Defence Research and Development Canada
Recherche et développement pour la défense Canada

Canadian Space-based Photometric Measurements of the Starlink Constellation

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Canada

Megaconstellation observing motivation

- **Megaconstellation-style infrastructures are growing in use:**
  - Starlink: 1383 objects, planning ~12,000
  - OneWeb: 146 objects, planning ~6300
  - Other mission proposals suggest ~100,000 space objects over next 10 years

- **Megaconstellations raised questions for the Space Situational Awareness (SSA), Astronomy community:**
  - What are key considerations when tracking constellation style infrastructure? What are their detection characteristics?
  - What is the impact on the orbital environment, astronomy, by adding thousands of reflective objects?
  - What are the technical implications for future Canadian SSA?

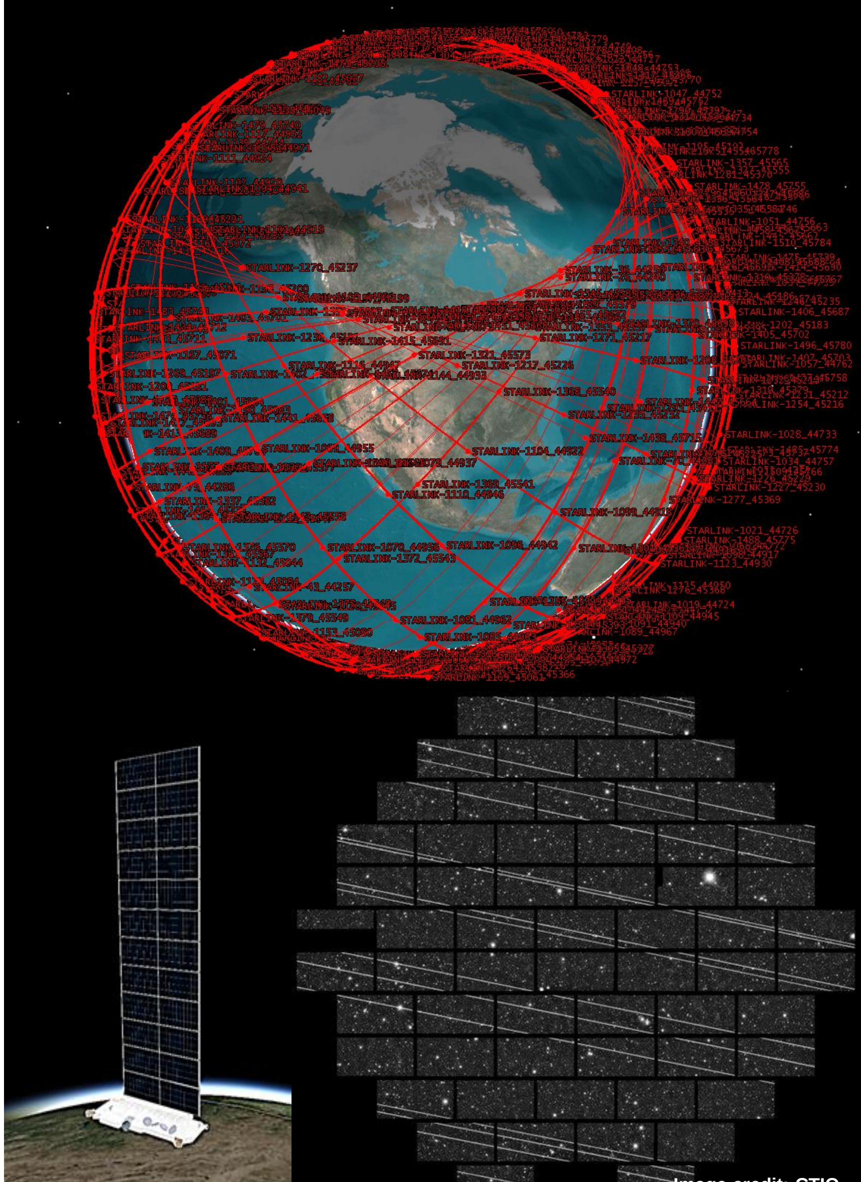


Image credit: CTIO

Megaconstellation observing motivation

- **DRDC began space-based Starlink constellation observing in 2020 using NEOSSat**
  - Objectives:
    - Ascertain issues observing Starlink/megaconstellation objects from space
    - Perform space-based photometric characterization of Starlinks to complement ground-based efforts
      - Adds low phase angle and dayside observing conditions
    - Compare Starlink darkening treatments used on *Darksat*, *Visorsat* with others in the constellation

- **NEOSSat: Canadian dual-mission research microsatellite:**
  - Space Situational Awareness (SSA), Astronomy R&D
  - Launched to 785 km Sun-sync orbit, 25 Feb 2013

- **Payload:**
  - 15cm visible light on-axis Maksutov telescope (E2V 4720 CCD)
    - 0.8° x 0.8° field of view, Open filter (400-1000 nm)
    - Chamfered baffle to track within 45° of the Sun

- **SSA Mission:**
  - Originally designed for geosynchronous object tracking
    - Collects angles-only position measurements, photometry
  - **Added LEO observations after attitude system changes (2016)**
    - Nodal crossing observations (used in this study)
    - Conjunction observations

