Satellite Visibility and Brightness

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My background – optical observations of orbital debris at GEO: survey and characterization. Funded by NASA Orbital Debris Program Office 2000-2016. Member, NASA delegation to IADC (Inter-Agency Space Debris Coordination Committee) 2001-2015.

Modern Astronomy
Wide variety of telescopes and fields of view

All sky camera

Field of view = 170 deg

Aperture few mm.

Many bright satellites at once.

ISS and tumbling R/B.

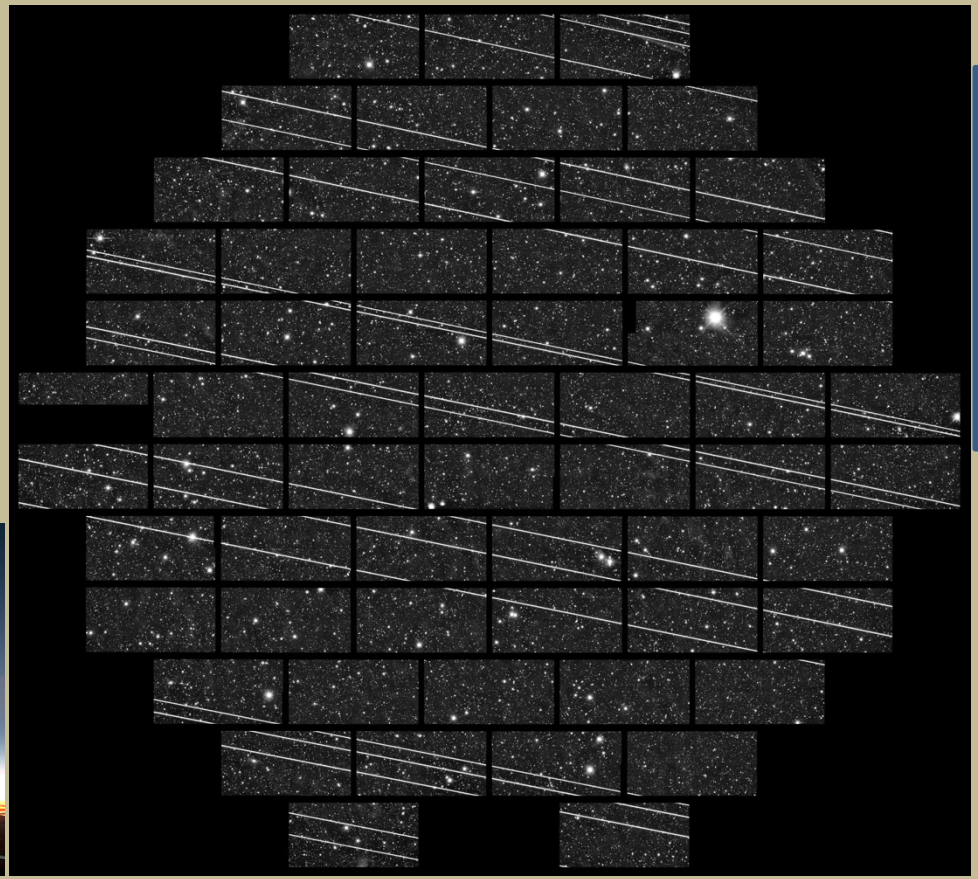
LSA ASTRONOMY
UNIVERSITY OF MICHIGAN

2019-Nov-18 0800 UT

NSF Blanco 4.0-m telescope

DECAM

Cerro Tololo, Chile



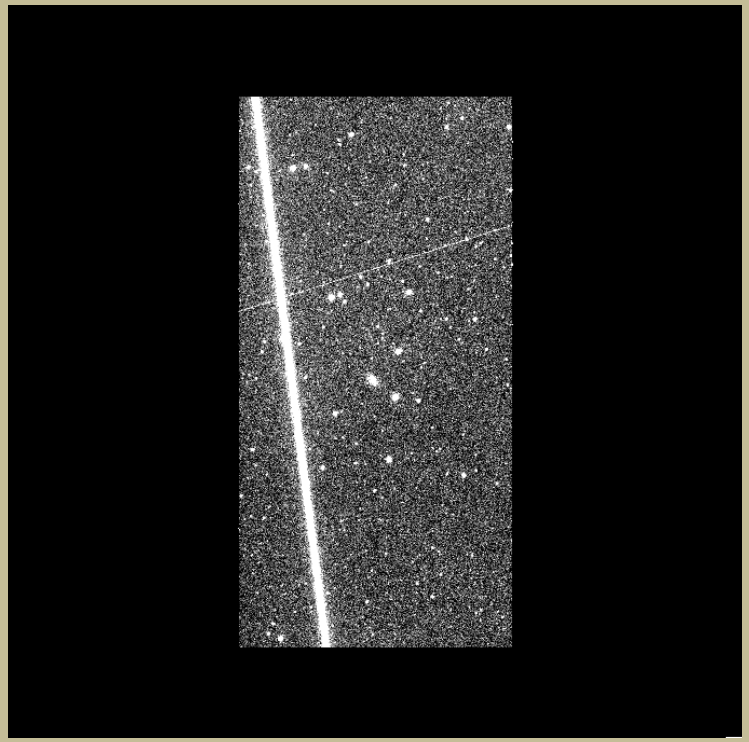
19 Starlinks crossing.

