75th International Astronautical Congress (IAC), Milan, Italy, 14-18 October 2024.

IAC-24-A6.11.6

Expert Centre for Space Safety: Validation and Qualification service for the ground based optical sensors acquiring data for SSA/STM applications

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Abstract

ESA Space Safety Expert Centre offers a range of services to its users and stakeholders in Space Situational Awareness/ Space Traffic Management domain. It has been developed within ESA Space Safety Programme (S2P) and hosted and operated by the Astronomical Institute, University of Bern. In this work, we present the operational results and advantages of offering one of the core services of the Expert Centre viz. Validation and Qualification of sensors characterizing resident space objects. Such a service is provided to the owners of ground based optical sensors across the world. From February 2023 to September 2024, Expert Centre has worked with 21 such sensors based in four continents, who have voluntarily participated in observation campaigns coordinated by us for the validation and qualification. We present the key operational details and statistics associated with such campaigns. Observation data is acquired in these campaigns using astrometry tracking, photometry, and survey observation techniques. Performance requirements are established separately for each observation technique and measured throughout the campaigns. By offering a transparent evaluation and feedback process to sensor operators, Expert Centre assists the improvement of these sensor data systems to be used for catalogue build-up, maintenance, and conjunction assessment applications. Although there is an increasing demand for and a growing establishment of such sensors in recent years, there are still some common issues faced by the sensor operators in this domain. We discuss such issues along with the important lessons learned while collaborating with established or new actors in this domain. A sensor operator's perspective on receiving this service and its benefits is also presented. Moreover, the greater impact of having this unbiased, independent evaluation service available from a non-profit organization to the Space Situational Awareness/Space Traffic Management community is addressed. We elaborate on our roadmap for future developments and collaboration opportunities. With this work, our vision for contributing towards safe and sustainable operations in space is presented.

Keywords: Expert Centre, Sensor Calibration, Validation and Qualification, Tracking, Photometry, Surveys.

Acronyms

ACM	Astros Command Message
AIUB	Astronomical Institute, University of Bern
CCSDS	Consultative Committee for Space Data Systems
CODE	Center for Orbit Determination in Europe
DEC	Declination
ESA	European Space Agency
ExpCen	Space Safety Expert Centre
FoV	Field of View
GEO	Geosynchronous Equatorial Orbit
GNSS	Global Navigation Satellite Systems
IADC	Inter-Agency Space Debris Coordination Committee
IGS	International GNSS Service
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MJD	Modified Julian Date
NEO	Near-Earth Object
NDA	Non-disclosure Agreement
OSC	Office of Space Commerce
OSM	Observation Scheduling Message
RA	Right Ascension
RMS	Root Mean Square
RSO	Resident Space Object
SCM	Scheduling and Commanding Message
SFTP	Secure File Transfer Protocol
SLA	Service Level Agreement
SLR	Satellite Laser Ranging
SSA	Space Situational Awareness
SST	Space Surveillance and Tracking
STM	Space Traffic Management
TDM	Tracking Data Message
TLE	Two-Line Element set
TraCSS	Traffic Coordination System for Space
TRK-C	GNSS targets used for sensor calibration
TRK-L1	targets used to compute the photometric precision
TRK-L2	targets with periodicity expected in their light curves
TRK-N	targets used for correlation check with TLE catalogue
V&C	Validation and Characterization
V&Q	Validation and Qualification

1. Introduction

1.1 Space Safety Expert Centre

Developed within the Space Safety Programme of European Space Agency (ESA), the Space Safety Expert Centre (hereafter ExpCen) is hosted at the Astronomical Institute, University of Bern (AIUB). It envisages broadening and advancing our understanding of near-Earth space environment and strives to contribute towards safer and sustainable space environment by providing services and support for the Space Situational Awareness (SSA)/ Space Traffic Management (STM). ExpCen supports a variety of applications including tasked tracking, survey, and characterization observations by means of ground based passive optical, satellite laser ranging (SLR), and radar techniques. Such observations are acquired through a network of sensors - encompassing heterogeneous types of sensors operated by commercial companies, academia, research institutions, government, and inter-governmental institutions. ExpCen manages the sensor planning, the data quality control, calibration, and reformatting of the data, if necessary, as well as the monitoring of Key Performance Indicators (KPIs) defined in service level agreements (SLA). Fig. 1 shows different stakeholders, services and types of sensors and observation techniques associated with the ExpCen.

For the last few years, ExpCen project has been under different phases of the development, testing, and deployment [1] [2] [3]. Several services have been developed and are being offered to its stakeholders. These include data acquisition service and attitude catalogue service for characterization of state or attitude of resident space objects (RSO), re-entry event or conjunction event observation support. For the sensor operators/owners, services around the data quality monitoring are offered such as Validation and Qualification (V&Q) service and data calibration service. ExpCen also addresses the standardization of data formats through review of existing standards and providing recommendations to improve such standards. Research and development is one of the fundamental elements of ExpCen activities, to advance our scientific understanding of and find solutions to space debris related problems.

Since February 2023, ExpCen has been under the service provision phase of one of the ESA contracts, through which it has been offering its V&Q services to various sensor operators. V&Q service is briefly introduced in the next subsection. In this work, we describe various aspects of this service and present operational insights of successfully offering it to several sensor operators around the globe for the past 20 months.

1.2 Validation and Qualification service

One of the core services of ExpCen is the V&Q of sensors for different observation types. ExpCen acts as an external entity that monitors data quality and format compliance for the observations useful for SSA/STM applications, by coordinating observation campaigns of specific configuration and requirements with the participating sensors. V&Q service includes technical support to participating sensor operators by ExpCen operators and experts to achieve compliance with data calibration and quality, as well as data formatting requirements. All formats and interfaces used by the ExpCen are based on international standards and the data quality requirements are derived from the user community.

The need for SSA data quality monitoring services is driven by the necessity to ensure accuracy and reliability of space tracking data. As near-Earth space becomes more congested, significant errors in orbital data (derived from raw observations) can lead to collisions, posing risks to assets in space and thus, to essential services like navigation and communication, and to human spaceflight operations. Independent evaluation is critical to validate the consistency of this data across multiple sources, ensuring unbiased assessments and enhancing decision-making. For example, the Office of Space Commerce (OSC) has procured such services under the Consolidated Pathfinder initiative. The OSC has collaborated with companies like Kayhan Space and SpaceNav to monitor and evaluate the quality of orbital data. These companies assess the accuracy and consistency of SSA data, supporting the OSC's efforts to develop the Traffic Coordination System for Space (TraCSS), which aims to provide a cloud-based platform for STM [4] [5]. ExpCen offers a similar service to sensor operators across the world for independent auditing of their acquired data.

