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.

'String of Pearls' – SpaceX Starlinks in the night sky shortly after launch

Thierry Legault

Marco Langbroek

Brighter than V = 3.

Ultimately > 42,000?

Temporary parking orbit.

All night long?

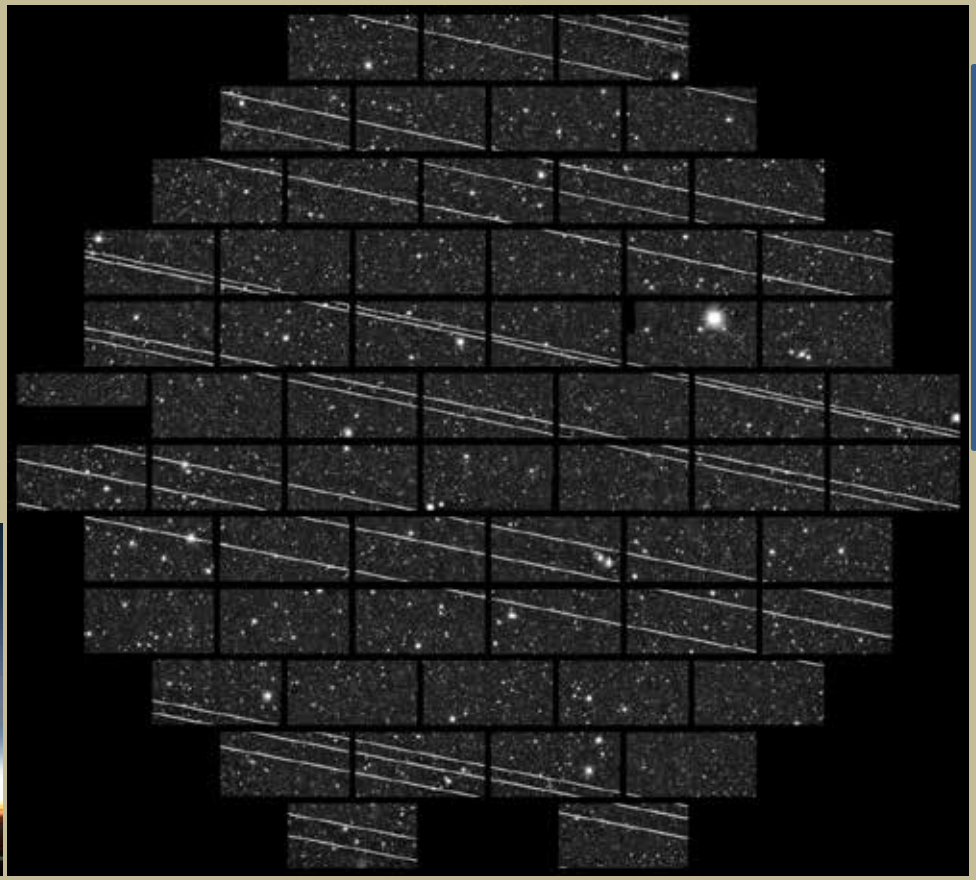
Is this the future of the night sky?

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.

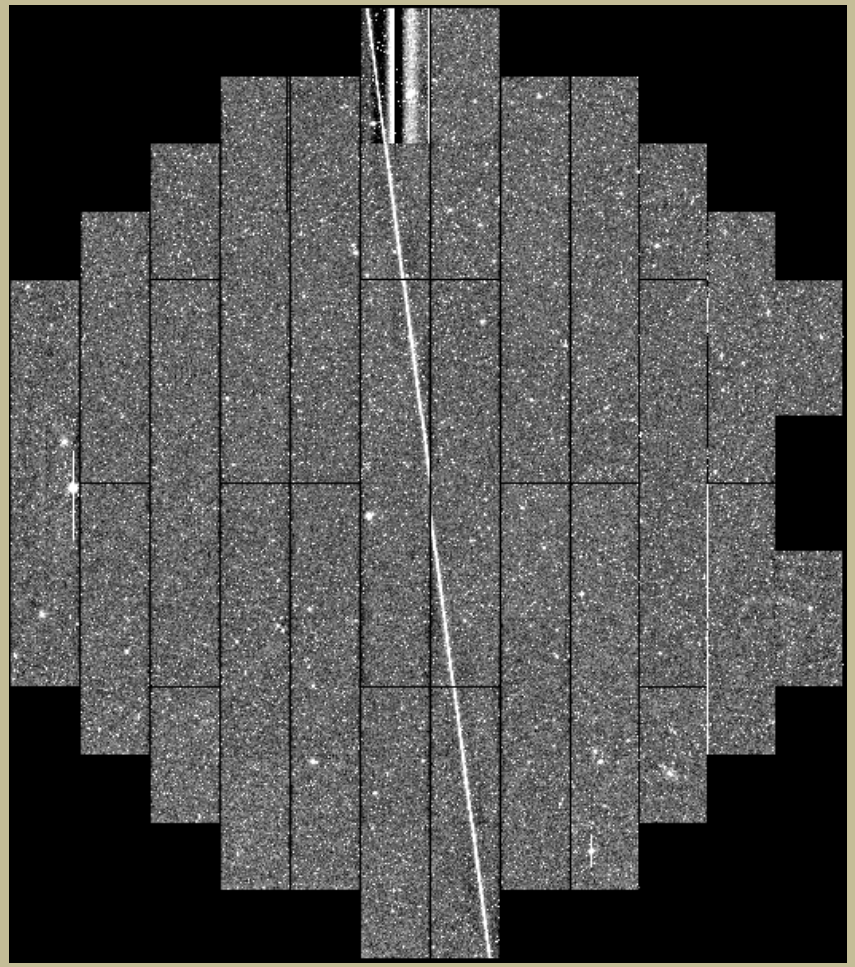
4 x diameter of full moon.