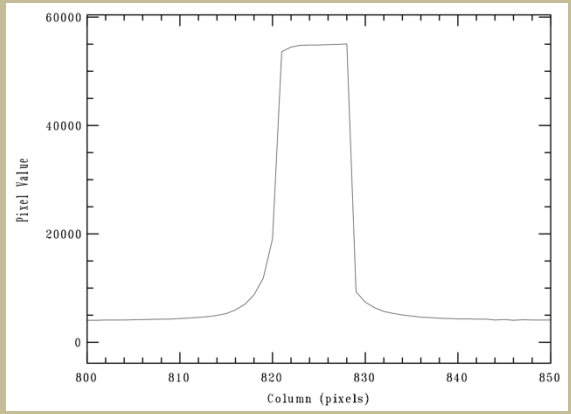
2019-Nov-11 launch.

~4 sec to cross field of view.

4 x diameter of full moon.

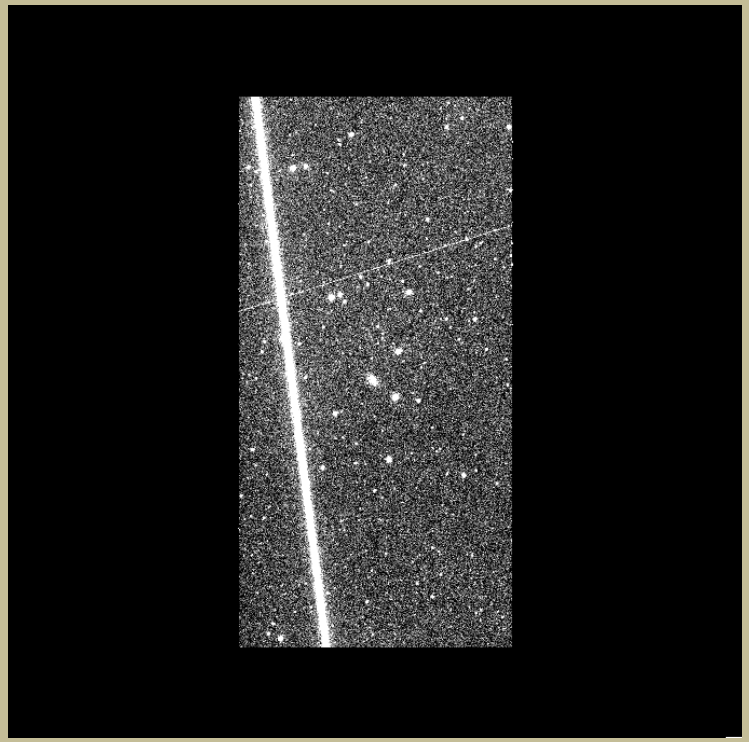
How do bright satellites affect observations on telescopes?
Bright satellite streak saturates detector!





- Loss of information in pixels.
- Cross-talk in electronics.
- Ghost images.
- Possible residual images.

How do bright satellites affect observations on telescopes?
Bright satellite streak saturates detector!



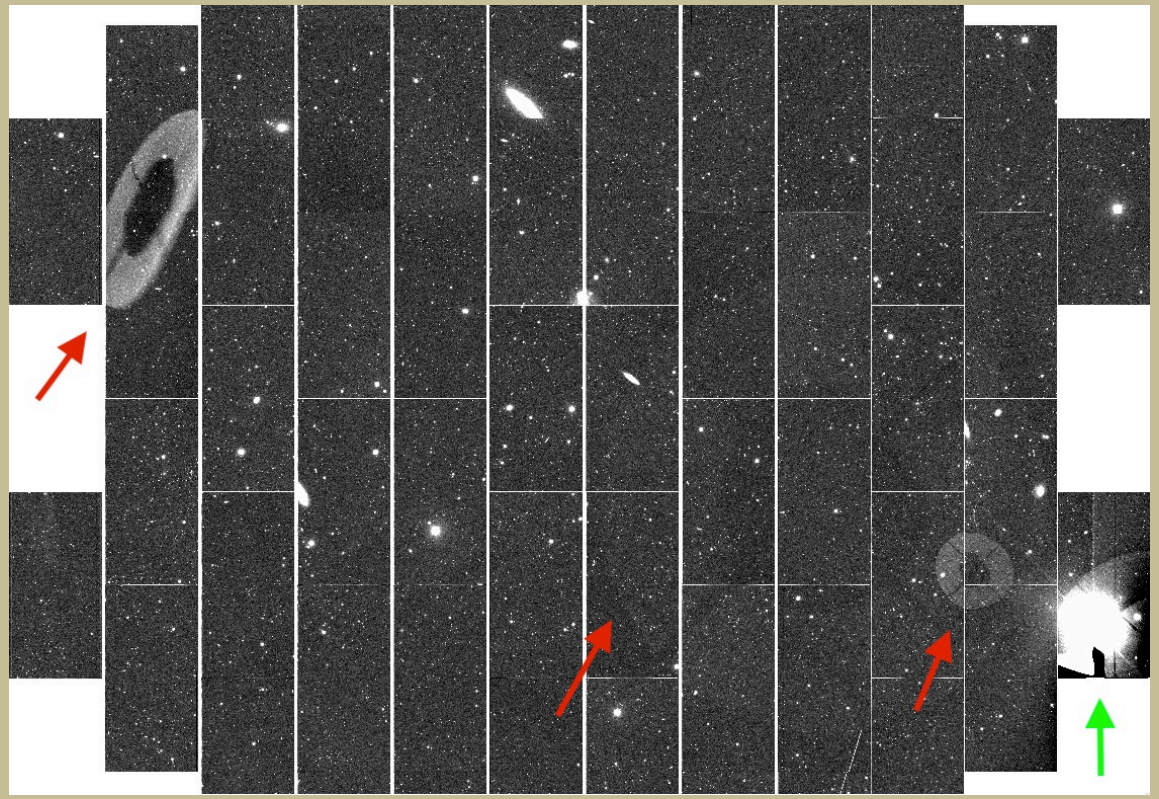
Exposure time for satellite is NOT image exposure time, but time it takes satellite to cross a pixel! This is milliseconds!

