SPACE SAFETY EXPERT CENTRE: SERVICES FOR THE SSA/STM ECOSYSTEM

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ABSTRACT

The Space Safety Expert Centre, developed within the framework of *ESA*'s Space Safety Programme (S2P) and hosted by the Astronomical Institute at the University of Bern, provides an extensive array of services to address the increasingly complex challenges of space debris. By fostering a robust network of diverse stakeholders and data providers, the Expert Centre is strategically positioned to offer a comprehensive suite of services for the Space Situational Awareness (SSA) and Space Traffic Management (STM) domain. Attitude catalogue service of the Expert Centre plays a pivotal role for the attitude motion characterization of the Resident Space Objects (RSO) based on the ground based observations. This characterization is crucial for the applications such as active debris removal and in-orbit servicing missions. We illustrate this service by presenting results from coordinated observation campaigns involving multiple sensors over the span of a year. These campaigns aimed to acquire more than 400 light curves of at least one hundred RSOs of varying shapes and orbital regimes. Following an overview of the infrastructure used to acquire and analyze these light curves, we discuss a selection of notable cases. Moreover, we summarize two other related services of the Expert Centre –Validation and Qualification (V&Q) of ground based optical sensors that contribute data towards SSA/STM applications and support in standardization of data formats. Recently, the V&Q service has been successfully offered to 21 sensors across the world. We highlight the benefits of this service for the sensor operators and their customers. On the other hand, Expert Centre has undertaken reviews of existing international data format standards and provided recommendations, improvised versions of these standards to aid further analyses based on the raw observation data. As the Expert Centre transitions to a new legal structure, we also outline our roadmap for upcoming developments and present avenues for collaboration, inviting the community to join us in advancing space safety initiatives and becoming a part of the solution for safe and sustainable operations in the space.

Keywords: Expert Centre, Space Safety, Light Curves, Attitude Catalogue, Validation, Qualification..

1. INTRODUCTION

Over past 10 years, Space Safety Expert Centre (hereafter the Expert Centre) has been developed within the European Space Agency's (*ESA*) Space Safety Programme (S2P). It is hosted at the Astronomical Institute, University of Bern (*AIUB*). Its mission is to enhance our understanding of the near-Earth space environment while contributing to a safer and more sustainable operations in space by offering services and support for Space Situational Awareness (SSA) and Space Traffic Management (STM). It facilitates various applications, including tasked tracking, survey, and characterization observations, currently utilizing ground-based passive optical systems, and satellite laser ranging (SLR) stations. These observations are sourced from a diverse sensor network, integrating commercial, academic, research, governmental, and intergovernmental institutions. The Expert Centre is responsible for sensor planning, data quality control, analysis, calibration, and applying format conversions/relevant corrections when necessary. While providing its services to the stakeholders, it oversees the monitoring of Key Performance Indicators (KPIs) as defined in Service Level Agreements (SLAs), ensuring the quality of data procured from several possible sources.

Over last decade, the Expert Centre project has been evolved through different phases of the development, testing, deployment, and operation [1] [2] [3] [4]. As a consequence of such phases, it is capable of offering a range of services tailored to its several stakeholders.

An overview of such services for the SSA/STM ecosys-

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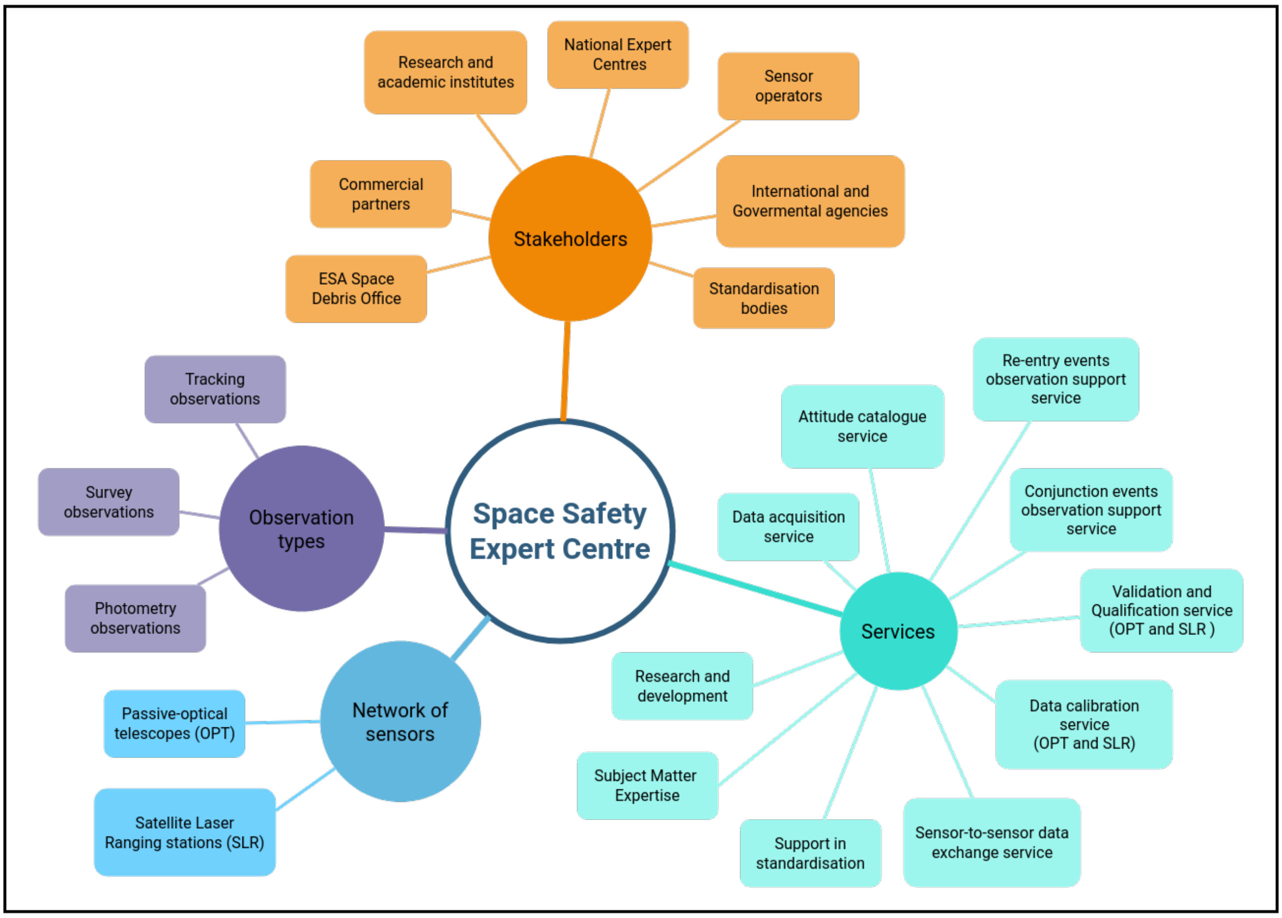

Figure 1. Space Safety Expert Centre: stakeholders, services, network of sensors and observation types [5].

tem is presented in Section 2. In Section 3, the attitude catalogue service of the Expert Centre is presented. In Section 4, a brief overview of Validation and Qualification (V&Q) service is provided while such service is described in details in [5]. Section 5 highlights the support to standardization offered by the Expert Centre. Subsequent section provides the road-map for future of the Expert Centre, with a possibility of increasing its service portfolio. Finally, acknowledgments for this work are presented.

2. OVERVIEW OF SERVICES

Figure 1 shows an overview of various stakeholders, services, types of sensors and observation techniques that the Expert Centre often works with. Current service portfolio of the Expert Centre includes data acquisition and attitude catalogue service for assessing the state or attitude of resident space objects (RSOs), as well as support for re-entry and conjunction event observations. For sensor operators and owners, it provides data quality monitoring services, such as V&Q and data calibration service. For those sensor owners and operators that need a deeper independent investigation of their data reduction software pipelines, hardware infrastructure, the Expert Centre can provide its subject matter expertise support. Additionally, the Expert Centre contributes to the standardization of data formats by reviewing existing standards and proposing improvements. Research and development remain a core aspect of its activities, driving scientific advancements and solutions for space debris-related challenges.

