Photometric Characterization and Trajectory Accuracy of Starlink Satellites

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ABSTRACT

Starlink is a Low Earth Orbit (LEO) satellite constellation produced by SpaceX which aims to provide global satellite internet access. Thus far, most observations of Starlink satellites have primarily been from citizen scientists' visual observations without using quantitative detectors. This paper aims to characterize Starlink satellites and investigate the impact of mega constellations on ground-based astronomy, considering both the observed magnitude and TLE residuals. We observed 97 different Starlink satellites with 736 total observations over a 16-month period and we found an average GAIA G magnitude of 5.6±0.13 with a 1-sigma standard deviation of 1.09. Over the span of the observations, we found that TLEs were accurate to within an average of 7.1 arcminutes in right ascension and 25.6 arcminutes in declination. The error is largely along-track and corresponds to a 0.6 second time error in the trajectory.

INTRODUCTION

SpaceX began launching Starlink satellites in May 2019, with approval to launch up to 12,000 satellites [1]. However, their hope is to eventually extend this to up to 42,000 satellites in LEO. As of June 2021, over 1,740 Starlink satellites have been launched [2]. For comparison, there are only about 4,300 active satellites currently orbiting Earth, including the Starlinks [1]. The nominal schedule calls for two Starlink launches a month, each deploying 60 satellites per launch [3]. The deployment of such large satellite constellations has important implications for ground-based astronomical surveys as the trails left by bright Starlink satellites can ruin both imaging and spectroscopy data [1]. In the early days after launch, brightness estimates of Starlink satellites were primarily derived from citizen scientists' visual observations without using quantitative detectors [3]. In response to concerns from the astronomical community, SpaceX has made some effort to mitigate the impact their satellites by attempting to reduce their brightness. One attempt was painting one of the satellites, dubbed "DarkSat", with a low albedo material thereby hoping that it will reduce the satellite's reflectivity. This cause thermal control issues and subsequently SpaceX implemented deployable sun visors, which reduces brightness by blocking sun glare from these "VisorSats." All Starlinks launched after August 7th 2020 are VisorSats. A possible mitigation strategy astronomers could employ is to close the camera shutter on large survey telescopes to prevent Starlinks from saturating the image. This requires accurate knowledge of a Starlink's position so shutter can be closed at the appropriate time without significant overhead. Although the US Space Command and SpaceX track Starlink satellites and provides TLEs, their accuracy deteorates over time. Our goal is to answer the following science questions: What is the apparent GAIA G magnitude of Starlink satellites? What is the apparent GAIA G magnitude of DarkSat and what does this imply about the effectiveness of painting the Starlink satellites? What is the apparent GAIA G magnitude of VisorSat and how does this show the effectiveness of sun visors in reducing the satellite's apparent brightness? What is the accuracy of TLEs in predicting the location of Starlink satellites?

HARDWARE AND METHODOLOGY

Data for this research was collected with the Stingray prototype located in Tucson, Arizona. This prototype consists of a 16 megapixel CMOS camera coupled with a 135 mm F/1.8 lens yielding a field of view of 7.5° x 5.7° and pixel scale of 5.81”/pixel. This wide field of view sensor allows us to collect multiple 0.2 second sidereal-tracked images of each Starlink satellite pass without significant trailing while still collecting enough background stars for metric calibration. Observation plans were constructed using the Planetarium program *TheSkyX*. Before data reduction, all images were calibrated using darks, flats, and bias frames collected at the time of observation. Data analysis was carried out using an astrometric and photometric reduction pipeline developed at The University of Arizona [4].