Higher altitude satellites travel slower, and thus have longer effective exposure time.

Current large telescope/camera combinations (in this case DECAM and future RUBIN) are so sensitive that the streak saturates!

Information also lost in non-saturated streaks.

Ghost images – internal reflections in optics



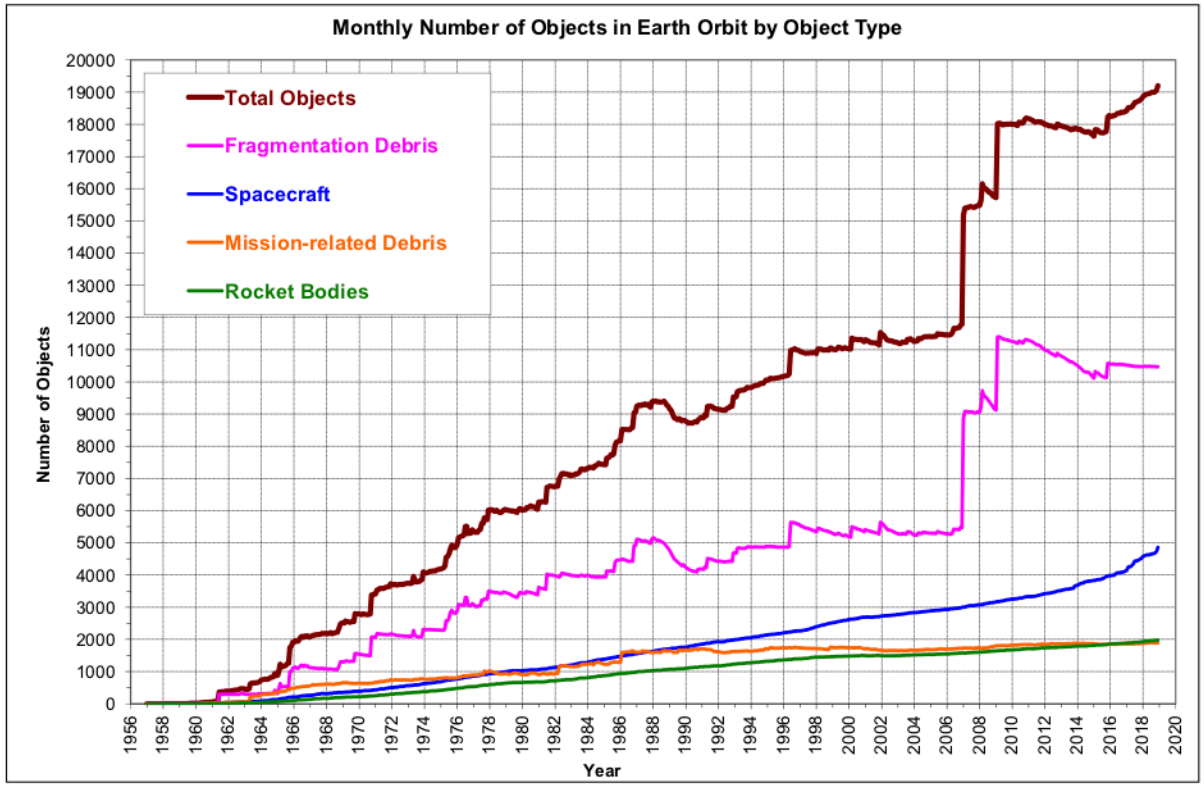
Bright star

When are satellites visible?

- Observer in darkness:
  - Latitude.
  - Time of year.

- Satellite in sunlight or penumbra – not in Earth shadow:
  - Orbital inclination.
  - Altitude.
  - Time of year.

What is in Earth orbit today?



Monthly Number of Cataloged Objects in Earth Orbit by Object Type. This chart displays a summary of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.

Any object in Earth orbit that reflects sunlight is of concern.