As illustrated in Figure 1, the Expert Centre's services cater to a wide array of stakeholders. In recent years, its primary focus has been on serving its main institutional client, the *ESA* Space Debris Office. However, it has also extended its specialized services to sensor operators who either provide or plan to provide observational data acquired through various Space Surveillance and Tracking (SST) techniques. Along with its affiliation with an academic research institution like *AIUB*, the Expert Centre has also frequently collaborated with other research and academic organizations. Additionally, certain services developed within the Expert Centre are particularly relevant to commercial and private-sector entities operating in the SSA domain. For instance, companies engaged in active space debris removal (ADR) missions benefit significantly from attitude motion characterization of RSOs of interest. Furthermore, the Expert Centre possesses both the expertise and the commitment to collaborate with other National Expert Centres, Centres of Excellence, international organizations, governmental bodies, non-governmental organizations (NGOs), and non-profit organizations — fostering partnerships in standardization efforts, policy-related initiatives, and capacity-building activities.

3. ATTITUDE CATALOGUE SERVICE

3.1. Introduction

With the growing population of space debris, the importance of attitude motion characterization of RSOs across different orbital regimes is widely recognized within the SSA domain. Estimating the rotational properties of these objects — such as spin period, spin-axis orientation, and their long-term evolution — is critical for future ADR and in-orbit servicing missions. Additionally, continuous monitoring is essential to study the long-term effects of various perturbing forces on their attitude motion. Recognizing this need and leveraging years of expertise in this area, the Expert Centre has developed the Attitude Catalogue service.

This service primarily utilizes ground-based observations of high-priority objects, including defunct payloads, rocket bodies, fragmentation debris, and uncorrelated objects detected during coordinated surveys. These observations are compilation of data packets referred to as *light curves*. A light curve is a time-series of discrete measurements of an object's brightness (intensity/magnitude) over a specific observation period [6] — which is typically equal to or shorter than the duration of its visible pass over a given sensor. To ensure comprehensive coverage, the Expert Centre collects observational data from multiple sensors, optimizing observation strategies while performing in-depth analysis of the received light curves data. The results of this analysis are then made available to key stakeholders, including *ESA*, academic researchers, and commercial partners, contributing to improved understanding and monitoring of such objects.

The Attitude Catalogue service is supported by a robust infrastructure, developed through previous *ESA* initiatives. SLAs for data procurement have been established, along with rigorous data quality monitoring procedures. Additionally, relevant software infrastructure has been developed, tested, and deployed to facilitate the storage of both raw observational data and processed results. This infrastructure is designed to be scalable, allowing future adaptations and enhancements. In principle, the Expert Centre can provide primary analysis, for estimated apparent rotation periods, for any selected object of interest as long as its visible (illuminated by Sun with adequate brightness) through its sensor network.

In Section 3.2, few key details about the data procurement and processing using the Expert Centre tools are provided. Section 3.3 then summarizes the results of recent observation campaigns that were coordinated to populate Expert Centre's attitude catalogue, serving as a key demonstration of the Attitude Catalogue service. In Section 3.4, remarks concerning subsequent possible analysis of such acquired data are provided.

3.2. Data procurement and processing

To deliver the Attitude Catalogue service, the Expert Centre coordinates observation campaigns with one or more ground-based optical sensors for a selected list of targets. As outlined earlier, SLAs with sensor owners establish the legal framework for data procurement and define agreed quality metrics. Detailed technical requirements for light curve observations—including data format specifications via an Interface Control Document (ICD) and expected data volume — are communicated to sensor operators. The target list is periodically reviewed based on sensor limitations, target observability, and the required observation timeline. Additionally, key sensor infrastructure details are documented using a sensor description form and stored in the Expert Centre's database.

Once all prerequisites are met, sensor operators schedule observations for the designated targets. The Expert Centre supports this process by providing tasking data (e.g. ephemerides, visibility windows) on a nightly/weekly basis and optimizing observation opportunities over weekly or monthly periods. If necessary and deemed feasible, simultaneous observations from multiple sensors can be requested for the same target. After each observation night, reduced light curve data is transferred to the Expert Centre via a predefined data exchange endpoint (such as the Expert Centre SFTP server). Any additional remarks, especially on the weather conditions during the observation night are also provided by the sensor operators to the Expert Centre.

Upon receiving the observation data, the Expert Centre operator ingests it into the attitude catalogue, incorporating any supplementary remarks. Each light curve is then analyzed, with an initial focus on estimating the apparent rotation period using the Generalized Lomb-Scargle Periodogram method [7]. The results are stored in dedicated database tables within the attitude catalogue for further reference.

The attitude catalogue features a graphical user interface with two interactive dashboards for data visualization. Figure 2 illustrates the dashboard used by Expert Centre operators to inspect each light curve of various objects. This dashboard allows visualization of magnitude information as well as supplementary information such as astrometric angles, elevation, phase angles. Meanwhile, as shown in Figure 3, another dashboard displays variations in estimated apparent rotation periods over time for a given object, providing valuable insights into its attitude evolution.

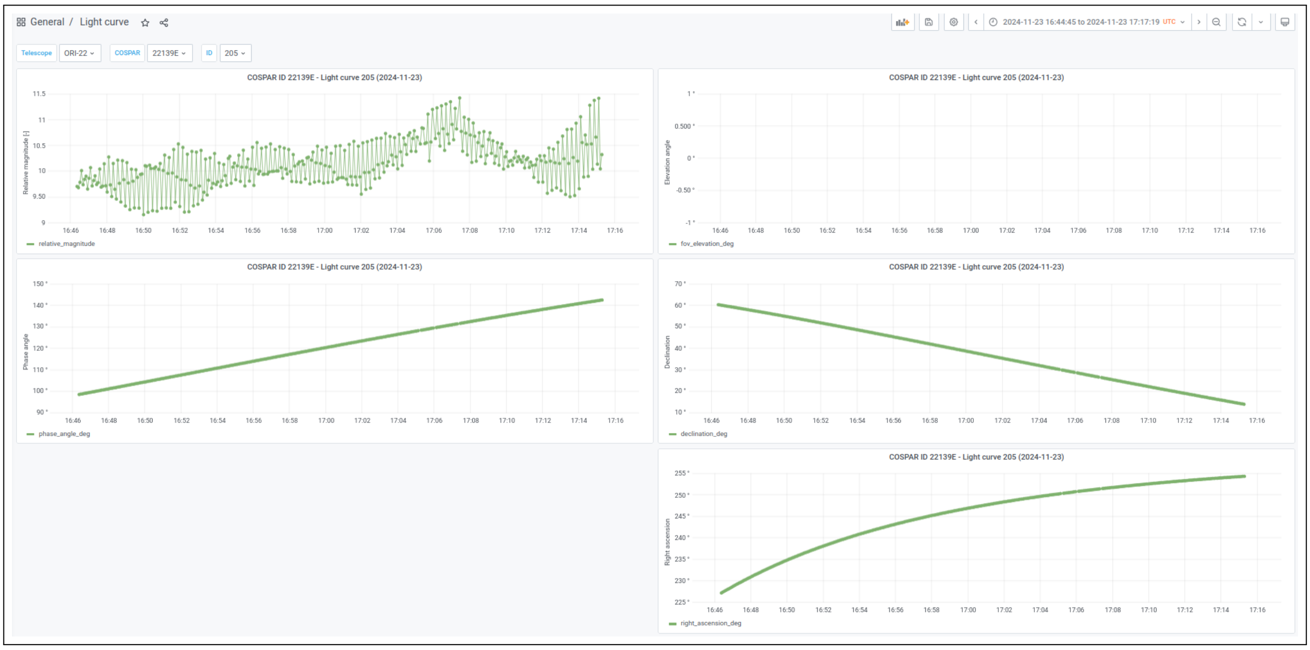

Figure 2. Example of 'Light Curve' dashboard connected to the Expert Centre Attitude Catalogue Database.

Figure 3. Example of 'Rotational Period' dashboard connected to the Expert Centre Attitude Catalogue Database.