V&Q services are offered by Expert Centre for different observation types and techniques, that are used to characterize RSOs using ground-based sensor infrastructure. In this work, we focus on three such variants for the passive optical sensors - viz. for tasked tracking (follow-ups) of RSOs in higher altitudes (MEO/GEO), for photometry (light curves) observations for RSOs in LEO/MEO/GEO, and for surveys of the RSOs in the GEO ring. Please note V&Q in case of light curves are referred to as Validation and Characterization (V&C) for technical reasons.

1.3 Structure

The structure of this work is as follows. In Sec. 2, the details of three distinct types of the V&Q services are briefly presented. Such description includes the objective, campaign configuration and performance parameters evaluated in each of the variants. In Sec. 3, we then highlight key operational metrics of the service provision phase, to present the scale of our operations regarding the V&Q service. Valuable insights from the point of view of a sensor operator are presented in Sec. 4, which is contributed by our partners from *Astros Solutions s.r.o.* Many lessons were learned while offering this service and important ones are presented in the subsequent section. In Sec. 6, we present our outlook for the upcoming developments and improvements. Finally, conclusions and acknowledgements for this work are presented.

2. ExpCen V&Q service

During the service provision phase of ongoing ESA activity, under which V&Q service was provided to several sensor operators, participation was on voluntary basis without any participation fee or charges. This allowed testing the operational capabilities of the ExpCen to its limits, and also benefited a number of sensor operators in their evaluation or monitoring of sensor's performance. V&Q service is provided to each sensor operator by coordinating observation campaign spanning at least 4 observation nights. These campaigns are hereafter referred to as V&Q campaigns (or V&C campaigns for light curves).

In each of the three variants described in this work, the validation sub-campaign serves to verify that all interfaces are in place (contractual & data exchange) and sensor adheres to the chosen data format standard while providing observation data. The qualification or characterization sub-campaigns, that follows validation sub-campaign, are used to evaluate different performance parameters for the sensor.

At the end of V&Q campaigns, a detailed report is provided to the sensor operator for each participating sensor that captures information about all observation nights and presents overall conclusions and any recommendations. Sensor is either qualified or provisionally qualified (when there is still scope for improvement) or not qualified. Re-calibration campaigns are proposed to be coordinated after 6 months and/or after sensor operator has applied corrective action to software/hardware based on the outcome of V&Q campaigns. Such re-calibration campaigns aim to

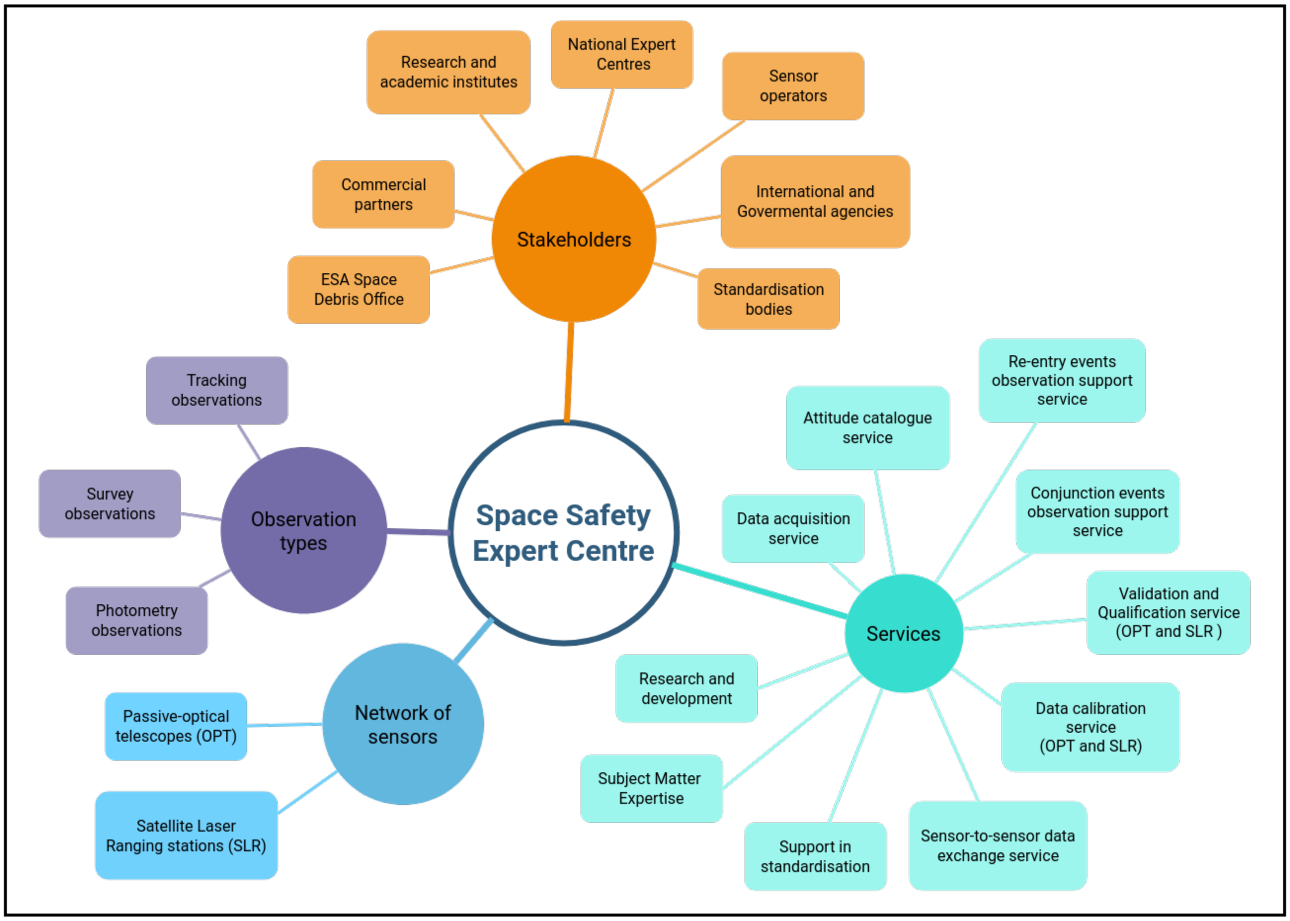

Fig. 1: Space Safety Expert Centre: stakeholders, services, network of sensors and observation types.

re-evaluate the sensor's performance.

2.1 Prerequisite

Following are the prerequisites before the V&Q campaign is coordinated with any candidate sensor that wishes to participate in the V&Q service:

- Letter of intent:
  Since the participation was on voluntary basis without any charges, it was required to have some agreement with the sensor operator to coordinate V&Q campaigns. This was often achieved by asking for a signed letter of intent from the sensor operator, that expresses a will to participate in the V&Q campaigns and a commitment to provide observation data meeting the requirements of these campaigns. In return, ExpCen committed to analyze the data and promptly provide feedback on the result of evaluation to the sensor operator.
- Non-disclosure agreement (NDA) clause, if necessary:
  Certain sensor operators might wish to have a NDA in place, that maintains confidentiality about sensor's evaluated performance or any other details, preventing tracing back information from third parties back to sensor operator[1]. If such condition is required, NDA can be signed between ExpCen and sensor operator or a confidentially clause can be added to the signed letter of intent/similar agreement document.