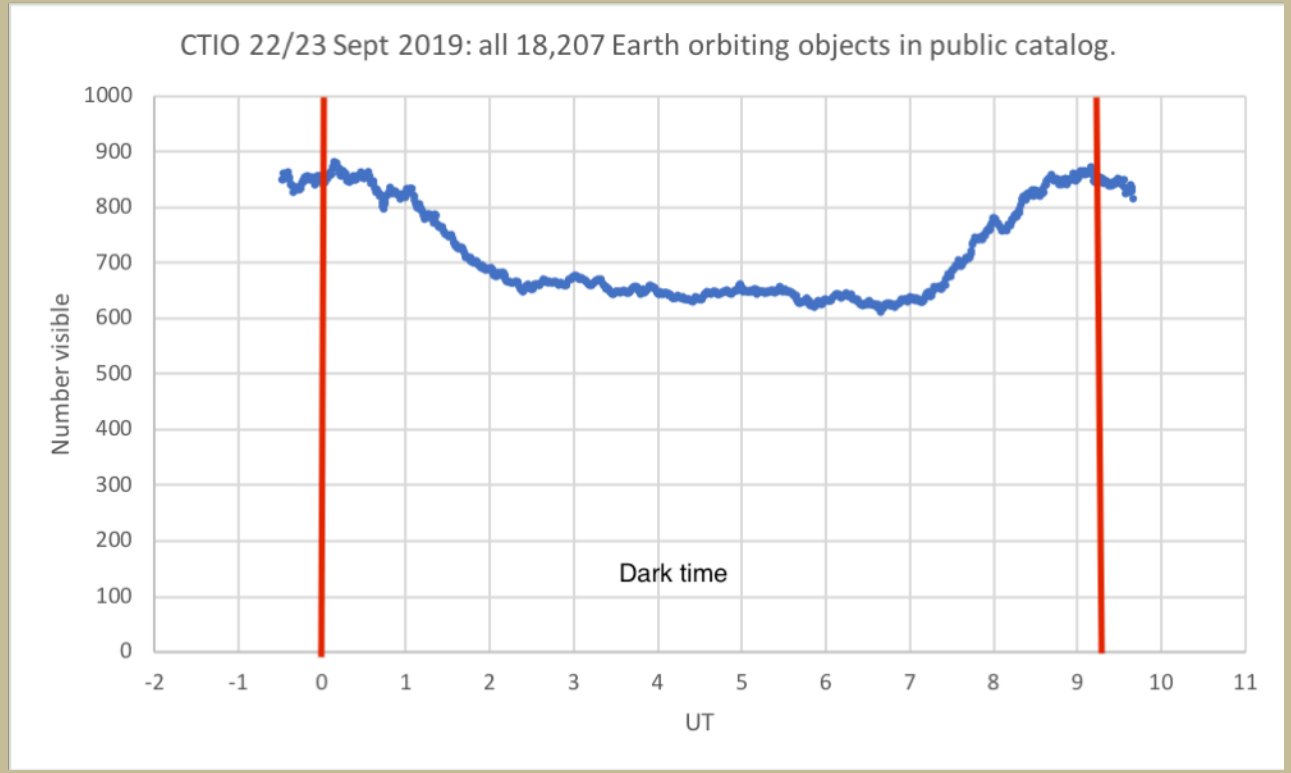
The top curve concerns astronomers and space safety.

Public catalog of objects > 10 cm.

Catalog incomplete.

NASA Orbital Debris Program Office

How many objects visible at night in springtime at Vera Rubin Obs in Chile?



Red lines –

Sun < -18 degrees elevation

Darkest part of the night

Calculated for satellites at elevation greater than 30 degrees.

Astronomical twilight: 23:59 – 09:12

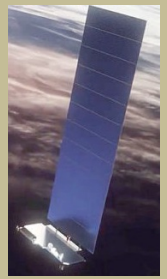
New Large Constellations

- If 600-700 objects now visible at any time during the night, why do we care if another 100-200 are added from new mega-constellations?
- **Brightness! The new satellites could be brighter than 99% of all objects in orbit now.**
- Now – maybe 200 objects can be seen with eye (not all at once).
- End of 2020 – SpaceX will add another 1584! 9x larger population.

3 Phases of a Constellation's Lifetime

1. Initial mission phase. *This is what we are observing now – satellites at low altitude and non-standard attitude/orientation.*
   a) Launch.
   b) Checkout and parking orbit .
   c) Orbit raising.

2. Operational phase.



3. Deorbit phase – high drag configuration?
   – Orbit lowered until satellite burns up in atmosphere.
   – Must do within 25 years after end of mission.

Brightness will be different in all three phases – distance from observer to satellite different and attitude/orientation of satellite different.

Modelling

- How visible will these satellite constellations be to astronomers?

- Initial Starlink constellation as approved by FCC (public filing):
  - 1584 satellites at 550 km altitude: 24 planes with 66 satellites per plane.
    - Superseded by current configuration of 72 planes with 22 satellites per plane.
  - Use as reference constellation to understand 'what if' questions.
  - See modelling for more constellations by McDowell (ApJL 2020), Hainaut & Williams (A&A 2020).

