Plaskett 1.8 m Observations of Starlink Satellites

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Abstract

We present observations of 23 Starlink satellites in the \textit{g'} bandpass, obtained from the Dominion Astrophysical Observatory’s Plaskett 1.8 m telescope. The targets include a mixture of satellites with and without brightness mitigation measures (i.e., visors). At the time of the observations (2021 July 16), Starlink satellites were sunlit throughout the night, and, even with strict elevation and azimuth limits, there were over 800 candidate Starlink arcs. The satellites altogether have a median range corrected brightness (550 km) of $H_{550}^{0} = 5.3$ mag. Dividing the targets into those without and with visors, their median range corrected magnitudes are $H_{550}^{0}$ (no visor) = 5.1 and $H_{550}^{0}$ (visor) = 5.7 mag, respectively. While the visor sample is dimmer in aggregate, the range corrected brightness distribution ranged from $H_{550}^{0}$ = 4.3 mag to 9.4 mag. The two brightest satellites have similar $H_{550}^{0}$ to within the uncertainty, but one is visored and the other nonvisored. The dimmest satellite we observed is one without mitigations. The intrinsic brightness dispersion among the full sample is $\sigma_{g} = 0.5$ mag.

Unified Astronomy Thesaurus concepts: Artificial satellites (68); Astronomical site protection (94)

1. Introduction

Large constellations of satellites will have a substantial impact on astronomy, particularly wide-field surveys, should they be deployed in their proposed numbers (e.g., Hainaut & Williams 2020; McDowell 2020). These so-called “megaconstellations” or “satcons” seek to place tens of thousands of communications satellites into low-Earth orbit (LEO), with Starlink (FCC 2016, 2017, 2020a, 2020b), OneWeb (FCC 2021), Amazon/Kuiper (FCC 2019), and GW/StarNet (Press 2021) proposing 65,000 satellites alone (see also Lawler et al. 2021). These numbers are continuously being amended, and while not all of the proposed satellites are expected to be deployed, other operators are entering the market. It is thus plausible to conceive that LEO will have hundreds of thousands of satellites in orbit in the coming decade should no restrictions be put into place. To emphasize this, we point to the ITU’s Advanced Publication Information (API), in which the constellations CINNAMON-217 and CINNAMON-937 have been filed with a combined number of 379,400 satellite slots, and the the constellation AEther (Kepler Communications) filed with over 114,000 slots. Again, such filings do not by themselves mean that the proposed systems will come to fruition. Indeed, the intended constellations might be only a fraction of that proposed; but, the filings emphasize that the concern voiced by astronomers (e.g., Venkatesan et al. 2020) of having over 100,000 satellites on orbit should be taken seriously.

There are ongoing efforts by astronomers to address the potential for NewSpace satellite light pollution to interfere with astronomy, including engaging in dialog with satcon operators, such as that described in the recent SATCON2 (Green et al. 2021; Hall et al. 2021; McDowell et al. 2021; Rawls et al. 2021; Venkatesan et al. 2021) and Dark and Quiet Skies II Working Groups (2022b) reports. Such dialog seeks to provide opportunities for exchanges of views and to establish a basis for cooperation, with identifying voluntary mitigation efforts for the short term and defining feasible and effective regulations or guidelines for the protection of the night sky in the long term. As part of this effort, it is incumbent upon astronomers to routinely measure satellites for the purpose of providing independent brightness assessments in astronomical observing bands and to verify mitigation practices.

Several groups have reported on LEO satellite magnitudes under various conditions (Horiuchi et al. 2020; Tyson et al. 2020; Tregloan-Reed et al. 2020, 2021; Mallama 2021a). This includes efforts to focus on specific satellites to assess mitigation attempts, such as “DarkSat” and “Visorsats”, representing albedo and reflection modifications, respectively.

We contribute to this effort by observing 23 Starlink satellites using the Plaskett 1.8 m telescope at the Dominion Astrophysical Observatory (48° 31’ 11” N, 123° 25’ 1” W, and 244 m altitude). The sample includes a mixture of unmitigated Starlinks and visored Starlinks, which we analyze together and separately.

2. Target Selection and Observing Method

The two-line elements for all Starlink satellites were obtained from Celestrak\textsuperscript{7} on 2021 July 15 UTC. Each element was then run through the JPL Horizons ephemeris service\textsuperscript{8}.