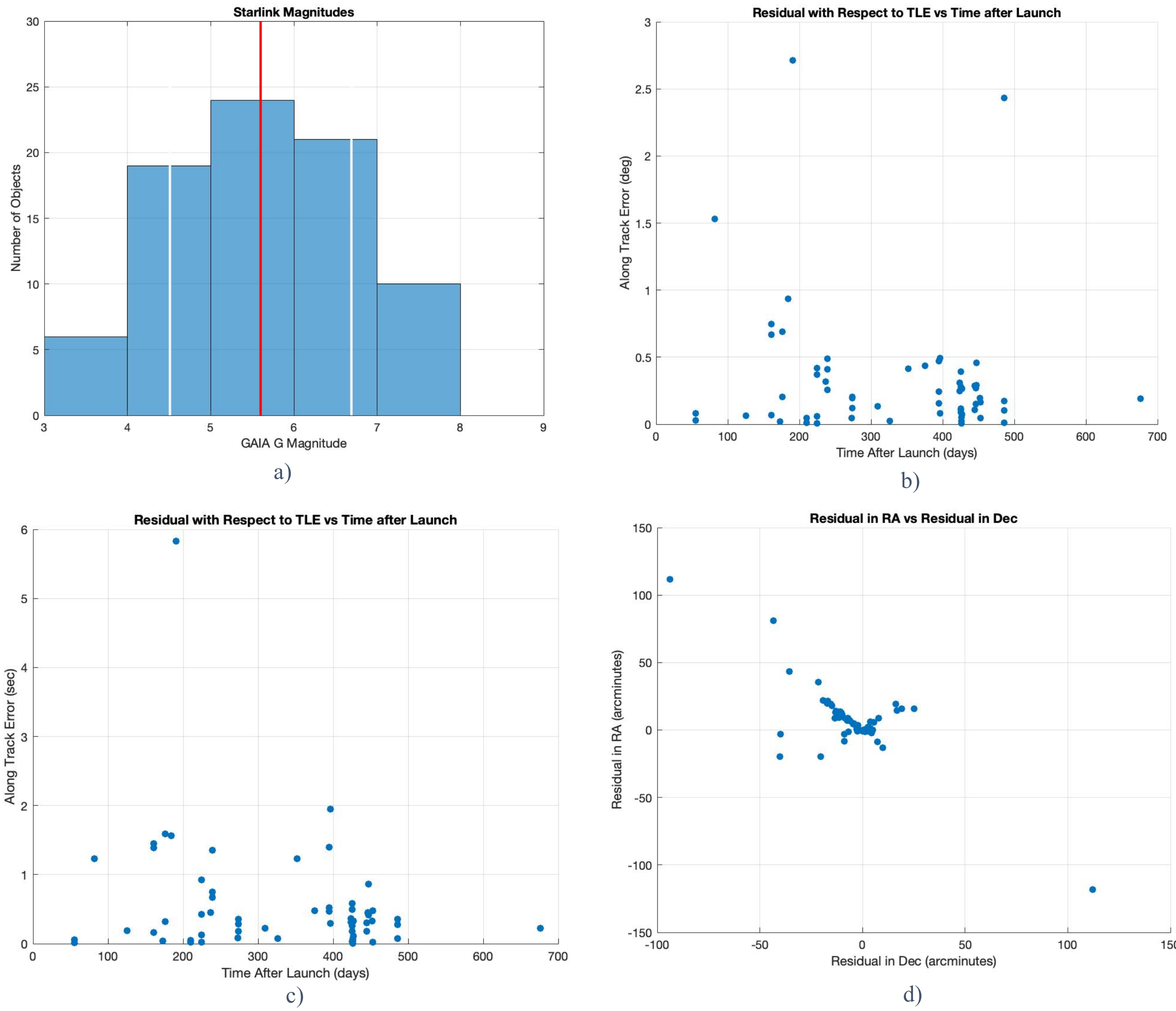

Fig. 1 a) Histogram showing the distribution of GAIA G band magnitudes of the 97 Starlink satellites we observed as part of this study. The red line indicates the average GAIA G magnitude of 5.6±0.13 with white lines indicating the 1-sigma standard deviation of 1.09, b) Along track astrometric error with respect to published TLE vs Time after launch in degrees for Starlink satellites, c) Same plot as (b) but showing the residuals in seconds, d) Residual in RA vs Residual in Dec. in arc minutes.

RESULTS AND DISCUSSION

We observed 97 different Starlink satellites were observed with 736 observations over a 16-month period. We found that the average apparent GAIA G magnitude across all observed Starlinks was 5.6±0.13 with a 1-sigma standard deviation of 1.09.. The brightness of DarkSat was found to average 7.3 ±0.13 with a 1-sigma standard deviation of 0.78. This makes DarkSat 4.8 times fainter than regular Starlinks. The brightness of VisorSat was found to be 6.1 ±0.13 with a 1-sigma standard deviation of 0.78. VisorSat is 1.6 times fainter than regular Starlinks. Thus, the DarkSat design is a better mitigation method at reducing brightness. However, since August 7th 2020, all Starlinks are VisorSats, due to thermal management issues in DarkSat [5]. The average difference in right ascension and declination between position measurements and the published TLE at epoch in arcminutes was found to be 7.1 and 25.6, with standard deviations of 5.41 and 23.06 arcminutes respectively, showing there is significant difference between published TLEs and the observed position. The average time difference is 0.6 seconds, with a standard deviation of 0.84 seconds. The time between launch date and observation seems to have little effect on positional uncertainty when observing more than two months after launch. The results show that although certain factors, such as sun visors on VisorSat, can reduce brightness, the satellites are still relatively bright especially for large ground-based telescope observations.

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