Ground-based Optical Observation Methods for Space Situational Awareness at the Astronomical Institute of the University of Bern

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***Abstract* — Due to the recent increase of Resident Space Objects (RSOs), the need for Space Situational Awareness (SSA) is rising. Amongst different measurement techniques, optical observations play a key role to get accurate estimates of the state of RSOs. The Astronomical Institute of the University of Bern (AIUB) has contributed to the SSA community by providing passive and active optical observations via multiple telescopes. In this paper the different measurement techniques, namely astrometry, photometry and satellite laser ranging are explained. The different measurement observables are highlighted and the derived information discussed.**

Keywords — SSA, SLR, space debris, SST, astrometry, photometry

I. Introduction

The rapid increase of Resident Space Objects (RSOs), both operational satellites and space debris, poses significant challenges to the long-term sustainability of space activities [1]. This growth in orbital traffic, particularly in Low Earth Orbit (LEO), heightens the risk of collisions, underscoring the critical need for Space Situational Awareness (SSA) to safeguard space assets.

Optical observation of RSOs is fundamental to SSA, to support functions such as RSO detection and tracking, orbit determination, and collision risk avoidance [2-3]. RSO observation can rely on different types of ground-based and space-based sensors (e.g., telescopes and lasers) which yield distinct data types. Astrometric observations [4-5] can provide precise measurements of an object's position in the sky relative to background stars, typically conducted using ground-based optical telescopes equipped with high-resolution charge-coupled devices (CCDs). Astrometric data accuracy can reach down to 1 arcsecond. Photometric observations [6-7], on the other hand, capture variations in an object's brightness over time, providing insights into its rotation, shape, and surface properties. These observations are conducted using telescopes equipped with photometers or CCDs capable of capturing light intensity across various wavelengths. While photometry can be less demanding in terms of equipment, it may be strongly influenced by factors like phase angle and albedo variations. Finally, satellite laser ranging (SLR) [8-9] is a precise measurement technique which allows for the determination of the distance and velocity of space objects with high precision. Traditionally, laser ranging has been used to track satellites equipped with retroreflectors, providing millimetre-level precision, but advancements have enabled its application to uncooperative targets, such as space debris. However, SLR also faces limitations, such as the need for precise tracking systems to maintain alignment with fast-moving objects.

Several stakeholders contribute to RSO observation worldwide. The US space surveillance network (SSN) [10] is a combination of optical and radar sensors used to support the Joint Space Operations Center’s (JSpOC) mission to detect, track, identify, and catalogue all manmade objects orbiting the Earth. The International Laser Ranging Service (ILRS) [11] coordinates a network of stations that perform satellite laser ranging, delivering high-precision distance measurements essential for tracking and characterizing RSOs. The European Space Agency's Space Safety Program [12] as well as the EU Space Surveillance and Tracking (EU SST) [13-14] programs rely on a wide network of sensors designed to survey and track space objects, thus offering services such as collision avoidance, re-entry analysis, and fragmentation analysis to over 200 organizations, safeguarding more than 500 satellites. The Mini Mega Tortora (MMT) [15] is a wide-field monitoring system with nine channels for optical observations of the sky, operated by

Special Astrophysical Observatory of Russian Academy of Sciences. The research and observations are focused on detecting meteor events, satellites tracking and multi-color data of celestial bodies. The system has the ability to detect objects with brightness level up to 10 magnitude. After the observation, a light curve is constructed, processed and published in online MMT catalogue. Finally, the Indian Space Research Organization's (ISRO) [16] is establishing a network of telescopes and radars across India to monitor space debris and safeguard space-based assets.

Within this global framework, the Astronomical Institute of the University of Bern (AIUB) has provided significant contributions to optical observations for SSA. AIUB operates advanced optical observation systems that have conducted both astrometric and photometric measurements, enhancing the understanding of RSO behaviours and characteristics. The institute's efforts include developing sophisticated data processing techniques to improve orbit predictions and participating in international collaborations to share data and methodologies.