2019-July-16 UT

Blanco 4.0-m DECAM

Cerro Tololo, Chile

2.2 deg FOV



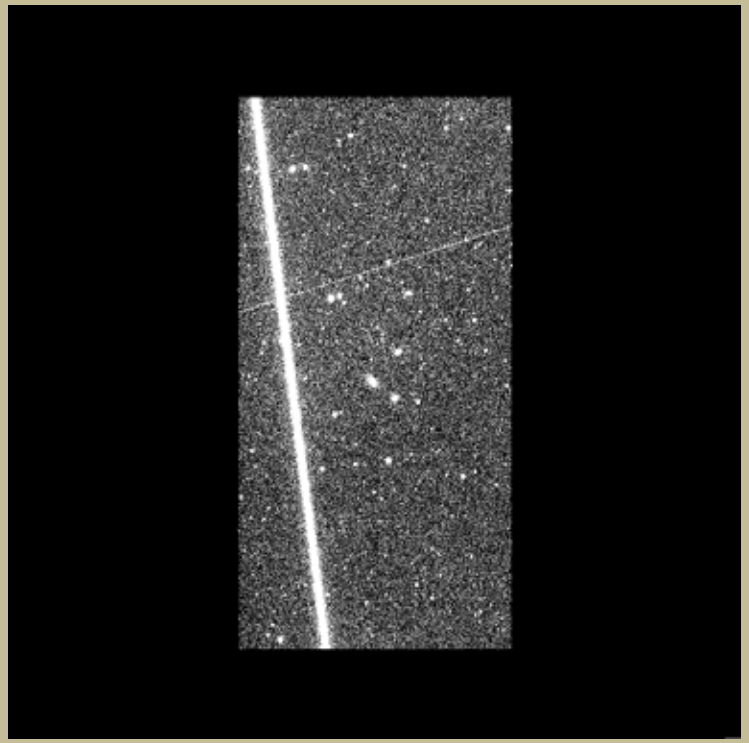
60 sec exposure
r' filter

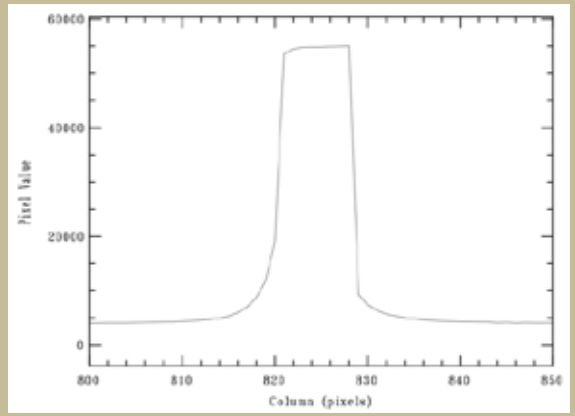
Atlas Centaur 2 R/B

1963-047A 00694

V ~ 4^{th} – 10^{th}

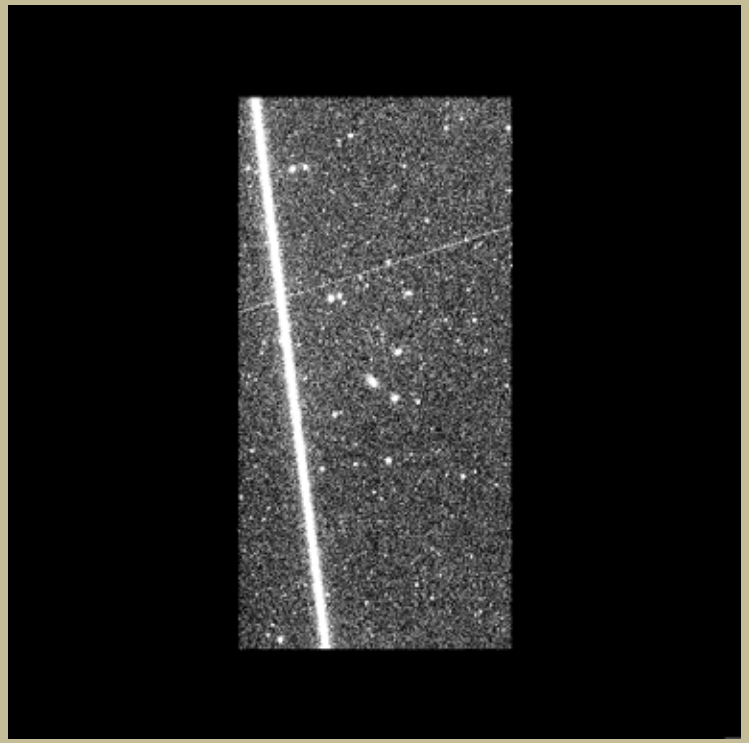
How do bright satellites affect observations on telescopes?
Bright satellite streak saturates detector!





- 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!