3.3. Observation Campaigns

This section presents the results of recent light curve observation campaigns coordinated by the Expert Centre. Following these observations, the attitude catalogue was updated with acquired light curves and the corresponding analysis results. The campaigns began in December 2023 and were conducted in three phases: build-up, maintenance, and priority. Each phase progressively focused on a smaller subset of targets that exhibited intriguing attitude motion characteristics. Table 1 summarizes the key specifications of the sensors involved in the first two phases of these campaigns.

For these observation campaigns, more than 150 RSOs of varying shapes and sizes[1], located across different orbital regimes[2], were selected as targets of interest. The following list outlines some of the key categories of selected targets. As seen, rocket bodies from multiple launch vehicles were included, along with payloads from various Global Navigation Satellite System (GNSS) constellations, such as Global Positioning System (*GPS*), *Galileo*, Global'naya Navigatsionnaya Sputnikovaya Sistema (*GLONASS*), and *BeiDou*.

- *Fregat* upper stage rocket bodies from *Soyuz* launch vehicle
- Rocket bodies from *Falcon 9* launch vehicle
- *SL-14* rocket bodies from *Tsyklon-3* launch vehicle
- Rocket bodies from *Pegasus* launch vehicle
- Rocket bodies from *Ariane 3/4/5* launch vehicles
- Rocket bodies from *H-2A* launch vehicle
- *GPS* satellites
- *Galileo* satellites
- *GLONASS* satellites
- *BeiDou* satellites
- Communication satellites such as *TDRS*[3], *Astra*, *Gorizont*

In total, more than 300 light curves were acquired for targets of interest such as above, since December 2023 until beginning of March 2025. Observation campaigns are still ongoing with particular focus on acquiring data using CMOS sensors (which provide higher sampling rate) during the priority phase.

[1] This information is obtained from [8].
[2] Orbital regime definitions follow those provided in [9].
[3] Tracking and Data Relay Satellite System

Table 1. Sensors currently participating in the observation campaigns coordinated for the Attitude Catalogue service provision by the Expert Centre.

Sensor name	Owner/operator	Observatory	Field of View [degrees]	Aperture [m]
AGO70	Faculty of Mathematics, Physics, and Informatics at Comenius University, Bratislava	Astronomical and Geophysical Observatory, Modra	0.475 x 0.475	0.7
ORI-22	Group of Astrodynamics for the Use of Space Systems (*GAUSS*) S.r.l.	ISON-Castelgrande Observatory, Castelgrande	4.0 x 4.0	0.22
ZimLAT-CCD	*AIUB*	Swiss Optical Ground Station and Geodynamics Observatory, Zimmerwald	0.22 x 0.22	1.0

In following sub-sections, some selected cases of acquired light curves and their analysis for the apparent rotation periods are highlighted. Sensor operators of *ORI-22* and *ZimLAT-CCD* sensor often provided outcome of their own analysis while providing observation data to the Expert Centre. Such an analysis by the sensor operator of *ORI-22* sensor was primarily based on the Phase Dispersion Minimization method [10] or sometimes the Lomb-Scargle Periodogram [11]. Sensor operator of *ZimLAT-CCD* sensor also provided outcome of independent analysis based on the Phase-diagram reconstruction method [6]. In following sub-sections, various targets are referred by their name and in brackets first international designator (i.e. COSPAR[4] ID) is listed, followed by associated NORAD[5] ID.

3.3.1. *Fregat* upper stage rocket bodies

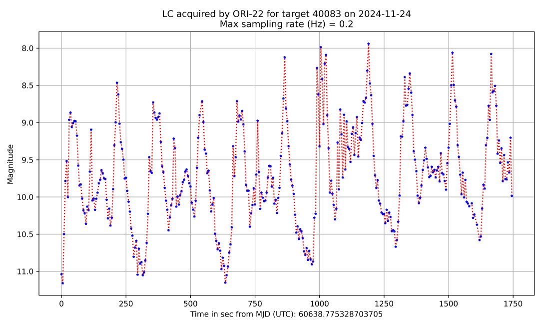

Figure 4. Light curve acquired for Fregat R/B (NORAD 40083) during the observation night of 2024-11-24 by ORI-22 sensor.

In this section, light curves for a particular *Fregat* rocket body are presented. Figure 4 and Figure 5 show the acquired light curves for '*Fregat* R/B (2014-038E/40083)' by the *ORI-22* sensor. This rocket body

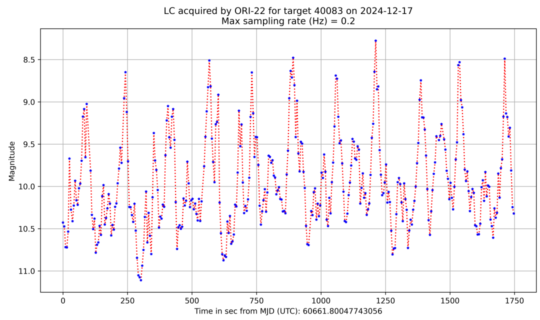

Figure 5. Light curve acquired for Fregat R/B (NORAD 40083) during the observation night of 2024-12-17 by ORI-22 sensor.

is in Medium Earth Orbit (MEO) and it has irregular shape (width/depth of 3.3 m and height of 1.7 m). Acquired light curves indicate that the rocket body is spinning. Sensor operator estimated apparent rotation periods as 324.25 seconds and 325.2 seconds respectively. Expert Centre's analyses led to estimated periods of 161.574 ±7.496 seconds and 163.271 ±6.112 seconds respectively. As per a prior work that tested different methods for spin period extraction [12], for rotation periods up to 40% of the observation duration (length of the light curve), the Lomb-Scargle algorithm has been found to detect period value or half of such value.

3.3.2. *Falcon-9* rocket bodies

One of the *Falcon-9* rocket body of interest was '*Falcon-9* R/B (2022-174C/54757)'. Figure 6 and Figure 7 show the light curves acquired for this target by *ZimLAT-CCD* sensor during early 2024. This rocket body is in MEO and it has cylindrical shape (diameter of 3.66 m and span/height of 15.53 m). Acquired light curves indicate that the rocket body is spinning. Sensor operator estimated apparent rotation periods as 135.4 seconds and 131.55 seconds respectively. In close agreement with such analy-

[4] Committee on Space Research
[5] North American Aerospace Defense Command

ses, Expert Centre's analyses led to estimated periods of 137.376 ±6.886 seconds and 132.292 ±19.884 seconds respectively. For the first light curve, sudden drop in the magnitude can be attributed to lower elevation of the target towards the end of observation duration.

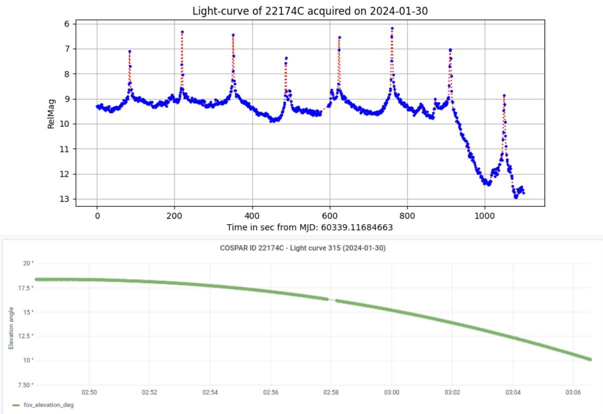

Figure 6. (Top) Light curve acquired for Falcon-9 R/B (NORAD 54757) during the observation night of 2024-01-29 by ZimLAT-CCD sensor. (Bottom) Elevation vs time during the observation duration.

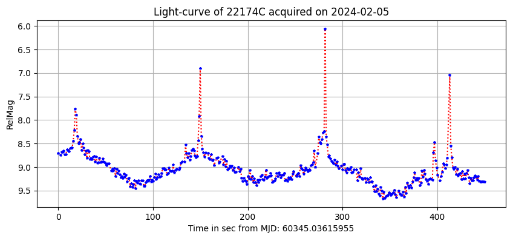

Figure 7. Light curve acquired for Falcon-9 R/B (NORAD 54757) during the observation night of 2024-02-04 by ZimLAT-CCD sensor.

