Mega-Constellations of Satellites and Optical Astronomy

Patrick Seitzer
Dept of Astronomy
University of Michigan

American Astronomical Society
Committee on Light Pollution, Radio Interference, and Space Debris

pseitzer@umich.edu
60 Starlink satellites passing over Paris, 31 Dec 2019

Altitude 350 km
Visual magnitude ~ 3
Total duration of passage ~ 10 min

50 km east of Paris
Ultimately 30,000?
All night long?

Courtesy Thierry Legault
333 second exposure
Filter I’
2019-074 launched 2019-Nov-11
19 Starlinks crossing
~4 sec to cross field of view

2019-Nov-18 0800 UT
Blanco 4.0-m DECam
Cerro Tololo, Chile
2.2 deg FOV
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 ~ 4th – 10th
Streak saturates Detector

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

- When are satellites visible?

- How many satellites are visible today?

- Visibility of SpaceX/Starlink constellation of 1584 satellites.
  - When completely operational at 550k km.
  - Immediately after launch and during deployment – *what one sees now, not representative of final steady state*.
  - Deorbit phase at end of mission.

- Other constellations.
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:
  – Angle between Sun-satellite-observer.
  – Characteristics of satellite – attitude, specular or diffuse reflection, …..
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.

• 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.
Geometric Visibility

• Geometric Visibility: observer has a line of sight to satellite.
• Assumed full constellation of 1584 in final orbits by June 20, 2019.
• Constraints:
  – Sun 12 deg or more below observer’s horizon (nautical twilight).
  – Satellite elevation $\geq$ 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).
Any object in Earth orbit that reflects sunlight is of concern.
CTIO 22/23 Sept 2019: all 18,207 Earth orbiting objects in public catalog.

Astronomical twilight: 23:59 – 09:12
New Mega-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 increase.
Results

• Three nights for initial analysis of visibility of all 1584 satellites:
  – June 20/21 2019: longest night of the year in Chile.
  – 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.
N = 1584
Multiply by ?

Astronomical twilight: 23:59 – 09:12
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 ~5\textsuperscript{th} magnitude) Starlinks after start of astronomical twilight in evening and before end of astronomical twilight in morning.

- If initial Starlink constellation of 1584 satellites was the only one to be launched, astronomers could handle this.

- Multiply previous number visible by 10? 20? If all mega-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 is worse.
Astronomical twilight: 23:59 – 09:12
N = 1584
Multiply by ?

CTIO 21/22 Dec: 1584 Starlinks @ 1150 km

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:

- For tracking object – $I(r) \sim r^{-2}$
- For streaked object – $I(r) \sim r^{-1.5}$
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The Future in LEO

• 1584 Starlinks just the start!
  – SpaceX: 12,000? 42,000? At 550 km, \( V \sim 5^{\text{th}} \).
  – Amazon: filed for 3,236 at 590, 610, and 630 km.
  – OneWeb: initially \( \sim 700 \), grow to 1980 (at 1200 km). At 1200 km, \( V \sim 8^{\text{th}} \)

• All SpaceX and Amazon satellites visible to unaided eye? Depends on design and surface treatment.

• OneWeb not visible to eye, still saturate detectors.

• No current national or international rules or guidelines for brightness of satellites.
Satellite Glints --> Transients

Satellites moving wrt star field

Transient galaxies!

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

Problem with GEOs?

Other topics – Thermal IR, occultations, scheduling to avoid satellites, where observe to avoid...
LSST and SpaceX

• The LSST survey is most impacted by bright satellite trails because of its unprecedented wide-deep-fast coverage of the sky 2022-2032.

• Original Starlinks will saturate LSST detectors.

• Joint LSST-SpaceX engineering teams working to change this:
  – Make satellites fainter to avoid LSST detector saturation.
  – Changes to LSST readout to reduce artifacts from trails.
  – Changes to scheduling to avoid most bright satellites.

• We find that SpaceX is committed to solving this problem.

Tony Tyson, LSST Chief Scientist
Conclusions

• Mega-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.

• ‘String of pearls’ probably not a good representation of final operational state.

• Largest uncertainty – who launches what, when, and where?

• You need to be concerned!
Final thoughts on Starlinks

• At operational orbit of 550 km and attitude, 1\textsuperscript{st} generation of Starlinks V ~ 5\textsuperscript{th} magnitude.

• Any sort of effort to reduce brightness should make next generation Starlinks fainter than eye limit.

• ‘Strings of pearls’ at parking/checkout/deployment orbits of 350 km will be increasingly common:
  – Two such strings now visible.
  – More to come.
  – Just visible till astronomical twilight.

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