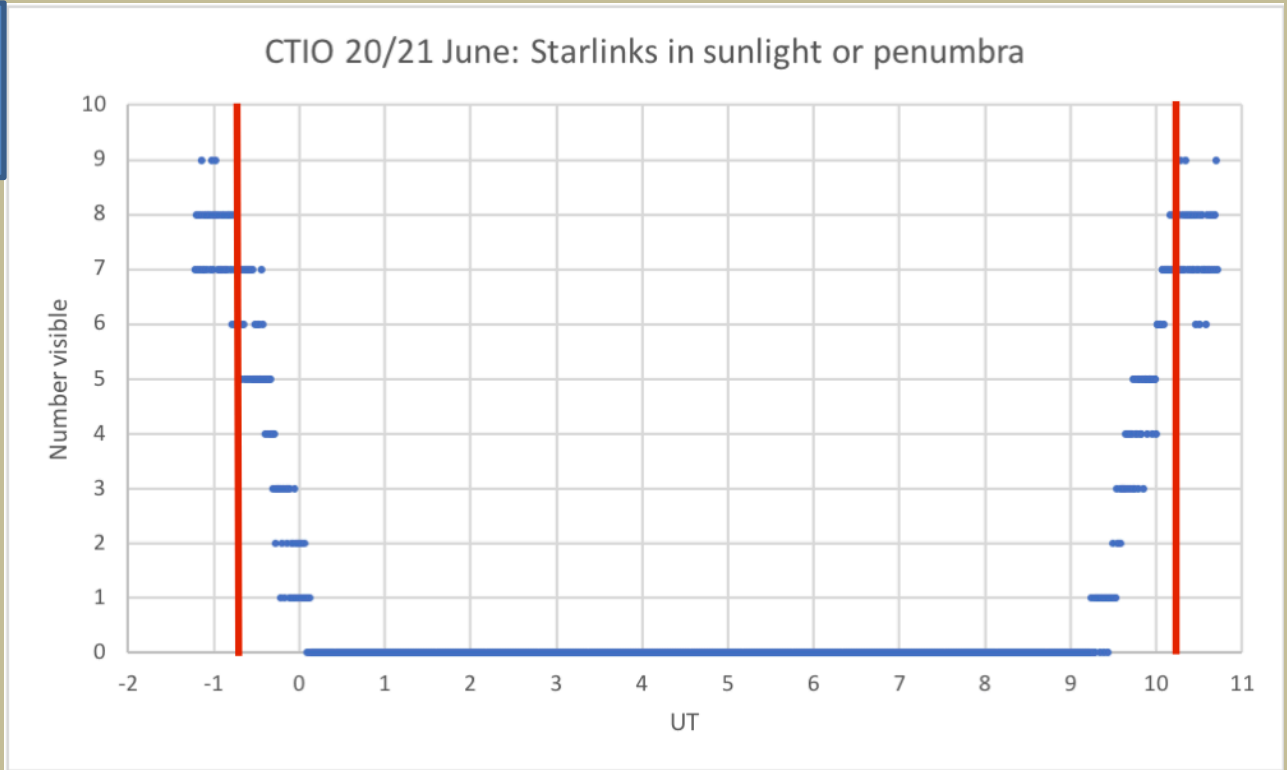
- Definitions of twilight:
  - Sun between 12 and 18 degrees below horizon: useful for calibration.
  - Sun 18 degrees or more below horizon: darkest time, observe faintest objects.
  - Sun at 18 deg - red line in plots.

- Satellites at elevation > 30 degrees as seen by observer.

Winter in Chile – longest night of the year

N = 1584

Multiply by ?

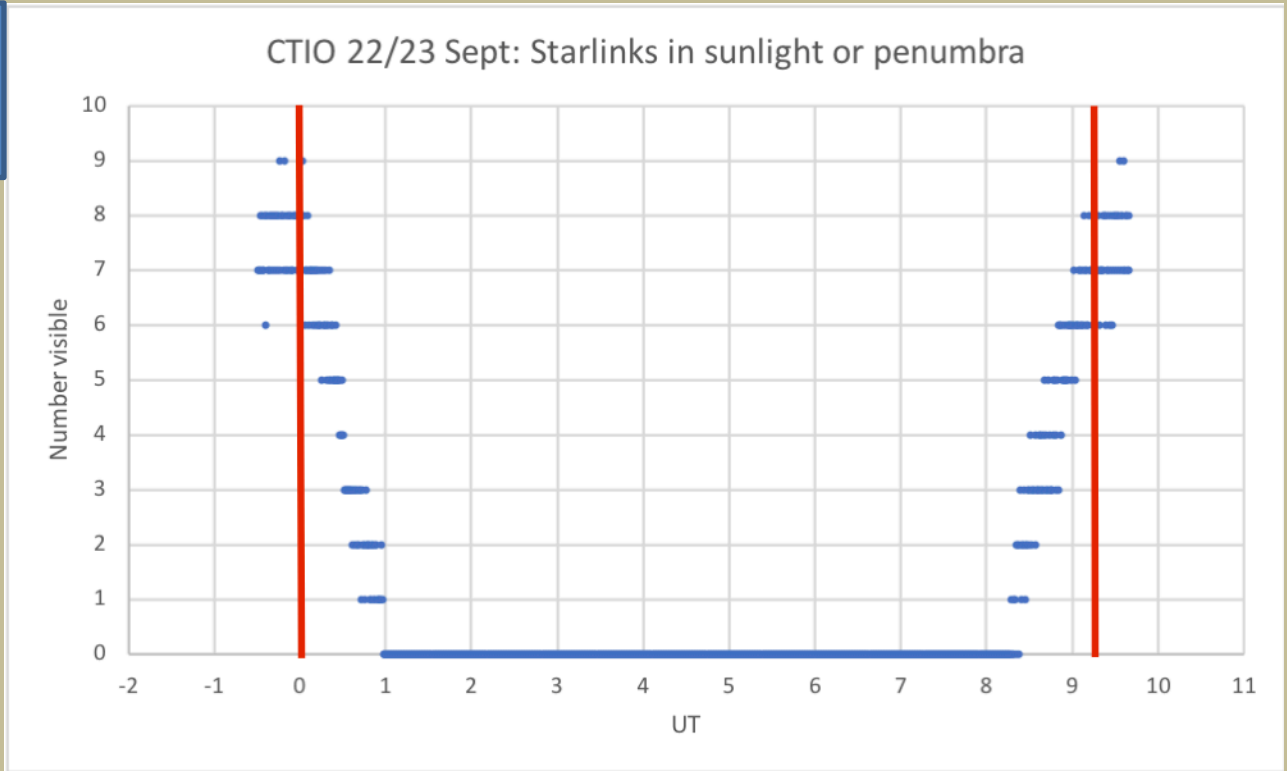


Astronomical twilight: 23:16 – 10:13

Spring in Chile

N = 1584

Multiply by ?

