Characterization of Satellite Mega-Constellations using Multi-Color Optical Array (MOA)

Owen Miller
Lunar and Planetary Laboratory,
The University of Arizona

Tanner Campbell
Department of Aerospace and Mechanical Engineering,
Lunar and Planetary Laboratory,
The University of Arizona

Neil Pearson
Planetary Science Institute

Dan Gray
Sidereal Technology

Scott Tucker
Starizona

Roberto Furfaro
Department of Systems and Industrial Engineering,
Department of Aerospace and Mechanical Engineering,
The University of Arizona

Vishnu Reddy
Lunar and Planetary Laboratory,
The University of Arizona

Abstract

Satellite mega-constellations are large groups of satellites that share a collective mission. The number of these large groups has increased dramatically in the last few years and are expected to continue to grow. Concerns about implications of mega-constellations on ground-based astronomy have guided recent research. We plan on expanding upon Halftery et al. (2022) by using a four-telescope array to simultaneously collect multi-color broadband photometry. We use unfiltered and Sloan g', r', i' filters which give simultaneous 4-color photometry to improve our characterization of these target satellites. Over the course of our observation period, we observed 16 Starlink satellites through over 580 images. The average GAIA G magnitude for all observed Starlinks was 5.997 ± 0.204 with a standard deviation of 0.829.

1. Introduction

Satellite mega-constellations are large arrays of satellites designed to produce more coverage for broadband internet connectivity. They are primarily created by large internet service providers such as OneWeb, AST Space Mobile, and most notably SpaceX. On May 23, 2019, SpaceX launched its first 60 Starlink satellites into a Low-Earth Orbit (LEO), as part of its planned internet service mega-constellation. As of July 18, 2023, there have been 4,646 launched, out of which 3800 are still active [2]. The astronomy community has continued to raise concerns about the potential for interference in their ground-based observations throughout the duration of the constellation's existence. The brightness and speed of LEO satellites have the potential to cause streaking in ground-based optical data. As more satellites are launched, it becomes increasingly difficult for observers to time their observations so they don't have unwanted objects in their field of view. Halferty et al. (2022) presented photometric characterization and trajectory accuracy of many Starlink satellites. They concluded that Starlink satellites are bright enough to require ground-based astronomers to create workarounds to avoid contamination of telescopic astronomical data. During their research, three versions of Starlinks were observed. They found that the average GAIA G magnitude of all observed Starlinks was 5.5 ± 0.13 with a standard deviation of 1.12. They found that the average of Darksat was 7.3 ± 0.13 with a standard deviation of 0.7. Finally, they found the average magnitude of Visorsats is 6.0 ± 0.13 with a standard deviation of 0.79. The current study will build on Halferty et al. (2022) in the following way: we will use MOA to simultaneously collect observations in four colors. Our secondary research goal is to carry out these observations automatically every clear night. The multi-color photometry should provide more insight into the measurable effects of Starlink satellites. We will attempt to answer the following questions: What is the brightness of Starlink satellites in Sloan g', r', i', and unfiltered? How does the Multi-Color Optical Array (MOA) compare to the instrument used in Halferty et al. (2022)?

2. Hardware

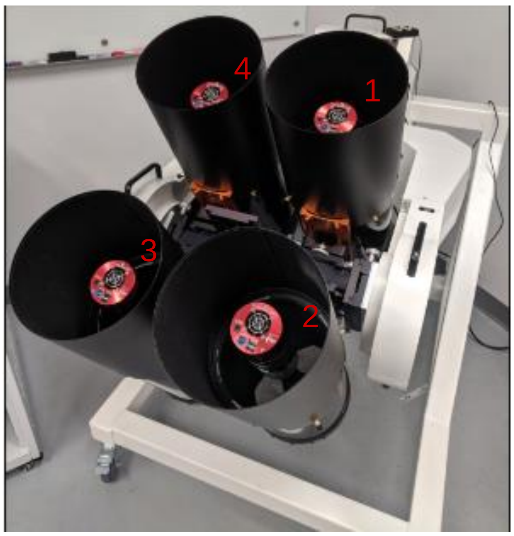

Fig 1. MOA (Multi-Color Optical Array) [3]