[1]Due to such confidentially clause in some cases and as the goal of this work is to highlight the general outcome of V&Q service provision rather than sensor-specific details, all sensors have been anonymized in this work. No specific information about sensor's location or sensor's owner/operator or sensor's software/hardware correlating with its performance has been revealed for any sensor, while abstracting performance of several sensor systems in this work.

- Sensor description form:
  Before beginning V&Q campaigns, ExpCen expects every sensor operator to fill in a questionnaire (i.e., complete a sensor description form) for each participating sensor. This provides relevant information to the ExpCen for generating tasking data[2] for a sensor or evaluating the received observation data.

- Data exchange endpoint:
  A common data exchange endpoint is established between sensor operator and ExpCen, to exchange tasking and observation data. Data exchange often occurs over a sensor-specific user account on secure SFTP server of the ExpCen.

- Agreement on campaign requirements and configuration:
  Detailed requirements and configuration of the V&Q campaigns are shared with sensor operator and any clarifications are provided, leading to agreement on the procedure to be followed during the campaigns. A list of targets or baseline requirements are adjusted in specific cases, without compromising the essence and quality of the evaluation process. For example, the list of targets was updated for one of the sensors, due to prevailing export control restrictions of the country in which sensor operator was located.

2.2 V&Q for high-altitude tracking

This variant of V&Q service focuses on the capability of ground based passive optical sensor for tracking observations for RSOs in MEO/GEO regime. Various aspects are described in the following sections.

2.2.1 Objective

Through V&Q campaigns for high-altitude tracking, ExpCen aims to assess that a ground based optical sensor can offer a reliable, high quality and on-demand tracking data provision service for the RSOs in MEO and GEO orbital regimes to its potential customers or stakeholders. ExpCen evaluates the accuracy and bias of sensor's data by comparing reduced measurements for GNSS calibration targets against their precise orbit solutions and checks the correlation quality of measurements for follow-up targets against TLE catalogue. Moreover, ExpCen monitors the data dissemination latency and adherence to standard data formats. By participating in the V&Q campaigns coordinated by the ExpCen, a sensor operator can demonstrate the capability of its infrastructure to provide data for catalogue maintenance operations or any other derived services relevant for applications in SSA/STM.

[2] Tasking data is the data generated by ExpCen for each coordinated observation night with a sensor, that provides TLEs, ephemerides, and visibility overview to the sensor operator for the targets of interest.

2.2.2 Campaign configuration

V&Q campaign for high-altitude tracking consists of at least 4 observation nights (dusk to dawn) - one validation and three qualification sub-campaigns, each spanning at least one night. Observations are expected in 2-3 'series' during each night, each 'series' meant to acquire data during different part of the observation night. In each series, it is expected that sensor acquires certain minimum number of observations for a combination of *TRK-C* and *TRK-N* targets (these terms are described in Sec. 2.2.3).

Upon availability of sensor and favourable weather conditions, a sub-campaign is coordinated. ExpCen operator generates and shares tasking data before the observation night. After observation night, sensor operator delivers the reduced astrometric measurements to ExpCen, along with comments on any/all planned observations that might have failed due to deteriorated weather conditions or technical reasons on sensor's side. After this, performance parameters described in Sec. 2.2.3 are evaluated and feedback is provided to sensor operator over email.

2.2.3 Parameters

- Data format compliance
  As mentioned earlier, one of the purposes of validation sub-campaign is to confirm that sensor operator can provide observation data in the agreed data format standard. For these V&Q campaign, such data format is CCSDS Tracking Data Message (TDM) v2.0. Data format compliance is monitored throughout the V&Q campaigns and feedback is provided to the sensor operator in case of any errors.

- Efficiency
  As mentioned earlier, a certain minimum number of measurements are expected during the observation night, to perform meaningful evaluation of various performance parameters. Therefore, efficiency of the data volume is checked and at least 75% efficiency (targets tracked and processed/targets required) is expected for each series in the qualification sub-campaign. V&Q sub-campaigns are repeated over multiple observation nights if a single night of observation does not have sufficient data volume of reduced measurements.

- Latency
  Data dissemination latency is evaluated for each sub-campaign. Reference epoch for latency computation is 09:00 AM local time for the sensor operator on the next calendar day. The baseline requirement is that the average latency be less than 6 hours over qualification sub-campaigns. However, for sensors with automated data reduction and delivery system in place, latency values were often negative (i.e., sensor uploaded data to ExpCen SFTP server before 09:00 AM of the next calendar day).

- Time offset (epoch bias)
  Due to any inaccuracies in the epoch registration system, time-tagging of reduced measurements by sensor's reduction pipeline might have a constant bias. Referred to as time offset or epoch bias, this is evaluated by comparing reduced measurements for GNSS targets with ground truth based on the precise orbit ephemerides generated by one of the global IGS analysis center - Center for Orbit Determination in Europe (CODE) [6] [7] [8]. Apart from the estimated value of time offset, stability of such offset value is also checked over the qualification sub-campaigns.

  Fig. 2 shows the estimated values of the time offsets for various sensors, that participated in the V&Q campaigns. Selected GNSS targets used for this calibration purpose are referred to as *TRK-C* targets.

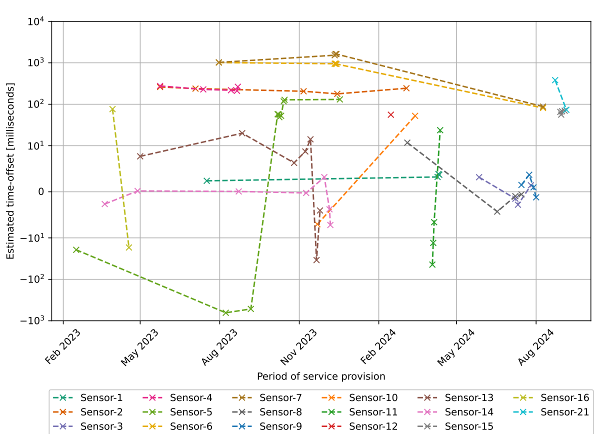

Fig. 2: Estimated time offsets (epoch biases) for various sensors, participating in the V&Q campaigns for high-altitude tracking.

- Astrometric accuracy

While evaluating time offset, the residuals (difference between observed value of an object's position and its 'true' position) associated with astrometric measurements can be used to compute the astrometric accuracy of the sensor. Before estimating this value, astrometric measurements are first corrected for the estimated value of time offset. Moreover, gross and statistical outlier measurements are removed from the observation datasets, and then the final value is compared with expected accuracy of the sensor as listed by the sensor operator in its sensor description form. Fig. 3 shows the estimated values of the astrometric accuracy for various sensors, that participated in the V&Q campaigns.

