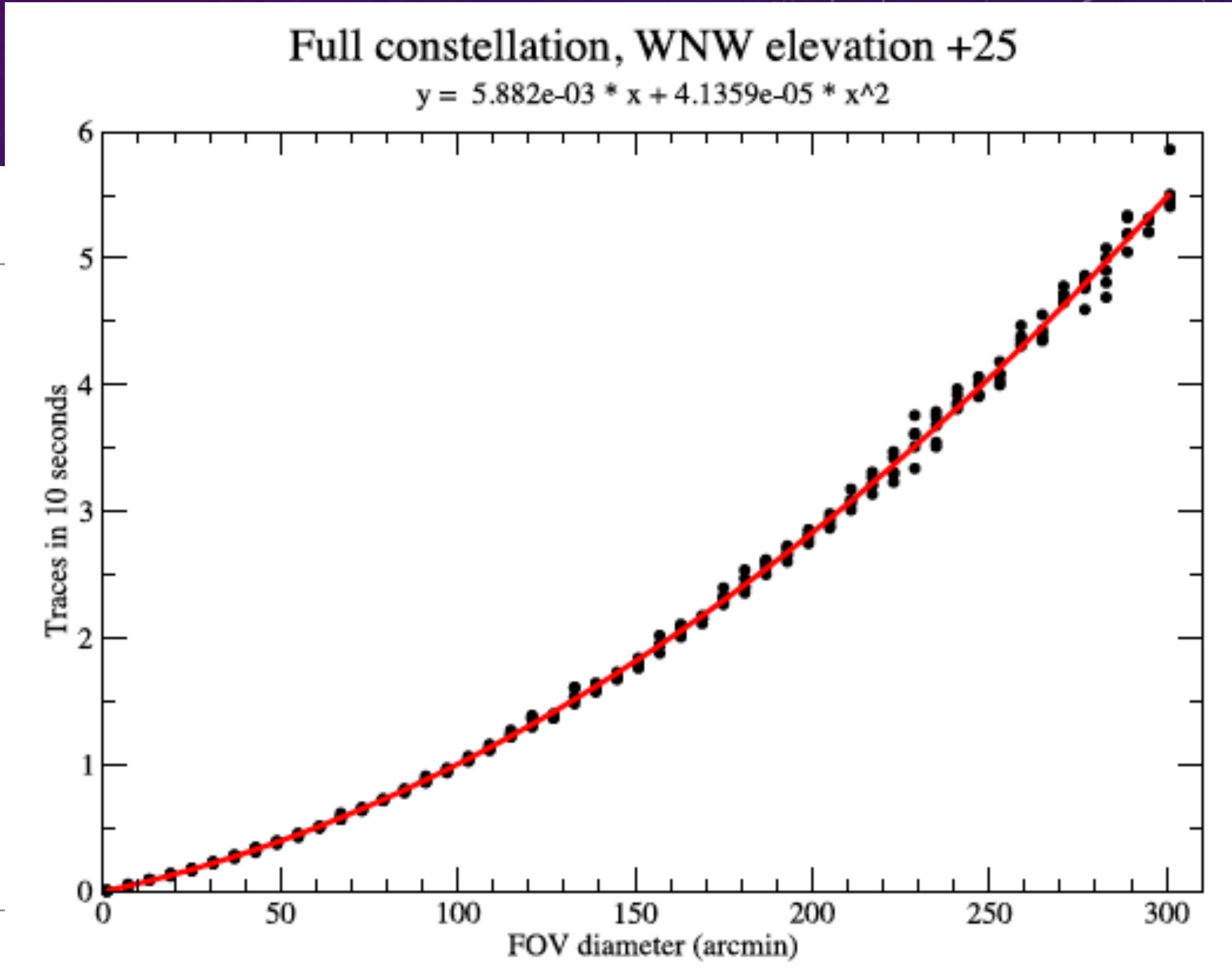
Published: August 25th 2020

Simulations Working Group scenario

- 33,000 satellites at 600 km or below (Starlink)
- 47,844 satellites at 1200 km (OneWeb)

