Extraction of light curve from passive observations during survey campaign in LEO, MEO and GEO regions

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ABSTRACT

Our telescope network is currently being deployed to ensure a global survey of the space objects populations, providing large amounts of astrometric data. Photometric data retrieved from observations allows us to characterize the current operational status of a satellite. This kind of measurement is often performed in a different way: usually, the light curve of a space object, i.e. the measurement of the space object luminosity as a function of time, is obtained by performing a tracking of the target over several minutes during its passage in the sky. Such a continuous photometric measurement allows to retrieve periodic variations due to the uncontrolled state of the space object attitude. However, astronomical images obtained during observational campaigns scanning the sky with sidereal tracking instead, also contain photometric data, as well as astrometric data.

Astronomical images performed during a survey are obtained by steering the telescope in a given direction, keeping a sidereal tracking, and acquiring consecutive images when the targeted satellite crosses the field of view. In these images, stars are point-like and satellites look like streaks. Along an individual streak, it is possible to extract a light curve, i.e. the luminosity variation of the space object during the exposure time of the image. The obtained light curve covers a time span equal to the passage duration in the field of view.

In this paper, we study light curves obtained by such passive observations of targeted space objects. Since the deployment the first station of its telescope network in 2020, Share My Space performs automated observations. Angular positions of satellite streaks are catalogued, along with their luminosity variations. Their analysis allows for the extraction of information, such as characteristic periods of rotation due to satellite tumbling motion. In the case of a time period larger than the passage duration in the field of view of the telescope, we investigate the possibility to merge measurements of several passages of the same object to reconstruct a larger time span.

1. INTRODUCTION

The optical sensors provide astrometric and photometric data to improve the knowledge of the space object population. The detection performances are mainly related to the ability to collect more light using larger-aperture telescopes. Currently, the US catalog maintained by the USSTRATCOM contains more than 25 000 space objects with a minimal size of about 10 cm although one million sizing between 1 cm and 10 cm are expected by statistical models[1]. Share My Space is deploying a network of multi-telescope station as described in Petit et al. [3]. This solution will perform a passive survey for space objects population in Earth orbit from LEO to GEO regions. The exploitation of astrometric data for catalogue building and maintenance is a great challenge but it will be completed by photometric data for space object charactisation.

Previously, we developed a model of the photon chain to assess the performance of detection and cataloging of the future multi-telescope stations. This model gives us precious insight of the signal such is should be received by our sensors. In particular, it helps us to characterise the observed objects. Thus, we provide an effort to continuously improve the model and compare with real data.

The aim of this paper is to go further in the modeling of the photon chain, focusing on the photometric measurements with and without tracking. In Section 2, we summarize the photon chain. In Section 3, we present some light curve measurements performed by Share My Space. In Section 4, we compare photometric measurements of light curves with magnitudes obtained from images presenting streak-like satellites. In Section 5, we introduce the process used for the construction of a light curve database. In Section 6, we draw some conclusions.

[1] https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers

2. PHOTON CHAIN

The modeling of the photon chain is critical for different purposes. This allows us to assess the performances of future detection systems, and helps us optimize image acquisition with appropriate camera settings and optimal phase angle. It also enables the characterization of the behavior of space objects. Each stage from the light reflected by the space object up to the measured signal is described. Moreover, we updated the model already introduced in our previous paper [3].

2.1 Photon flux

When a space object is not in the Earth umbra, it is illuminated by the Sun and it reflects part of the received sunlight. The mathematical law giving the proportion of reemitted light depends on the phase angle formed by the Sun, the space object and the observer, also named Sun phase angle. In a first approximation, the observed object is modeled by a Lambert sphere assuming that the luminous power reaching the observer is proportional to the visible surface. The reflected flux depends on the albedo and the phase function which varies with the solar phase angle. More sophisticated models also include the modeling of each facet of the object, their albedo, and their orientation with respect to the Sun and the observer [1].

A photon flux reflected by the space object and emitted by the atmosphere (background) is received by the observatory.