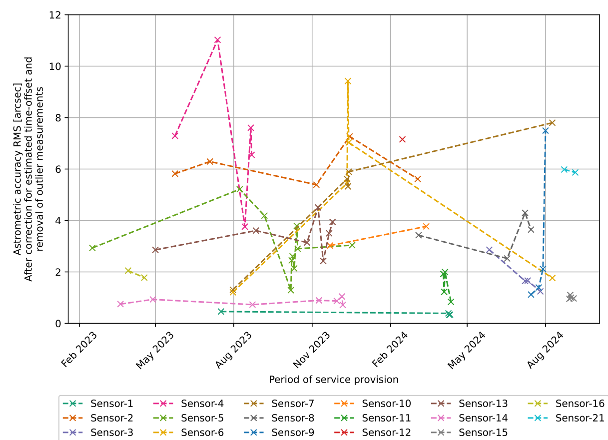

Fig. 3: Estimated values of RMS astrometric accuracy, for various sensors participating in the V&Q campaigns for high-altitude tracking.

- Outliers
  Details of gross and statistical outlier measurements, rejected during the time offset/astrometric accuracy evaluation process, are provided in the feedback to the sensor operator. This information can be used by the sensor operator to further investigate the cause of having such outliers in the observation data. Percentage of outlier measurements is quantified.

- Miss-correlation
  During V&Q campaigns for high-altitude tracking, targets other than GNSS targets are expected to be observed. Referred to as *TRK-N* targets, these are the RSOs without publicly available precise ephemerides (such as space debris - rocket bodies, defunct payloads etc.). Their tracking (follow-up) observations are used

to gather astrometric measurements, which are then correlated with TLE catalogue using two different correlation tools available at AIUB. Astrometric measurements showing conclusive miss-correlation are reported back to the sensor operator and the percentage of such measurements is quantified.

After the completion of V&Q campaigns, a detailed report is provided to the sensor operator that consolidates results of entire campaign coordination and evaluation process. This report contains helpful visualizations, for example shown in Fig. 4. Moreover, a certification of qualification is also provided to the sensor operator. These deliverables can be used by the sensor operators for the improvements/investigations on their side or can be presented as proof of their evaluated performance to potential customers in SSA/STM domain.

Some of the performance parameters mentioned earlier are stored in the ExpCen database as KPIs. KPIs are then continued to be monitored for quality assurance if sensor operator establishes a Service Level Agreement (SLA) or other contract with ExpCen for data provision.

2.3 V&Q for Surveys in GEO

V&Q service is also provided by ExpCen to the ground based passive optical sensors that can perform survey observations in GEO. Product of such observations are the reduced astrometric measurements for all identified targets within the field of view (FoV) of the sensor, without any correlation analysis performed by the sensor. ExpCen then evaluates the capability of sensor to observe given region of the geostationary ring and acquire data for the targets expected in that region at the time of observations. More details are provided in the following sections.

2.3.1 Objective

Through V&Q campaigns for surveys in GEO regime, ExpCen aims to assess that a ground based optical sensor can offer a reliable, high-quality, and on-demand surveillance data provision service for the RSOs in GEO regime to its potential customers or stakeholders. By checking the efficacy of coverage and correlation of reduced measurements with the TLE catalogue for GEO objects, and by monitoring data dissemination latency, ExpCen evaluates the performance of a sensor that can be tasked with survey observations. By participating in the V&Q campaigns coordinated by the ExpCen, a sensor operator can demonstrate the capability of its infrastructure to provide data for catalogue build-up operations or any other derived services relevant for applications in SSA/STM.

2.3.2 Campaign configuration

V&Q campaign for GEO survey also consists of at least 4 observation nights - one validation and three qualification sub-campaigns, each spanning at least one night. For each sub-campaign, one 'GEO Sector' is selected by the Expert Centre. A GEO sector is a chosen range in geocentric longitude ($\approx 15.0°$) and latitude ($1.0°$ around the equator). 10 different GEO sectors of interest are identified. Objective of the survey observations is then to observe a selected GEO sector and detect different RSOs on the acquired images.

Upon availability of sensor and favourable weather conditions, a sub-campaign is coordinated. During the observation night, the sensor is expected to observe the chosen GEO sector through appropriate scheduling. The sensor operator is free to choose any number of 'Survey Fields' to cover the entire GEO Sector and optimize its scheduling strategy. In this context, a survey field is the region of sky that a sensor is actively "surveying" at a given epoch to detect RSOs. After the observation night, the sensor operator is expected to provide reduced astrometric measurements from all survey fields as well as time-tagged information about the field centers of all survey fields. Like V&Q campaigns for tracking observations, sensor operator is expected to provide comments on any/all planned observations that might have failed due to deteriorated weather conditions or technical reasons on sensor's side. After this, performance parameters described in Sec. 2.3.4 are evaluated and feedback is provided to sensor operator over email.

2.3.3 Prerequisite

Before commencing V&Q campaigns, it is required that that mean/RMS value of time offset associated with the measurements delivered by that sensor is known to ExpCen. If the sensor has participated in V&Q campaigns for high-altitude tracking, then such values are known to ExpCen. If the sensor has not participated in such campaigns, then it is recommended that sensor operator provides reduced TDMs for *TRK-C* targets, before coordinating survey observation campaigns. Measurements from two or more observation nights, at least for 8 *TRK-C* targets are expected to perform robust analysis.