SATCON1 SOC report

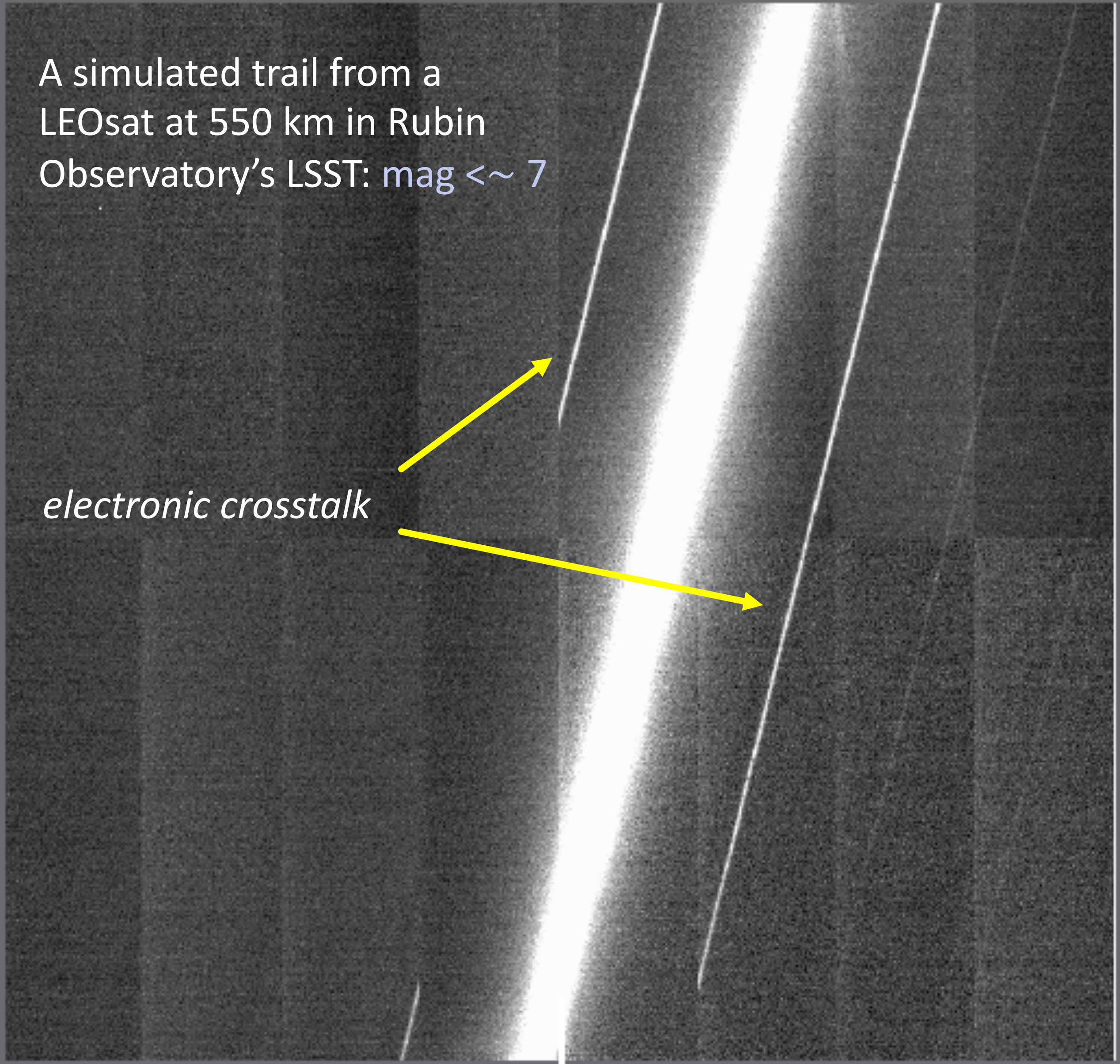


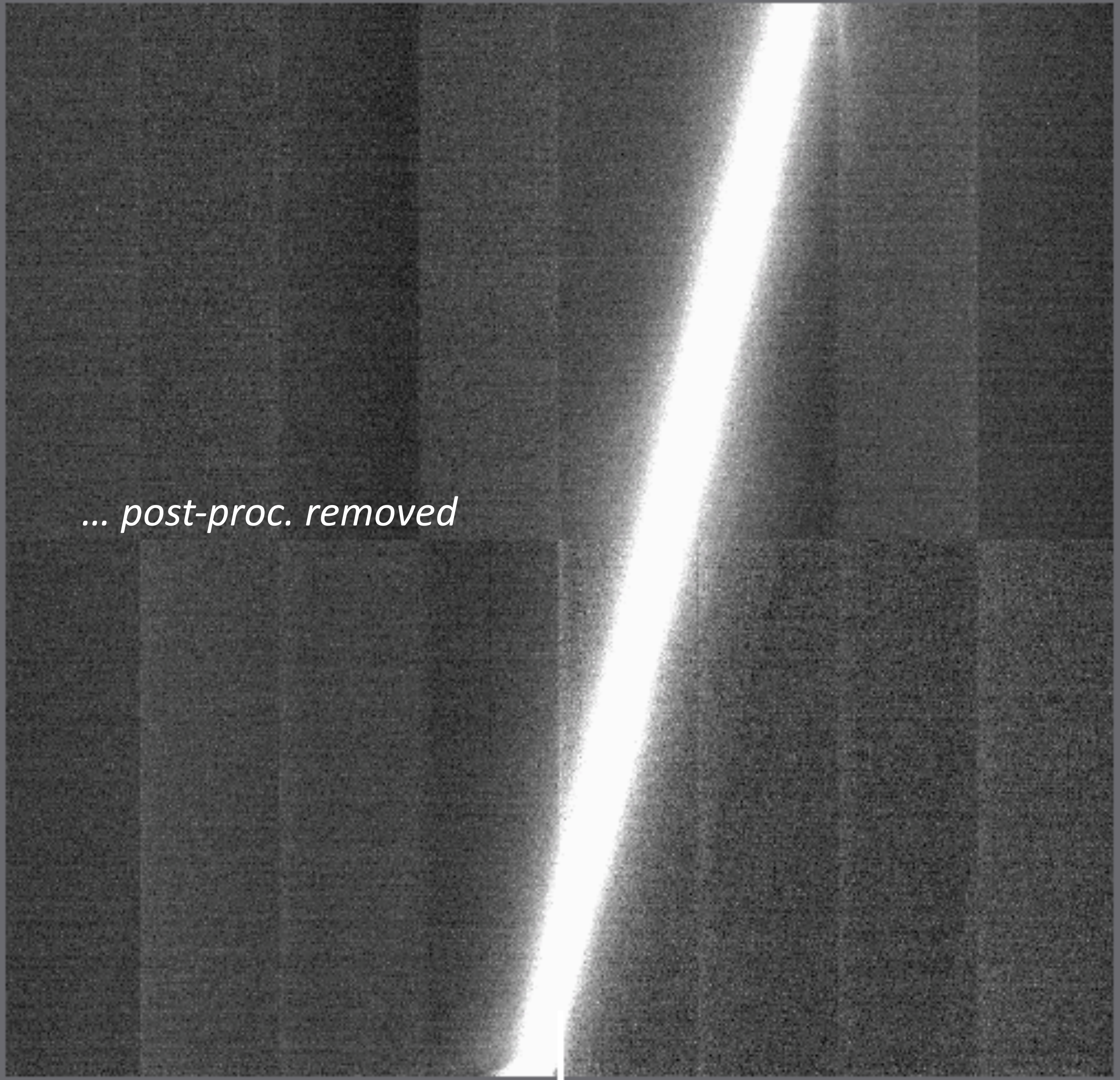


H. Krantz (U. Arizona) 2020

D. Galadi (SAS) 2020

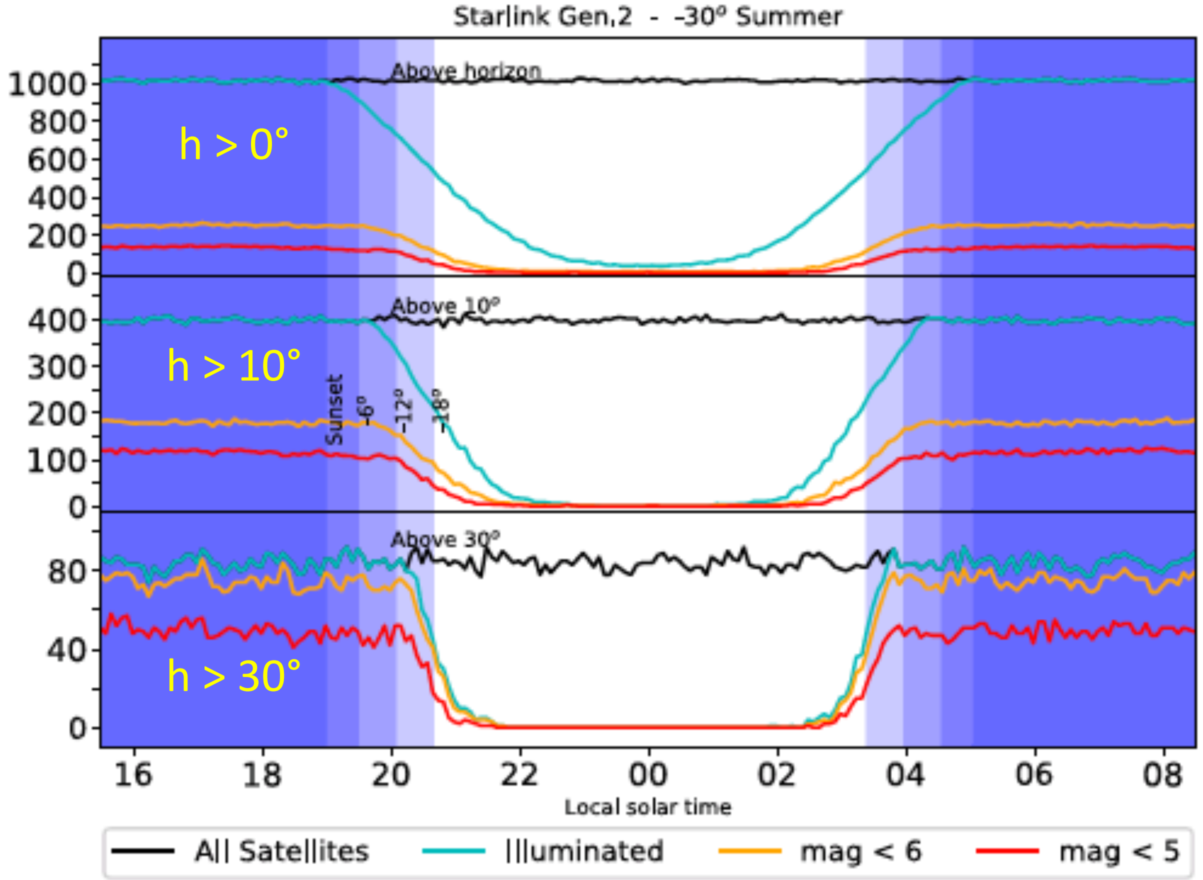