This paper provides an overview of the optical observation activities carried out by AIUB's optical astronomy group until 2024, highlighting their methodologies, achievements, and contributions to advancing space situational awareness. The remainder of the paper is organized as follows. Section 2 provides an overview of the infrastructure available to AIUB as of January 2025. Section 3 and 4 highlight different passive and active optical observation techniques and their uses. In Section 5 conclusions and possible future works are discussed.

II. Infrastructure

AIUB has access to several facilities to enable measurements to RSOs. The Swiss Optical Ground Station and Geodynamics Observatory (SwissOGS) Zimmerwald is located near the city of Bern and operated by AIUB. SwissOGS has multiple telescopes available. The Zimmerwald Laser and Astrometry Telescope (ZimLAT) is a 1 m Ritchey-Chrétien multipurpose instrument that is capable to perform SLR as well as Astrometry and Photometry with its CCD camera. The CCD sensor has a field of view (FOV) of 26 by 26 arcminutes. The telescope ZimMain, an 80 cm Ritchey-Chrétien telescope, can be equipped with a CCD or CMOS camera with an FOV of 38 by 38 or 10.4 by 8.8 arcminutes respectively. ZimMain has been used to perform follow up and survey observations. The telescope ZimSmart is a 20 cm Newtonian telescope with a FOV of 3.5°. Because of the large FOV it has been mostly used for astrometric surveys. Due to the geographical location of Zimmerwald, between 25 and 30% of nights are suited for observations. The time for night observations ranges from 6 hours in summer to 13 hours in winter. Besides the telescopes at SwissOGS, AIUB also plans space debris observations using the 1 m telescope at the ESA optical ground station (OGS) in Tenerife. The telescope at the OGS covers a field of view of 0.7° and the location of the site enables it to detect objects up to magnitudes of 21 [17]. It is used by AIUB for astrometric surveys to catalogue the population of space debris.

III. Passive Optical Observations

Passive optical observations make use of telescopes and CCD or CMOS sensors to image RSOs illuminated by the sun against the dark background of the night sky. These observations can be used to compute an astrometric position of the observed object and determine its orbit or to characterize the object's reflective properties and attitude state. For a perfectly diffuse sphere with diameter d at distance R from the observer, the irradiance received by the observer (i_{obj}) in $[W/m^2]$ is given by (1).

$$i_{obj} = i_{sun} \frac{\pi d^2}{4} \frac{1}{4\pi R^2} \frac{8}{3} \rho_{bond}\, p(\theta) \tag{1}$$

The irradiance is proportional to the solar irradiance at the object i_{sun}, the bond albedo ρ_{bond}, and the phase function $p(\theta)$ which takes the form

$$p(\theta) = \frac{1}{\pi}(\sin\theta + (\pi - \theta)\cos(\theta) \tag{2}$$

for the Lambert sphere. The angle θ between the view direction and the direction of the sun is called phase angle and it indicates how well illuminated an object is in the current observation geometry. Due to the inverse square law passive optical observations are particularly suited for RSOs in MEO or GEO which are costlier to observe with active sensors such as radar.

A. Astrometry

Astrometry, in the context of SSA, is the precise measurement of an RSOs position and velocity via angular measurements (e.g. right ascension and declination) [4]. Astrometry can be performed as a survey or follow-up mode.

For surveys observed with telescopes like the 1 m telescope at OGS, or telescopes like ZimSmart or ZimMain at SwissOGS, the ground-based telescope stares at a fixed point in the sky until an RSO crosses its field of view. Depending on the exposure time of the detector, i.e. the amount of time the sensor is exposed to light sources, the detected object can appear as a streak or as a point which moves between consecutive exposures. Such a streak can be seen in Fig. 1 in the upper half of the image. Since the telescope is tracking a fixed point relative to the orbital regime (e.g. GEO), the stars appear as diagonal streaks from bottom left to top right. The object streak appears almost horizontal in comparison and is also shorter. By determining the relative position of the object with respect to the stars that are also visible in the frame, the position of the object can be determined in celestial coordinates, i.e. right ascension and declination, by utilizing the catalogued position of the stars. In particular, at AIUB the Tycho 2 and the Hipparcos catalog are used for this procedure [17], achieving angular accuracies below one arcsecond. The time series of the angular coordinates corresponding to a sequence of frames is called *tracklet*. The obtained angular coordinates can be utilized, using additional a-priori information (e.g. assuming circular orbit), to perform initial orbit determination (IOD) and to compute the next window of visibility. Additional passes can be used to refine the estimated orbit.