\textsuperscript{7} See https://www.celestrak.com/
\textsuperscript{8} See ssd.jpl.nasa.gov/horizons.cgi

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using an API to determine the observing opportunities on July 16, 2021 UTC. An initial selection was made for Starlink satellites that (1) were visible from DAO during the observing night, including astronomical twilight, (2) reached a maximum elevation that was greater than 45°, and (3) reached their maximum elevation in the southern sky, with the latter being mainly a telescope slewing consideration. This resulted in over 800 observing opportunities during the approximately three hours of useful night.

Refining the targets further was motivated largely by the satellite observing method. The Plaskett 1.8 m is unable to track the initial outcry from astronomers, with the designs themselves carried out this program demonstrated that a slightly faster cadence would be possible for similar future observing plans. In the end, the time between the planned observations varied that the spacing between observations was 12 minutes or more conservatively. Altogether, we required that the initial selection was made for Starlink satellites that (1) were visible from DAO during the observing night, including astronomical twilight, (2) reached a maximum elevation that was greater than 45°, and (3) reached their maximum elevation in the southern sky, with the latter being mainly a telescope slewing consideration. This resulted in over 800 observing opportunities during the approximately three hours of useful night.

One of the largest uncertainties in the observing plan is the reduction of light pollution (e.g., see discussion in Tyson et al. 2020). Early attempts to characterize this retrofitted mitigation showed some promise in the reduction of light pollution (e.g., Walker et al. 2020; Working Groups 2022a; Mallama 2021a), but as we will show, there is significant variability in satellite brightness. For ease of discussion, we distinguish between the original Starlink design and the visorsat addition as Starlink and Starlink-V, respectively.

The target satellites and select observing details are listed in Table 1. All observed satellites were at orbital altitudes of approximately 550 km. Starlink-1037, the only inactive satellite in the sample, showed the largest deviation at an altitude of about 540 km. We, unfortunately, cannot confirm that the satellites indicated as Starlink-Vs do indeed have visors or that the visors are correctly deployed. Starlink-1436 is the first visorsat (e.g., see discussion in Tregloan-Reed et al. 2021), placed on orbit as a test case and widely discussed on social media. Additional Starlink satellites were launched without visors until the tenth Starlink mission (called L9, the ninth mission with operational satellites). According to SpaceX (SpaceX 2020), deployable visors were included on all of the corresponding 57 Starlink satellites on board that 2020 August 6 Falcon 9 launch (L9). Mission summaries on SpaceX’s website do not clarify whether subsequent satellites also include visors. However, SpaceX personnel have stated publicly that visors would be included on all satellites after the August L9 launch.9 With this in mind, public satellite

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**Table 1** Target Information