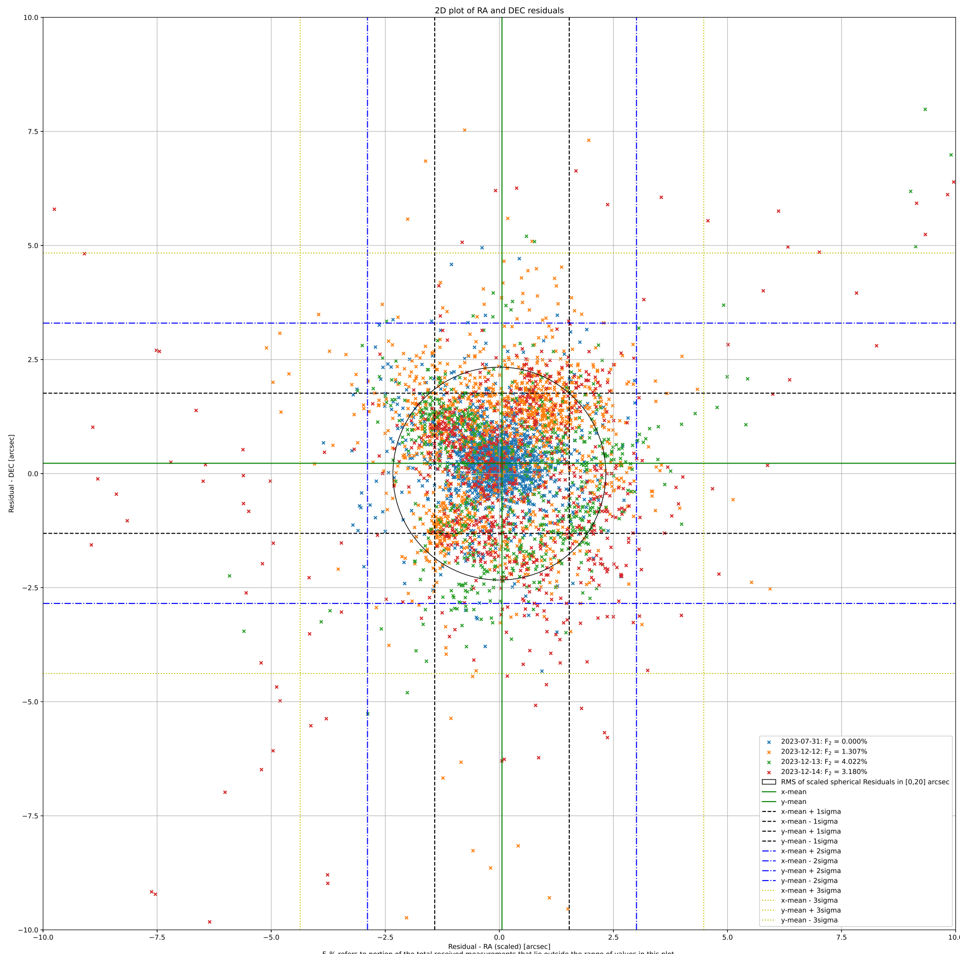

Fig. 4: Example plot showing distribution of residuals (RA vs DEC), after the correction for estimated time-offsets are applied to the astrometric measurements, for each night separately.

2.3.4 Parameters

- Data format compliance
  Validation sub-campaign is primarily used to confirm that sensor operator can provide observation data in the agreed data format standard. For these V&Q campaigns, such data format is also CCSDS TDM v2.0. For receiving metadata information about the field centers of survey fields, JSON file format is used. Template for such a file is provided to the sensor operator. Data format compliance is monitored throughout the V&Q campaigns and feedback is provided to the sensor operator in case of any errors.

- Latency
  Data dissemination latency is evaluated for each sub-campaign with reference epoch being 09:00 AM local time for the sensor operator on next calendar day, with similar baseline requirement for the average value.

- Coverage
  It is confirmed that sensor observed at least 90% of selected GEO sector during the qualification sub-campaigns (75% in case of validation sub-campaigns). Percentage of coverage is noted, and any under-performance is immediately reported back to the sensor operator.

- No-shows
  The astrometric measurements provided by the sensor operator are correlated by ExpCen with the TLE catalogue. Upon reception of observation data, ExpCen performs correlation analysis focused on all GEO ob-

jects within a selected GEO Sector. The number of catalogued GEO RSOs that were expected but not observed by a sensor in a chosen GEO sector is evaluated as a 'No-shows' parameter. Baseline requirement on maximum No-shows is 20%.

- Outliers
  During the tracklet[3]-to-catalogue correlation analysis, it is also checked if any astrometric measurements within a tracklet are outliers, leading to failed correlation. The percentage of any such outliers is quantified for the tracklets belonging to the GEO objects in the observed GEO sector.

Similar to the V&Q campaigns for tracking, after the completion of V&Q campaigns for GEO surveys, a detailed qualification report and a certification is provided to the sensor operator that consolidates results of entire campaign coordination and evaluation process.

2.4 V&C for Light Curves

This variant of V&Q service focuses on the capability of a ground based passive optical sensor to consistently deliver light curves data for objects in different orbital regimes using standardized data format, that can be further used to characterize the attitude motion of such objects. Various aspects are described in the following sections.

2.4.1 Objective

Through V&C campaigns for light curve observations, ExpCen aims to assess that a ground based optical sensor can offer a reliable, high quality, and on demand photometry observation data acquisition service for the RSOs in different orbital regime to its potential customers or stakeholders. ExpCen evaluates the precision and maximum sampling rate of such measurements, that are often used for the attitude motion characterization of the RSOs. Moreover, ExpCen monitors the data dissemination latency and adherence to data format standard. By participating in the V&C campaigns coordinated by the ExpCen, a sensor operator can demonstrate the capability of its infrastructure to provide photometry observation data crucial for applications such as the attitude motion characterization of the RSOs for various research activities, rotation rate estimation for the objects of interest for the active debris removal missions.

[3] In this context, tracklet refers to time series of consecutive astrometric measurements for an object of interest.

2.4.2 Campaign configuration

Like observation campaigns for the other two variants, V&C campaign also consists of one validation sub-campaign, followed by three characterization sub-campaigns. Each of these spans one or more observation night(s), with reduced photometric measurements collected for 8 different targets of interest. Depending upon the orbital regime for the target of interest and duration of its visible pass, minimum required length of light curve series is defined. Data is expected to be collected for *TRK-L1* and *TRK-L2* targets (these terms are described in Sec. 2.4.3). Procedure like V&Q campaigns for high-altitude tracking (see Sec. 2.2.2) is followed for the coordination of each sub-campaign.

2.4.3 Parameters

The following performance parameters are evaluated after each observation night, upon reception of observation data from the sensor operator. Feedback is then provided to the sensor operator after the evaluation process.

- Data format compliance
  Like the other two variants, format compliance is checked for the delivered observation data set (through validation sub-campaign). In case of light curves, chosen data format standard is either CCSDS TDM with additional keywords defined by ExpCen or ExpCen adapted version of the IADC recommended format for the light curves data.

- Efficiency
  In order to guarantee meaningful evaluation of various performance parameters, minimum number of measurements are confirmed for each observation night through evaluation of efficiency for data volume. 75% of efficiency is expected with respect to the campaign requirement for the number of light curves expected from each observation night.

- Latency
  Data dissemination latency is evaluated for each sub-campaign with reference epoch being 09:00 AM local time for the sensor operator on next calendar day. Similar baseline requirement of 6 hours exists for the average data dissemination latency over the characterization sub-campaigns.

- Photometric precision
  Photometric precision is computed as RMS value after a polynomial de-trending of each light curve data for specifically selected targets. Referred to as *TRK-L1* targets, these objects are known not to show any

intrinsic periodic features in the measured brightness. *TRK-L1* targets are radar calibration spheres or SLR satellites such as Lageos-1/2 or attitude stabilized payloads in the orbit. Fig. 5 shows an example of light curve acquired for one such target, that can be used to estimate photometric precision after de-trending step.