NEOSSat during mass properties testing - 2012

LEO observing geometry during nodal crossings

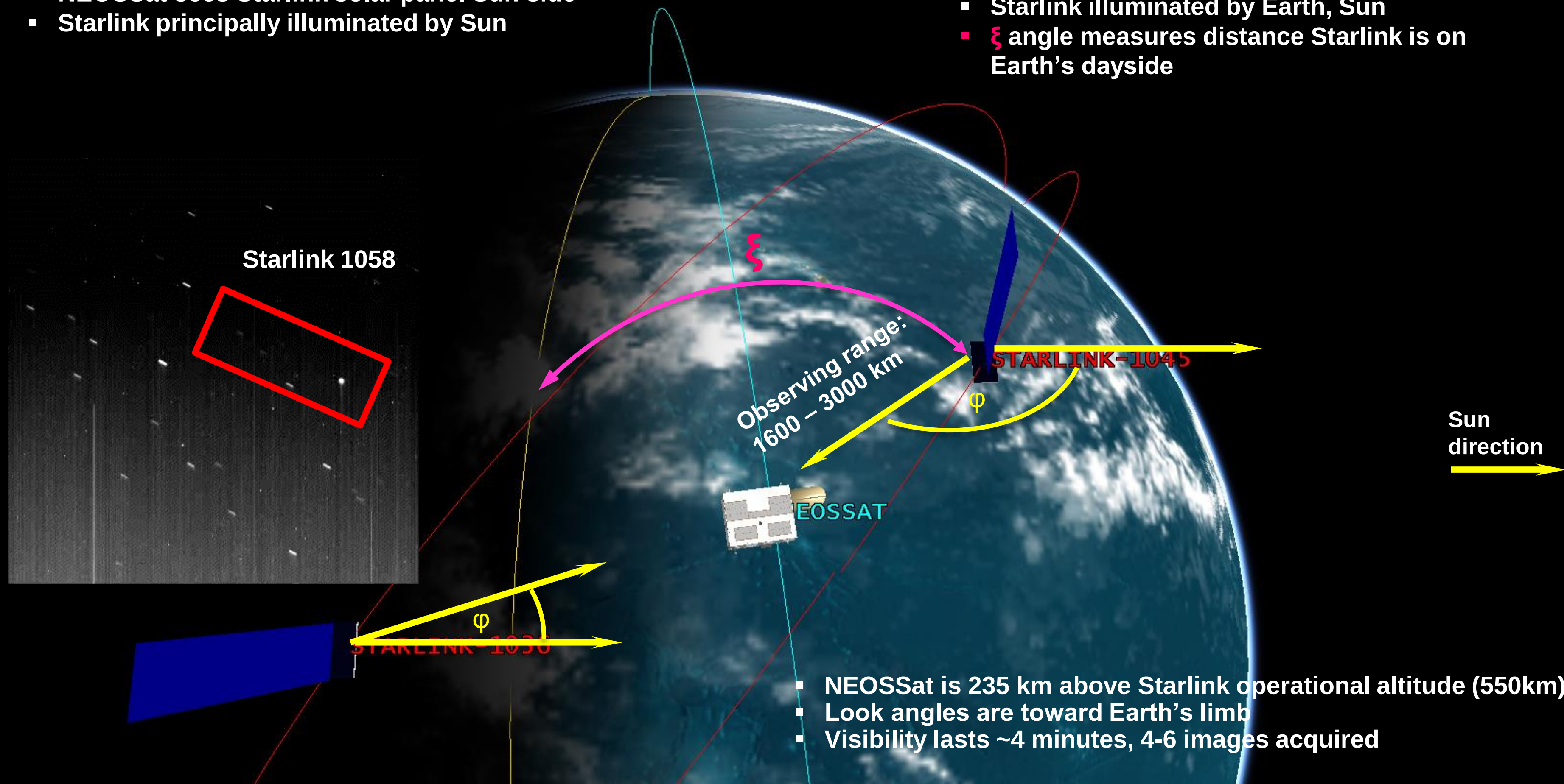
Earth's Nightside

- Phase angle **φ** is small
- NEOSSat sees Starlink solar panel Sun side
- Starlink principally illuminated by Sun

Earth's Terminator

Earth's Dayside

- Phase angle **φ** is large
- NEOSSat sees Starlink solar array backside
- Starlink illuminated by Earth, Sun
- ξ angle measures distance Starlink is on Earth's dayside



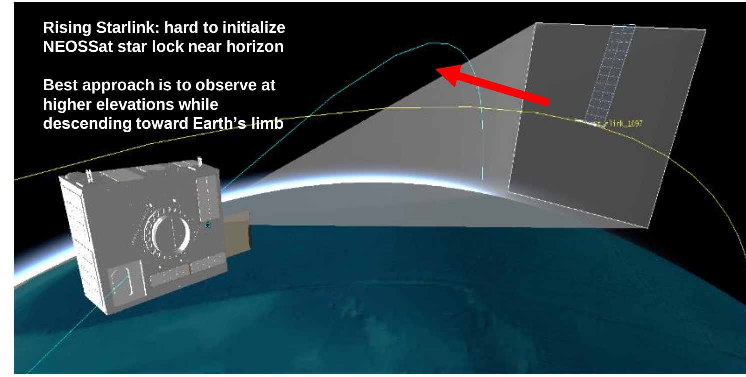
- NEOSSat is 235 km above Starlink operational altitude (550km)
- Look angles are toward Earth's limb
- Visibility lasts ~4 minutes, 4-6 images acquired

Ephemeris issues pertaining to tracking Starlink from space

- **Initially low success rate due to:**
  - **Earth limb interrupting NEOSSat's star tracker**
  - Causes NEOSSat star tracker struggle to lock onto stars
  - Especially problematic when imaging "rising satellites near the dayside Earth limb" (see example right)
  - Mitigated by observing "setting" Starlinks relative to NEOSSat
  - **When Star Tracker functioning - Starlinks frequently not in frame due to Two-line element (TLE) orbit quality**
    - **30% failure rate**
    - Observing Starlink during orbit raising phase (60-120 days) where electric propulsion is used were routinely unsuccessful.
      - NEOSSat photometric observations focused on Starlinks at their operational altitude (550 km)

- **When observing Starlink at on-station altitude:**
  - Supplemental Starlink TLEs derived from operator ephemeris (via Celestrak.com) **more trustworthy for pointing NEOSSat's imager as orbit quality is given (RMS values)**