SATCON1 SOC report – 2

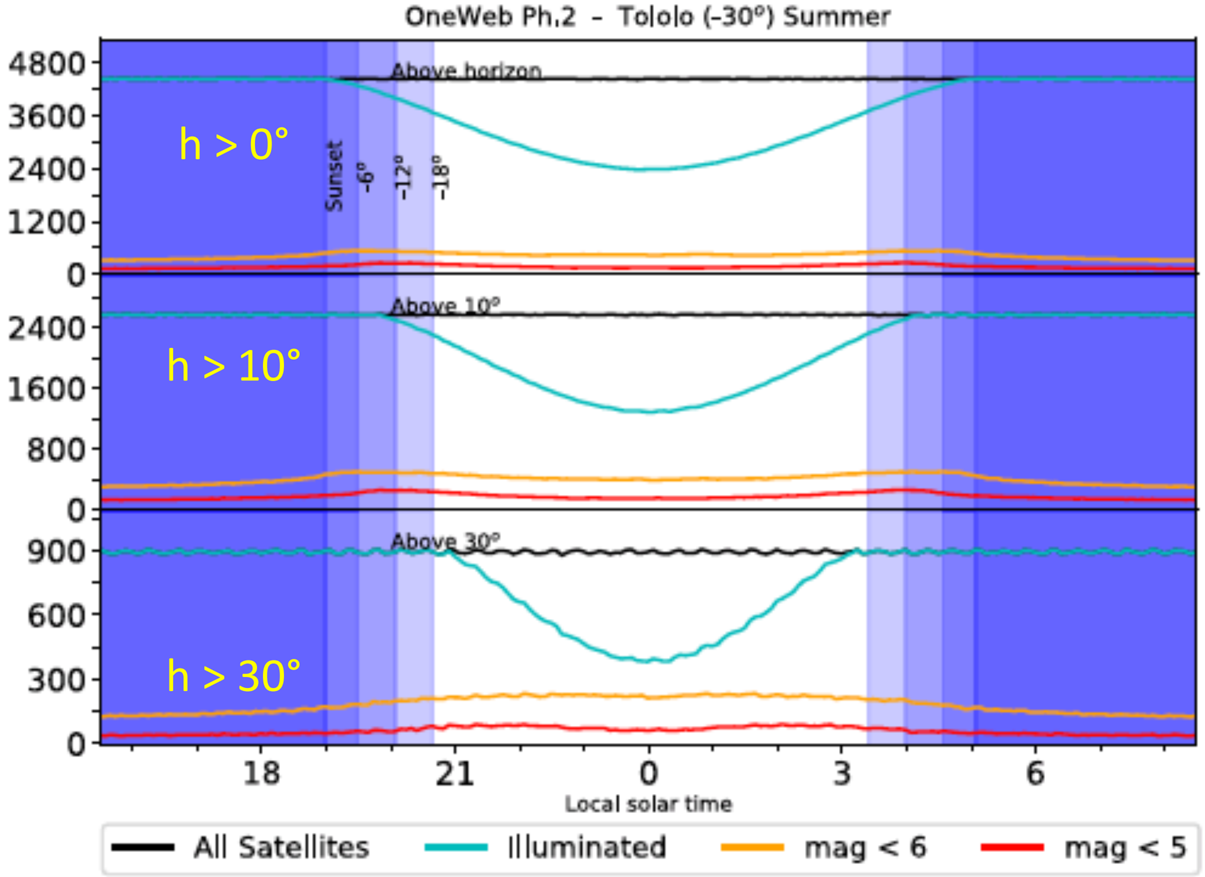




SATCON1 SOC report – 3

Satellites visibility from **Vera C. Rubin** observatory (30° latitude South) at summer solstice