The on-ground solar spectrum reflected by the object depends on the elevation. It will be dimmed as the elevation decreases, due to the increase in atmospheric depth according to Beer-Lambert's law.

The photons emitted by the atmosphere, often reffered to as the sky brightness and measured in orders of magnitude, vary as a function of the observatory altitude, the local elevation of the object and the Moon position. The magnitude of a good sky is considered between 20 and 22 and is computed according to the Krisciunas and Schaefer model [2]. To preserve unit consistency, a conversion from sky magnitude to photonic flux is then performed using the background stars flux, their known magnitude and a model of the night sky spectrum filtered in the V-band shown in Fig. 1.

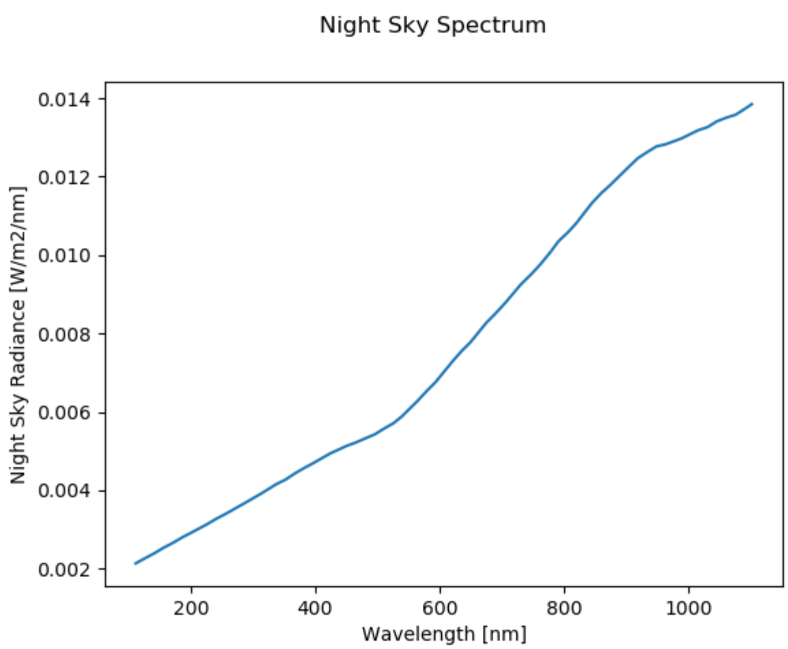

Fig. 1: Night Sky emission spectrum filtered in V-band

The accuracy of this spectrum has been validated by comparing various spectra, either using that of the Sun or that of the night sky. These spectra have been evaluated using V-band filters in order to evaluate their accuracy. The following cases have been evaluated for the RASA-14 telescope equipped with the QHY600 sensor, located at Baronnies Provençales (France), for a night without Moon:

- On-Ground Solar Flux spectrum
- On-Ground Solar Flux spectrum + Photopic Filter
- On-Ground Night Sky spectrum measured at the Mauna Kea (Hawaii) + Photopic Filter
- On-Ground Night Sky spectrum measured at the Mauna Kea (Hawaii) + V-band Bessel Filter
- On-Ground Night Sky spectrum model (used at the Baronnies observatory) + large V/R-band Filter

By comparing the ADU flux given by the various models and the ADU flux measured in the images for magnitudes computed by the PRISM software[2], one can notice that the spectrum used is very important, and that using the spectrum of the sun for instance cannot give accurate values. Using a diverse array of filters also shows the importance of using the correct one. The gaps between measured and computed ADU flux values for a same initial spectrum are due to the filter's length, thus showing its importance to determine the flux from a magnitude. As magnitudes are always measured considering a specific array of wavelenghts, it is crucial to use the same filter that has been used to generate the magnitudes of the star catalog used, in order to obtain that of the night sky. This is why the Hawaii model does not seem accurate enough compared to that of the Baronnies: the V or V/R band filter used is not the same. The results of these comparisons are shown in Fig. 2.