- **Constellation operator ephemeris and derived products were necessary for tracking efficacy**



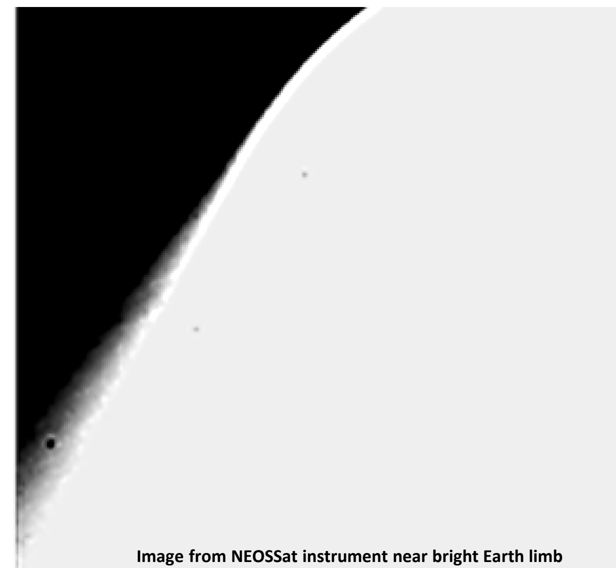
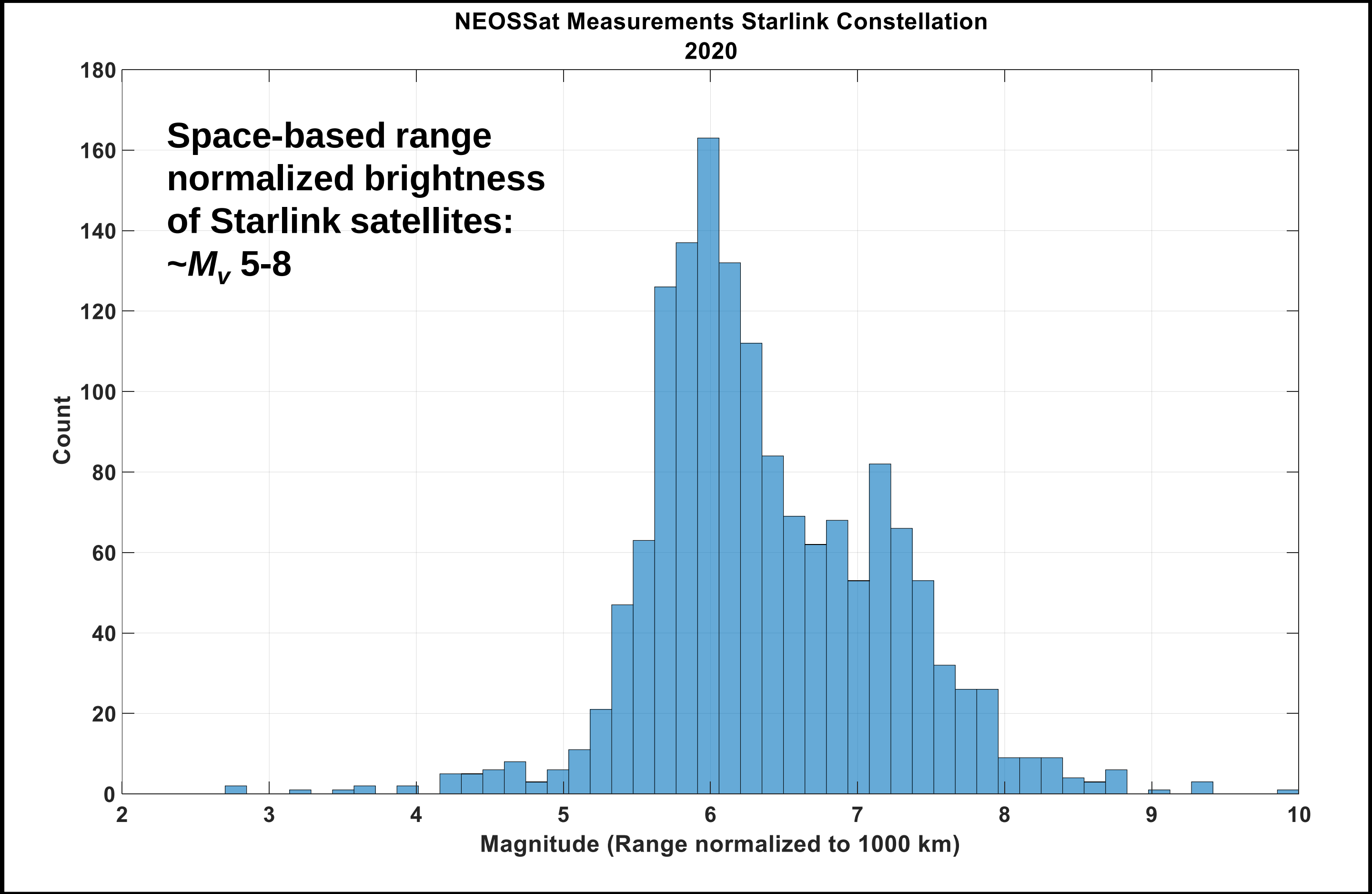


Image from NEOSSat instrument near bright Earth limb

Starlink use of constant thrust routinely problematic for space-based observation

Observing Starlink from above,
247 unique Starlink satellites, 1519 observations)