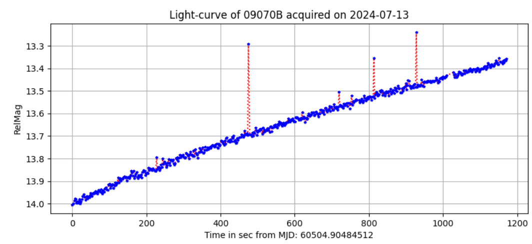

Fig. 5: Example of light curve acquired for one of the *TRK-L1* targets.

- Outliers
  While estimating photometric precision, any statistical outlier photometric measurements are iteratively ignored with 3σ filtering criterion. The percentage of such outlier measurements is then quantified and provided along with the estimated value of photometric precision for each light curve of *TRK-L1* target.

- Light Curves with periodicity
  During characterization sub-campaigns, sensor is expected to acquire light curves for another type of targets of interest. Referred to as *TRK-L2* targets, their light curves are known to show periodicity in the measured brightness. It is confirmed that sensor can also provide reduced light curves for such targets and their apparent synodic rotation periods are extracted using two different tools. Fig. 6 shows an example of light curve acquired for one such *TRK-L2* target, which shows periodicity upon visual inspection. Such observations will confirm the ability of a sensor system to provide data that is useful for attitude related analysis of the RSOs.

- Sampling rate
  The maximum value of the sampling rate based on the delivered data set from each observation night is also computed and compared against the specified value in the sensor description form. This performance parameter aims to reflect on the maximum possible resolution of acquired photometry data along time axis.

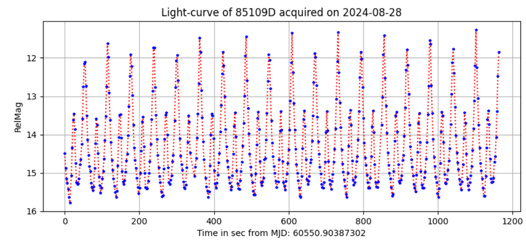

Fig. 6: Example of light curve acquired for one of the *TRK-L2* targets.

Similar two deliverables are provided to the sensor operator after the completion of V&C campaigns and can be further used as a testament of sensor's capabilities.

3. Operational Metrics

Table 1 provides operational metrics for the latest operational phase that provided V&Q service to various sensor operators. As seen in this table, 21 different sensors participated in the V&Q campaigns, located in 4 continents. These sensors are operated by private companies, universities, research institutions or space agency. Some of these sensor infrastructures are newer (established within last 1-2 years) while some are older. Some of the sensor operators have experience of more than 10 years of contributing data towards SSA/STM applications. 17 sensors participated in V&Q for high-altitude tracking and re-calibration campaigns for the same variant. 2 sensors participated in V&Q for GEO surveys and 3 sensors participated in V&C for light curves.

Table 1 also provides details on the number of sensors that successfully completed their V&Q campaigns and were qualified. Sensors that met some of the baseline requirements regarding the performance parameters described in earlier sections but still showed some potential for further improvement were 'provisionally' qualified. 3 sensors participated in the re-calibration campaigns, after changes to their infrastructure (software or hardware changes) to re-evaluate their performance. 21 sensors participating within a course of 20 months implied more than 1 V&Q campaign on average for every month of operation. The total effort for every sensor included negotiations with sensor operator to agree on timeline, clarify requirements, establish prerequisites as mentioned in Sec. 2.1, coordinating campaigns (planning, processing, feedback provision) on multiple observation nights, and compilation of the deliverables. Some sensors

Table 1: Operational metrics: ExpCen V&Q service

Duration of the service	February 2023 to September 2024
# participating sensors	21†
FoV of participating sensors	Min: 0.35°x0.35° Max: 4.0°x4.0°
Aperture of participating sensors	Min: 0.2 m Max: 1.0 m
# validated sensors	5+0+0
# qualified sensors	6+2+2
# provisionally qualified sensors	3+0+1
# re-calibrated sensors	3+0+0
# planned nights	120
# nights with data acquisition	99
# nights completely failed due to unfavourable weather	9
# nights completely failed due to technical reasons	12
# nights partially failed due to unfavourable weather	17
# nights partially failed due to technical reasons	4
# *TRK-C* targets planned	Up to 56
# total acquired mea. for *TRK-C* targets	65,594
# total filtered mea. for *TRK-C* targets	3,414
# *TRK-N* targets planned	Up to 45
# acquired mea. for *TRK-N* targets	34,608
# miss-correlated mea. for *TRK-N* targets	181
# *TRK-L1* targets planned	Up to 90
# acquired mea. for *TRK-L1* targets	29,168
# *TRK-L2* targets planned	Up to 40
# acquired mea. for *TRK-L2* targets	12,629
# distinct GEO sectors planned	4
# acquired mea. in survey fields	9,067
# Correlated GEO targets observed in survey fields	Up to 18
# Unique targets observed in survey fields apart from GEO targets	Up to 37

= number of, Min. = minimum, Max. = Maximum, mea. = measurements. In case of tracking or survey observations, single measurement refers to a reduced pair of topocentric astrometric positions (RA/DEC) at an epoch. In case of light curve observations, single measurement refers to magnitude measured at an epoch, for the object of interest. †One of these sensors participated in both V&Q for high-altitude tracking and V&C for light curves.

were only validated because they either did not complete all qualification campaigns or failed to be successfully or provisionally qualified. It should also be noted that negotiations were also ongoing with other sensor operators but did not lead to coordination of campaigns within the timeline.

In total, 120 observation nights were planned in coordination with the sensor operators. Fig. 7, Fig. 8, and Fig. 9 show the details of nights failed to acquire data due to weather or technical reasons on sensor's side. The number of nights that partially failed to acquire the required data volume are also shown. For such nights, the received partial amount of data was still analyzed and feedback was provided to the sensor operator. Total loss due to weather and technical reasons was 7.5 % and 10 % respectively. Partial losses in acquiring data due to similar reasons were 14.17 % and 3.33 % respectively. Thus, in total about 13.33 % of the planned observation nights were somehow affected by technical issues on sensor's side. This highlights the fact that it is not always straightforward to complete these campaigns in a single attempt, especially for newer establishments that lack operational experience of several years.