Another target of interest was '*Falcon-9* R/B (2021-001B/47307)'. Figure 8 and Figure 9 show the light curves acquired for this target by *ZimLAT-CCD* sensor during April 2024. Although it has same shape and dimensions as '*Falcon-9* R/B (2022-174C/54757)', this rocket body is in Highly Eccentric Earth Orbit (HEO). Sensor operator estimated apparent rotation periods as 157.913 seconds and 158.25 seconds respectively. On the other hand, Expert Centre estimated periods of 79.251 ±2.699 seconds and 79.213 ±2.367 seconds respectively.

3.3.3. *SL-14* rocket bodies

Two *SL-14* rocket bodies are shown as examples for this category of targets. Figure 10 and Figure 11 show the light curves acquired for '*SL-14* R/B (1996-009G/23793)' and '*SL-14* R/B (1987-068B/18313)' respectively. Both of these rocket bodies are in Low Earth Orbit (LEO), and have cylindrical shape (diameter of

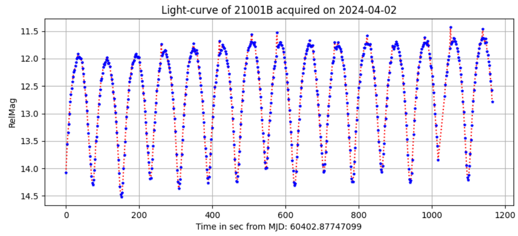

Figure 8. Light curve acquired for Falcon-9 R/B (NORAD 47307) during the observation night of 2024-04-02 by ZimLAT-CCD sensor.

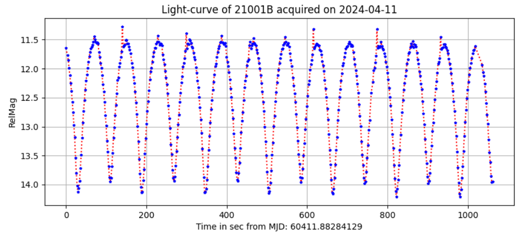

Figure 9. Light curve acquired for Falcon-9 R/B (NORAD 47307) during the observation night of 2024-04-11 by ZimLAT-CCD sensor.

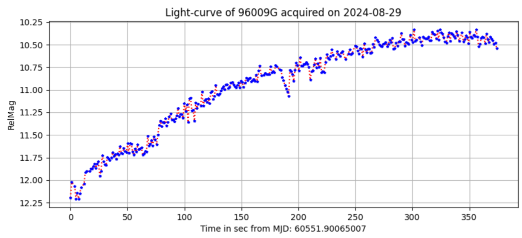

Figure 10. Light curve acquired for SL-14 R/B (NORAD 23793) during the observation night of 2024-08-29 by ZimLAT-CCD sensor.

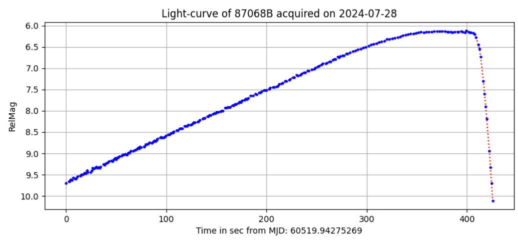

Figure 11. Light curve acquired for SL-14 R/B (NORAD 18313) during the observation night of 2024-07-28 by ZimLAT-CCD sensor.

2.4 m and span/height of 2.7 m). Acquired light curve seemed 'stable' - without indicating any apparent rotation period (when independently analyzed by the sensor operator and by the Expert Centre). Simple signal present in these light curves, seen when visually inspected, is the result of changing phase and elevation angles for the target during the observation duration. For the second light curve, sudden drop in the magnitude can be attributed to target's entrance into Earth's shadow towards the end of observation duration.

3.3.4. *Ariane 5* rocket bodies

One of the *Ariane 5* rocket body of interest was '*Ariane 5* R/B (2016-069E/41863)'. Figure 12 and Figure 13 show the light curves acquired for this target by *ZimLAT-CCD* sensor while Figure 14 shows the light curve acquired by *ORI-22* sensor. This rocket body is in Navigation Satellites Orbit (NSO)/MEO, and has cylindrical shape with a cone (diameter of 3.9 m and span/height of 4 m). For the light curve shown in Figure 12, sensor operator estimated period of 4.361 seconds, while the Expert Centre estimated period of 4.3606 ±0.0065 seconds. In this figure, outcome of analysis by the Expert Centre is also shown as an example.

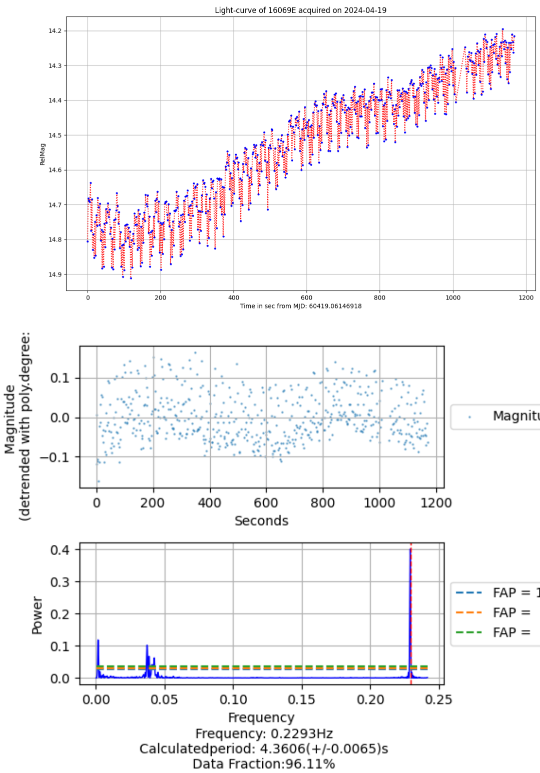

Figure 12. (Top) Light curve acquired for Ariane 5 R/B (NORAD 41863) during the observation night of 2024-04-18 by ZimLAT-CCD sensor. (Bottom) Outcome of power-frequency analysis using the Generalised Lomb-Scargle Periodogram.

Following the first light curve, further observations of this rocket body also indicated that it is a fast rotator object. For the light curve shown in Figure 13, sensor operator and the Expert Centre estimated periods of 4.364 seconds and 4.362 seconds respectively. For the light curve shown

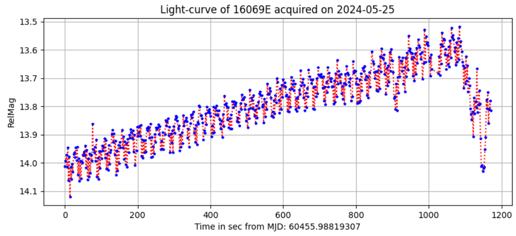

Figure 13. Light curve acquired for Ariane 5 R/B (NORAD 41863) during the observation night of 2024-05-25 by ZimLAT-CCD sensor.

in Figure 14, another sensor operator and the Expert Centre estimated periods of 4.36 seconds and 16.934 seconds respectively.

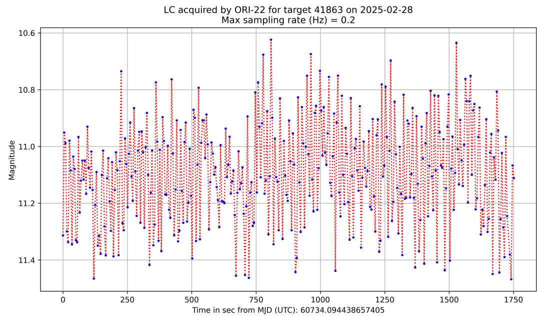

Figure 14. Light curve acquired for Ariane 5 R/B (NORAD 41863) during the observation night of 2025-02-27 by ORI-22 sensor.

Moreover, another *Ariane 5* rocket body was also observed - '*Ariane 5* R/B (2020-005D/45029)'. This rocket body is in LEO-MEO Crossing Orbit (LMO), and has cylindrical shape with a nozzle (diameter of 5.45 m and height/span of 7 m). Figure 15 shows a light curve acquired for it by *ZimLAT-CCD* sensor. For such a light curve, sensor operator estimated period of 2.919 seconds, while the Expert Centre estimated period of 6.333 ±0.127 seconds. Further observations (not shown here) and analysis also led to the conclusion that this target is a fast rotator object.