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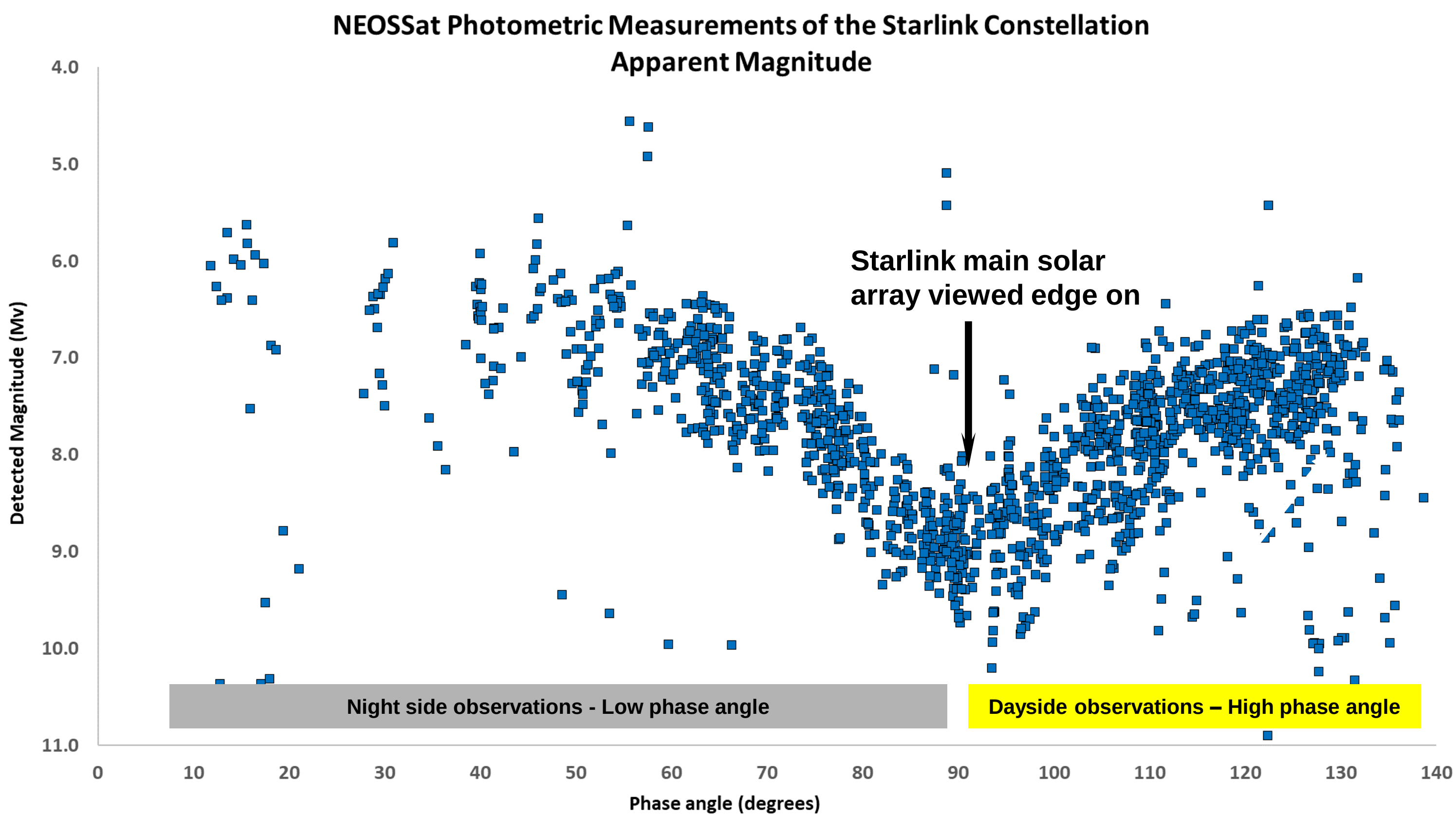
Photometry of Starlink (apparent)

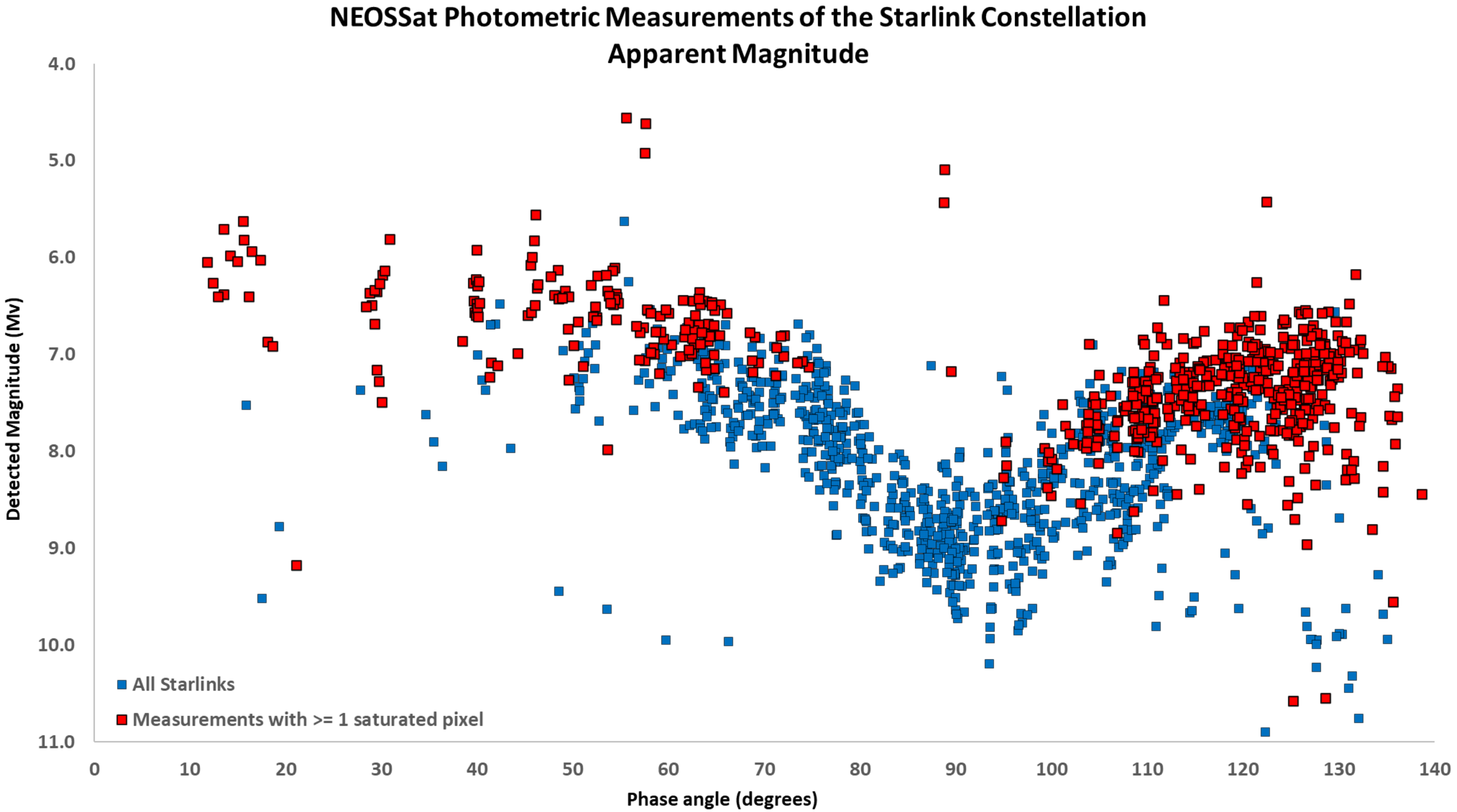
- 1494 successful images
- 247 unique Starlink Satellites
- 32 measurements of Starlink-1130 (“Darksat”)
- 21 measurements of Starlink-1436 (“Visorsat”)