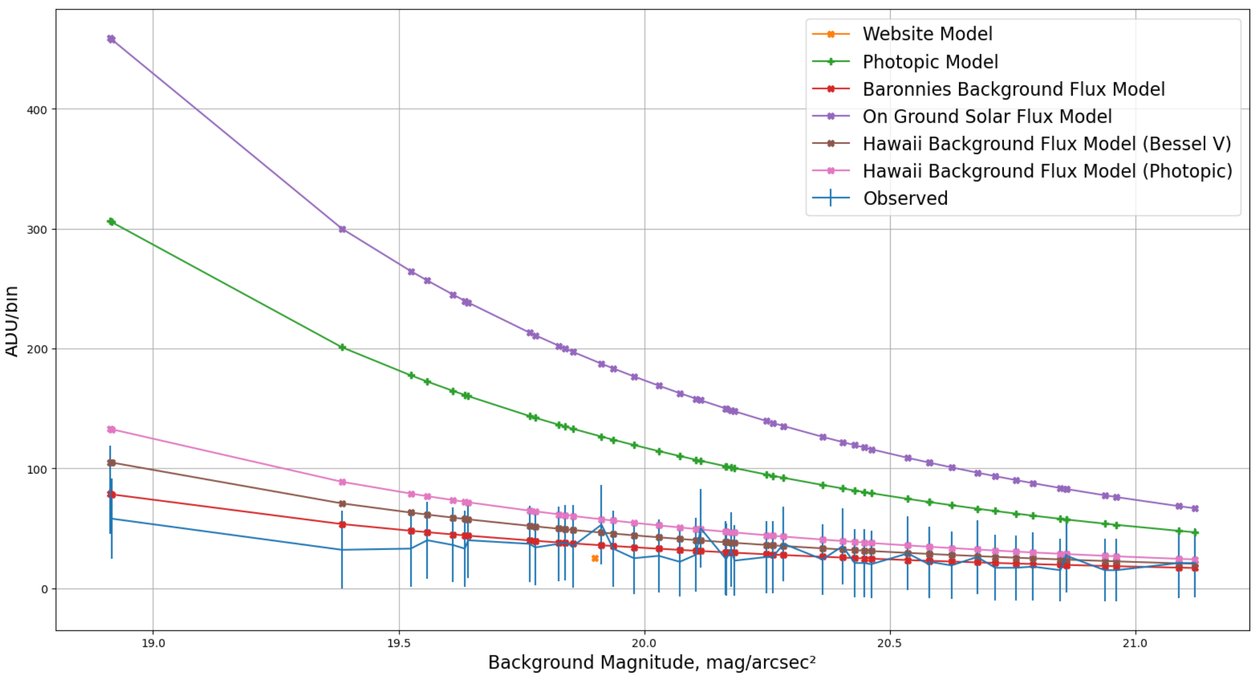

Fig. 2: ADU flux predicted/measured with the RASA-14 + QHY600 Camera using different spectra. One can see the effect on the choice of the spectrum as well as the influence of the filter used to obtain the filtered spectrum.

2.2 Sensor

The signal of space objects and background depends on the light collected by the telescope and converted into electrons by the camera, before being read to form an image where the electronic (thus analogic) charge in each photosite, also known as pixel, is converted to ADU (Analog-to-Digital Units). The aperture, the focal length, the obstruction and the optical transmission characterize the telescope. The quantum efficiency is intrisic to the camera. It can be considered as an additionnal filter on either spectrum of the light sources for the sake of simplicity, representing the photon to electron conversion rate for each wavelength.

[2] `http://www.prism-astro.com/`

Additional settings are used to enhance detection capabilities in order to increase contrast between the object and other light sources considered to be noise, prior to the image conversion in ADU:

- The system gain defines the conversion rate from electron to ADU, allowing to see fainter objets with the use of a higher gain setting, but also increasing noise sources, risking pixel saturation;
- The camera offset, or bias, adds the same ADU base value to every pixel on the image. Camera offset is mostly used to make up for the irregularities of the photosites detection threshold.