Table 1. Bandpass for Photometric Filters [3]

Filter (Camera #)	Wavelength (nm)
Unfiltered (Camera 3)	320-385
g' (Camera 4)	401-550
r' (Camera 1)	562-695
i' (Camera 2)	695-844

The instrument we used to collect data for this research is called the Multi-Color Optical Array (MOA), which consists of four Schmidt-Cassegrain telescopes, each with an aperture of 0.203 m and a focal length of 0.425 m and is shown in Figure 1 [3]. The four telescopes are mounted on an alt-alt mount as described in [3]. The individual telescopes are bore sighted with each other and have a 2.4 deg x 1.8 deg field of view with a pixel scale of 1.84"/pixel when mated with a 4.6k x 3.5k CMOS camera [3]. Each of the four telescopes uses a different filter to observe in different wavelengths simultaneously. The bandpass and filters chosen are given in Table 1. Table 2 gives an overview of general parameters of the MOA telescope.

Table 2. Multi-Color Optical Array Specs [3]

Name	Camera	Aperture (m)	Focal Length (m)	FOV (deg)	Pixel Scale ("/pixel)
MOA	4 x 4.5k x 3.5k CMOS	4 x 0.203	0.425	2.4 x 1.8	1.8

3. Methodology

LEO satellites are best viewed immediately after sunset or right before sunrise by optical. To capture as many objects as possible, we start observing as soon as the sun is low enough for objects to be clearly visible, this is typically close to nautical twilight. After cooling each camera to -10 degrees Celsius we begin finding satellites using our custom satellite tracking software. We set each camera to take images simultaneously as we capture each object three times along its path while sidereally tracking. The cameras take pictures until the object is completely out of the field of view. To process our data, we use a custom astrometric and photometric reduction pipeline [3]. The astrometric and photometric reduction was done using the GAIA DR2 star catalog. Figure 2 shows an example of the photometric correction applied to a single set of images collected of a Starlink satellite. The details for the photometric correction are given in [1].

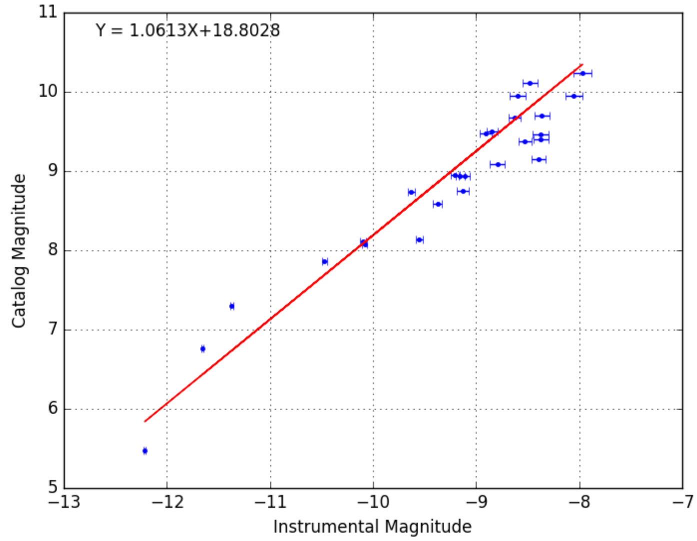

Fig 2. Example of the photometric calibration from a single field of Starlink data.