Photometry of Starlink (saturated)

- 883 (611) images
- 247 unique Starlink Satellites
- 25 (7) measurements of Starlink-1130 ("Darksat")
- 6 (15) measurements of Starlink-1436 ("Visorsat")

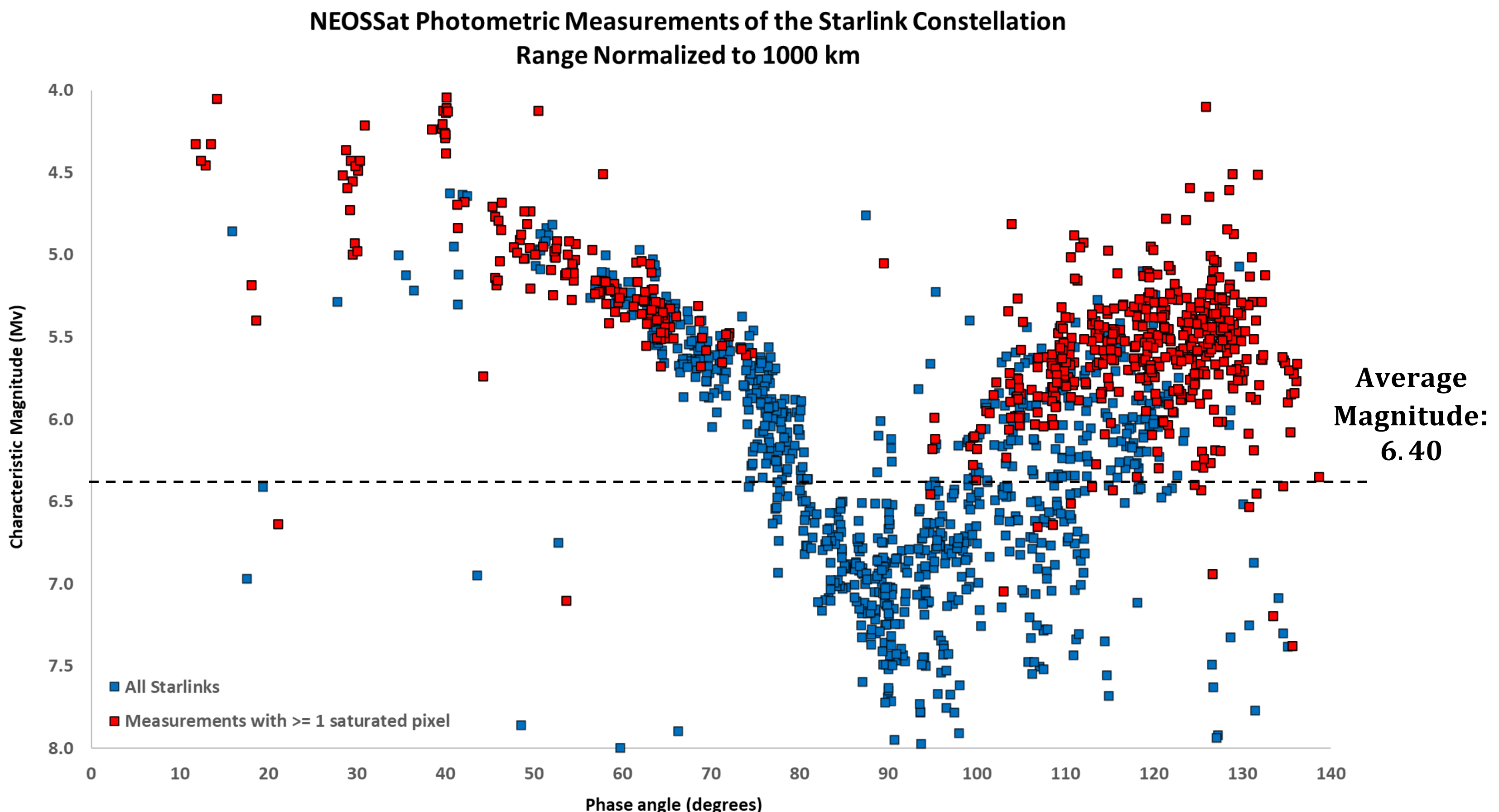
*Images with at least 1 saturated pixel not included in data analysis