2.3 Implementation of the model

The model of the photon chain was implemented in Python to predict the measured signal of the background and of the observed object. It is dependent on a couple of paremeters mentionned previously in this paper: the distance between the object and the observer, the phase angle, the albedo, the size, the shape of the object and its orientation, the altitude and the azimuth, the Moon and the Sun location in the sky, and the epoch.

3. LIGHT CURVE MEASUREMENTS

3.1 Examples

A light curve is a measure of the received flux by the sensor from the targeted object as a function of time. For controlled objects, i.e. when the orientation of the satellite is maintained in a fixed direction, the magnitude varies with the phase angle. But in the case of an uncontrolled object, variations are due to the rotation of which the main period ranges between a few secondes up to several minutes or more. For this study, we provide study cases of a few objects with different behaviors.

Share My Space operates an observatory located in Baronnies Provençales (South of France) equipped with a RASA telescope with a 350 mm of aperture and a mount GM3000 of 10micron allowing fast tracking of space objects in LEO orbit. The camera QHY600 allows image acquisition with a rate up to 10 Hz. In Fig. 3, the light curve obtained by the tracking of the upper stage SL-6 (#23587) shows short-term variation of the luminosity.

3.2 Comparison of the measured magnitude with the model

The model provides the theoretical measured flux. Using the flux of a star of reference, we can compute the apparent magnitude of the object and compare it with the magnitude measured from observations. At the time of this study, the account for the satellite rotation was not yet implemented in our magnitude model. For this reason, we consider a spherical satellite, of which the magnitude is independant from its orientation. We study the case of Lageos (#8820), a geodesic satellite located at an altitude of 5 955 km, with an inclination of 109.9 degrees. In Fig. 4, the measured light curve of Lageos is plotted, showing its measured magnitude as a function of time as well as the evolution predicted by our model. Although the period seems consistent between the model and the measurement, the curve trend shows a discrepency. This is due to some elements that were not modeled: for example atmospheric perturbations, which have a significant impact on the stability of the measurement.

4. STREAK PHOTOMETRY

To obtain accurate astrometric measurements of a space object, the common mode for image acquisition is to steer the telescope in a given direction with sidereal tracking, waiting for the object's pass in the field of view. The stars appear like dots; the satellite as a trail of light named streak. After image processing, the flux of both the background and streak are obtained, and the magnitude is computed by comparison with the flux of a star of reference extracted from the background.

Moreover, the variation of luminosity along the streak can be extracted from the image, having first detected the start and the end coordinates of the streak in each image. In Fig. 5, a streak of the satellite Ajisai (#16908) is visible, which was obtained with an exposure time of 800 ms. Consecutive images are acquired during the passage of the satellite in the telescope field of view. In each one the variation of luminosity can be extracted along the streak and extracted to form a short light curve as shown in Fig. 6. As it is already visble in Fig. 3, the light curve shows strong variation in luminosity intensity. Even during a short period of time limited by the passage in the telescope field of view or the exposure time, the luminosity variation can be characterized.

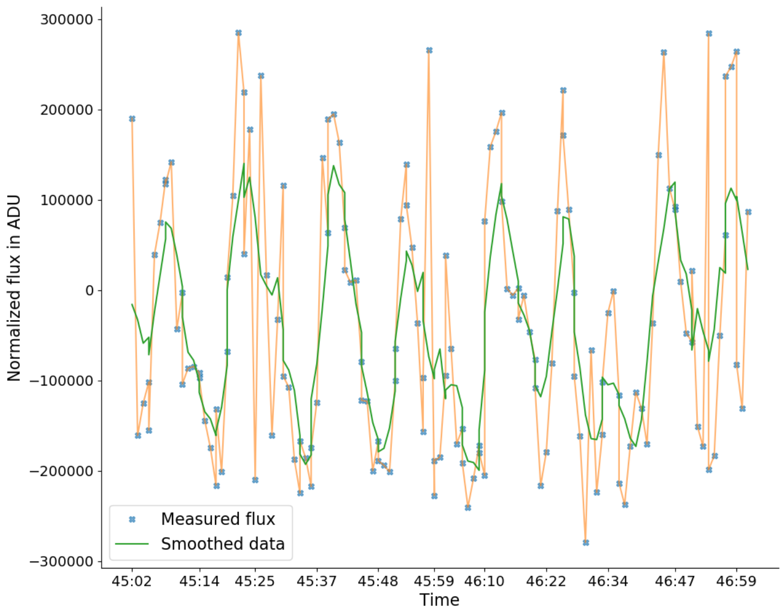

Fig. 3: Light curve of the upper-stage SL-6 (#23587)