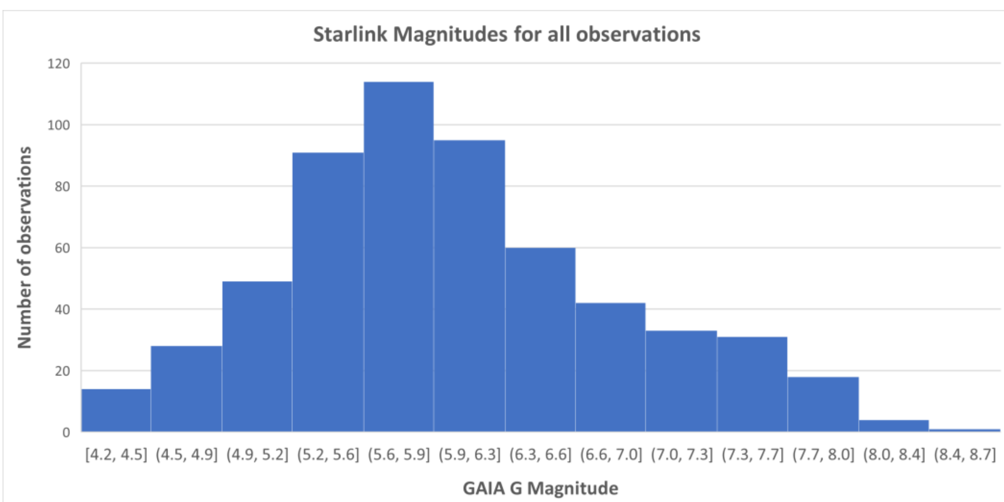

Fig 3. GAIA G magnitudes for all observations from all 4 cameras

4. Results and Analysis

Our observations were taken from the Biosphere 2 Space Situational Awareness Observatory (IAU MPC code 853) between April 2 and June 21, 2023. During this period, we observed 16 Starlink satellites with over 580 observations. Of those 16 satellites, all were Visorsats. The average photometric RMS error across all acceptable observations is 0.204 ± 0.077 (1σ) magnitudes. We found the average GAIA G magnitude across all observed Starlinks to be 5.997 ± 0.204 with a standard deviation of 0.829. A histogram of all observations is given in Figure 3. This agrees with the results from Halferty, et al. (2022) which found that the average magnitude of all Visorsats observed was 6.0 ± 0.13 with a standard deviation of 0.79. The average magnitudes of across all observed Starlinks for Camera 1 (r') to be 5.957 ± 0.183 with a standard deviation of 0.824 (Figure 4). The average magnitudes of across all observed Starlinks for Camera 2 (i') to be 5.790 ± 0.208 with a standard deviation of 0.624 (Figure 5). The average magnitudes of across all observed Starlinks for Camera 3 (unfiltered) to be 6.030 ± 0.213 with a standard deviation of 0.989 (Figure 6). Finally, we found the average magnitudes of across all observed Starlinks for Camera 4 (g') to be 6.135 ± 0.212 with a standard deviation of 0.859 (Figure 7).

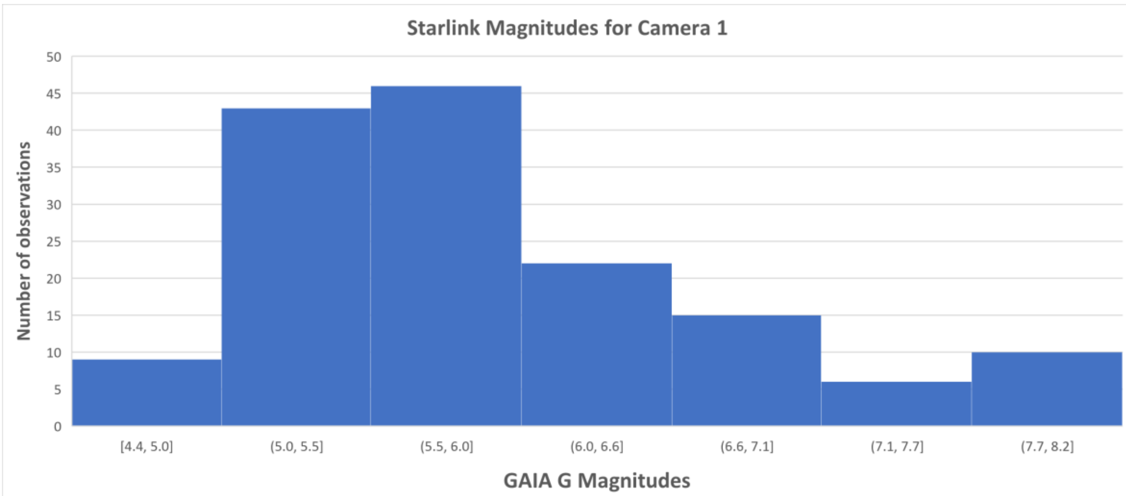

Fig 4. GAIA G Magnitudes for all observations on Camera 1 (r')