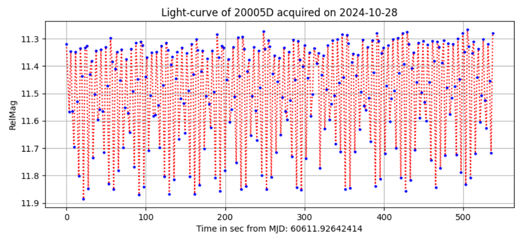

Figure 15. Light curve acquired for Ariane 5 R/B (NORAD 45029) during the observation night of 2024-10-28 by ZimLAT-CCD sensor.

3.3.5. *H-2A* rocket bodies

As an example of *H-2A* rocket body, light curves are shown in this section for '*H-2A* R/B (2006-004B/28938)'. This rocket body is in LMO, and has cylindrical shape (diameter of 4 m and span/height of 9.2 m). During the initial build-up phase, light curves for this object were acquired only by *ORI-22* sensor and these are shown in Figure 16 and Figure 17. Sensor operator estimated periods of 287.63 seconds and 284.36 seconds respectively based on these light curves. In close agreement with such results, Expert Centre's independent analyses led to periods of 289.726 ±15.923 seconds and 281.935 ±22.885 seconds respectively. Due to such interesting outcome, the target was selected for further observations under the subsequent maintenance phase, to be observed by *AGO70* sensor.

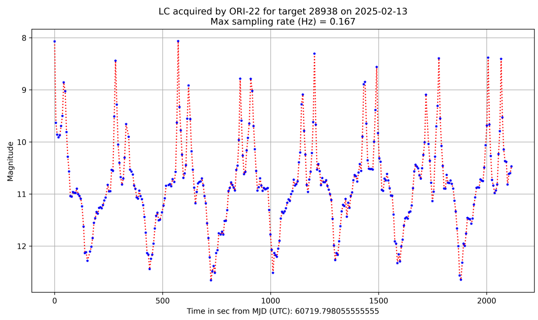

Figure 16. Light curve acquired for H-2A R/B (NORAD 28938) during the observation night of 2025-02-13 by ORI-22 sensor.

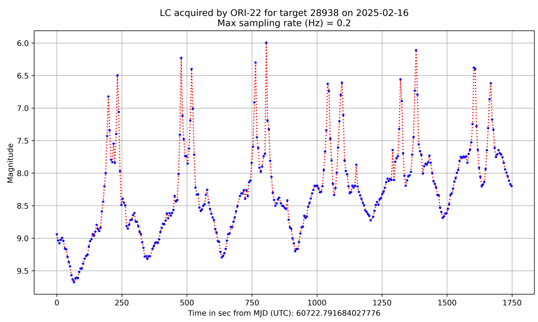

Figure 17. Light curve acquired for H-2A R/B (NORAD 28938) during the observation night of 2025-02-16 by ORI-22 sensor.

Figure 18 and Figure 19 show the light curves acquired for '*H-2A* R/B (2006-004B/28938)' by *AGO70* sensor. Expert Centre's analyses for these light curves led to periods of 153.826 ±10.164 seconds and 158.482 ±10.335 seconds respectively. More observations are foreseen for this target during the subsequent phase of observations. Further characterization of rotation axis orientation for such rocket body is also possible, given its shape and reflective properties of various surfaces.

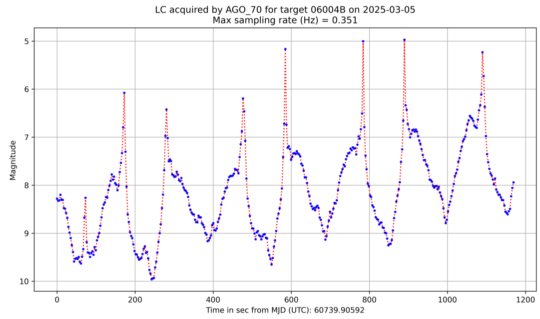

Figure 18. Light curve acquired for H-2A R/B (NORAD 28938) during the observation night of 2025-03-05 by AGO70 sensor.

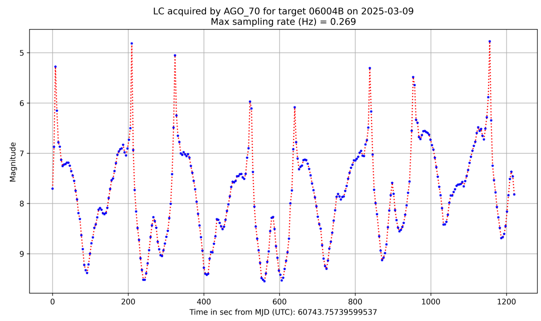

Figure 19. Light curve acquired for H-2A R/B (NORAD 28938) during the observation night of 2025-03-09 by AGO70 sensor.

3.3.6. *GPS* satellites

One of the *GPS* satellites of interest was '*NAVSTAR 31* (1993-017A/22581)'. This is an inactive/retired *GPS* satellite in NSO/MEO regime with box-wing[6] shape (width/depth of 1.8 m, span of 5.3 m, and height of 2.4 m). Figure 20 and Figure 21 show the light curves acquired for this payload by *ORI-22* sensor during November 2024. While for the first light curve, neither sensor operator nor the Expert Centre could reliably estimate any period, the second light curve led to estimated period between 7.479 and 7.488 seconds by the sensor operator, and a period value of 15.453 ±0.231 seconds was estimated by the Expert Centre.

Due to such interesting outcome, the target was selected for further observations under the subsequent maintenance phase, to be observed again by *ORI-22* sensor. Figure 22 shows the light curve acquired recently for this target. Although sensor operator could not estimate any period value, Expert Centre's analysis led to estimated period of 16.962 ±3.452 seconds.

An example of light curve acquired for active/operational *GPS* satellite - viz. '*NAVSTAR 65* (2010-022A/36585)' - is shown in Figure 23. This payload is in NSO/MEO regime with box-wing shape but different dimensions

[6]Box and two solar-panels.

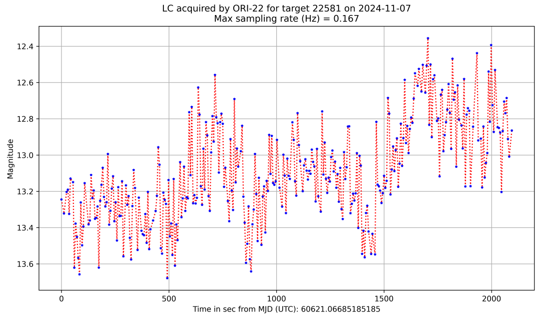

Figure 20. Light curve acquired for NAVSTAR 31 during the observation night of 2024-11-06 by ORI-22 sensor.

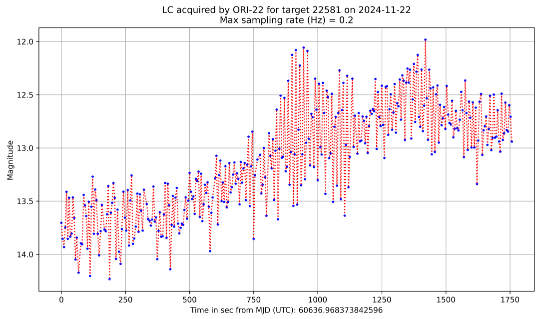

Figure 21. Light curve acquired for NAVSTAR 31 during the observation night of 2024-11-22 by ORI-22 sensor.

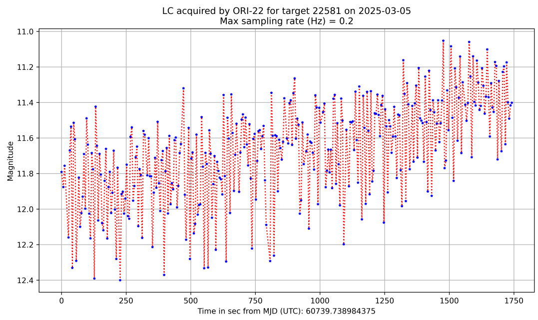

Figure 22. Light curve acquired for NAVSTAR 31 during the observation night of 2025-03-05 by ORI-22 sensor.