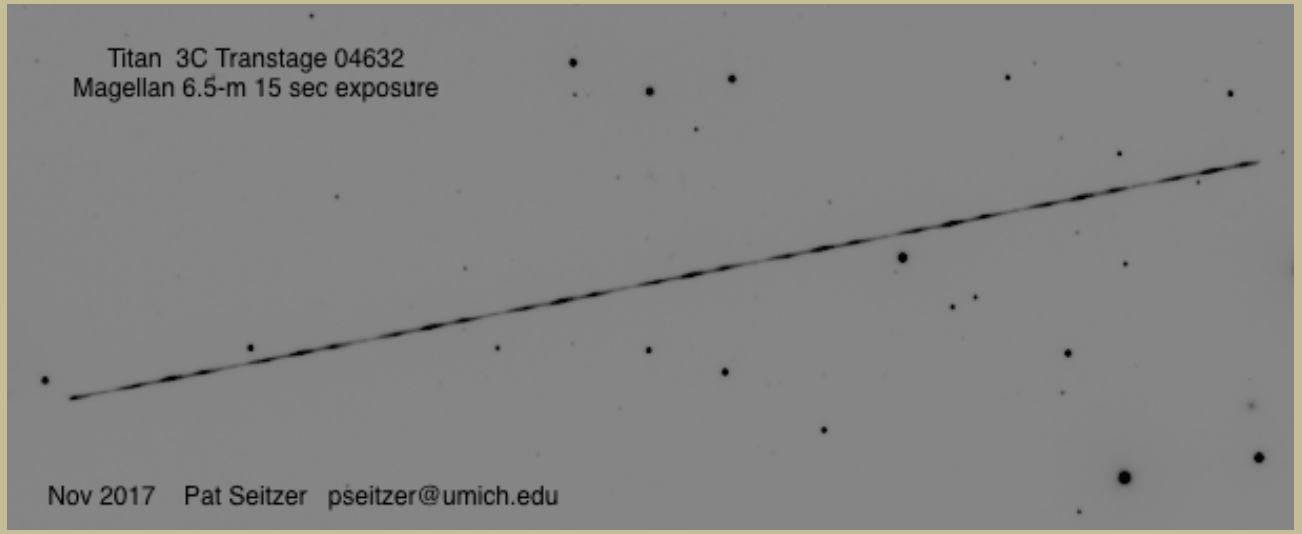


Exposure time for satellite is NOT image exposure time, but time it takes satellite to cross a pixel! This is milliseconds!

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.

Challenge - Satellite Glints --> Transients



Satellite moving wrt star field.

Transient galaxies!

Only very, very short glints could not be distinguished from stars.

Problem with GEO objects?

Topics

- Why large constellations?
- When are satellites visible?
- How many satellites visible today before large constellations?
- Phases of a large constellation lifetime.
- Modelling visibility of SpaceX/Starlink constellation of 1584 satellites in operational phase.
- Conclusions.

Why Large Constellations?

- World-wide Internet access.
  - Internet of Things.
- Low latency –
  - 10's of ms at LEO (Low Earth Orbit)
  - 100's of ms at GEO (Geosynchronous orbit).
  - 40% faster than fiber due to index of refraction difference between air/vacuum and optical fiber.
- Large number of satellites needed at LEO to keep enough above a user at any one time. 1%?

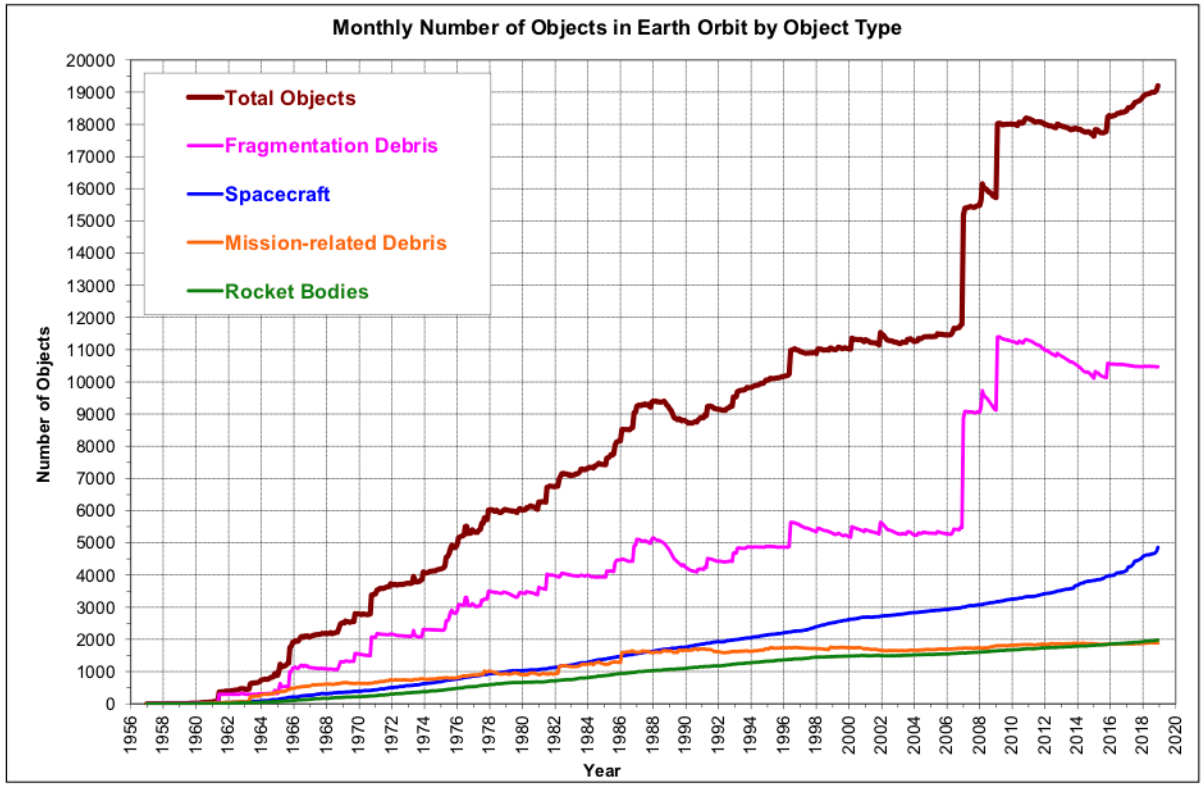
When are satellites visible?

- Observer in darkness:
  - Latitude.
  - Time of year.
- Satellite in sunlight or penumbra – not in Earth shadow:
  - Orbital inclination.
  - Altitude.
  - Time of year.
- Brightness of satellite:
  - Distance between observer and satellite.
  - Angle between Sun-satellite-observer: topocentric solar phase angle.
  - Characteristics of satellite – attitude, specular or diffuse reflection, shape, self-shadowing, …..
  - Satellites are not spherical!

Telescope in Darkness, Satellite in Sunlight

Inside Viasat

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.