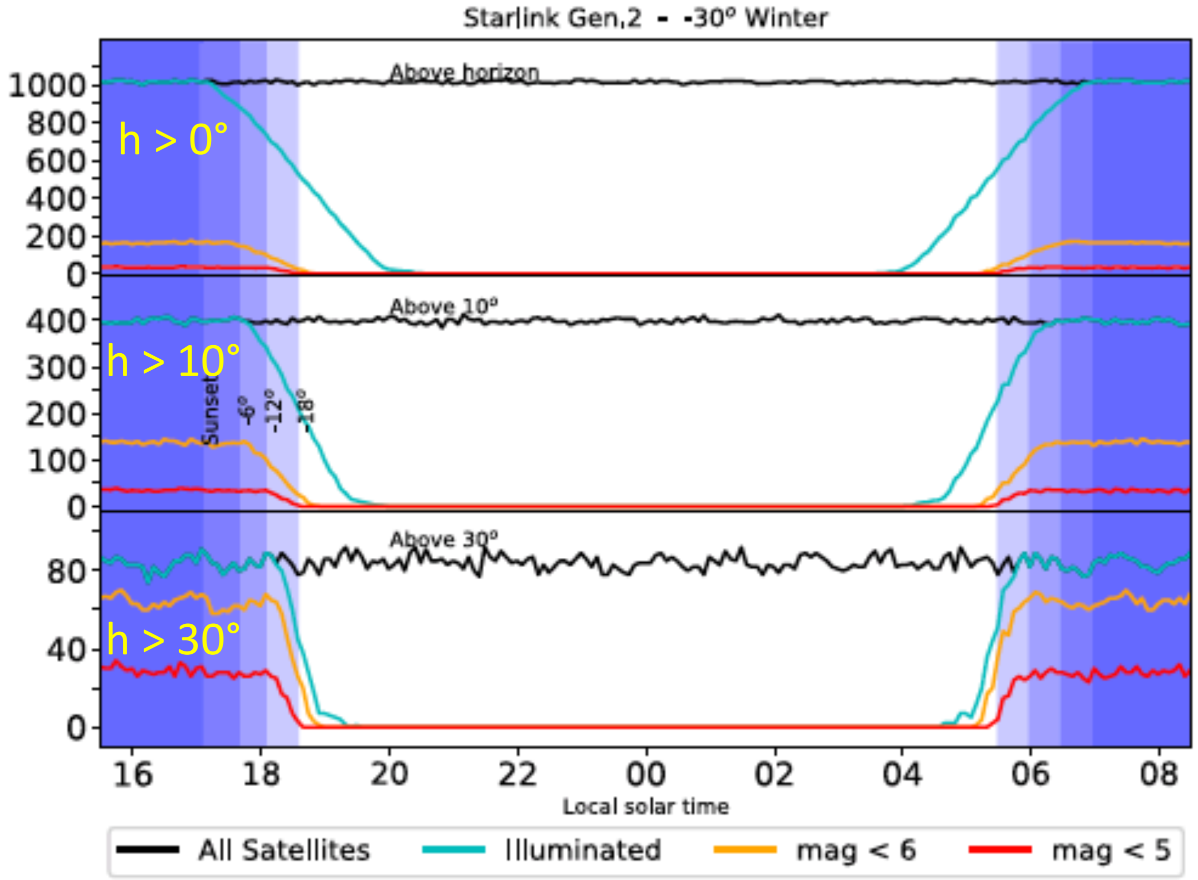


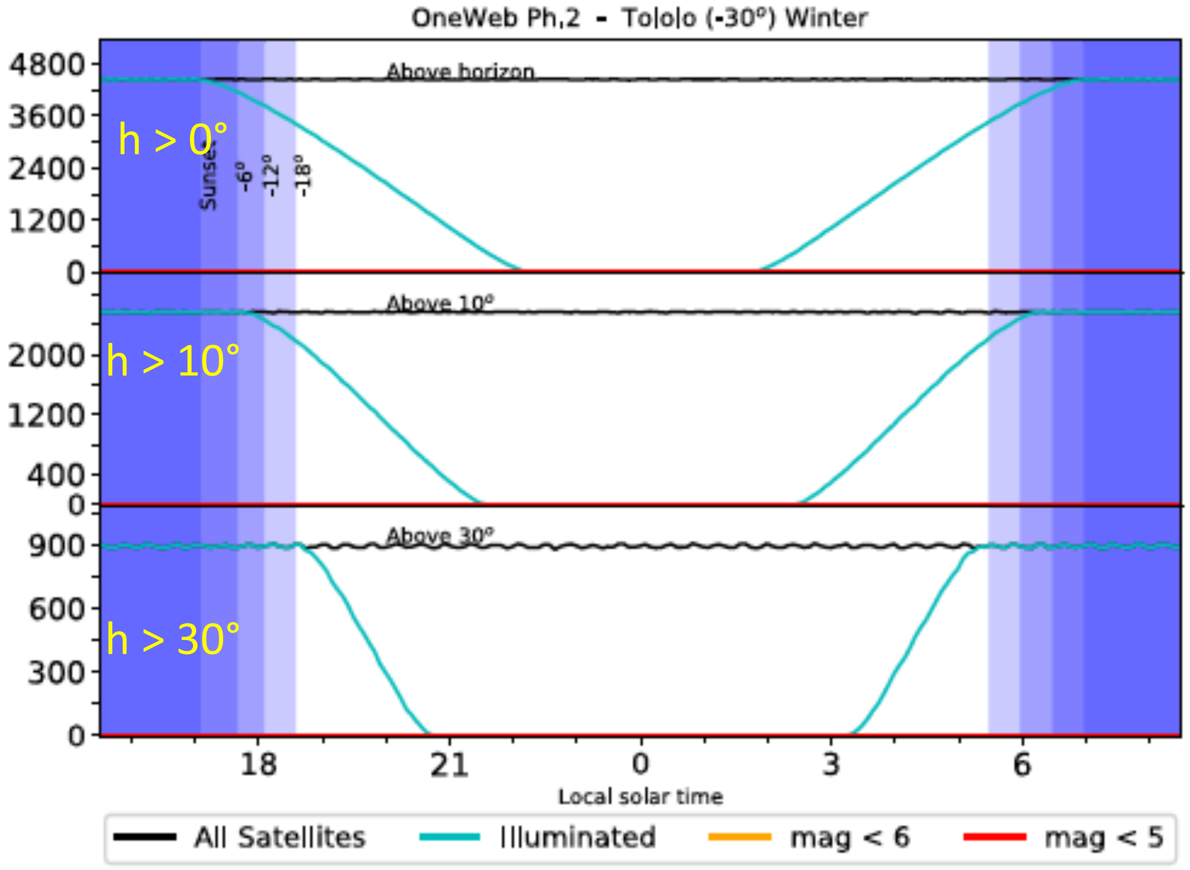
Starlink gen. 2: **30,000** satellites mostly at ~ 350 km

OneWeb: **50,000** satellites at ~ 1200 km

SATCON1 SOC report – 4

Satellites visibility from **Vera C. Rubin** observatory (30° latitude South) at winter solstice





Starlink gen. 2: **30,000** satellites mostly at ~ 350 km

OneWeb: **50,000** satellites at ~ 1200 km

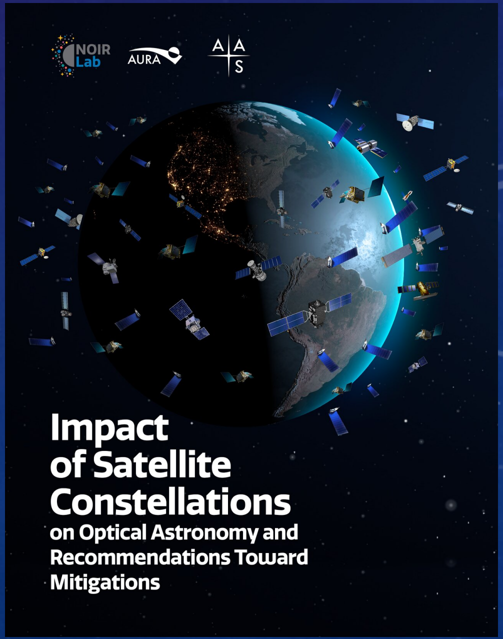
Hainaut (ESO) 2020

Representative "vulnerable" science cases / observations

1. "One-shot" rare events: gravitational waves, GRB, FRBs
2. Deep, wide, extragalactic imaging : cosmology (dark matter and dark energy), study of extended low surface brightness objects
3. NEOs
4. Deep multi-object spectroscopic surveys
5. Deep wide-field near-infrared (NIR) imaging
6. Imaging of large extended low surface brightness targets
7. Exoplanet transits in wide-field surveys
8. Discovery of new phenomena
9. Citizen science, amateur astronomers, and stargazers worldwide

3 impact levels

- **Negligible**: the program will be realized as originally planned essentially unchanged
- **Significant but tolerable**: science goals will be somewhat compromised, additional time or resources being required to offset losses
- **Extreme**: science goals cannot be realized



Note: for the details please refer to the SATCON1 SOC technical report https://noirlab.edu/public/products/techdocs/techdoc003/

Mitigation actions: summary

Satellite operators

- Reduce satellites reflectance
- Avoid higher orbits
- Deliver precise and up-to-date orbit ephemeris
- Collaboration with the astronomical community
- In all cases it has to be:

  V_{mag} > **7** for ~ **550 km** orbits

  V_{mag} > **8** for **1200 km** orbits

$$7.0\ V_{mag} + 2.5 \times \log(A_{orb} / 550\ \text{km})$$

Observatories

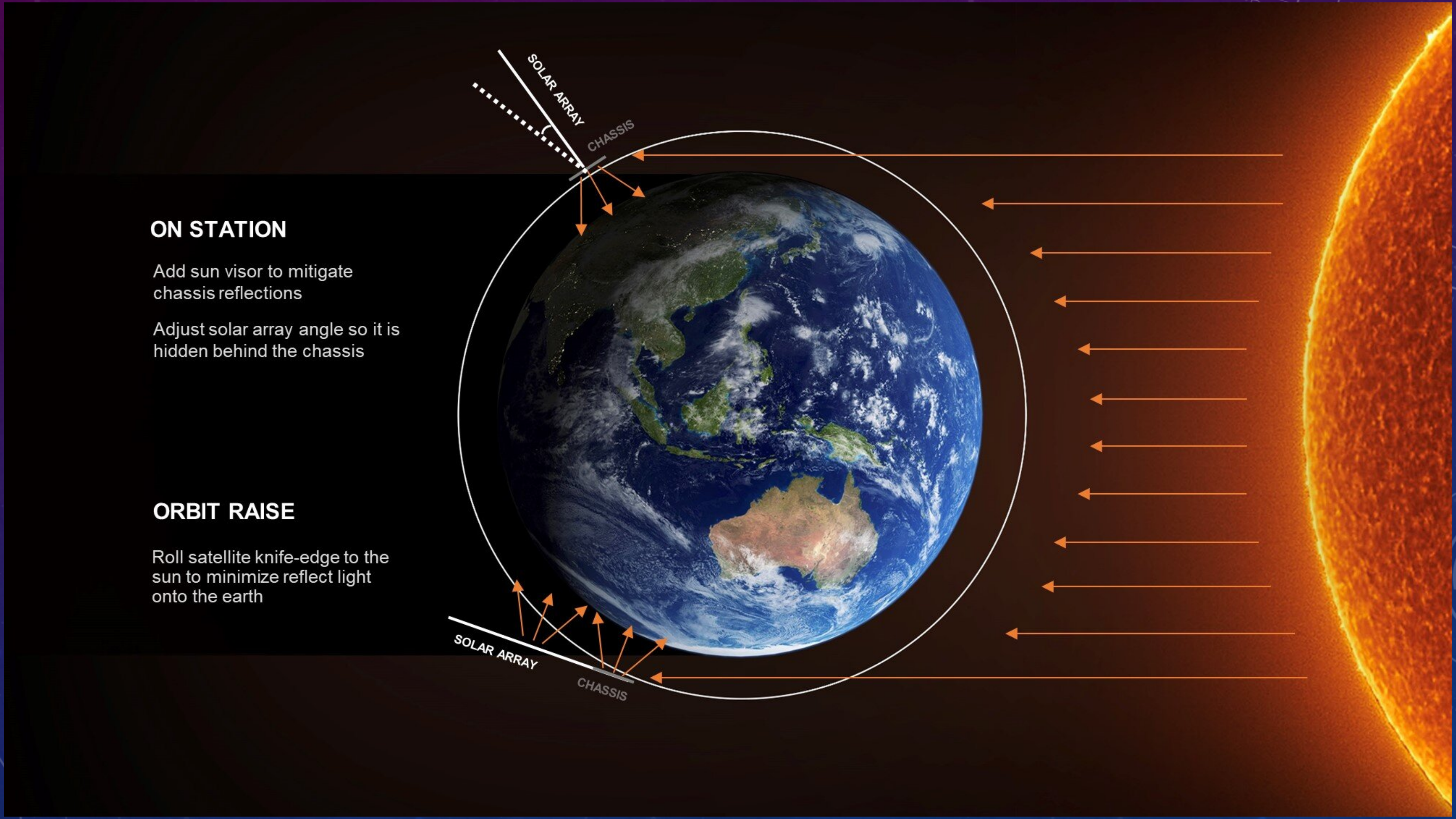
- Schedule observations in the direction of the Earth shadow
- Use ephemeris information to schedule and/or interrupt observations
- Use multiple shorter exposures
- Implement new software for smart scheduling and image cleaning

  … decadal-scale

- Develop new instruments capable of mid-exposure shuttering
- Investigate CMOS detectors for pixel shuttering

Note: any action has drawbacks. For some observational programmes some actions could be not applicable!