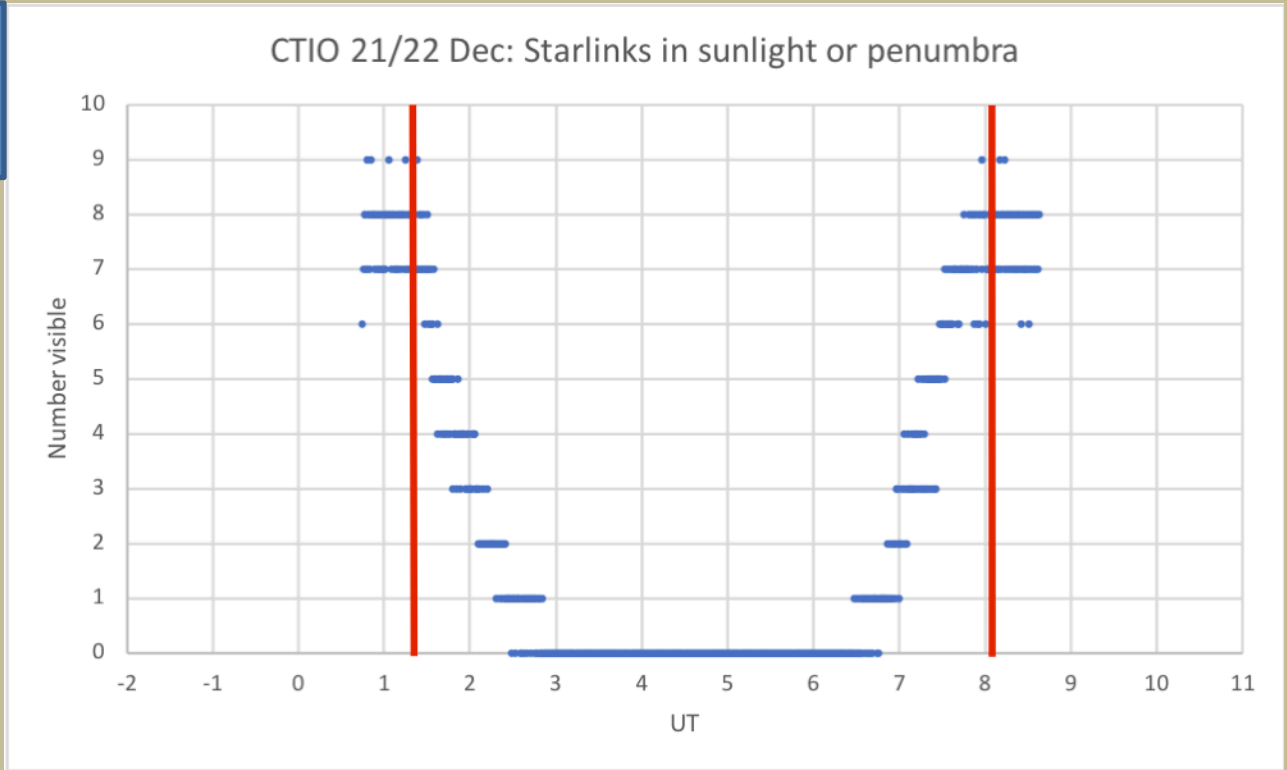


Astronomical twilight: 23:59 – 09:12

Summer in Chile – shortest night of the year

N = 1584

Multiply by ?



Astronomical twilight: 01:20 – 08:01

What if?

- SpaceX had launched 1584 satellites into original planned orbit of 1150 km.