(width/depth of 1.8 m, span of 18 m, and height of 2.5 m). However, its light curve seems to be 'stable' and such a behavior is expected for 3-axis stabilized spacecraft. Neither sensor operator nor the Expert Centre could estimate any period based on this observed light curve. Simple signal present in this light curve, seen when visually inspected, is the result of changing phase and elevation angles for the target during the observation duration.

3.3.7. *Galileo* satellites

As an example of *Galileo* satellites, light curves are shown in this section for '*GIOVE-A* (2005-051A/28922)'.

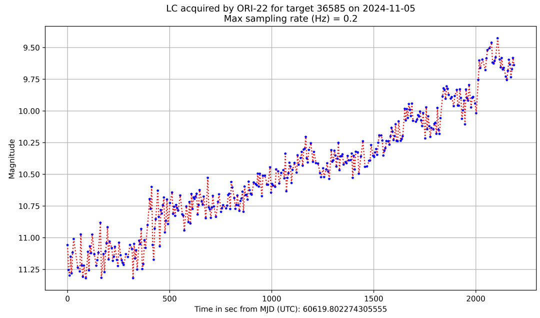

Figure 23. Light curve acquired for NAVSTAR 65 during the observation night of 2024-11-05 by ORI-22 sensor.

This is an inactive/retired *Galileo* satellite in NSO/MEO regime with box-wing shape (width/depth of 1.8 m, span of 11 m, and height of 1.3 m). Figure 24 and Figure 25 show the light curves acquired for this target by *ORI-22* and *AGO70* sensors respectively. For the first light curve, sensor operator reported estimated period value of 1204.8 seconds. Expert Centre's analysis based on first light curve led to estimated period value of 301.466 ±10.407 seconds. For the second light curve, period value of 265.455 ±29.199 seconds was estimated by the Expert Centre. Another light curve (not shown here), with observation duration over 40 minutes, also led to estimated apparent rotation period of 275.135 ±9.306 seconds.

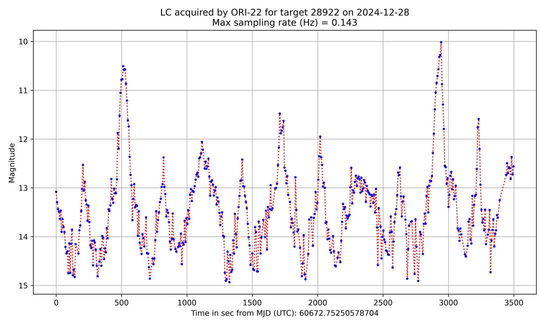

Figure 24. Light curve acquired for GIOVE-A during the observation night of 2024-12-28 by ORI-22 sensor.

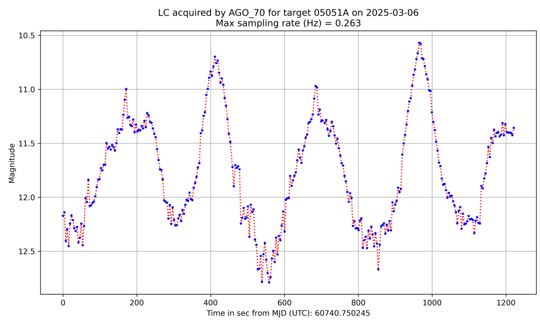

Figure 25. Light curve acquired for GIOVE-A during the observation night of 2025-03-06 by AGO70 sensor.

3.3.8. *GLONASS* satellites

Satellites of the *GLONASS* constellation were other targets of interest, and two examples are described in this section. '*COSMOS 1413* (1982-100A/13603)' is retired/inactive *GLONASS* payload in NSO/MEO regime. It has cylindrical shape with 2 solar panels (span of 8.356 m, diameter of 1.01 m, and height of 3.47 m). Figure 26 and Figure 27 show the light curves acquired for this target by *AGO70* sensor during January 2025. Expert Centre's analyses for the apparent rotation period revealed that this is a fast rotator object, with estimated periods of 10.905 ±0.053 seconds and 10.935 ±1.8237 seconds respectively.

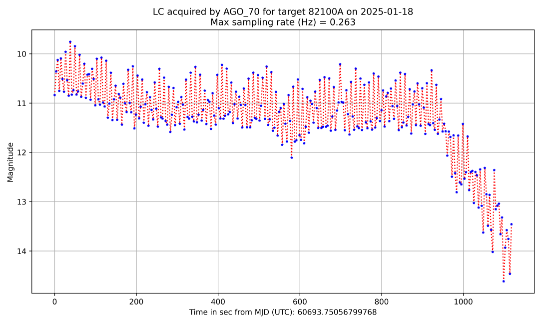

Figure 26. Light curve acquired for COSMOS 1413 during the observation night of 2025-01-18 by AGO70 sensor.

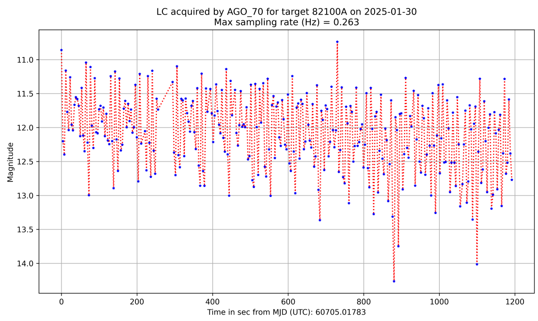

Figure 27. Light curve acquired for COSMOS 1413 during the observation night of 2025-01-29 by AGO70 sensor.

On the other hand, observations were also coordinated for another retired/inactive *GLONASS* payload - '*COSMOS 1520* (1983-127B/14591)'. Two light curves acquired for this target during November 2024 by *AGO70* sensor are shown in Figure 28 and Figure 29. This target is in the same orbital regime and has same shape and dimensions as that of *COSMOS 1413*. However, Expert Centre's analyses for the apparent rotation period revealed that this is comparatively slower rotating object, with estimated periods of 222.943 ±20.436 seconds and 223.296 ±16.631 seconds respectively.

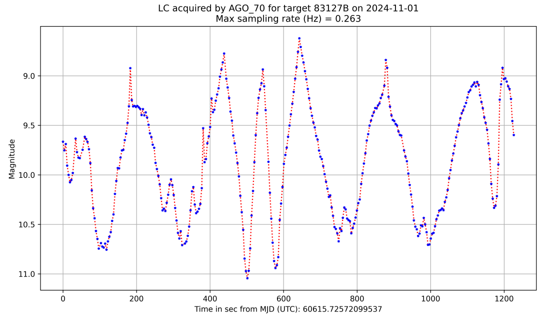

Figure 28. Light curve acquired for COSMOS 1520 during the observation night of 2024-11-01 by AGO70 sensor.

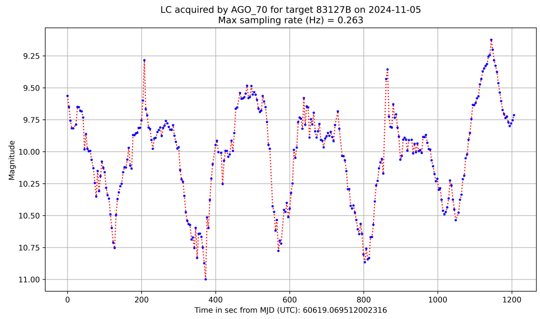

Figure 29. Light curve acquired for COSMOS 1520 during the observation night of 2024-11-04 by AGO70 sensor.

3.3.9. *BeiDou* satellites

As an example of *BeiDou* satellites, light curves are shown in this section for '*Beidou 1B* (2000-082A/26643)'. This is an inactive/retired *BeiDou* satellite in Extended Geostationary Orbit (EGO) with box-shape and one panel (width/depth/height of 3 m, and span of 6 m). Figure 30 and Figure 31 show the light curves acquired for this target by *ZimLAT-CCD* and *ORI-22* sensors respectively. For these three light curves, sensor operators reported estimated apparent rotation periods of 30.12 seconds, 30.157 seconds, and 30.157 seconds respectively. The Expert Centre estimated apparent rotation period of 7.528 ±12.738 seconds for light curve shown in Figure 30. For the two light curves acquired during the night of 2024-10-30, periods of 29.657 ±0.2904 seconds and 30.179 ±0.1502 seconds were estimated respectively. Figure 30 also shows an example of phase-diagram generated by the sensor operator of *ZimLAT-CCD* during the analysis using Phase-diagram reconstruction method.