Possible mitigation actions



Possible mitigation actions – 2

Satellite operators

- Darker surfaces and solar shields
- Avoiding the use of non-rigid specular materials on the nadir face of the satellites to reduce false transients
- Laboratory reflectance simulation analysis
- Best efforts for attitude control of satellites to have predictable nadir-facing specular surfaces in direction of ground-based observatories
- Potentially adjusting attitude to avoid flares projecting onto major ground-based observatory sites

Observatories

- Software for image post-processing in order to identify, model, subtract and mask pixel with satellite trails
- Detailed simulations of the effects on data analysis systematics and data reduction signal-to-noise impacts of masked trails on scientific programs affected by satellite constellations
- With precise ephemerides of entire constellation suites, and for those facilities where it may be practical, close shutters for the seconds around predicted passage
- Pointing avoidance when possible (dynamic observation scheduling)

In collaboration

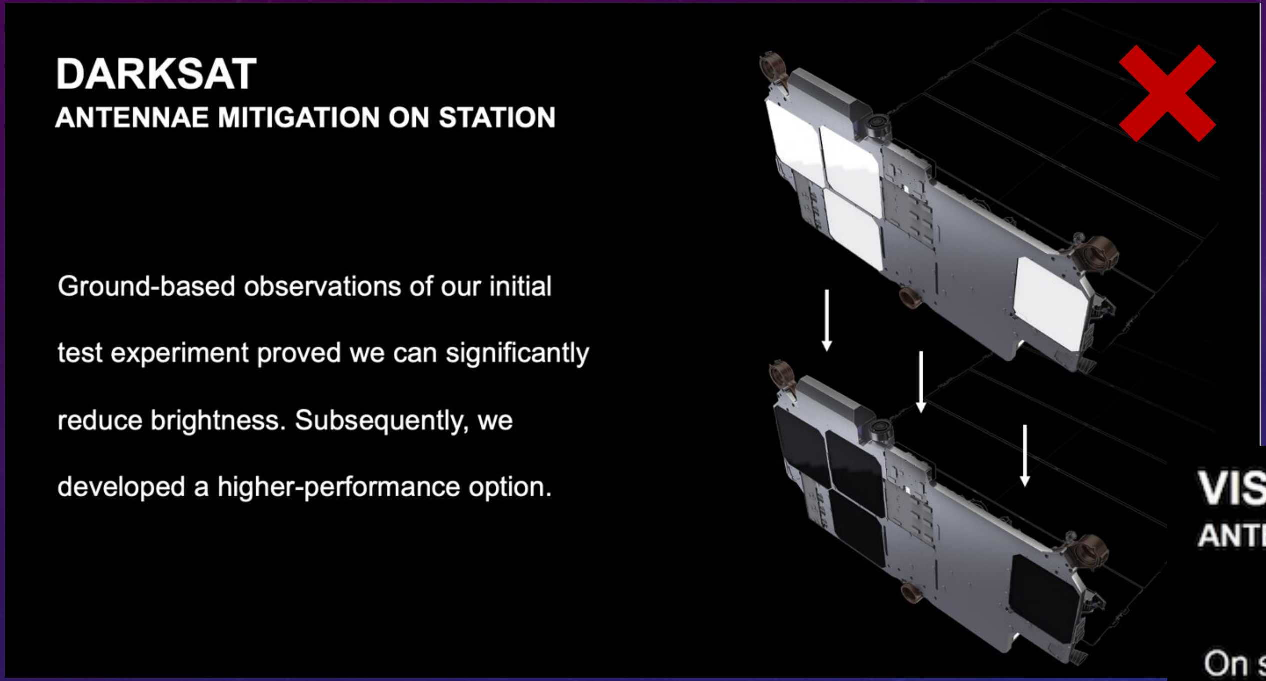
Ephemeris: accurate, public, frequently updated, new format (now TLE) including covariance etc.

Possible mitigation actions – 3

Ephemeris related

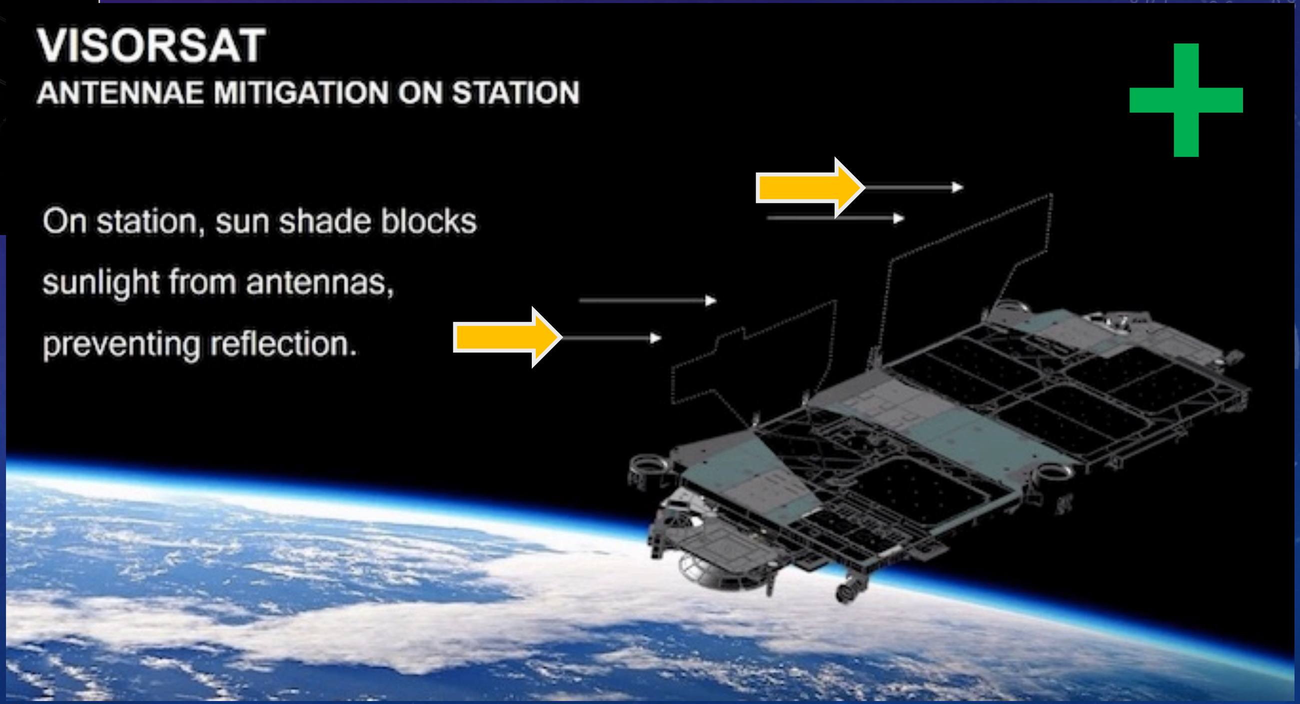
- New standard format for publicly available ephemerides beyond two-line-elements (TLEs)
- Update cadence and quality must allow a minimum improvement of the cross-track positional determination by a **factor of 10**
- Transits across the field to be predictable within 12 hours in advance of the observation, to an accuracy of **2 s** in time and position of the track to within **6 arcmin** in the cross-track direction and position angle (10 s and 12 arcmin pre/post-stable orbit)
- Support development of a **software application** available to the general astronomy community that predicts the time and projection of satellite **transits** through an image, **flares**, …
- Support an immediate coordinated effort for optical observations of LEOsat constellation members, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations

Possible mitigation actions: Starlink



Pro: reduction of 1 mag
Con: problems of heat dissipation

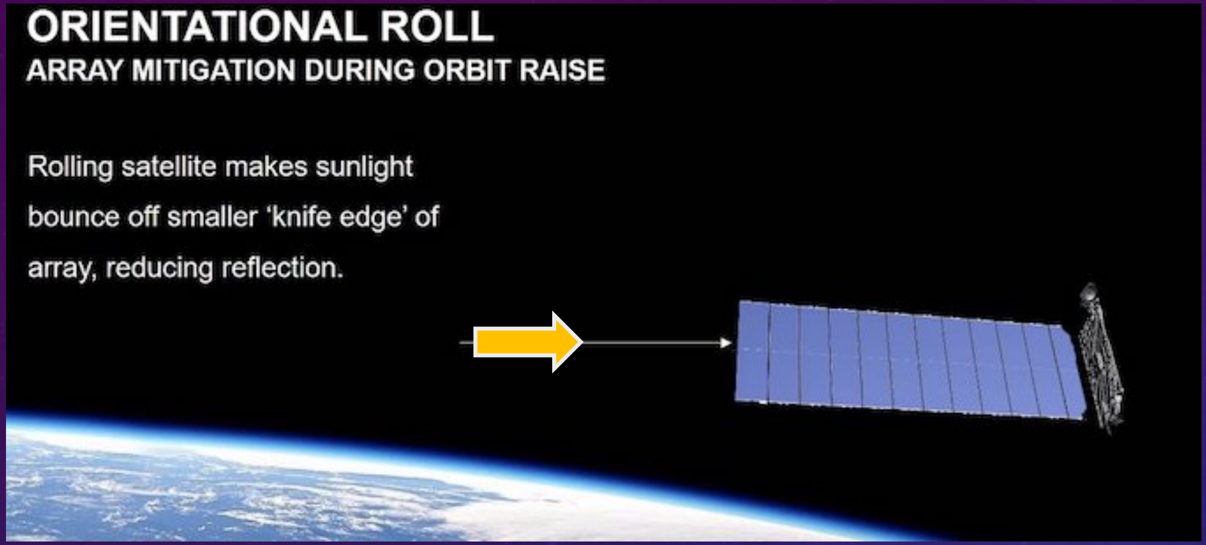
Pro: reduction (estimate) of > 2 mag
Con: possible mechanical problems

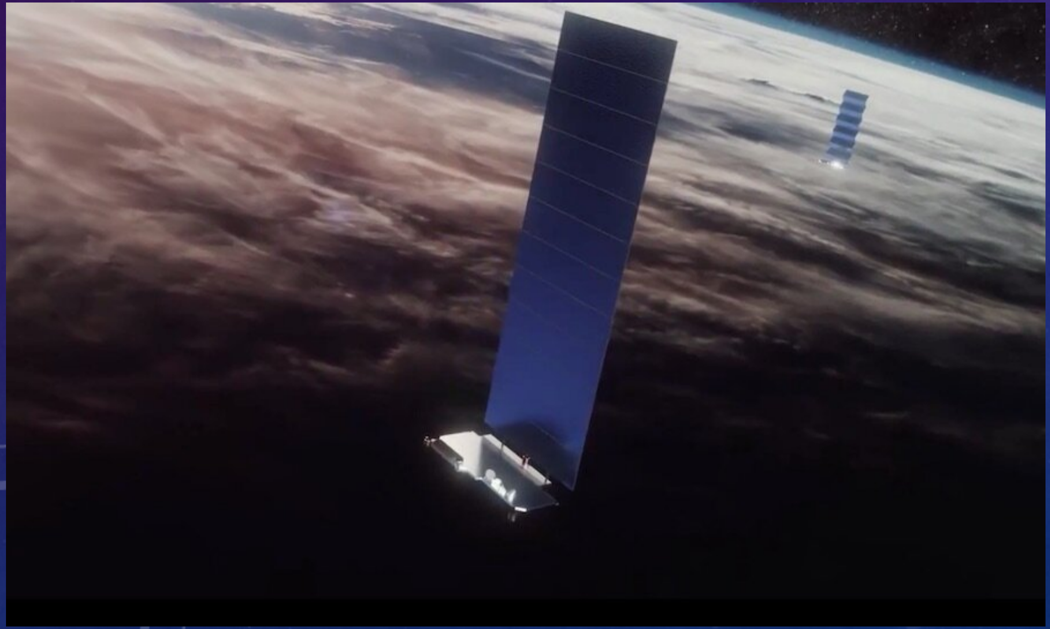


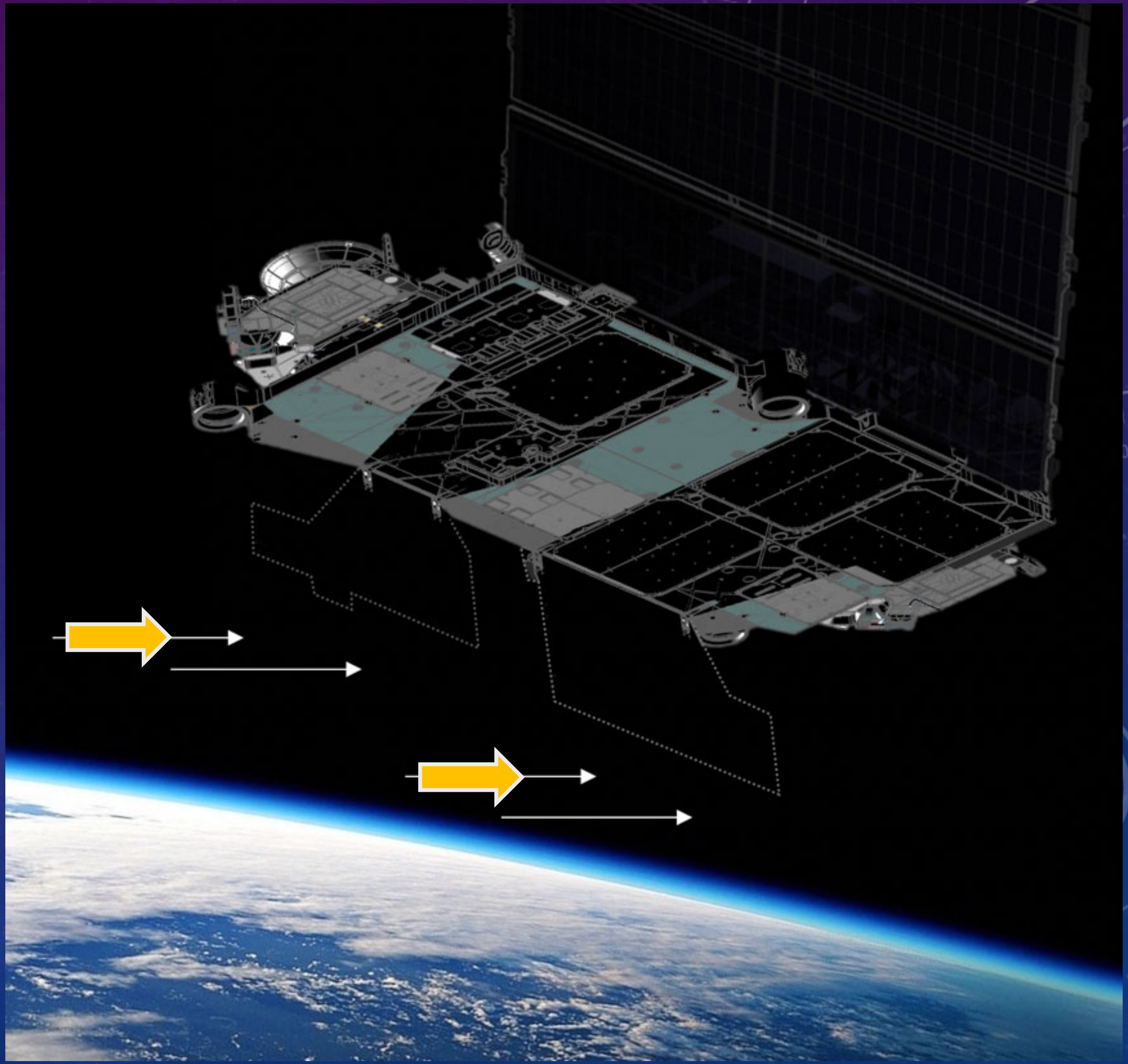
Starlink will no longer put (or reduce?) satellites in the 1100 – 1300 km orbit!