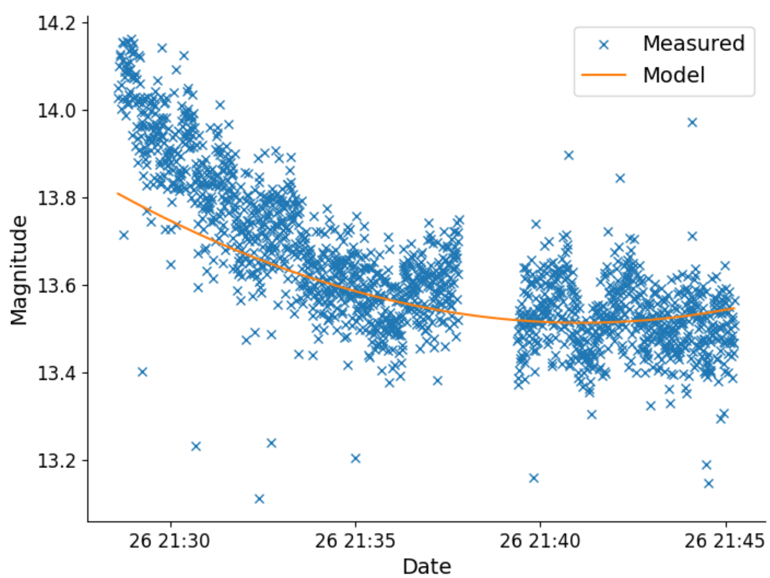

Fig. 4: Light curve of Lageos (#8820)

5. MAINTENANCE OF A LIGHT CURVE CATALOG

In the previous section, it has been shown that the images with streaks allow to extract photometric data and to partially characterize the dynamic state of the space object object. We propose to take advantage of photometric data provided

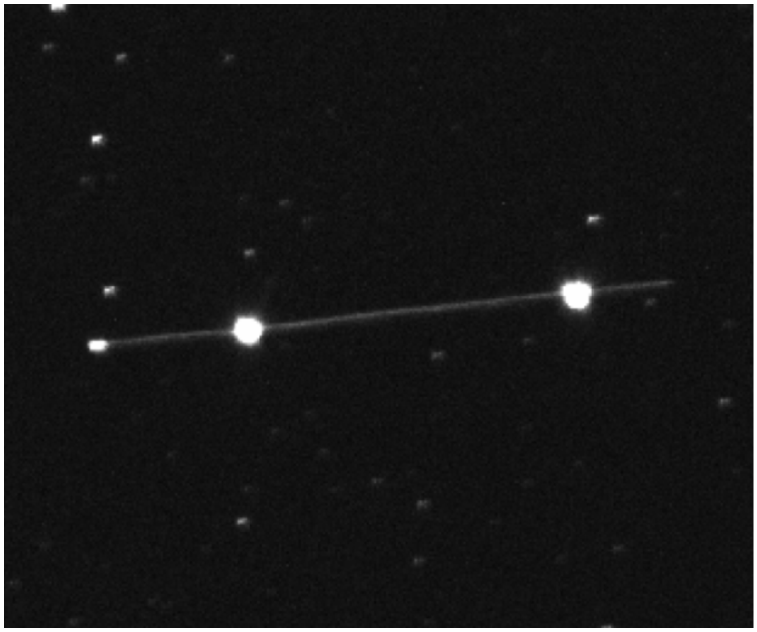

Fig. 5: Image of the satellite Ajisai (#16908) obtained with an exposure time of 800 ms

