The Method of Visual Satellite Photometry

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1. Summary

Large constellations of artificial satellites are beginning to interfere with observation of the night sky. Visual magnitude measurements of these spacecraft are useful as empirical data for monitoring and characterizing their brightness. This paper describes the method used for recording brightness by eye. Selected findings from previous studies of visual satellite luminosity are summarized.

2. Context

When the SpaceX company launched 60 Starlink satellites on a single rocket in 2019 professional and amateur astronomers were alarmed. Experienced visual observers immediately began recording the magnitudes of these spacecraft. SpaceX responded to the concerns of astronomers the following year by adding a sunshade to Starlink satellites. This new model, called VisorSat, was significantly dimmer. However, SpaceX stopped installing sunshades in 2021 because they blocked light from the lasers used for communication. This latest Starlink design is brighter than VisorSats and fainter than the original design.

Starlink satellites are already beginning to interfere with astronomical observations (Mroz et al. 2022). This impact is expected to worsen as the number of spacecraft increases from the current 2,000 to about 12,000 over the next few years. Moreover, numerous satellites in the OneWeb constellation are
also in orbit, and other entities including the Amazon company and the government of China plan to have their own satellite constellations (Mallama and Young 2021).

Visual magnitude measurements will be needed in order to characterize the brightness of all these constellations. They will also be critical for monitoring magnitudes for various designs of satellites from any one entity. The brightness of Starlink satellites has already changed twice as noted above and another variation is expected when the larger Starlink 2.0 spacecrafts are launched as indicated in this video featuring SpaceX CEO Elon Musk https://youtu.be/XP5k3ZzPf_0?t=561.

3. Equipment

Satellite observation requires an optical instrument with enough light gathering power to show stars of magnitude 8 or fainter. Binoculars with 50 mm objective lenses and 7 power magnification are a reasonable choice in some circumstances. However, in locations with significant light pollution larger aperture or higher power might be needed to attain magnitude 8. Binoculars with electronic image stabilization can be effective for magnifications above 7 times. Likewise, high power binoculars or a small wide-field telescope can be mounted on a tripod for stability. The author used 15x50 image stabilized binoculars for most of the observations published to date.

4. Planning observations

The magnitudes needed for photometric study are those obtained after satellites reach their operational altitude. For the Starlink satellites launched so far that altitude ranges from about 540 to 560 km, while for OneWeb spacecraft it is around 1,200 km. The following discussion centers on observation planning for Starlink satellites at their operational altitude.

One useful resource is the web-site https://heavens-above.com/. The home page has an option to generate ‘daily predictions’ of satellites for the observer’s location which produces a table of visible passes. Clicking on an individual pass opens a star map of the whole sky showing the spacecraft trajectory along with ancillary information including the satellite orbital altitude. Clicking on any location of the star chart gives a close-up view. In order to show Starlink satellite passes the box labeled ‘exclude Starlink passes’ must be unchecked.
Another option in Heavens-Above is ‘Starlink passes for all objects from a launch’ which gives a similar table. The individual passes for satellites from a single launch are usually separated by about 5 minutes of time which is sufficiently long to find a star field, observe the satellites and record the resulting magnitude.

The author uses the Heavens-Above web-site for planning. However, the planetarium program called Stellarium may also be used for this purpose.

5. Measuring brightness

The brightness of a satellite is determined by comparison to reference stars in the same field of view. Figure 1 is a sky chart showing 2 stars of known magnitudes and a satellite track. As an example of brightness determination, suppose that the satellite is slightly more luminous than star B whose magnitude is 7.6 but distinctly fainter than star A of magnitude 7.2. Interpolation indicates that the magnitude of the satellite is 7.5.

Figure 1. This chart identifies reference stars A and B whose magnitudes are known, and shows the track of a satellite. The stars and the satellite track are fictitious.
Reference star magnitudes can be displayed by planetarium programs such as Stellarium and TheSky. The goal of visual photometry is to record satellite brightness with an accuracy of 0.1 magnitudes.

6. Recording results

The information needed for analysis of satellite magnitudes includes the geodetic coordinates of the observer along with the following data for each observation: the identity of the satellite, the UT date and time, the satellite elevation and azimuth, the observed magnitude, the altitude of the satellite above the Earth, and the solar elevation and azimuth. Coordinates of the Sun, the satellite and the observer are required for investigating the effect of Sun-satellite-observer geometry on brightness. When a satellite is too faint see that result must also be noted. An example of this information entered on a spreadsheet is shown in Figure 2.

![Spreadsheet](image)

**Figure 2.** This is a sample spreadsheet containing the information needed for the study of satellite brightness.

7. Previous findings

The mean apparent visual magnitude of the original Starlink spacecraft was 4.63 (Mallama 2020). After SpaceX added sunshades to the VisorSats they were significantly dimmer with a mean magnitude of 5.93 (Mallama 2021) which is about 30% of the original brightness. However, when SpaceX stopped installing
sunshades this latest Starlink design became 0.5 magnitudes brighter than VisorSats although it was still 0.8 fainter than the original satellites (Mallama 2022).

End notes

The procedures described in this paper were originally outlined in How to Estimate Satellite Magnitudes on the SeeSat-L web-site. More information about satellite observing techniques can be found on the Visual Satellite Observer’s Home Page. The method of magnitude determination is adapted from the AAVSO Visual Observing Manual.

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