3.3.10. Communication satellites

As examples of light curves acquired and analyzed for the communication satellites, we discuss two cases - for one of the *Gorizont* satellites and the *AMC-5* satel-

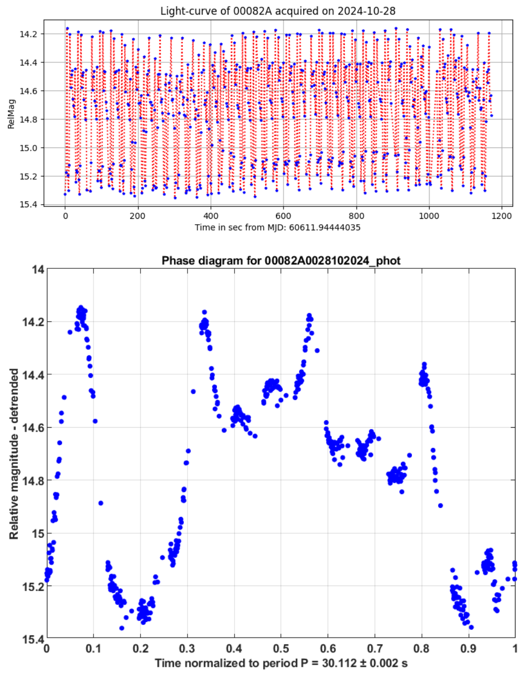

Figure 30. (Top) Light curve acquired for Beidou 1B during the observation night of 2024-10-28 by ZimLAT-CCD sensor. (Bottom) Phase-diagram generated during the analysis of acquired LC by the sensor operator.

lite. '*Gorizont 3* (1979-105A/11648)' is a decommissioned Russian civil communications satellite. It is in EGO/Geostationary Orbit (GEO), and has a cylindrical shape with two panels (height of 5.44 m, diameter of 3.3 m, and span of 9.5 m). Two light curves were acquired for this target by the *AGO70* sensor on two consequent nights, as shown in Figure 32 and Figure 33. Expert Centre's analysis led to apparent rotation periods of 28.344 ±0.2758 seconds and 28.32 ±0.2678 seconds respectively based on these light curves.

On the other hand, '*AMC-5/GE-5* (1998-063B/25516)' is retired commercial communications satellite, currently in EGO orbital regime. It has box-wing shape (width/depth of 1.6 m, height of 2.2 m, and span of 22.4 m). Two light curves were also acquired for this target by the *AGO70* sensor in January 2025, as shown in Figure 34 and Figure 35. Expert Centre's analysis led to apparent rotation periods of 105.311 ±4.5477 seconds and 104.244 ±3.5377 seconds respectively based on these light curves.

3.4. Follow-up analysis

In this work, only the results of primary analysis for the apparent rotation periods based on light curves are shown. In certain cases, even further characterization of attitude motion is possible for the RSO, given known information about its shape (e.g. availability of 3D model), surface properties, precise/reference orbits etc. The pos-

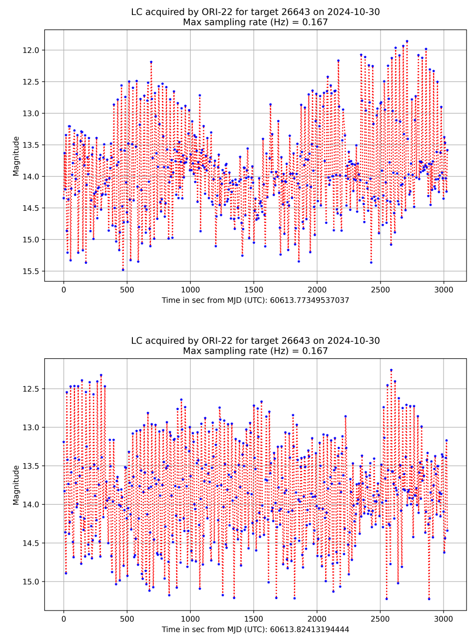

Figure 31. Two light curves acquired for Beidou 1B during the observation night of 2024-10-30 by ORI-22 sensor.

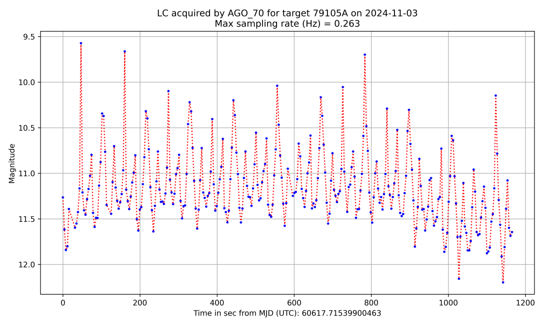

Figure 32. Light curve acquired for Gorizont 3 during the observation night of 2024-11-03 by AGO70 sensor.

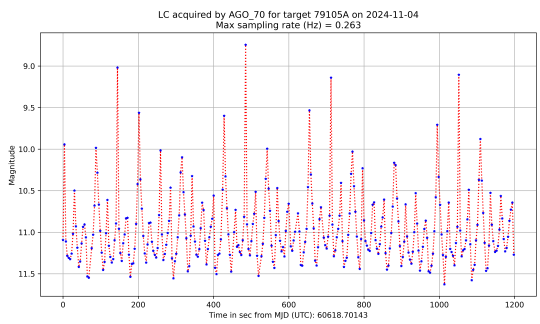

Figure 33. Light curve acquired for Gorizont 3 during the observation night of 2024-11-04 by AGO70 sensor.

sibility of such analysis is decided case-by-case and often driven by the scientific interest for research on attitude

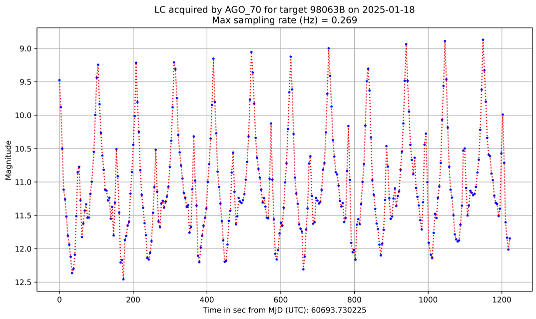

Figure 34. Light curve acquired for AMC-5/GE-5 during the observation night of 2025-01-18 by AGO70 sensor.

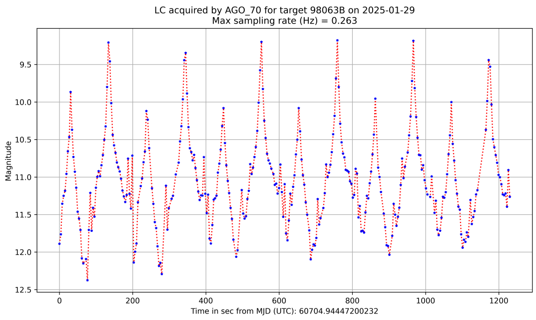

Figure 35. Light curve acquired for AMC-5/GE-5 during the observation night of 2025-01-29 by AGO70 sensor.

determination algorithms or by the requirements of various stakeholders that the Expert Centre works with. For example, a number of light curves acquired in the aforementioned observation campaigns were used for the research on attitude determination algorithms, which was part of the same *ESA* activity.

4. V&Q SERVICE

The V&Q service is one of the core functions of the Expert Centre, ensuring the data quality and format compliance of a sensor's observations for applications in the SSA/STM domain. The Expert Centre acts as an independent data quality auditor, coordinating observation campaigns and providing technical support to sensor operators for data calibration, quality assurance, and formatting compliance based on international standards.