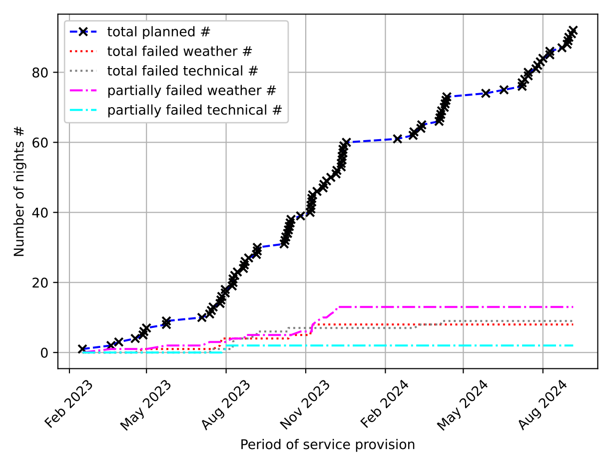

Fig. 7: Number of planned and failed observation nights: V&Q for high-altitude tracking (including re-calibration campaigns)

These figures also highlight the continuity in the operation of ExpCen, with breaks occurring primarily due to periods of unfavourable weather and sometimes due to holiday periods. For all three variants, ExpCen received more than 150,000 measurements in total during this

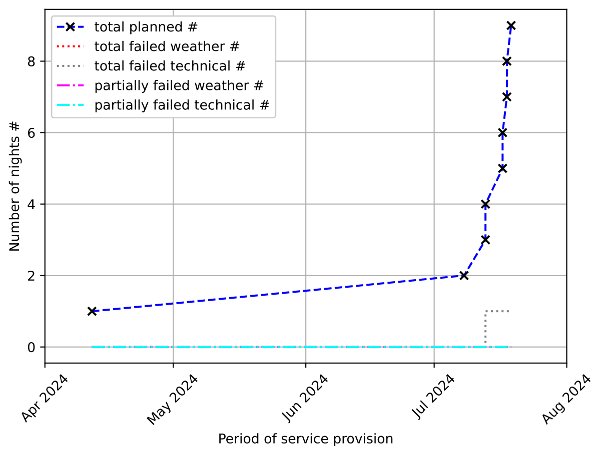

Fig. 8: Number of planned and failed observation nights: V&Q for GEO surveys

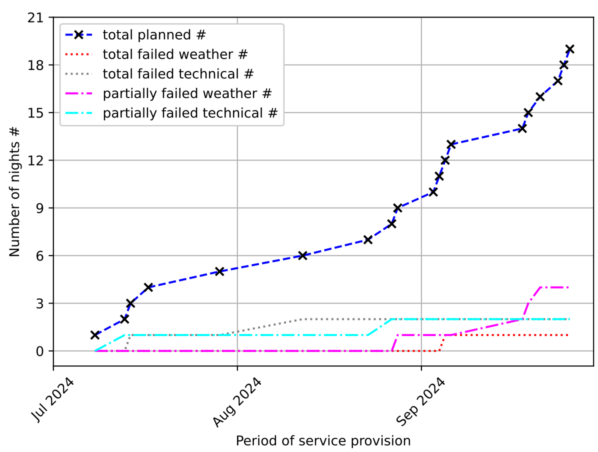

Fig. 9: Number of planned and failed observation nights: V&C for light curves

period. Automation of ExpCen software helped to process this large amount of data but human intervention was also necessary to review the outcome and perform additional analysis wherever it was necessary.

Table 1 provides some additional metrics for three variants of the V&Q service. During V&Q for high-altitude tracking, 5.2% of the total measurements for *TRK-C* targets had to be filtered as outliers while estimating of time offset and astrometric accuracy. Fig. 2 show the estimated values of time offsets for various sensors after such a filtering process - where some sensors clearly showed better calibrated epoch registration systems. After removal of outlier measurements and correction for the estimated time offsets, astrometric accuracies as shown in Fig. 3 were found for various sensors - with best RMS value of 0.334 arcsec and worst value of 11.025 arcsec during an observation night. On the other hand, in total 0.52% of measurements for the *TRK-N* targets were miss-correlated with TLE catalogued states for these objects on those nights.

4. Sensor operator's perspective

In this section, we present the perspective of one of the sensor operators that voluntarily participated in the V&Q service offered by the ExpCen. Following sections provide overview of *Astros Solutions s.r.o*, participation of their sensors in the V&Q campaigns, and highlights the advantages of such participation.

4.1 Astros Solutions: Overview

Astros Solutions s.r.o. (hereafter Astros) primarily focuses on optical measurement acquisition and processing for SSA/SST applications, the deployment of SST/NEO ground stations (including LEO tracking), and providing expertise in these areas.

Astros operates four sensor sites: one sensor (*AST2*) at the Astronomical and Astrophysical Observatory in Modra (*AGO*), one (*AST4*) at the Astronomical Observatory on Kolonica Saddle in eastern Slovakia, one at a private location in central Slovakia at the Luckystar Observatory in Važec (*AST5*), and one (*AST3*) in South Africa. All sensors are depicted in Fig. 10. The telescope network functions autonomously, with a single operator overseeing it. Originally, the V&Q campaigns included the *AST1A* and *AST1B* sensors deployed at our testing site.

Owing to successful participation in previous ESA activities, Astros has developed a suite of software solutions called *SENCOM*, which manages sensor network planning, tasking, and data processing. *SENCOM* can be extended to integrate external sensors, which can be tasked via Scheduling and Commanding message (SCM), Observation Scheduling Message (OSM), Astros Command Message (ACM), or other custom formats.

4.2 Participation in the ExpCen V&Q

Astros decided to participate in the Validation and Qualification campaign with the ExpCen immediately after deploying its first sensors. The campaign began with the qualification of the *AST1A* sensor in May 2023. The decision to join was made to ensure an external audit of

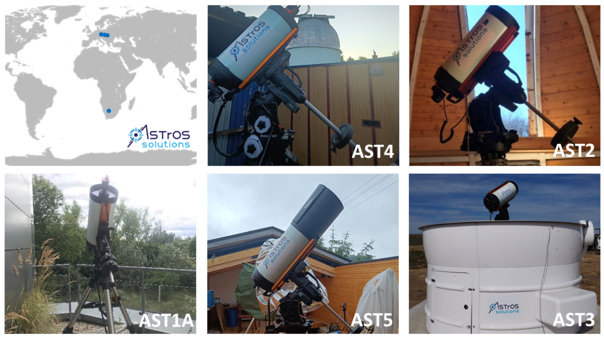

Fig. 10: Overview of the Astros network with sensors visualization. Sensor *AST1A* and *AST1B* were initially installed at Astros testing premises and were first sensors used for the ExpCen campaign. Once the campaign was concluded, these sensors were relocated to the *AST4* and *AST5* sites.

our data quality. Additionally, the Expert Centre helped us validate and fully test our data delivery pipeline, as well as verify our internal data quality checking utility.

In the summer of 2023, Astros added the *AST1B* sensor to the campaign. Both sensors performed well in terms of data provision. Most of the nights concluded successfully, delivering the required number of calibration and nominal targets for the campaign. By the fall of 2023, both sensors had been validated, and the campaigns were completed. Throughout the campaign, the ExpCen assisted in identifying weak points in our pipeline, testing the full data delivery system, and improving data quality in terms of epoch bias stability and astrometric accuracy.

Following the *AST1B* campaign, Astros relocated this sensor to its permanent location at the private Luckystar Observatory in Važec, Slovakia. Once installed and tested, Astros opted to bypass the full Validation and Qualification process, after discussion with the ExpCen, as the hardware and software components remained identical. Instead, re-calibration observations were performed during the summer of 2024.