Saturated pixels found during NEOSSat imaging (0.4 second exposures)

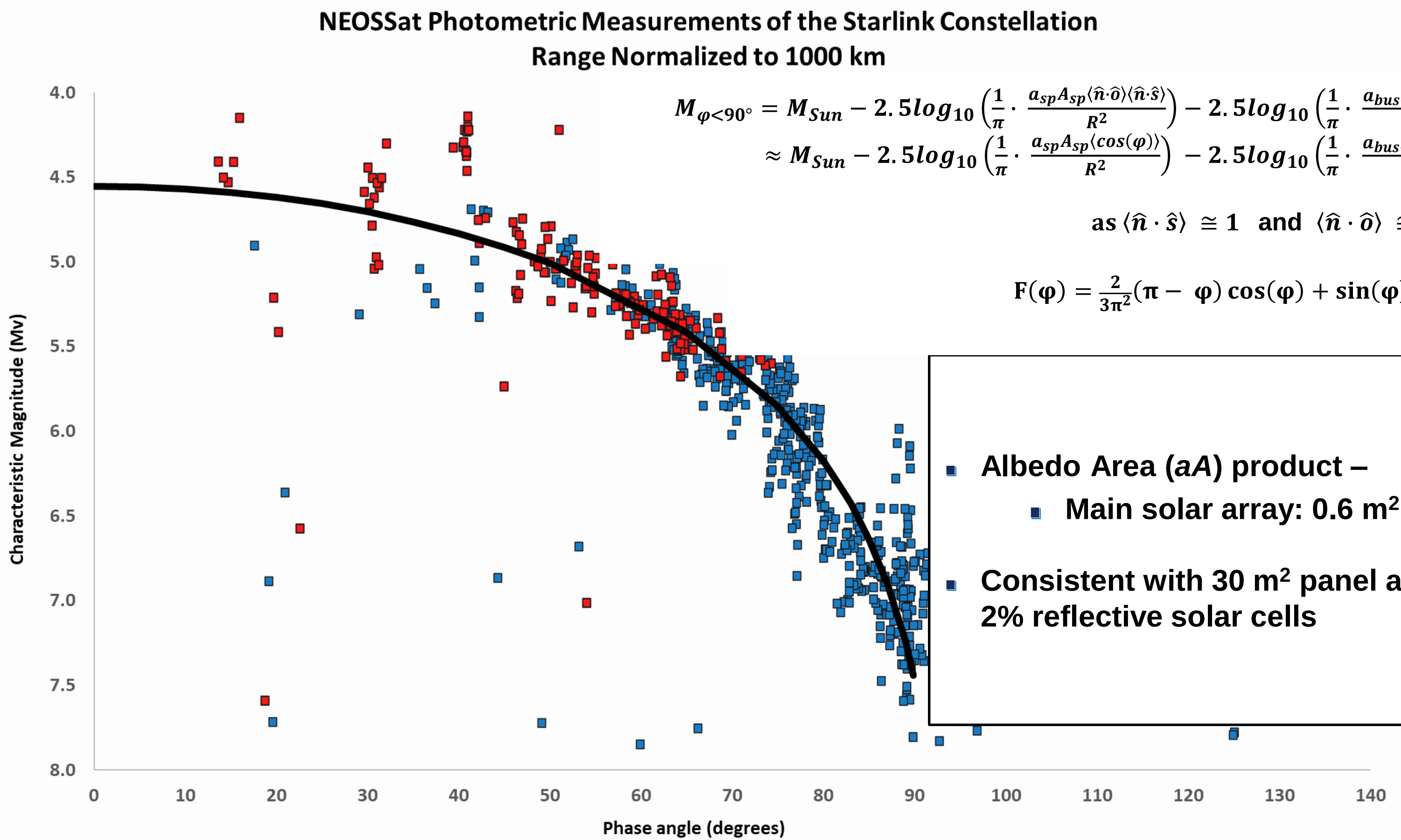
Photometry of Starlink (Range normalized)

$$M_{norm} = M_{detected} - 5log_{10}(R/R_0)$$



Observations range normalized to 1000 km to standardize comparison between different constellations
Clear differentiation between nightside and dayside brightness behaviour

Antisolar (Nightside) Model



$$M_{\varphi<90^\circ} = M_{Sun} - 2.5log_{10}\left(\frac{1}{\pi}\cdot\frac{a_{sp}A_{sp}\langle\hat{n}\cdot\hat{o}\rangle\langle\hat{n}\cdot\hat{s}\rangle}{R^2}\right) - 2.5log_{10}\left(\frac{1}{\pi}\cdot\frac{a_{bus}A_{bus}F(\varphi)}{R^2}\right)$$

$$\approx M_{Sun} - 2.5log_{10}\left(\frac{1}{\pi}\cdot\frac{a_{sp}A_{sp}\langle cos(\varphi)\rangle}{R^2}\right) - 2.5log_{10}\left(\frac{1}{\pi}\cdot\frac{a_{bus}A_{bus}F(\varphi)}{R^2}\right)$$

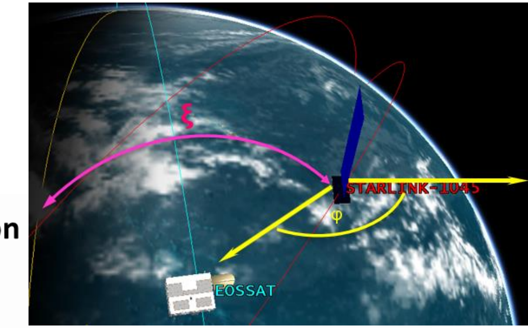
as $\langle\hat{n}\cdot\hat{s}\rangle \cong 1$ and $\langle\hat{n}\cdot\hat{o}\rangle \cong \cos(\varphi)$