Fig. 1. Example survey frame on ZimMain taken on the 17.02.2024. The detected object is highlighted.

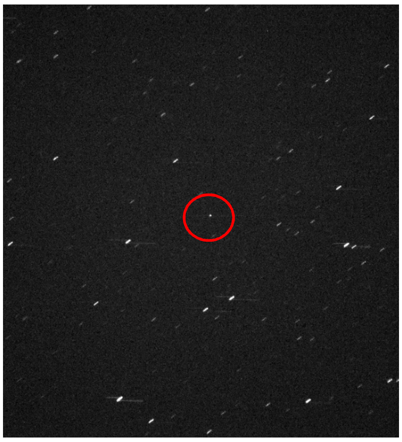

Fig. 2. Example follow-up frame of Navstar 47 taken on the 01.01.2024 by the telescope ZimMain. The stationary object is highlighted.

To determine if a tracklet belongs to an already discovered object, new tracklets are compared against a catalog of other tracklets. Such a strategy is used at ESA's OGS to find new objects in GEO and GTO orbits. The resulting data is used to validate and improve ESA's MASTER-model [18]. Comparing the number of expected observable objects based on the MASTER-model with the number of actually detected objects, allows for an external validation and improvement of the models [19].

If an approximate orbit is already known, for example via IOD, the telescope can instead be tasked with a follow-up observation. The telescope tracks along the RSO estimated orbit, assuming that the tracked object lies within the sensor's FOV. If the object is within the FOV, it appears as a point source within the frame, while background stars appear as streaks, as can be seen in Fig. 2. The image reduction can also process star streaks and use them to compute an astrometric position corresponding to the mid-exposure-time position of the object. The resulting angular coordinates can be used to improve the accuracy of the initial orbit using a least-squares algorithm.
After a new object has been discovered by an OGS-survey with at least three correlated tracklets, follow-up observations may be scheduled at SwissOGS using the telescope ZimLAT.

B. *Photometry*

Tracked observations like those performed for follow-ups can also be reduced to the intensity of the point source over time. In astronomy, the analysis of intensity time series is called photometry. The reduced measurements are referred to as *light curves.* A key parameter affecting photometric data acquisition is the object-Sun-observer relative geometry. In particular, data can be acquired if the object is well illuminated and not near a bright background object such as the moon. For this reason, many targets in the Low Earth Orbit can only be observed at the beginning and at the end of the night as they enter the Earth shadow between these times. For higher orbits, the Earth shadow only occludes a smaller portion of the orbit. Therefore, GNSS or GEO satellites can be observed throughout the night. The process of acquiring a light curve starts with capturing a full-frame image (2048 × 2048 pixels) centered on the coordinates provided by the ephemeris at the beginning of each series. The observer uses this image to find and mark the object on the frame manually. Then, the system performs the subsequent acquisition of subframes with a resolution of 200 × 200 pixels (2.60' × 2.60'), increasing the light curve sampling frequency. For CCD images, typical frequencies range from 0.1 to 1 Hz. Frequencies higher than 10 Hz can be reached using a CMOS sensor installed on the ZimMain Telescope. The exposure time for image acquisition depends on the orbital regime: LEO objects are usually observed using less than 1 sec exposure time while MEO and GEO with at least 1 sec exposure time. As of January 2025, AIUB database contains more than 5000 light curves from more than 550 objects which cover all orbital regions. In particular, circa 44% of the objects are in LEO, 18% in MEO, 31% in GEO and 7.0% on High Eccentric Orbits.

Light curves can be reduced to provide information about the current attitude state of the RSO [20], the time evolution of its spin period and its surface properties. Fig. 3 shows an example of a light curve, in particular of object 2000-061D (of the space-track catalogue).