4.3 Advantages of participation in the V&Q campaigns

For Astros, the role of the ExpCen as an external body for data quality assurance and certification is crucial. Each customer requiring SST data must first verify that the quality and latency of the delivered data meet their specific requirements. To achieve this, customers often conduct extended validation campaigns before real data provision can begin. However, weather conditions can delay these campaigns, sometimes indefinitely. By providing the certification process, ExpCen can significantly reduce the time required for customer-specific validation, enabling faster setup of interfaces between the data provider and the customer.

During the V&Q campaigns, Astros reported that the target list for the campaign was not fully optimized for small-aperture sensors, as it included very small debris targets observable only by highly sensitive telescopes. Given that small-aperture telescopes are generally more reliable, especially for Low-Earth Orbit (LEO) observations, and are more cost-effective, the ExpCen allowed us to review the target list and select only the accessible targets for our campaigns, without compromising the quality of qualification process (evaluating same performance parameters as per the original baseline requirements).

Additionally, during the V&Q campaigns, the ExpCen can provide valuable insights into system development and data accuracy. Astros had numerous productive discussions with the ExpCen during our V&Q campaigns, which greatly improved the stability of our system's data quality. This collaboration allowed us to simulate the highest customer data quality requirements and handle various operational scenarios for our network. From this perspective, we see great potential in the ExpCen initiative.

5. Lessons learned

While providing V&Q service, the following were some of the important lessons learned. Such lessons are crucial to both ExpCen and sensor operators, to coordinate V&Q observation campaigns in future.

- Standard procedures for three V&Q variants have been established and were shared with all sensor operators before the commencement of campaigns. Despite this, unforeseen situations occurred several times during service provision that required additional analysis than described in the standard procedures. There was often a need for further investigation and discussion between sensor operators and ExpCen operators/experts to resolve doubts, find solutions, make minor adaptations without compromising the quality of the evaluation process. Since such problems varied from case to case, V&Q service is an exercise with certain elements specific to a given sensor and it demands clear and active communication between both parties involved in this exercise.

- Amount of effort anticipated for the successful completion of V&Q campaigns should not be underestimated. This lesson was especially true for the sensor operators with newer infrastructure contributing to SSA/STM domain, in comparison with those sensor operators that have been operating their infrastructure for years. From minor to major technical issues can prevent successful qualification of newer sensor infrastructures simply with 4 observation nights.

- Fig. 2 shows estimated time offsets for various sensor systems. Higher than ±100 milliseconds time offsets were often found for the sensor systems that are equipped with CMOS cameras and rolling shutter. Based on these results and interaction with operators of such sensor systems, it can be concluded that sensors with rolling shutters especially require careful calibration of their epoch registration methods.

- Even after successful qualification or characterization of the sensor for any observation type, there is still a necessity to have re-evaluation of sensor's data for quality assurance after periodic intervals (e.g., every 6 months). Such re-evaluation is useful to ensure that none of the intended or unintended changes to a sensor's infrastructure have unintentionally deteriorated quality of sensor's data since last evaluation. ExpCen recommends re-calibration campaigns or subscribing to its 'Data calibration service' in this regard.

- Data format compliance might seem quite easy part, but several cases were found in which some TDMs were found to be invalid. Such cases occurred due to typos made by human operator or errors introduced by the automated reduction chain on the sensor's side, as confirmed by sensor operators in such cases.

- In certain cases (such as V&C for light curves), there was a need to enhance existing data format standard or define new standards to exchange additional data/metadata useful for the evaluation. This aligned well with the 'Support in standardization' service of ExpCen.

- As in the case of any observation campaigns with ground based passive optical sensors, dependency on favourable weather conditions significantly affected success or failure of the V&Q campaigns. As shown in Table 1, about 7.5 % of planned observation nights completely failed while 14.17 % partially failed in acquiring required amount of data, as weather conditions worsened during the course of these nights.

- During the course of V&Q campaigns, it is advantageous to have a stable software and hardware infrastructure on a sensor's side, to evaluate the performance of a consistent system. This was not always possible as new sensor operators constantly tried to improve their infrastructure, especially data reduction software pipeline (for obvious reasons). This often required finding correlation between deviation in the performance parameters and any upgrades on such sensor's side and sometimes it prolonged the successful qualification of these sensors.

- For some sensor operators that already contribute to several projects, frameworks, contracts in the SSA/STM domain, there seemed to be no strong financial incentive to prioritize the free V&Q campaigns with ExpCen. It appears that some of these sensor operators did not complete their V&Q campaigns due to other priorities. Sensor operators of well-established observatories were primarily interested in external evaluation of their data quality and optimized existing observation schedule of their observatories to accommodate ExpCen V&Q campaigns.

6. Outlook

After the conclusion of this V&Q service provision phase of ExpCen, following are some of the important perspectives for the future:

- In this work, we described V&Q service for the ground based passive optical sensors. ExpCen is also capable of processing SLR measurements and supporting software infrastructure already exists for the V&Q for Space Debris Laser Systems [9]. Campaigns for at least two such sensors are currently being discussed.

- As seen in Fig. 8 and Fig. 9, V&Q service for GEO surveys and light curves was offered for a fewer months when compared with about 1 and a half years of operation for high-altitude tracking V&Q service (see Fig. 7). This was due to the time it took to first develop procedures and supporting software for these two variants and then to negotiate campaigns with different sensor operators. In future, we hope these two variants will also get positive response from the sensor operators and eventually benefit from all lessons learned while providing these services for more sensors.

- Currently, ExpCen is investigating options for its future and actively seeking collaboration with different partners from the community. Through such partnerships, we seek support for the currently offered services and develop new services and products relevant to SSA/STM domain.

7. Conclusions

In this work, we presented the details of V&Q services for the ground based passive optical sensors that were successfully offered by ExpCen to various sensors operators from February 2023 to September 2024 period. Key details of such services for the high-altitude tracking observations, light curves observations, and GEO surveys were presented. By offering standardized procedures for the V&Q campaigns, through evaluation of various performance parameters based on the received observation data, and via active & detailed feedback provision mechanism, ExpCen strives to assist sensor operators around the world to improve their infrastructure in providing high quality data for the applications in SSA/STM domain. With a unique position within the SST ecosystem, ExpCen provides the subject matter expertise to support various sensor operators while serving as an unbiased and independent entity for data quality evaluation. Our lessons learned while performing this role were discussed in this work, along with the foreseen roadmap. ExpCen is looking forward to collaborating with new stakeholders from the community, to continue contributing towards safer and sustainable usage of the near-Earth environment.

Acknowledgements

ExpCen V&Q service provision phase was funded by and performed within the scope of ESA Contract (4000135345/21/D/MRP). Authors would like to acknowledge all the support from ESA and all participating sensor owners/operators to successfully complete the service phase.

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