| Name          | UTC   | R.A. (J2000) | δ(J2000) | Azimuth (deg) | Elevation (deg) | Angular Speed (°/s) | Range (km) | STO** (deg) | SIA** (deg) | OA** (deg) |
|---------------|-------|--------------|----------|---------------|-----------------|---------------------|------------|-------------|-------------|------------|
| STARLINK-2077(v) | 05:45:11 | 15 28 26.31  | +08 53 52.7 | 216.00 | 45.16 | 2021 | 749.0 | 69 | 76 | 40 |
| STARLINK-1392 | 05:57:29 | 15 52 24.66  | +12 22 50.4 | 214.71 | 50.41 | 2171 | 697 | 66 | 76 | 36 |
| STARLINK-1747(v) | 06:13:47 | 18 57 30.34  | +16 29 47.3 | 145.59 | 53.97 | 2263 | 668 | 39 | 72 | 33 |
| STARLINK-1728(v) | 06:28:56 | 18 45 17.69  | +27 54 54.4 | 148.44 | 66.96 | 2537 | 596 | 51 | 72 | 21 |
| STARLINK-1355 | 06:41:17 | 17 42 31.87  | +40 37 24.5 | 207.97 | 81.21 | 2705 | 558 | 68 | 73 | 8 |
| STARLINK-1300 | 06:50:00 | 19 35 38.36  | +17 45 39.1 | 145.94 | 55.45 | 2300 | 658 | 39 | 69 | 31 |
| STARLINK-2476(v) | 07:07:22 | 19 59 51.14  | +12 51 33.2 | 144.76 | 49.83 | 2154 | 703 | 34 | 68 | 36 |
| STARLINK-2565(v) | 07:11:25 | 18 35 44.49 | +48 04 10.5 | 154.91 | 89.52 | 2734 | 552 | 71 | 71 | 0 |
| STARLINK-1529(v) | 07:28:02 | 18 13 43.49 | +34 24 40.8 | 209.57 | 74.29 | 2642 | 572 | 60 | 70 | 14 |
| STARLINK-2530(v) | 07:43:20 | 17 26 41.52 | +08 48 58.9 | 216.05 | 45.12 | 2022 | 749 | 45 | 67 | 40 |
| STARLINK-1549(v) | 07:55:38 | 17 51 22.27 | +13 20 05.0 | 214.55 | 50.47 | 2172 | 697 | 44 | 67 | 36 |
| STARLINK-1012 | 08:11:54 | 20 55 40.42  | +16 21 13.5 | 145.74 | 53.91 | 2263 | 669 | 42 | 67 | 33 |
| STARLINK-1009 | 08:28:28 | 20 42 08.85  | +28 54 50.0 | 148.93 | 68.18 | 2558 | 591 | 52 | 68 | 20 |
| STARLINK-1498 | 08:42:05 | 21 41 52.96  | +10 30 13.8 | 143.73 | 47.02 | 2076 | 729 | 43 | 67 | 39 |
| STARLINK-1561(v) | 08:55:55 | 19 24 09.88 | +26 48 08.4 | 211.13 | 65.84 | 2518 | 600 | 48 | 68 | 22 |
| STARLINK-1576(v) | 09:09:34 | 20 32 40.24 | +48 16 44.6 | 192.59 | 89.83 | 2733 | 552 | 71 | 71 | 0 |
| STARLINK-1037 | 09:24:58 | 21 53 23.21  | +23 00 29.2 | 147.19 | 61.48 | 2460 | 615 | 55 | 70 | 26 |
| STARLINK-1060 | 09:39:47 | 22 07 49.16  | +22 57 10.8 | 147.42 | 61.47 | 2436 | 621 | 57 | 70 | 26 |
| STARLINK-2063(v) | 09:55:00 | 20 23 29.08 | +26 28 37.0 | 210.80 | 65.58 | 2518 | 600 | 49 | 71 | 22 |
| STARLINK-1464 | 10:10:00 | 22 54 30.14  | +16 16 48.5 | 145.60 | 53.83 | 2261 | 669 | 60 | 72 | 33 |
| STARLINK-2252(v) | 10:25:17 | 21 12 44.06 | +34 10 07.6 | 208.36 | 74.25 | 2643 | 572 | 59 | 74 | 14 |
| STARLINK-2249(v) | 10:41:41 | 20 56 12.20 | +21 04 56.1 | 212.77 | 59.38 | 2396 | 631 | 46 | 74 | 28 |
| STARLINK-2195(v) | 10:53:10 | 22 51 39.83  | +35 54 22.5 | 149.43 | 75.93 | 2598 | 581 | 73 | 77 | 13 |

Notes. Positional information and range as provided by the JPL Horizons ephemeris service.

1 UTC times represent the expected passage of the satellite through the center of the FOV.

2 Visorsat Starlink satellites are denoted with a "(v)."

3 Solar-target-observer (STO) angle (essentially the solar phase angle), as reported by the JPL Horizons ephemeris service.

4 Solar incident angle (SIA), which is the angle between the nadir direction and the solar direction, as seen from the satellite.

5 Observer angle (OA), which is the angle between the nadir direction and the observer direction, as seen from the satellite.

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9 See, e.g., the summary at https://directory.eoportal.org/web/eoportal/satellite-missions/s/starlink.
information does not confirm either way, other than referencing the public statements. Nonetheless, if we take the available information at face value, then roughly satellites Starlink-1514\textsuperscript{10} onward, as well as Starlink-1436, have deployable visors.

Table 1 further shows the OA and the SIA. These are the angles between the nadir and the observatory directions and the nadir and the solar directions, respectively, as seen from the satellite. The angles were calculated directly from the state vectors for the satellite, observatory, and the Sun, obtained using the JPL Horizons ephemeris service, and confirmed using the OCS software (Hickson 2019).

### 3. Observations and Measurements

All observations were taken using a $g'$ filter with 30 s exposures. Each integration began 15 s prior to the central UTC time listed in Table 1 to ensure that the satellite would be observed as it passed through the Plaskett’s $22' \times 11'$ (edge-to-edge on the CCD) FOV.