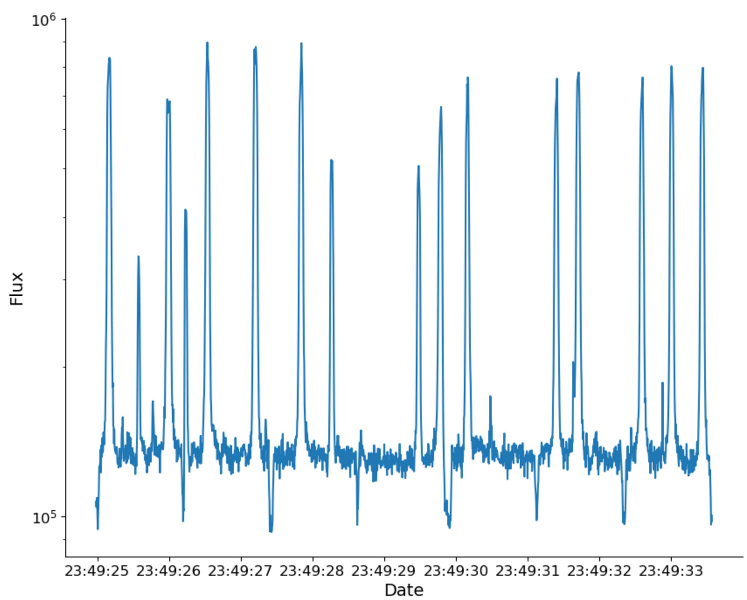

Fig. 6: Light curve of the satellite Ajisai obtained by an extraction of the flux along the streak in consecutive images

by passive observations, albeit partial, to assess changes in the rotational dynamics of the space objects and to schedule new observation with tracking in order to produce light curves over a significant time span, enough to fully characterize the rotation. In Fig. 7, the process is illustrated: starting with the image processing, including streak detection, to the upload of astrometric measurements of each streak. Once the streaks are detected, their flux in ADU is extracted. If a flux variation (periodic or secular) is observed, the space object is a candidate for characterization with light curve measurements from tracking acquisitions.

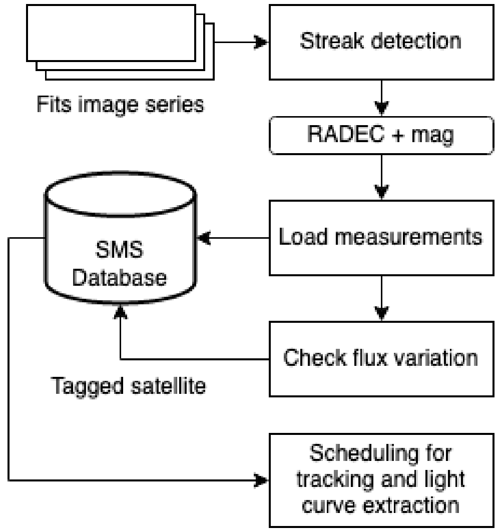

Fig. 7: Process to detect variations of luminosity from streaks and to schedule light curve measurements

6. CONCLUSIONS

Share My Space proposes to tackle SSA and STM issues by building the largest catalog of space objects with an innovative network of optical sensors. A catalog of 150 000 space objects is expected by 2025. The way to build this catalogue is based on passive observations without the tracking of space objects. Thus, the produced photometric data is limited to the duration of the exposure time (about 300 ms).

The paper proposes to analyse photometric data obtained with different mode of acquisition: passive or active with tracking. Both modes are experienced by Share My Space to propose services like on-demand observations or space object cataloging and characterisation. Moreover, photometric measurement are used to challenge and improve the model of the complete photon chain. It was shown how our model was improved and the agreement with light curve measurement for satellite with a simplified geometry (sphere). However, to be used for the rotation characterisation, the orientation of the satellite in space has to be taken into account, with the computation of the BRDF. It will be useful to fully exploit the database of light curve maintained by Share My Space. This database is built by taking advantage of photometric data extracted from images obtained without tracking. Luminosity variation are detected to indentify candidates for light curve production.

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