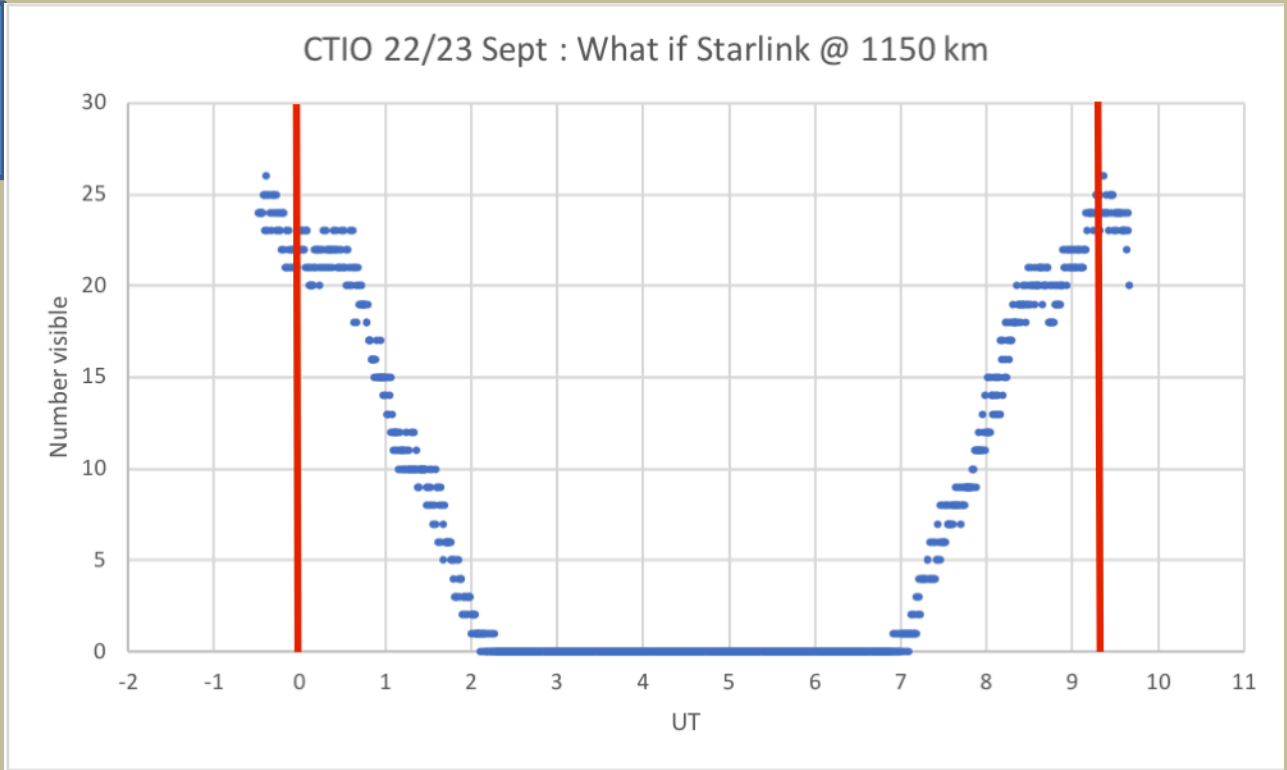
- Simulation shows:
  - Satellites fainter and probably not visible to eye, but still saturate detector.
  - More satellites visible at any one time – factor of 3-4 times more!
  - Visible longer past twilight and into darkest part of the night.

- From astronomers' perspective, this could be worse.
  - Streaks brighter than predicted from distance considerations alone – angular velocity.

Spring in Chile

N = 1584

Multiply by ?