With increasing congestion in near-Earth space, accurate and reliable orbital data is essential to prevent collisions that could endanger space assets, navigation, communication services, and human spaceflight. Independent data quality assessment by the Expert Centre helps to maintain consistency across multiple sources, reducing errors and improving decision-making. The Expert Centre offers V&Q services for various observation types and techniques used to characterize RSOs via ground-based sensors. Four variants of such V&Q service are currently offered:

- Tasked tracking (follow-ups) of RSOs in MEO and GEO
- Photometry (light curve) observations for RSOs in LEO, MEO, and GEO
- Surveys of RSOs in the GEO ring
- Space Debris Laser Ranging observations

A comprehensive description of the various V&Q variants is provided in [5], which also highlights the provision of this service to 21 different sensors. For light curve data, the service is referred to as Validation and Characterization (V&C) due to technical reasons. Figure 36 illustrates the standard road-map for the V&Q process applicable to any candidate sensor seeking to participate in these observation campaigns. During the campaigns, sensor operators receive prompt feedback after each observation night, following the reception and analysis of the acquired dataset. At the conclusion of V&Q campaigns, a comprehensive report is provided, detailing the analyses conducted across multiple observation nights and summarizing key findings and high-level conclusions. Additionally, a *Certificate of Qualification* is issued, aptly summarizing the sensor's performance and the criteria for which it has been qualified. These documents serve as valuable assets for sensor operators, enabling them to showcase their infrastructure capabilities to potential customers and systematically audit their data reduction pipelines for quality assurance.

From the perspective of sensor operators, some of the key benefits of the V&Q service are as follows [5]:

- Accelerated customer validation
  Expert Centre's independent and neutral qualification process reduces the time needed for customer-specific validation, allowing for faster integration between sensor operators and data users. This minimizes delays caused by extended validation campaigns, as the ground based observations are often affected by unfavorable weather conditions.
- Improved system development
  Expert Centre provides valuable feedback on data accuracy, system stability, and operational scenarios, helping sensor operators refine their processes to meet the expected customer requirements.
- Increased operational readiness
  By simulating real-world challenges and high-performance standards, the V&Q campaigns prepare sensor operators for diverse customer demands, ensuring their data meets stringent quality expectations.

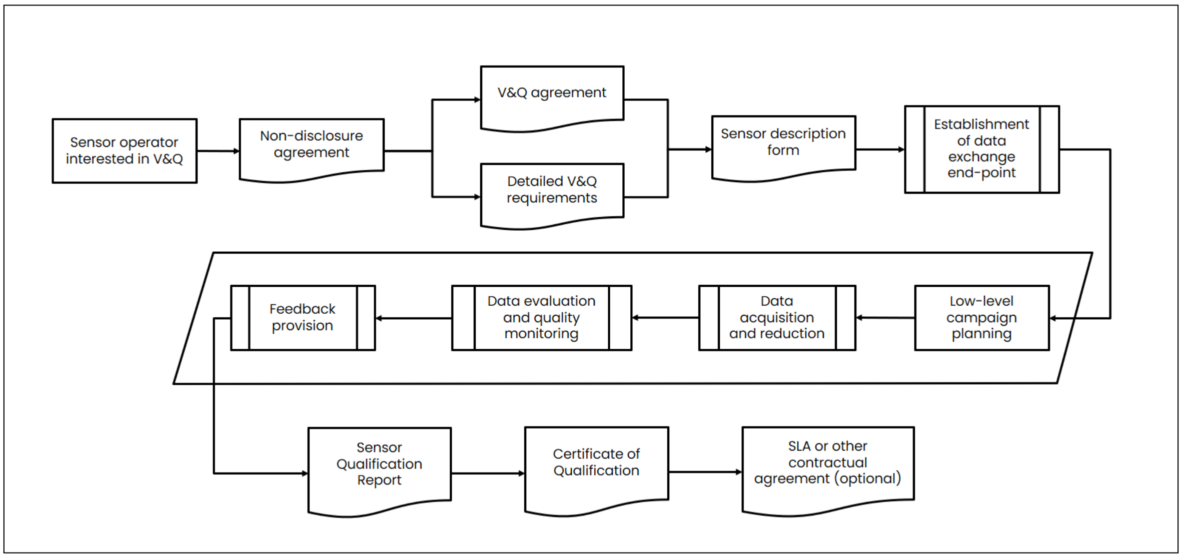

Figure 36. Road-map for the Validation and Qualification service offered by the Expert Centre.

5. SUPPORT TO STANDARDIZATION

One of the other services of the Expert Centre is the support offered for the standardization of various elements such as data formats. The Expert Centre collaborates with various stakeholders such as institutional customers (e.g. *ESA*), sensor operators, satellite operators, etc. to define new data format standards or to revise existing data format standards in order to increase the scientific/operational benefits of using captured metadata and data. Such standardization support can also extend beyond data format standards, applying it to various procedures and practices followed specifically in the SST domain.

In the context of ongoing *ESA* activity, a particular exercise was undertaken to review the existing data format standards relevant to exchange of light curve observation data. First part of such an exercise focused on the review of Tracking Data Message (TDM) v2.0 data format as defined by Consultative Committee for Space Data Systems (CCSDS) [13]. After a thorough review, an extended version of this data format was formulated and an ICD was created. ICD for this extended version - referred to as 'ExpCen-TDM' format - was then shared with various sensor operators providing light curve observation data. Based on the feedback received from the sensor operators, minor errors in the ICD were fixed, clarifications were added at some places, and a format validation tool was also implemented. 'ExpCen-TDM' format essentially provides additional keywords in the data and metadata section of the TDM, that can capture values for additional parameters of interest for the light curve analysis. For example, it allows provision of time-series of phase angle values, which can be quite useful to understand & analyze brightness variations apart from those due to inherent attitude motion of the object. A sensor operator providing data using this data format standard can also provide uncertainty information about estimated magnitudes, uncertainty characterization procedure, calibration information etc.

Second part of the exercise focused on yet another data format standard for the exchange of light curves. In one of the previous *ESA* activities, a data format for the light curve observation data exchange, as recommended by the Inter-Agency Space Debris Coordination Committee (IADC) was selected for ingesting the raw observation data into Expert Centre's attitude catalogue database. However, during implementation, it was also realized that IADC's recommended data format standard can accommodate few minor changes to enhance it further. In this activity, such improved version was clearly defined and referred to as 'ExpCen-IADC' format standard. ICD was formulated, and appropriate conversion tools were also implemented. Similar to 'ExpCen-TDM' format, it also provides additional keywords in the data and metadata section and it is well suited for quick reading by a human operator.

It should be noted that standardization exercise for the data format standards also compliments the validation of various candidate sensors by the Expert Centre. For example, all sensors mentioned in this work, first participated in the V&C campaigns for light curve observations as coordinated by the Expert Centre. During the validation phase, it was confirmed that they can provide reduced light curve data in a valid 'ExpCen-TDM' or 'ExpCen-IADC' format standard. After successful validation and characterization, these sensors contributed to the observation campaigns mentioned in Section 3.3.

6. ROADMAP FOR FUTURE

The Expert Centre is currently exploring future possibilities and actively pursuing collaborations with various community partners. Having successfully completed its development & deployment under the *ESA* S2P, it is now equipped with the necessary infrastructure and operational expertise to offer its services under a commercial model. Currently undergoing a transition in its legal structure, the Expert Centre aims to maintain its focus on its core mission — delivering independent, unbiased quality assessments. By doing so, it aims to support sensor operators, academic institutions, governmental bodies, institutional and private sector clients in ensuring high-quality SST data. The Expert Centre seeks to leverage the knowledge of its experts, having over 30 years of expertise, and draw upon its strong heritage in research and development. By forming new partnerships, the Expert Centre will support existing services and drive the development of new offerings relevant to the SSA/STM domain.

ACKNOWLEDGMENTS

Observation campaigns mentioned in this work and the data format standardization exercise was funded by and performed within the scope of *ESA* Contract (4000135345/21/D/MRP). Authors would like to acknowledge *ESA* and all participating sensor owners/operators for their support and feedback during such campaigns and review process.

Moreover, for extracting information related with shapes and sizes for various targets of interest, we used information from *ESA DISCOS* (Database and Information System Characterising Objects in Space), a single-source reference for launch information, object registration details, launch vehicle descriptions, as well as spacecraft information for all trackable, unclassified objects. We acknowledge *ESA*'s efforts to maintain and operate this database with its APIs.

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