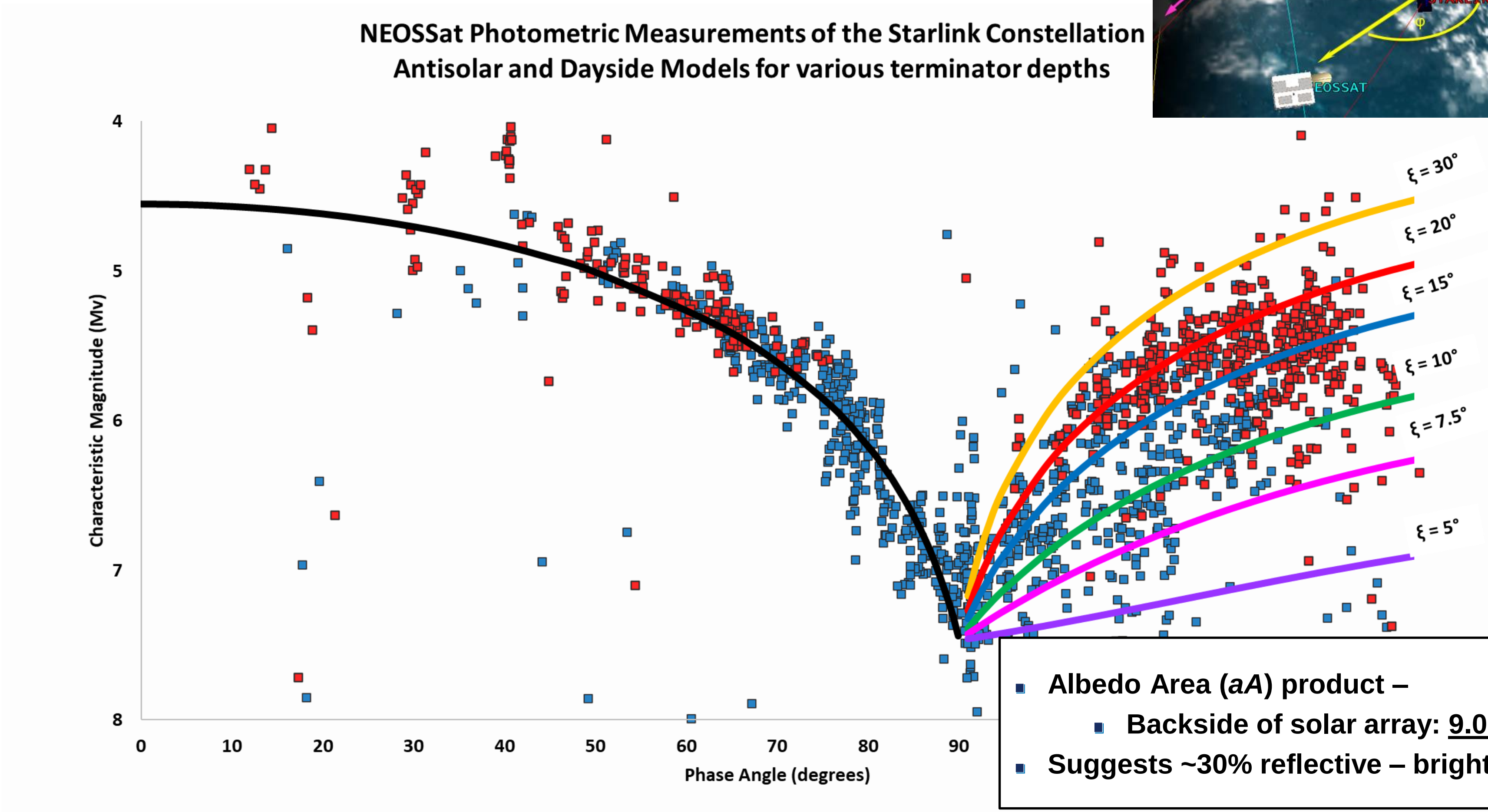
$$F(\varphi) = \frac{2}{3\pi^2}(\pi - \varphi)\cos(\varphi) + \sin(\varphi)$$

- Albedo Area (*aA*) product –
  - Main solar array: 0.6 m^2
- Consistent with 30 m^2 panel area with 2% reflective solar cells

Nightside observations suggest Starlink main solar array is Sun-pointing, and well modelled as a flat plate