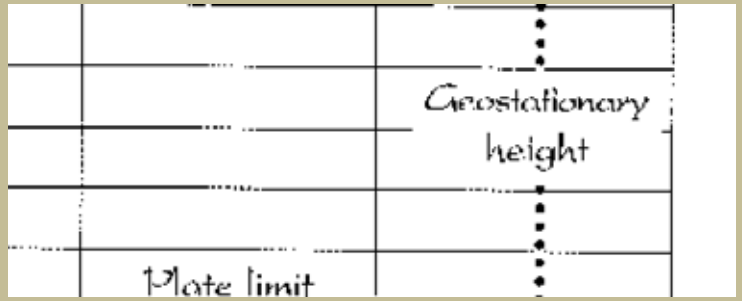
The top curve concerns astronomers and space safety.

Public catalog of objects > 10 cm.

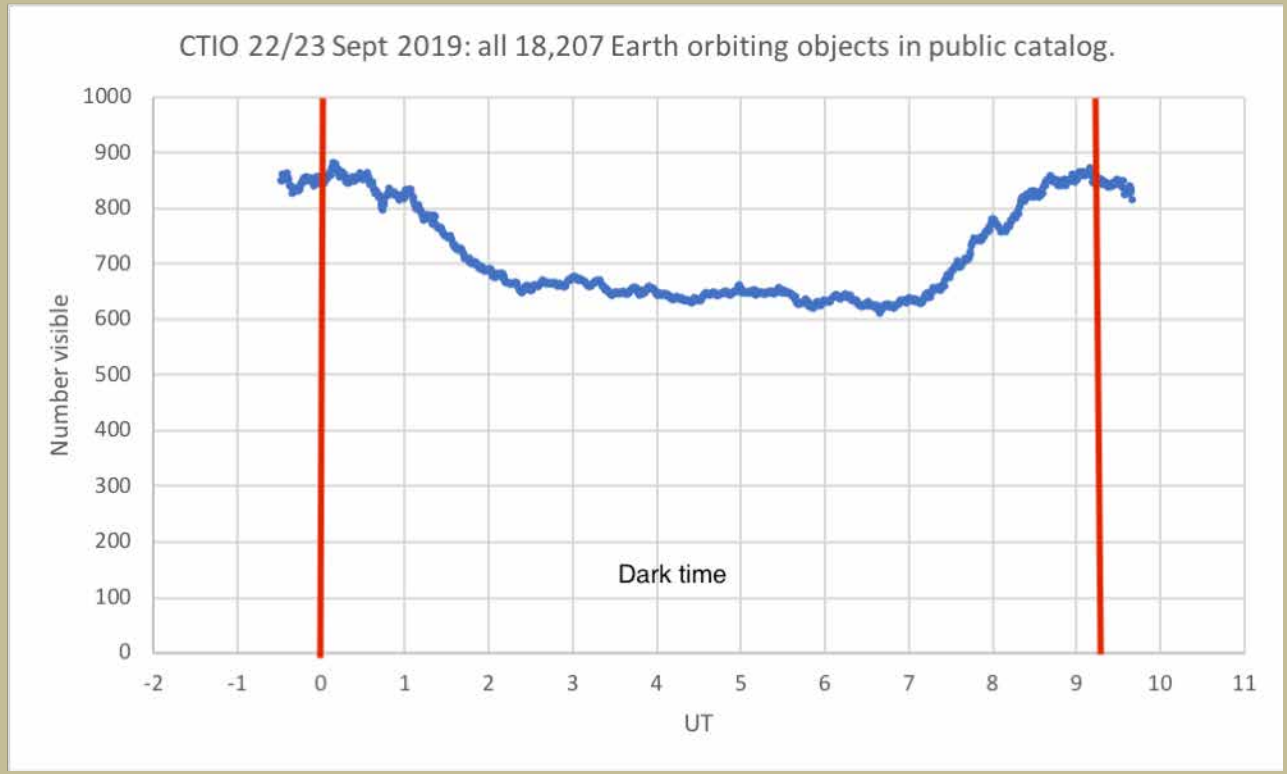
Catalog incomplete.

NASA Orbital Debris Program Office

Satellite Streaks in Photographic Sky Surveys



1992 – ESA Messenger: Fosbury, Turtle, and Black.



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.
   – 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 satellites 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.