Images were processed in two ways to check for consistency. The first method used the Spaceguard pipeline (Tatum et al. 1994), which includes bias subtraction, flat fielding, image flattening, and filtering for the removal of image artefacts (e.g., hot pixels, cosmic rays, etc.). For each image, source catalogs are generated of all stars in the field using Gaussian fitting. One of a selection of astrometric catalogs are then queried (Tycho2, PPM, Carlsberg Meridian Circle, USNO, and 2MASS) and predictions of the detector positions of each catalog source are calculated using the world coordinate system (WCS) information in the image header as a first pass. The two lists are then cross correlated, the catalog source positions are recalculated using Gaussian fitting, and the final WCS is determined. All pixels are then resampled to tangential projections with constant scale ($0''/62$) in the ICRS reference frame. All resampling maintained flux conservation for each image.

The second method used astropy and python scripts to bias subtract, flat-field, flatten, and median filter the images. The flattening was done by subtracting from a given pixel the median value as determined from 128 $\times$ 128 pixel grid. The large grid was needed to avoid forming peak-and-valley structure in the images along the streaks and the brightest stars. To speed up this process, a subgrid consisting of 20 $\times$ 20 pixel bins was used, with the median subtraction done on all subgrid pixels using the large window centered on the subgrid. Each image was then astrometrically calibrated using the astrometry.net software package (Lang et al. 2010).

With the astrometrically calibrated images, bright stars were selected that sample the relevant image area (i.e., in the vicinity of the satellite streaks) and, to the extent possible, were free of contamination from other stars or image artefacts. Some fields were very crowded, so the selected stars were often not the brightest stars in the field. Fortunately, the 30 s integration times used on each image provided plenty of very high signal-to-noise ratio ($S/N$) stars for calibration.

The selected stars were cross referenced with the Gaia catalog, and their $g$ magnitudes were obtained by using the Gaia $G$, $G_{RP}$, and $G_{BP}$ photometry with the SDSS12-Gaia photometric transformation fits for GEDR3, with a reported uncertainty of $\sigma_{\text{trans}} = 0.075$ mag.\textsuperscript{11} Transformations to the $g$ band were required because observations in that band were unavailable for the selected fields. However, as a consistency check, we used reported $B$ and $V$ band observations for select calibration stars, as given in SIMBAD,\textsuperscript{12} to again transform the stars to $g$ band. This was done using stellar ugriz-Johnson-Cousins transformations.\textsuperscript{13} The results typically agreed to within 0.1 mag. The two different methods for astrometric calibration were self-consistent with source identification and cross referencing with Gaia positions.

The transformed Gaia magnitudes, $m_{\text{Gaia}}$, were then compared with the corresponding instrumental magnitudes, $m_{\text{inst}}$, as determined through aperture photometry. The zero point for each star was set according to $m_{0} = m_{\text{Gaia}} - m_{\text{inst}}$. The resulting distribution of zero points were clipped to remove outliers. The $m_{0}$'s for an image, which included a minimum of five stars after clipping, were averaged to determine the image’s zero point. The clip-and-average results were typically within about 0.01 mag of the median value for the zero points.

We note that we use a $g'$ filter, but have calibrated the photometry using $g$ magnitudes. The difference between the two bands is small ($\leq 0.01$; Tucker et al. 2006), much smaller than the uncertainty $\sigma_{\text{trans}}$ in the transformation from Gaia bands to $g$. We therefore report the magnitudes as $g$ band to reflect the calibration.

In determining the satellite magnitudes, there are several complications that are introduced by the wait-and-catch method, all of which were anticipated: (1) a satellite remains in the FOV for only a small fraction of the 30 s exposure; (2) the streaks cut across multiple stars and image artefacts; and (3), the streaks could, in principle, vary in brightness across the image. Fortunately, we did not see large streak brightness variations, although there were measured variations on the level of a few tenths of a mag in a few cases.

To address the second issue, we did not use the entire streak. Rather, we selected as long of a section as practicable that was free of substantial contamination. In a few cases, several regions were selected and combined. Altogether, the shortest streak length that we used was $62''$, while the longest was about $370''$. The lowest $S/N$ (just taken to be Poisson dominated) is 120, which corresponded to the dimmest satellite in the sample. The typical $S/N$ was a few hundred. The total flux inside a rectangle along the selected section of the streak was used for the photometric measurements, with adjacent regions used to determine the background for subtraction.