Musk words:
"Your data rate is going to be four times better than say at 1,100 kilometers. That's a close approximation. It's also better for ***astronomy****."*

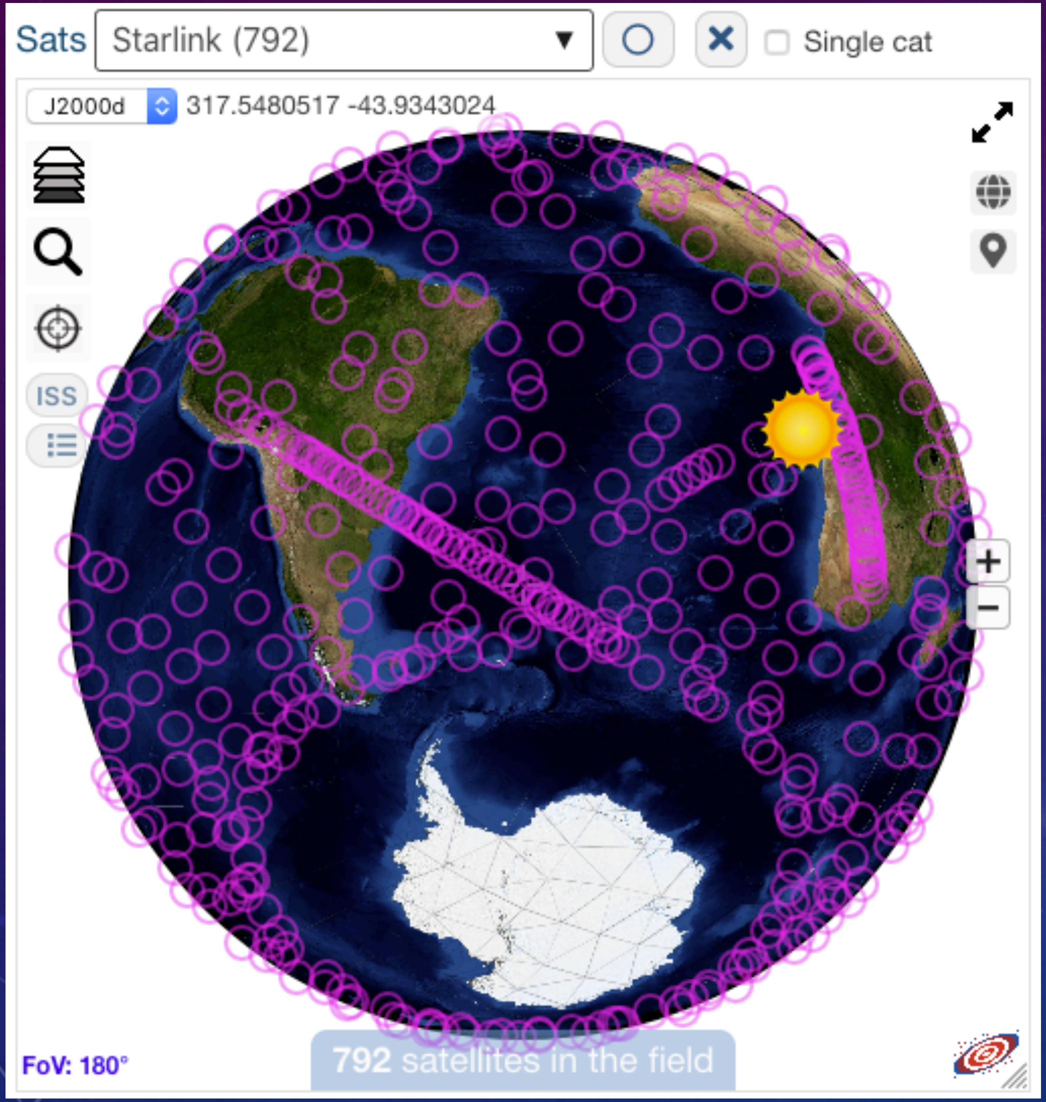
Possible mitigation actions: Starlink – 2