Geometric Visibility

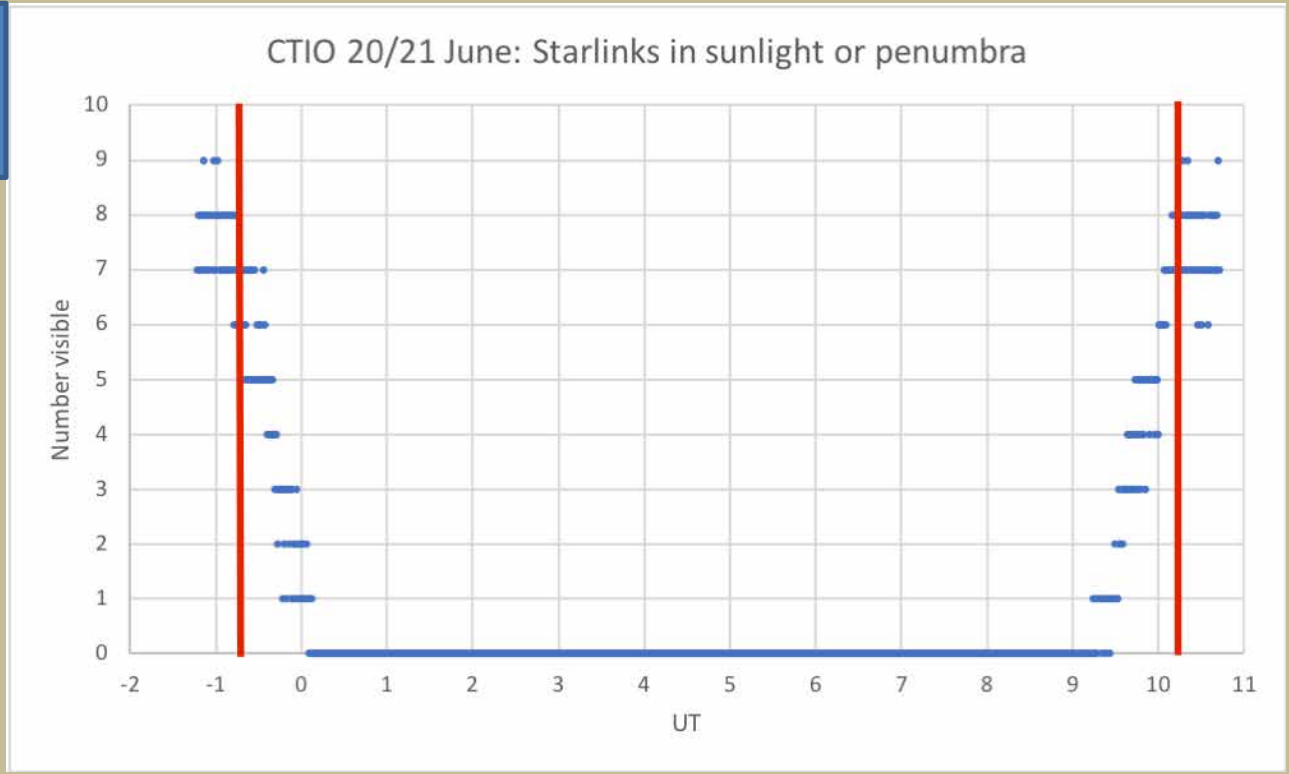
- Geometric Visibility: observer has a line of sight to satellite.
- Assumed full constellation of 1584 in final orbits by June 20, 2019.
- Individual satellite orbits initialized at 1600 UT for each day, then propagated forward for 24 hours.
- Constraints - when visible:
  - Sun 12 deg or more below observer's horizon (nautical twilight).
  - Satellite elevation ≧ 30 degrees. Airmass = 2.0, typical astronomical limit.
  - Satellite is in full sunlight or penumbra.
- Visibility computed for Univ of Michigan Curtis-Schmidt at Cerro Tololo Inter-American Observatory (CTIO) in Chile [LSST just south of this site].
  - Long = -70.80627 latitude = -30.16908 altitude 2216 meters (WGS84).

Simulations of Initial Starlink Constellation

- Three nights for initial analysis of visibility of all 1584 satellites @ 550 km:
  - June 20/21 2019: longest night of the year in Chile.
  - Sept 22/23 2019: equinox.
  - Dec 21/22 2019: shortest night of the year in Chile.
- Plots run from evening nautical twilight (Sun -12 deg) to morning nautical twilight.
- Temporal bin width of 0.01 hours (36 secs) far less than plot resolution. Solid lines are not solid lines, just closely spaced markers.
- At 550 km, Starlinks observed V ~ 5th. DarkSat at 6th.

N = 1584

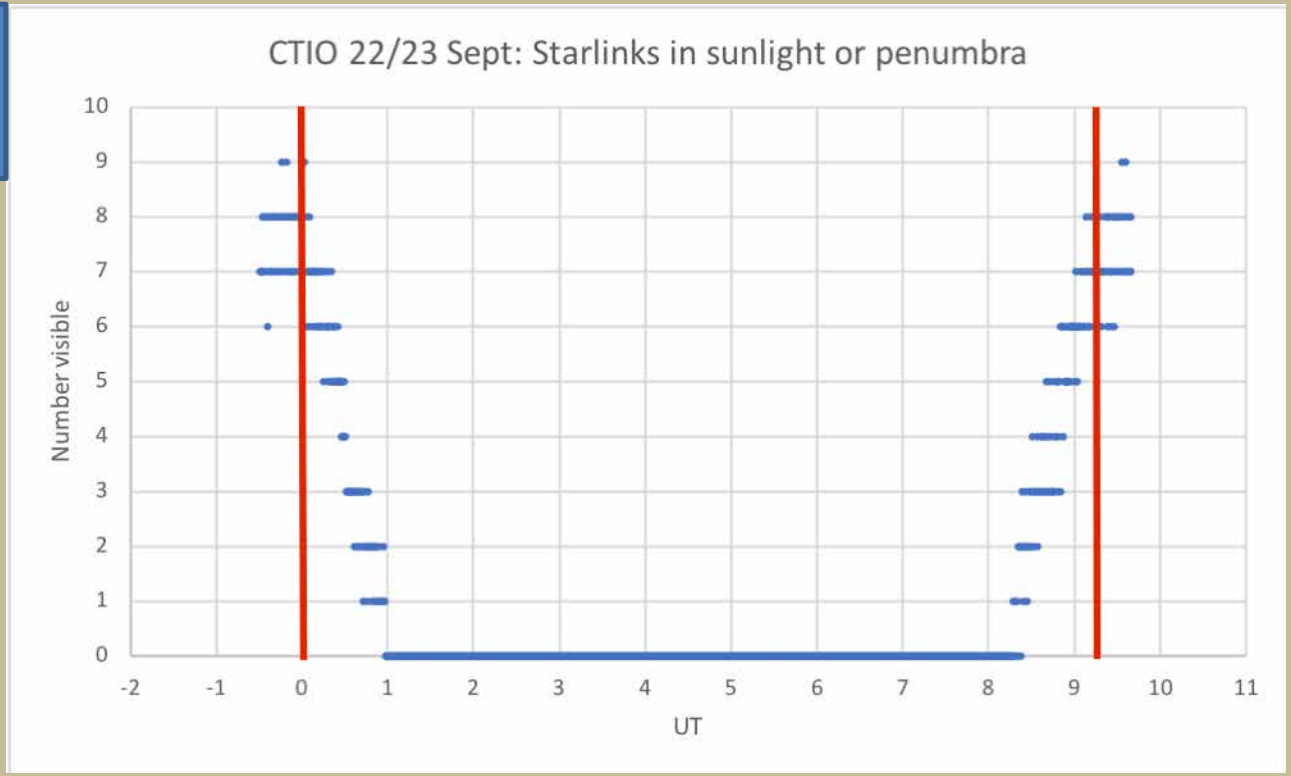
Multiply by ?