The extrapolated magnitude for each satellite is then calculated using

$$m_{g} = \langle m_{0} \rangle + m_{\text{inst}} - 2.5 \log_{10} \left( \frac{R}{L_{\text{EXP}}} \right),$$

where $R$ is the on-sky angular speed of the satellite as determined from the JPL ephemerides, $L$ is the measured streak length, and $I_{\text{EXP}}$ is the exposure time, which again is 30 s for these observations.

Finally, we define an “range corrected magnitude,” $H_{g}^{550}$, for the satellites as the brightness the satellite would be if seen from 550 km. We note that different papers use a different

\textsuperscript{10} This is the lowest Starlink number associated with the L9 launch, according to the satellite catalog, available at celestrak.com. To confirm whether a given satellite might have a visor, its launch date, as given in the satellite catalog, should be on or later than 2020 August 7.

\textsuperscript{11} Available at: https://gea.esac.esa.int/archive/documentation/GEDR3/Data_processing/chap_cu5pho/cu5pho_sec_photSystem/cu5pho_sec_photRelations.html.

\textsuperscript{12} Available at: http://simbad.u-strasbg.fr/simbad/.

\textsuperscript{13} Available at: https://www.sdss.org/dr12/algorithms/sdssubvritransform/.
standard for this, but we use 550 km to reflect the orbital altitude for the satellite shell in question. To be verbose, 
\[ H^{550}_g = m_g - 5 \log_{10} \left( \frac{r}{550 \text{ km}} \right). \]  

**4. Results**

The measurements are presented in Table 2. The apparent brightness distribution varies between \( m_g = 4.7 \text{ mag} \) and 10.0 mag, with the two brightest being Starlink-V and Starlink satellites (to within the uncertainty) and the dimmest a Starlink satellite.

Table 2 is visualized in Figure 1. The median for the apparent magnitudes is \( m_g = 5.7 \text{ mag} \), while it is \( H^{550}_g = 5.3 \text{ mag} \) for the range corrected distribution. Their respective standard deviations are 1.4 mag and 1.3 mag. This includes the general trend of the satellites with STO, which is discussed further below. When the trend is removed, the magnitude variation is 0.5 mag for the apparent magnitudes. Isolating just the Starlink-V and Starlink distributions, the apparent magnitude medians are \( m_g \text{(visor)} = 6.1 \text{ mag} \) and \( m_g \text{(no visor)} = 5.2 \text{ mag} \), respectively. The range corrected magnitudes are likewise \( H^{550}_g \text{(visor)} = 5.7 \text{ mag} \) and \( H^{550}_g \text{(no visor)} = 5.1 \text{ mag} \). Thus, the Starlink-V mitigation efforts through visors have a measurable effect, at face value, with an overall dimming by \( \Delta H^{550}_g = 0.6 \text{ mag} \). However, the medians of both distributions are still bright and are naked-eye visible. Moreover, the difference of the medians is comparable to the intrinsic brightness spread of the individual satellite populations, suggesting the result should be taken with caution.

The result is nonetheless interpreted to reflect a real difference, even if the magnitude is highly uncertain, given similar findings by other groups (see, e.g., summaries in Working Groups 2022a, 2022b; Rawls et al. 2021). Altogether, this suggests that mitigation needs to be part of the design process, and that retrofits may have limited impacts, as the satellites can still be bright a large fraction of time.

The satellite distributions can further be shown against their STO, range, and time (Figure 2). There is a general trend of dimming with increasing STO. This behavior is nontrivial in that a satellite passing near the observer’s zenith will have an STO that approaches 90°, but adjusted for the Sun’s angular distance below the horizon. This is also when the satellite is closest to the observer, which by itself would tend to make the satellite brighter. However, a shallower STO is able to compensate for the difference in range, up to a point, which places the shallower STOs here among the brightest observed satellites. Of course, the STO is not unique to a given range, and that retrofits may have limited impacts, as the satellites can still be bright a large fraction of time.

A surprising feature in the data is the dimming of the satellites at an STO of about 43°. This dimming cannot be explained by range. The time of observation also does not show clear evidence alone for this feature given that the dimmest two satellites are separated by one of the brightest. Moreover, there is not a significant change in the image zero points to suggest that there is a local sky phenomenon that is compromising some of the measurements.