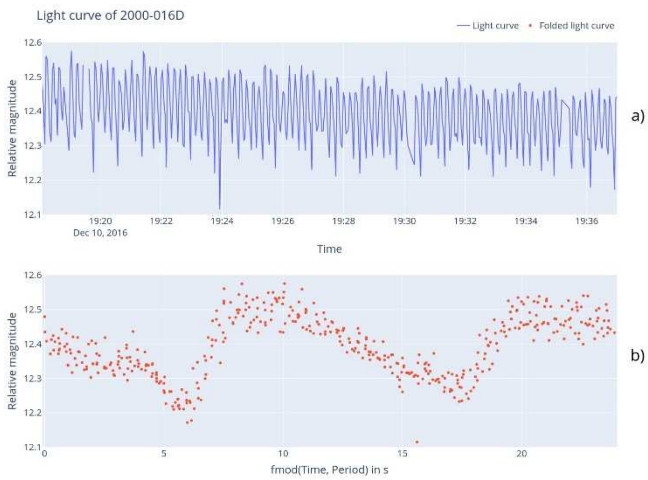

Fig. 3. Example light curve of object 2000-016D (a) and the resulting folded light-curve (b)

If a light curve such as the one shown in Fig. 3a) features an evident periodic pattern, this is a clear indication that the object is in a tumbling mode and an apparent spin period can be estimated. There are several methods to extract the apparent period of rotation from light curves, including the analysis of the frequency content using the FFT, the Lomb-Scargle method [21], as well as phase dispersion minimization [22]. A "folded" light curve is obtained by a modulo transformation of the time axis using the best fitting period, as shown in Fig. 3b). These periodic features can be used in some cases to infer a spin axis [23] and, when multiple light curves are available, to assess the long-term attitude evolution of the RSO.

IV. Active optical observations

In contrast to passive optical observations, where the observed object is illuminated by the sun, active optical observations employ their own source of illumination. Active observation techniques include radar and satellite laser ranging. SLR as well as some forms of radar determine the range to the target via the round-trip time-of-flight of radiation pulses. As the pulses have to travel up to several thousands of kilometers on their round trip and traverse the atmosphere twice, the detected signal can be orders of magnitude weaker than the sent signal-power. Analogous to the radar link equation [24], the number of detected photo-electrons per pulse n_{pe} can be estimated by utilizing the optical link-equation (3) [25] for a given SLR setup. The link-equation uses the detectors quantum efficiency η_q, pulse energy E_p, wavelength λ, transmit efficiency η_t, transmitter gain G_t, optical cross-section σ, telescope aperture A, receive efficiency η_r and the atmospheric transmissivity T_{atm}. h is the Planck constant and c denotes the speed of light in vacuum.

$$n_{pe} = \eta_q \left(E_p \frac{\lambda}{hc}\right) \eta_t G_t \sigma \left(\frac{1}{4\pi R^2}\right)^2 A \eta_r T_{atm}^2 \qquad (3)$$

In contrast to (1), the resulting signal of active optical observations scales with R^{-4}. This makes active optical observations more suitable in orbital regimes closer to Earth like LEO and MEO. At SwissOGS SLR is performed on the ZimLAT telescope.

A. Satellite Laser Ranging

Since 1964 Satellite Laser Ranging has been used to get high accuracy position information for spacecraft applications [26]. The range between an SLR ground station and a suitable RSO is indirectly measured via the round-trip time of flight of a laser pulse. First the laser pulse is emitted from the SLR ground station and is pointed and collimated towards the RSO by an optical telescope. The laser pulse is reflected by the RSO, which in most cases is equipped with corner cube retroreflectors to increase the amount of light back towards the incident direction. The reflected pulse travels back towards the ground station to be detected by a telescope equipped with a single-photon detector capable of discerning optical signals in the single photon regime. Assuming a constant speed of light c_0 along the optical path and that the uplink path is identical to the downlink path, the one-way slant-range R to the RSO can be calculated from the round-trip time of flight τ as:

$$R = \frac{c_0 \tau}{2} \qquad (4)$$

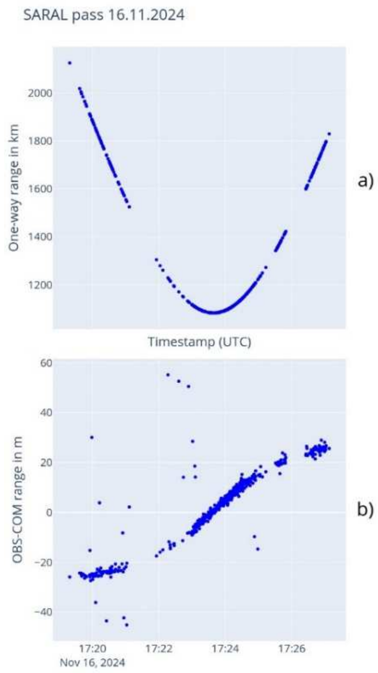

Fig. 4. Example of SLR data from the Satellite Saral observed with a 10 ns laser. a) shows absolute distance measurements, while b) shows the range residuals, with respect to the computed CPF-orbit.

Using short-pulse lasers ($t_{pulse} \approx 30\,ps$), range uncertainties below 1 cm can be achieved [25]. These high-precision ranges can be utilized to improve the accuracies of orbital prediction of satellites [27]. Fig. 4 shows the range measurements to Saral, an oceanography and atmosphere mission operated by the French and Indian space agencies, during a single pass of six minutes. As Saral is part of the scientific missions regularly tracked by the ILRS, up to date orbit predictions are made available. In particular, Fig. 4.a) describes the absolute range to the target over time. As expected, as the satellite rises over the horizon, culminates and sets, the absolute ranges in Fig. 4.a) follow the shape of a parabola, reaching the minimum range at culmination. As a model of the orbital motion is already available to the SLR-station, in the form of a consolidated prediction file (CPF), it is useful to analyze the differences between the observed and computed ranges, as shown in Fig. 4.b). This plot can reveal systematic deviations (time-bias) as well as the fundamental uncertainties of the model (e.g., position of the center of gravity, location of the retroreflectors over the surface of the satellite) and the system setup (e.g. laser pulse length, detector time walk). By aggregating multiple signal data points into a so-called normal point, the files are kept small with a marginal loss of information. This is done by removing any trends from the data, binning along the epoch axis and combining the signal events of one time-bin into one data point. AIUB provides normal-point and full range data to the ILRS, which coordinates the collection of SLR data as well as the calculation of estimated CPF-orbits. The resulting data is utilized in satellite geodesy [28], spacecraft operations [27] or geoscience [29].

Almost all regularly tracked objects by the ILRS are equipped with one or more retroreflectors, to increase the optical cross-section σ in the optical link equation (3). However, most RSOs are not equipped with retroreflectors, and some are no longer attitude-controlled like Envisat, which means retroreflector visibility from the ground station is not guaranteed. For these “non-cooperative” ROSs, σ is dominated by the diffuse reflective properties, which results in a diminished signal. To compensate for the decrease in σ, the pulse energy E_p can be increased [30]. This is especially useful for space debris, to support accurate orbit determination and effective collision avoidance.

V. Conclusion

In this contribution different measurement methods for SSA performed by AIUB until 2024 have been shown and their impact on the wider space community have been highlighted. The infrastructure at OGS and SwissOGS enables active and passive optical measurements, allowing for the characterization of RSOs as well as orbit and attitude estimation. Astrometric measurements with sub-arcsecond accuracy enable the discovery of new RSOs, as well as keeping up-to date orbital information on already known objects. This contributes to the accurate modeling of RSO populations. Photometry enables the estimation of the attitude motion of RSOs via light curves. By observing periodic patterns in the variation of the object's apparent brightness over time, the spin or tumbling rate can be determined. Satellite laser ranging allows highly accurate range measurements to RSOs. By utilizing short pulse lasers with retroreflector-equipped objects, range estimation with uncertainties below 1 cm are possible. AIUB contributes with data to the ILRS, which in turn provides data for a multitude of topics in geoscience. By increasing the optical power of the laser system, RSOs without retroreflectors like space debris can be ranged to providing high accuracy orbital estimates.

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VII. References

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