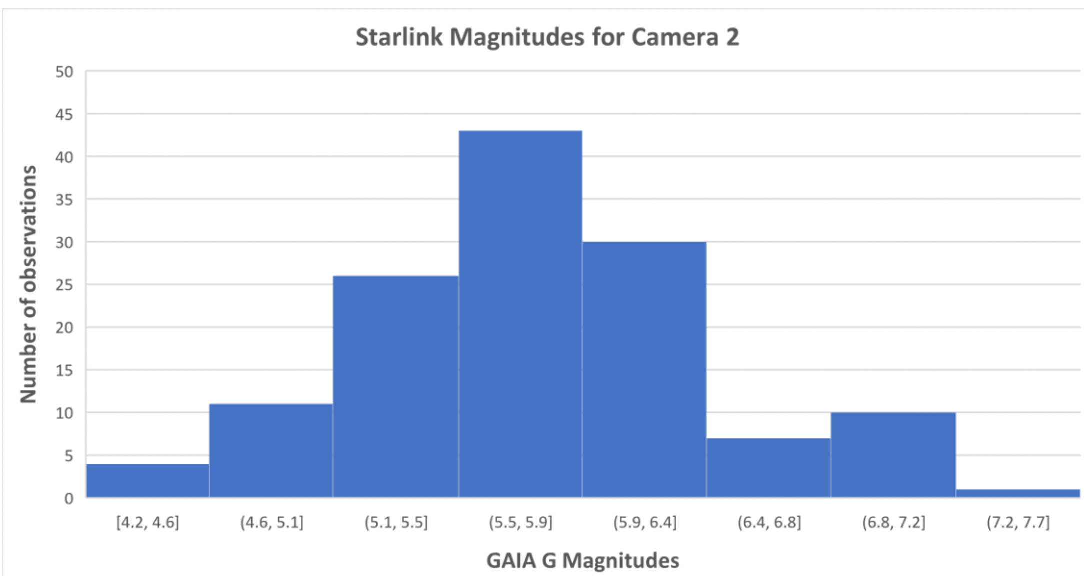

Fig 5. GAIA G Magnitudes for all observations on Camera 2 (i')

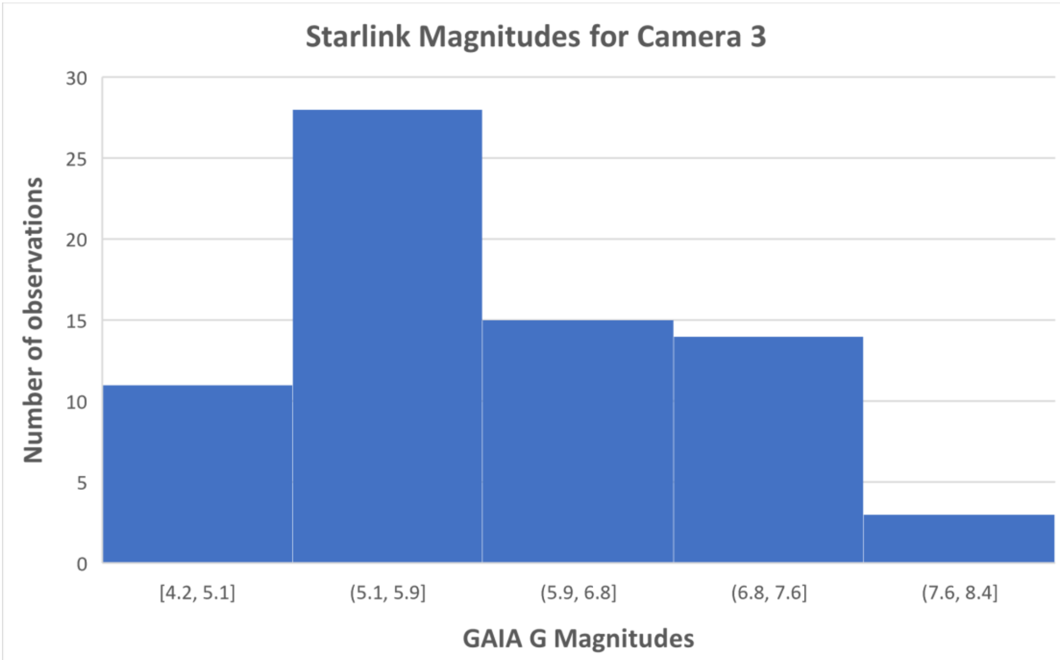

Fig 6. GAIA G Magnitudes for all observations on Camera 3 (Unfiltered)