### Table 2

| Number | Name               | Apparent Magnitude \((m_g)\) | Range Corrected Magnitude \((H^{550}_g)\) |
|--------|--------------------|------------------------------|-----------------------------------------|
| 1      | STARLINK-2077\(^v\) | 6.5                          | 5.8                                     |
| 2      | STARLINK-1392      | 5.7                          | 5.2                                     |
| 3      | STARLINK-1747\(^v\) | 5.3                          | 4.8                                     |
| 4      | STARLINK-1728\(^v\) | 5.4                          | 5.2                                     |
| 5      | STARLINK-1355      | 5.2                          | 5.1                                     |
| 6      | STARLINK-1300      | 4.8                          | 4.4                                     |
| 7      | STARLINK-2476\(^v\) | 4.9                          | 4.3                                     |
| 8      | STARLINK-2565\(^v\) | 6.5                          | 6.5                                     |
| 9      | STARLINK-1529\(^v\) | 6.4                          | 6.3                                     |
| 10     | STARLINK-2530\(^v\) | 7.9                          | 7.2                                     |
| 11     | STARLINK-1549\(^v\) | 8.2                          | 7.7                                     |
| 12     | STARLINK-1012      | 8.5                          | 8.1                                     |
| 13     | STARLINK-1009      | 5.2                          | 5.0                                     |
| 14     | STARLINK-1498      | 10.0                         | 9.4                                     |
| 15     | STARLINK-1561\(^v\) | 5.7                          | 5.5                                     |
| 16     | STARLINK-1576\(^v\) | 6.8                          | 6.8                                     |
| 17     | STARLINK-1037\(^b\) | 6.2                          | 5.9                                     |
| 18     | STARLINK-1080      | 5.2                          | 4.9                                     |
| 19     | STARLINK-2063\(^v\) | 5.0                          | 4.8                                     |
| 20     | STARLINK-1464      | 5.1                          | 4.7                                     |
| 21     | STARLINK-2252\(^v\) | 5.4                          | 5.3                                     |
| 22     | STARLINK-2249\(^v\) | 4.7                          | 4.4                                     |
| 23     | STARLINK-2195\(^v\) | 6.9                          | 6.7                                     |

**Notes.** All measurements are in the \(g\) filter. Uncertainties estimated to be about 0.1 mag. Row numbers are for comparisons with figures.

\(^a\) As seen at 550 km, but without a STO (phase angle) correction.

\(^b\) Inactive.
5. Discussion

Characterizing the brightness distribution of satellites, their variability, and dependence on STO (solar phase angle) is necessary for assessing the degree to which satellites will interfere with astronomy and stargazing. It is further required for modeling the impacts of proposed satellite systems (e.g., Lawler et al. 2021), as well as monitoring mitigation efforts and, to the extent practicable, identifying possible regulation and industry best practices that would have the greatest impact on reducing light pollution while allowing the development of orbital infrastructure.

The observations here show that the satellites have significant scatter in brightness, which is not improved when...
correcting to a range of 550 km. This is not surprising given the range of STOs among the satellites. We thus can consider different phase models, with the simplest being the diffuse sphere (Pradhan et al. 2019). Specifically, the model for magnitude is

\[ m_g = -26.47 - 2.5 \log_{10}(\boldsymbol{R}_m) + 2 \left( \frac{1}{3 \pi} \right) \zeta \left( \frac{\pi}{2} \right) \left[ \cos(\text{STO}) + \sin(\text{STO}) \right]^{26.47 - 2.5 \log_{10}(\boldsymbol{R}_m)} + 2.5 \log_{10}(\boldsymbol{R}_m). \]  

where \( \zeta \) is the effective area of the satellite in square meters (i.e., the product of the albedo and cross-sectional area), \( \boldsymbol{R}_m \) is the range in meters, and the index \( p = 1 \).

The result is shown in Figure 3. We use \( \zeta = 0.7 \) m\(^2\), which provides a reasonable match to the low STO satellites, but does not dim fast enough for higher STOs. Noticing that a faster dependency is required, we explore possible variations of the diffuse sphere model in which \( p \neq 1 \).