Astronomical twilight: 23:16 – 10:13

N = 1584

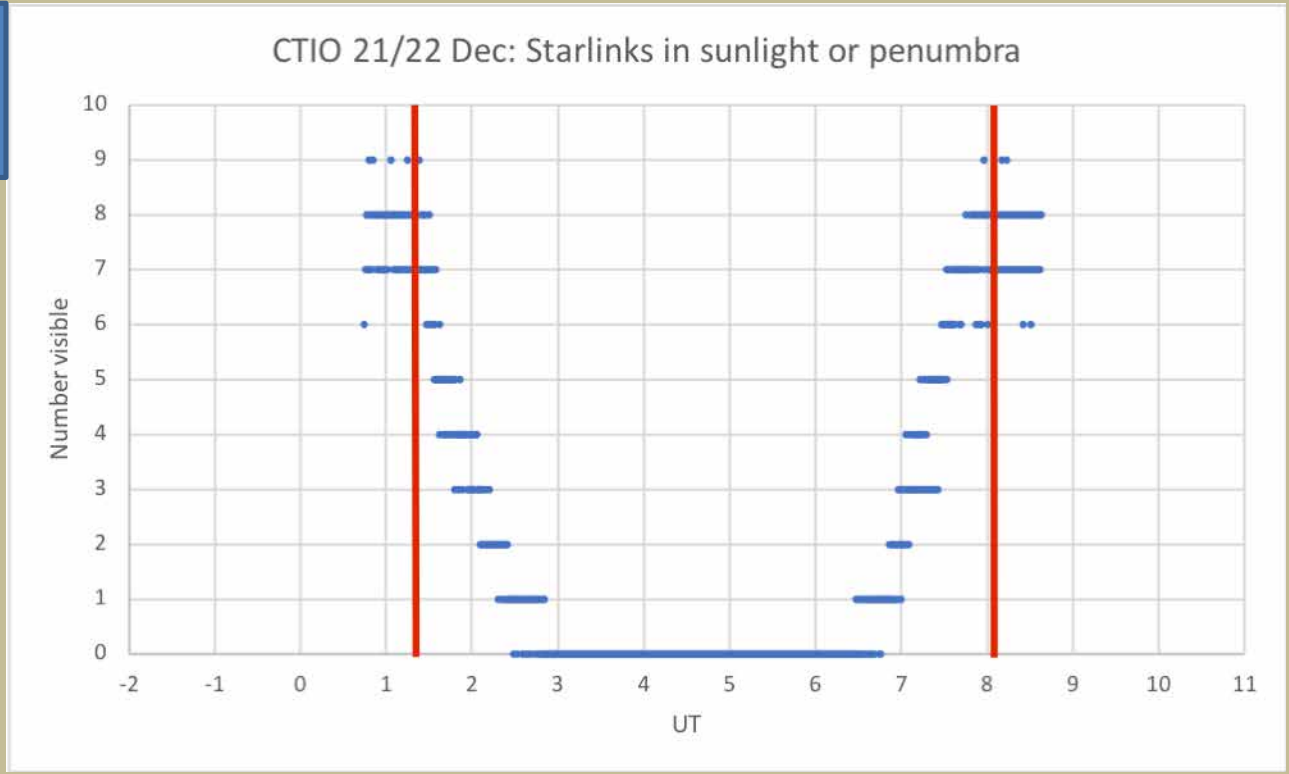
Multiply by ?



Astronomical twilight: 23:59 – 09:12

N = 1584

Multiply by ?



Astronomical twilight: 01:20 – 08:01

Conclusions

- As expected for Low Earth Orbit (LEO) satellites, Starlinks at 550km are visible only at start and end of night.
- Concern: during entire year, there are significant numbers of bright (V ~5th magnitude) Starlinks after start of astronomical twilight in evening and before end of astronomical twilight in morning.
- If initial Starlink constellation of 1584 satellites @ 550 km was the only one to be launched, astronomers could handle this.
- Multiply previous number visible by 10? 20? 30? 40? if all large constellations launched.

What if?