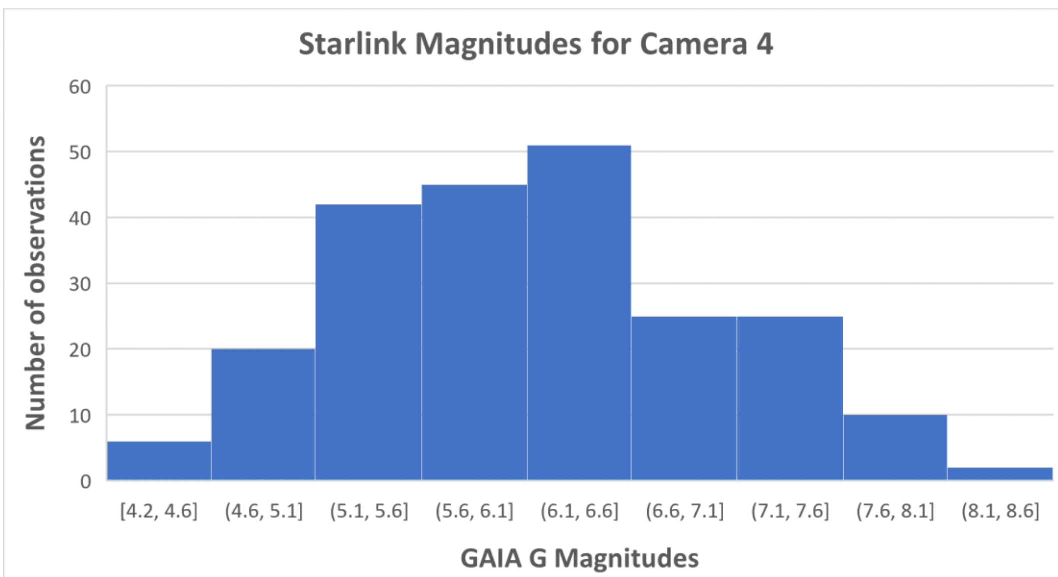

Fig 7. GAIA G Magnitudes for all observations on Camera 4 (g')

5. Summary

The number of satellite mega-constellations has increased dramatically in the last few years and are expected to continue to grow. Concerns about implications of mega-constellations on ground-based astronomy have guided recent research. Using the Multi-Color Optical Array (MOA) telescope to simultaneously collect multi-color broadband photometry of Starlink satellites we have expanded on the work done in Halferty, et al. (2022). We use unfiltered and Sloan g', r', i' filters which give simultaneous 4-color photometry to improve our characterization of these target satellites. Over the course of our observation period, we observed 16 starlink Visorsats and found the average GAIA G magnitude for all observed satellites was 5.997 ± 0.204 with a standard deviation of 0.829. This is in agreement with the values published in Halferty, et al. (2022) for Visorsats. We intend to continue this research to extend to other mega-constellations as they come online and to continue to characterize the different revisions of Starlink satellites.

Acknowledgements

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References

[1] Grace Halferty and others, Photometric characterization and trajectory accuracy of Starlink satellites: implications for ground-based astronomical surveys, *Monthly Notices of the Royal Astronomical Society*, Volume 516, Issue 1, October 2022, Pages 1502–1508, https://doi.org/10.1093/mnras/stac2080

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[3] Campbell, T., Reddy, V., Furfaro, R., Tucker, S., "Characterizing LEO Objects using Simultaneous Multi-Color Optical Array," AMOS Technologies Conference, Maui Economic Development Board, Kihei, Maui, HI, Sept. 2019