A Monte Carlo Markov Chain routine is written in python using a Metropolis–Hastings algorithm with a Gibbs sampler (sufficient for this application), using uniform priors to explore possible \( p \) and \( \zeta \). We assume the data have uncertainties of 0.1 mag and exclude the four dimmest satellites at \( \text{STO} \approx 43^\circ \). The chains converge quickly and can be reproduced using the script in the linked GitHub repo. The results are \( \zeta = 1.1 \) m\(^2\) (1.00, 1.19 m\(^2\)) and \( p = 3.1 \) (2.98, 3.26), which are the quantities in parentheses are the 68% credible intervals. The best model is shown in Figure 3.

The heuristic model magnitudes are subtracted from the data (Figure 3), resulting in a dispersion of 0.5 mag among the residuals (excluding again the four dimmest satellites). We caution against reading too much into this model at this time, as additional data are needed to test it. Moreover, we only cover a small range of STOs.

With this in mind, an additional behavior can be noted. First, the Starlink-Vs appear to fall off in brightness slightly more rapidly with STO than the Starlink satellites. This is consistent with the differences in the median magnitudes for the two populations, but also shows that so far the effectiveness of Starlink-Vs is highly variable and does not help with some of the brightest orientations.

Recent work by Mallama (2021b) combines about 10,000 MMT-9 robotic observations of Starlink-Vs using a clear filter. They report that the magnitudes are within about 0.1 mag of the Johnson \( V \) band. The median of their Starlink-V observations corrected to 550 km is 5.5 \( V_{\text{MMT}} \) mag.\(^{14}\) When we take into account the \( g - V = 0.3 \) color of the Sun, assuming no wavelength dependence for the albedo, their median \( H_{g,\text{MMT}} \) = 5.8 mag compared with our \( H_g^{550} \) = 5.7 mag, consistent within uncertainties.

Mallama (2021b) also find that a quadratic fit to the \( g \)-brightness dependence can explain their observations. We note that the quadratic fit behaves nearly identically to a diffuse Lambertian sphere over the range shown in Figure 3 (this work), but with the leading term set to 3 instead of their nominal value. That correspondence means our data exhibits a slightly different dependence on STO than the MMT-9 data. The origin of this is unclear, and we refrain from discussing it further other than to note that because the satellites are not actually spheres, the detailed viewing angle will matter. Regardless, this study and Mallama (2021b) find an inherent satellite magnitude dispersion of about 0.5 mag after subtracting their respective STO trend. We conclude that this is an inherent dispersion due to the shape of the satellite and that the visors do not prevent this from occurring.

The results can be used in modeling the impacts of satellites on the night sky, as done in Lawler et al. (2021), at least for Starlink-like satellites. We note that they employ a diffuse sphere phase model. Although we find a steeper dependence, their choice is reasonable at this time. First, they include a full range of STOs; something that is not covered here. Second, the Lawler et al. (2021) modeling calibrated their magnitude model by comparing their on-sky distribution for a Starlink-like 550 km shell with our measurements, using the same observing biases for their satellite selection. As additional photometric data are acquired in astrophysical bands, we will be able to ensure higher fidelity between observations and models, at least in a statistical sense.

The scatter demonstrates that analysis of mitigation efforts must be done statistically, with the need to consider observations that span a wide range of STOs and orientations of the spacecraft relative to the observer.

\(^{14}\) The subscript is used to denote that the observations are based in the clear MMT-9 filter and transformed to an approximate \( V \) band.
These observations only measure the brightness of Starlink satellites in a single filter. Additional observations in different bandpasses are needed, as well as measurements of different satellite designs (e.g., OneWeb). As part of seeking cooperation with satellite operators toward minimizing the impact that their satellites have on the sky, we need to be vigilant with independent verification of their mitigation efforts. We also need to consider assessments of single satellite magnitudes, while investigating cumulative impacts when practicable. Astronomy is a fundamental way to explore space, test our understanding of physical laws, and detect impact hazards, among many other things—interference with astronomy has wide ramifications for science, education, and safety.

The observational planning scripts, calibrated images, associated photometry, and analysis scripts used for this paper are available at 10.5281/zenodo.6072360. The astropy simple reduction tools are available at https://github.com/norabolig/ABIRL.

The University of British Columbia is situated on the traditional, ancestral, and unceded territory of the Musqueam people. The University of Regina is located on Canadian Treaty 4 land, which is the traditional territories of the nêhiyawak, Anihšināpēk, Dakota, Lakota, and Nakoda, and the homeland of the Métis/Michif Nation.

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