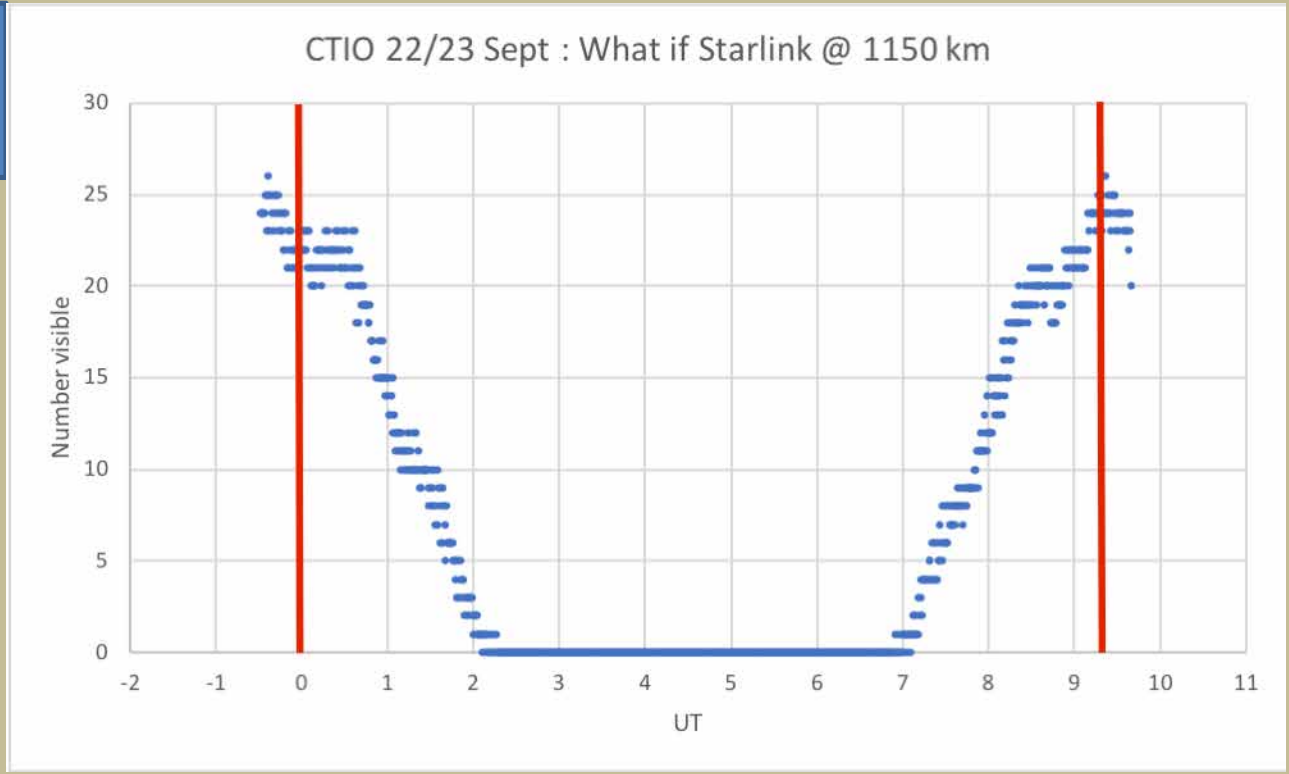
- SpaceX had launched 1584 satellites into original planned orbit of 1150 km.

- 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.
  - Relative streak brightness greater than predicted from distance considerations alone.

N = 1584

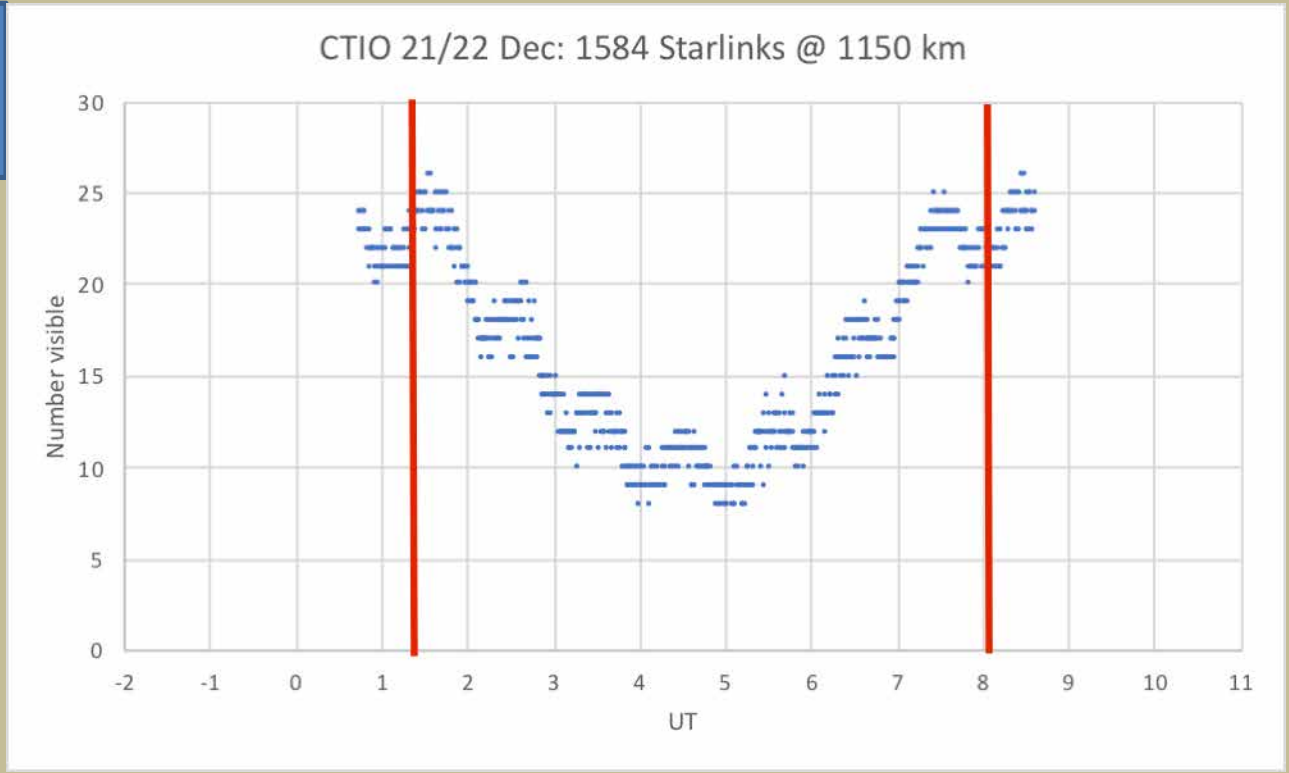
Multiply by ?