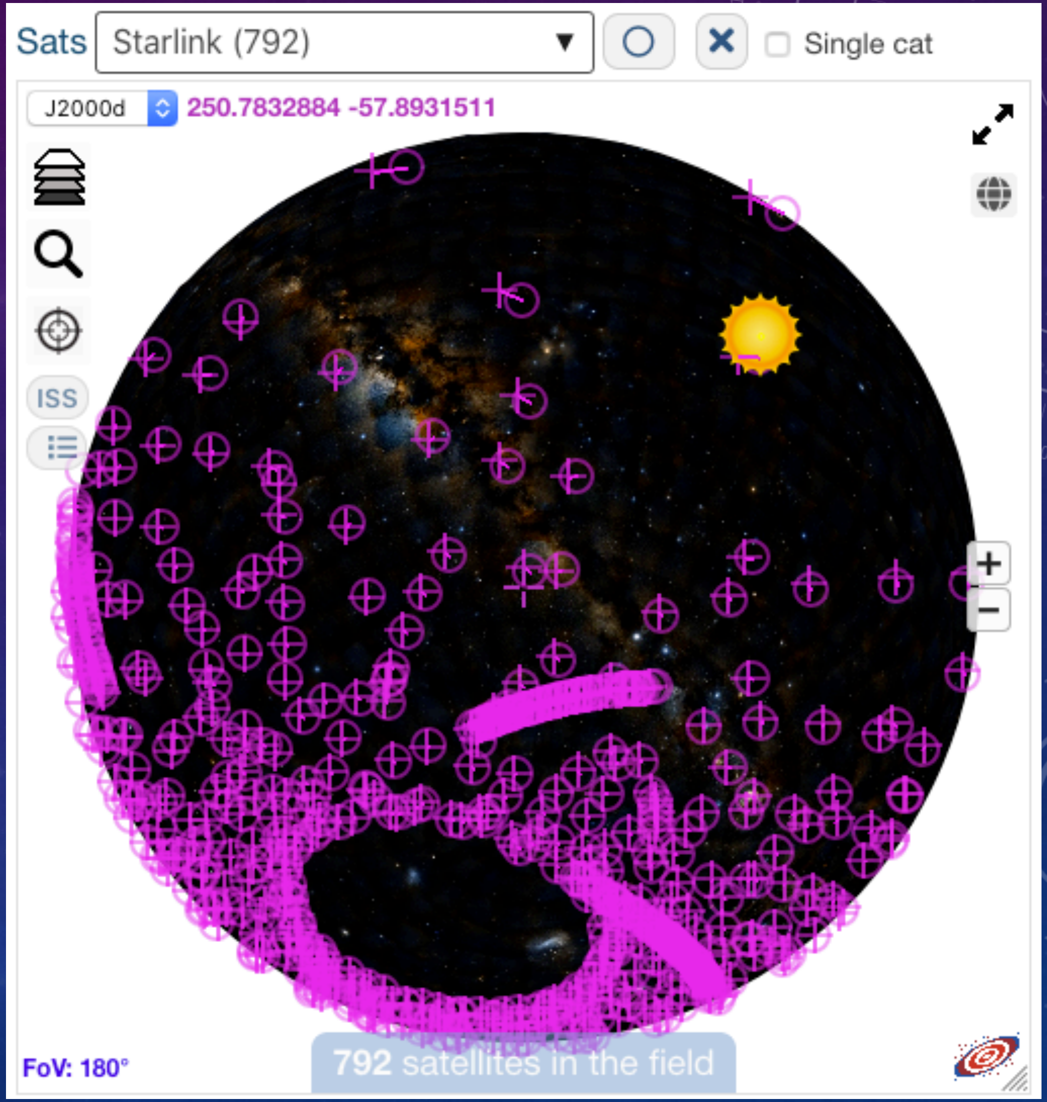






Tracking satellites: an astronomy oriented tool





https://cats.oas.inaf.it/SatSkyweb/

Tracking satellites: an astronomy oriented tool

https://github.com/lnicastro/SatSkyMap

- Standard C
  - make – mv to bin dir.
- Read TLE files (single or aggregate list)
- Use standard SGP4, SDP4 perturbation models
- Main input options
  - Epoch + Δt, Sky coords + size, Obs. site, satellite ID
- Output
  - JSON (apparent Sky and Geodetic coords)
- Utils
  - Sun params
  - HEALPix ID
  - TLEs retrieval

TODO

- Mag estimate
- Ephemeris JSON input
- Read TLE remotely
- Daemonize

Tracking satellites: ephemeris

- Several software packages and tools around, desktop and web
- All rely on ephemeris distributed by various Institutions
- The reference one is *Combined Force Space Component Command* (CFSCC) that distributes the data from *Space Situational Awareness* (SSA) at *United States Space Command* (USSPACECOM)

Two Line Elements (TLE)*

```
1 NNNNNC NNNNNAAA NNNNN.NNNNNNNN +.NNNNNNNN +NNNNN-N +NNNNN-N N NNNNN
2 NNNNN NNN.NNNN NNN.NNNN NNNNNNN NNN.NNNN NNN.NNNN NN.NNNNNNNNNNNNNN
----------------------------------------------------------------------
1234567890123456789012345678901234567890123456789012345678901234567890
         1         2         3         4         5         6         7
```

reference line

International Space Station

```
ISS (ZARYA)
1 25544U 98067A   20280.49890347  .00001541  00000-0  36289-4 0  9999
2 25544  51.6439 157.7018 0001205 111.8063 310.3708 15.48837713249270
```

International designator

NORAD catalogue number and classification

* Typically 3 rows

https://www.space-track.org/documentation#/tle https://cats.oas.inaf.it/SatSkyweb/

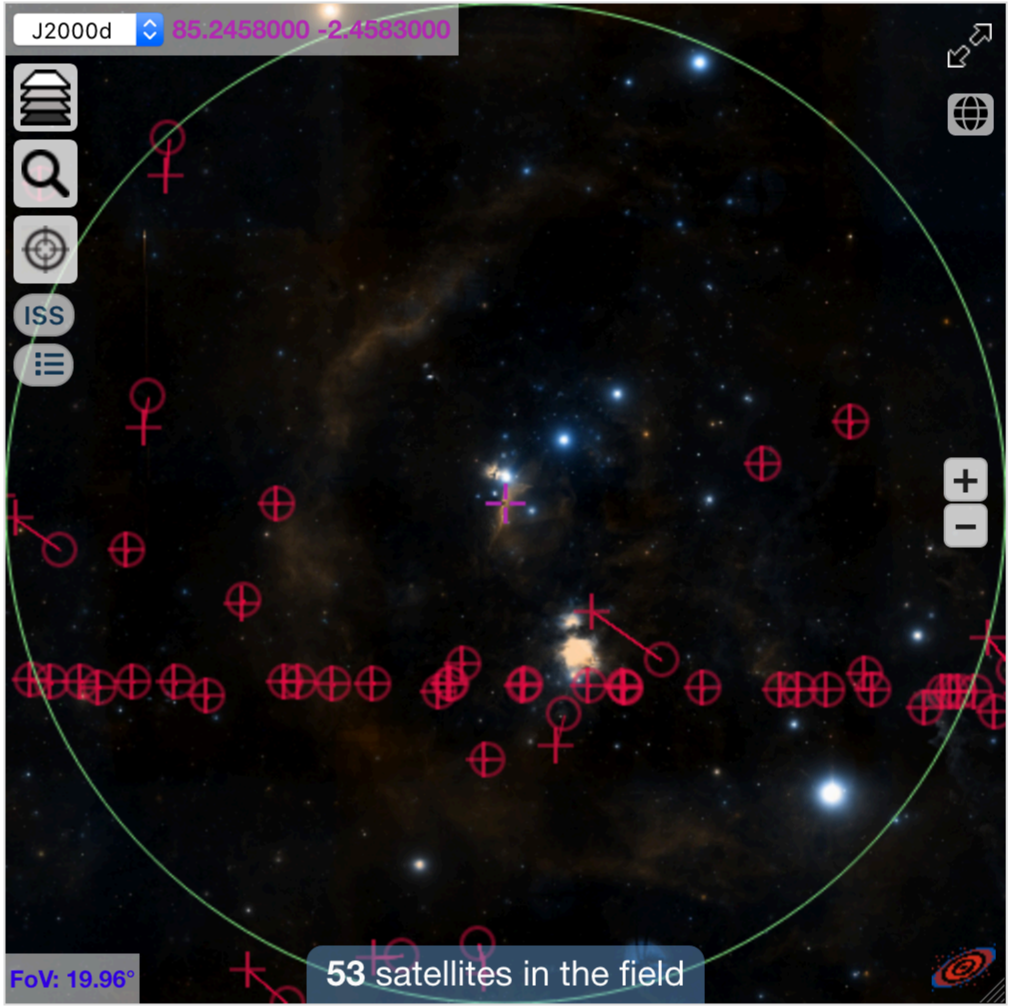
INAF

SatSky* – satellites browser, Version 0.2d – Data from **CelesTrak** – updated every 6 hours **Work in progress*

11 / 02 / 2020 | 08 : 11 : 27 PM | Now | 10 | 44.52324, 11.33914, 23 | 85.2458 -2.4583 | Z | 10 ° | any | 1000 | View

Step (s): 2 | Add to 2nd epoch | Collection active | Show/hide table

Sats | Active (3179) | Single cat | Toggle columns | Focus follows pointer



Show 10 entries | Search:

	Name	IntlName	NORAD	RA	Dec	Dist.	Sep.	PA
	TJS-4	2019-070A	44637	74.7855	-6.2256	41245.91	11.0879	89
	RADIO ROSTO (RS-15)	1994-085A	23439	75.0274	-5.7369	4844.14	10.7052	39
	BEIDOU 16	2012-059A	38953	75.3592	-6.5808	41315.42	10.6813	88
	GALAXY 30	2020-056C	46114	75.767	-6.2023	41328.84	10.1646	89
	HORIZONS 2	2007-063B	32388	76.1006	-6.1888	41351.21	9.8512	89
	RADUGA-1M 2	2010-002A	36358	76.268	-6.1918	41364.37	9.698	89
	INTELSAT 15 (IS-15)	2009-067A	36106	76.4105	-6.2001	41376.16	9.5703	89
	INSAT-4B	2007-007A	30793	76.7656	-6.5163	41448.43	9.3761	89
	KAZSAT-2	2011-035B	37749	77.8267	-6.1625	41477.82	8.2724	89
	FENGYUN 2E	2008-066A	33463	77.9946	-5.8405	41455.73	7.9829	85

Showing 1 to 10 of 53 entries | Previous 1 2 3 4 5 6 Next