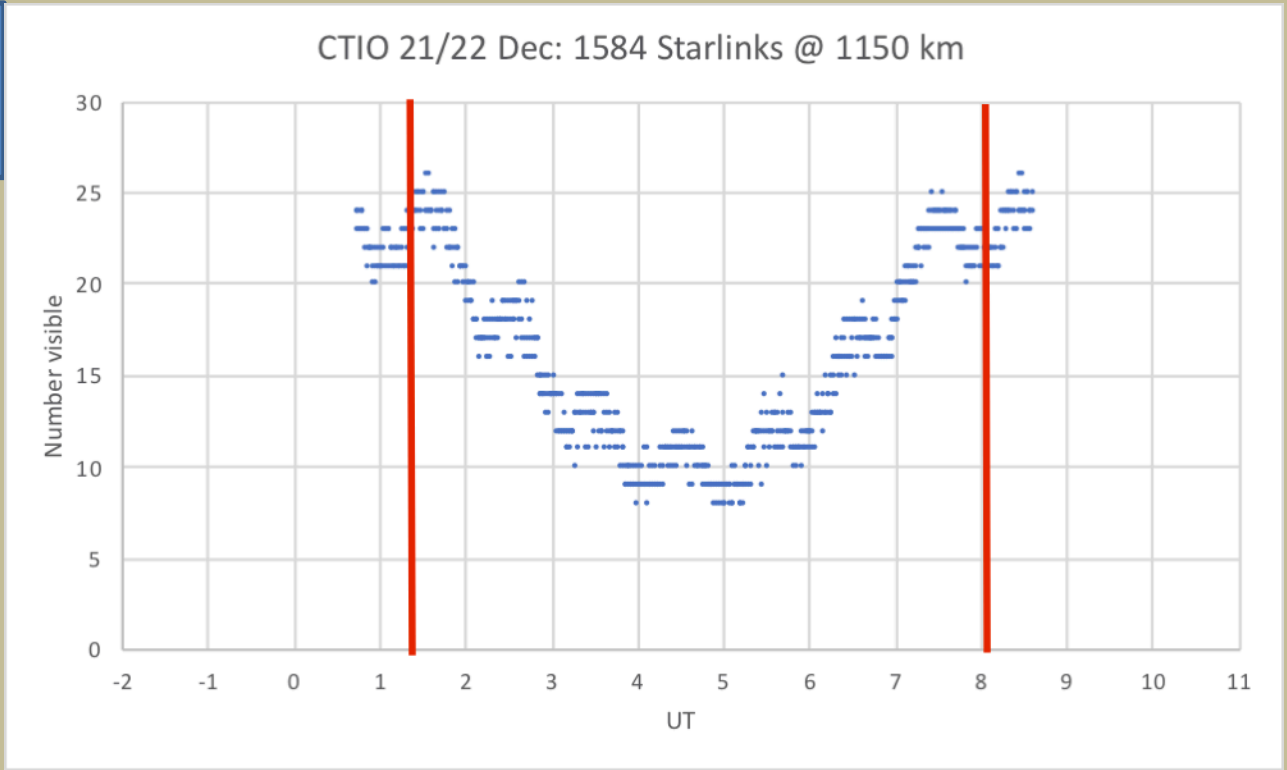


Astronomical twilight: 23:59 – 09:12

Summer in Chile – shortest night of the year

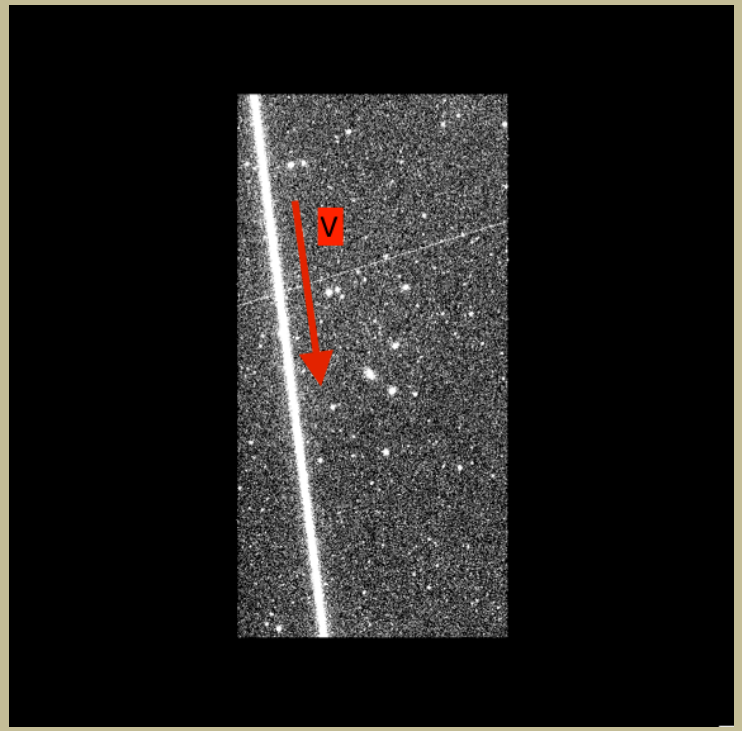
N = 1584

Multiply by ?



Astronomical twilight: 01:20 – 08:01

Streak Brightness



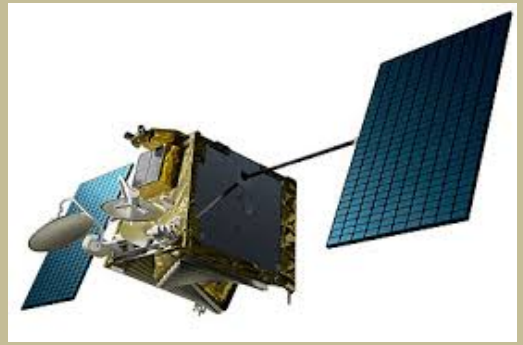
- Also depends on angular velocity v.
- Objects in higher orbits have smaller angular velocity.
- Thus greater time on each pixel.
- For geocentric observer:
  - Tracking object – $I(r) \sim r^{-2}$
  - Streaked object – $I(r) \sim r^{-1.5}$
- Objects at 1200 km – in focus – sharp peak. Not true for objects at 350 km – out of focus for large, fast telescopes. Streak broader, more pixels lost.

Brightness of satellites

Starlink

Complicated problem!

- Altitude (range).
- Attitude (orientation).
- Albedo.
- Size.
- Surface characteristics.
- Specular vs diffuse reflection.
- Self-shadowing.
- Solar phase angle.



OneWeb

- Satellites are not Lambertian spheres!

The Future in LEO – the Big 3

- 1584 Starlinks just the start.
  - SpaceX: 12,000? 42,000? At 550 km, observed V ~ 5th.
    - SpaceX filed with FCC to replace 2,825 satellites @ 1,110-1,325 km with 2,824 satellites @ 540-560 km. *Better for astronomy in many cases.*
  - Amazon: filed for 3,236 at 590, 610, and 630 km.
  - OneWeb: initially ~700, grow to 1980 (at 1177 km). At 1177 km, observed V ~ 8th

- Amazon satellites visible to unaided eye? Depends on design and surface treatment.

- OneWeb at station not visible to eye, still saturate detectors at 1177 km! *What is future of OneWeb project?*
  - 6 satellites at 1177 km altitude.
  - 34 orbit raising to 1177 km.
  - 34 orbit raising and will hold at 600 km.
  - Rest of proposed 1980???

Conclusions

- New satellites brighter than 99% of current objects in orbit.
- Only small fraction of total constellation visible at any one time. *Could be very large number if thousands and thousands launched.*
- Constellation at higher altitude – more satellites visible at any one time. Could be visible all night long.
  - Not as faint as expected from 1/r^2 law due to slower angular motion – Newton's laws!
- Consider full lifetime of a constellation for impact on astronomy – initial, operational, and deorbit.
- Brightness of satellite complicated problem – many factors! Analyze before construction.
- If only one constellation of 1584 satellites launched, astronomers could handle this. But multiply this by 10? 20? 30? 40?