Astronomical twilight: 23:59 – 09:12

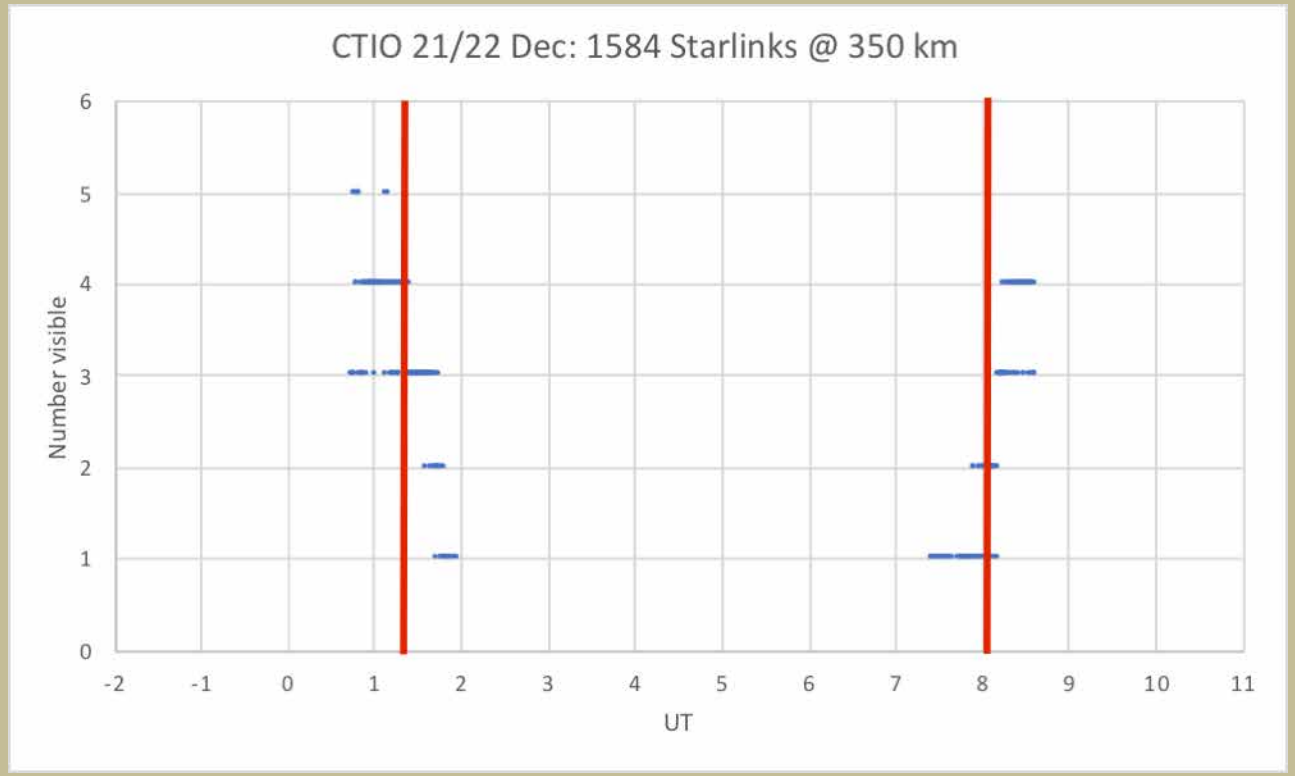
N = 1584

Multiply by ?



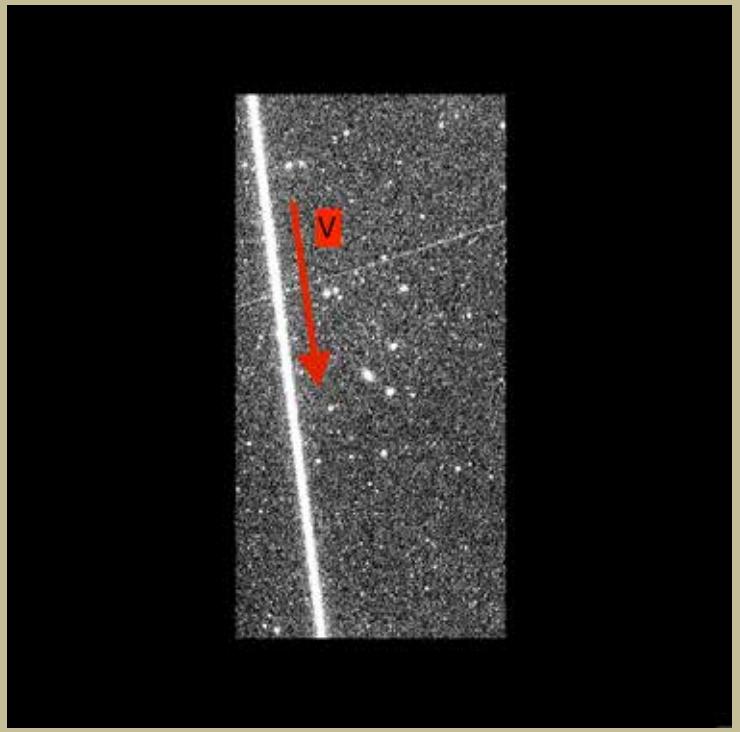
Astronomical twilight: 01:20 – 08:01

Low parking orbit for initial mission phase.



Astronomical twilight: 01:20 – 08:01

Streak Brightness



- Also depends on angular velocity v.
- Objects in higher orbits have smaller angular velocity.
- Also during single pass – angular velocity greatest at zenith.
- Thus greater time on each pixel.
- For geocentric observer:
  - Tracking object – $I(r) \sim r^{-2}$
  - Streaked object – $I(r) \sim r^{-1.5}$

The Future in LEO

- 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.
  - Amazon: filed for 3,236 at 590, 610, and 630 km.
  - OneWeb: initially ~700, grow to 1980 (at 1200 km). At 1200 km, observed V ~ 8th
- Amazon satellites visible to unaided eye? Depends on design and surface treatment.
- OneWeb not visible to eye, still saturate detectors. *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 pending???
  - Rest of proposed 1980???

Conclusions

- Large constellations at LEO are coming and coming fast.
- New satellites brighter than 99% of current objects in orbit.
- Only small fraction of total constellation visible at any one time.
- Constellation at higher altitude – fainter, but more satellites visible at any one time and longer.
- Consider full lifetime of a constellation for impact on astronomy – initial, operational, and deorbit.
- If only one constellation of 1584 satellites launched, astronomers could handle this. But multiply this by 10? 20? 30? 40?
- Largest uncertainty – who launches what, when, and where? Not everyone files with the FCC.