Nightside + Dayside Model

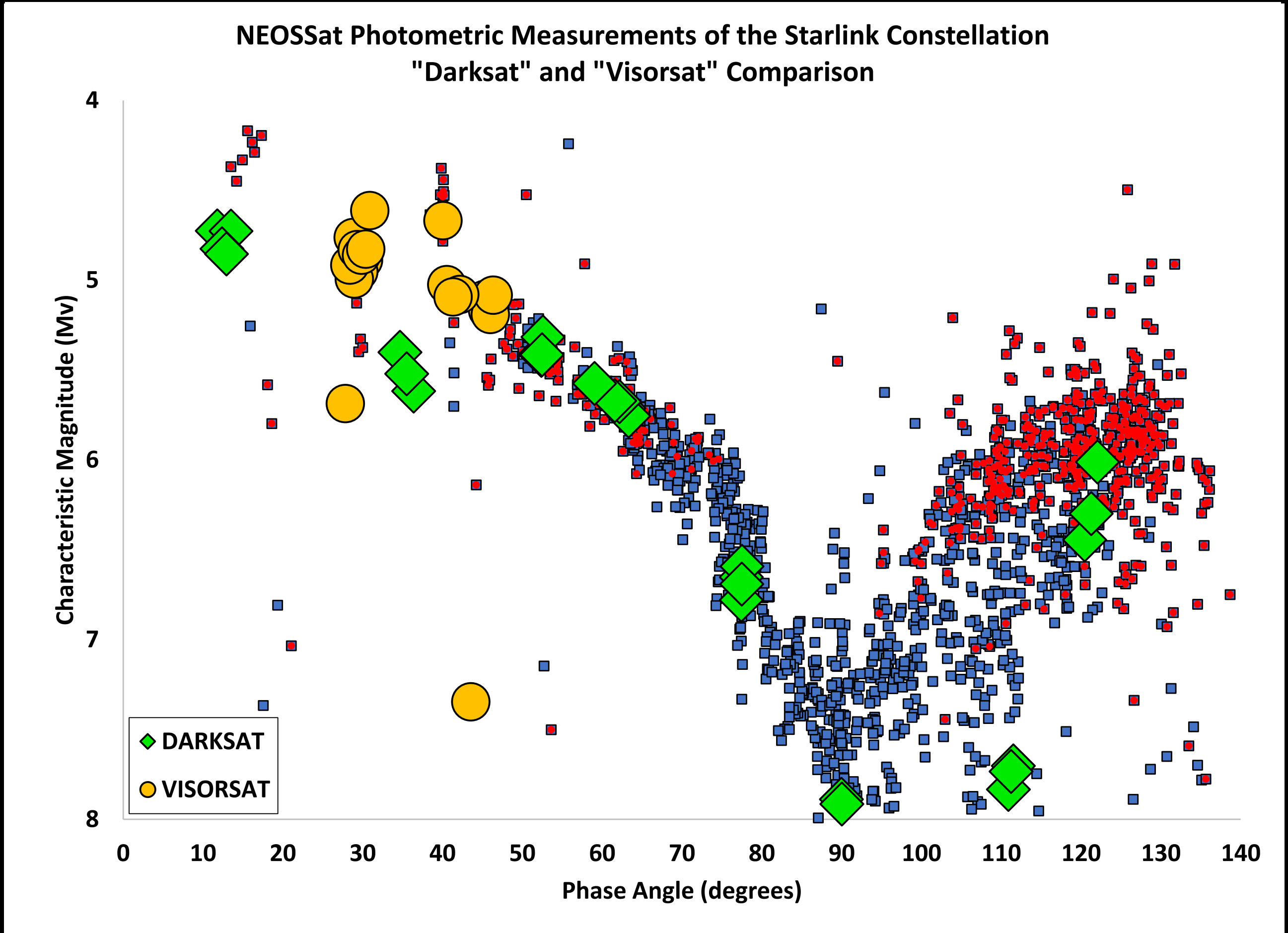




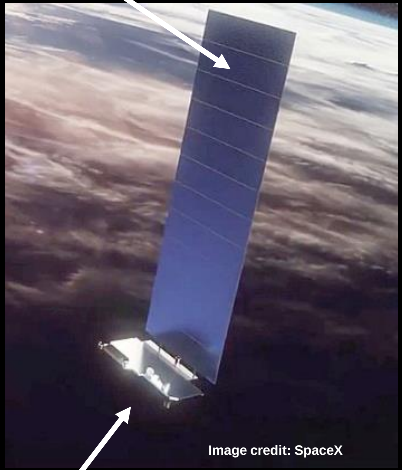
- Albedo Area (*aA*) product –
  - Backside of solar array: <u>9.0 m^2</u>
- Suggests ~30% reflective – bright!

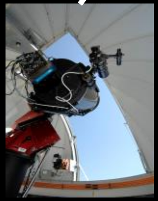
Distance that Starlink is over Earth's dayside determines brightness as observed from space

Darksat and Visorsat comparison with other satellites in constellation



NEOSSat sees Starlink solar array from above





Ground based observer sees nadir bus face from below

Treatments apply to this portion, so behaviour is foreseeable

Starlink 'Darksat' and 'Visorsat' darkening treatments have no noticeable impact when viewed from orbit

Key Findings on Starlink

- **Electric thrust systems makes tracking Starlink challenging from orbit:**
  - 70% success rate when observing
  - Orbit raising phase particularly problematic to collect observations
- **Photometric measurements**
  - Starlink exhibits ***V*-shaped** light curve over phase angle (range normalized)
  - High variability over dayside explained by Earth illumination and albedo
  - Starlink averages M_v 6.4 (range normalized)
  - Starlink solar panel albedo area product (*aA*)
    - Sun-facing side: 0.6 m^2
    - **Back side: 9.0 m^2**
      - **Suggests 30% reflective backside of panel**
- **Darksat and Visorsat brightness mimics other satellites in Starlink constellation**
  - No notable brightness difference compared to other Starlinks in constellation when viewed from orbit
  - \- Anticipated as treatments focus on Starlink's Earth (nadir)-facing sides

Recommendations

- **Constellation operator ephemeris is key**
  - NEOSSat experience suggests Starlink TLEs in error by >14-42 km (depending on range)
  - Operator ephemeris or derived orbit products recommended for future research. **Operator participation strongly aids in the tracking of constellation space objects**
  - Conjunction derisk with other satellite operators will benefit if orbital ephemeris data is made available

Current/Future Work

- **NEOSSat continuing observations on other constellations**
  - Acquiring measurements on polar Starlinks, OneWeb, Planetlabs, Kepler and Swarm to compare their photometric characteristics
  - Results to be presented at AMOS 2021

References

- **Johnson, C., Scott, R.L, Thorsteinson, S.E., "Space-based Photometric Observations of the SpaceX Starlink Constellation Satellites – Preliminary Findings", ASTRO 2020 Virtual Conference, 12 Nov 2020 https://casi.ca/resources/Documents/ASTRO/2020/NEOSSat_Observations_Starlink-CASI_Astro_2020.pdf**

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