QUALIFICATION APPROACH FOR SPACE DEBRIS MONITORING OPTICAL SENSORS

Alexandru Mancas[(1)], Beatriz Jilete[(2)], Tim Flohrer[(3)]

[(1)] *GMV Insyen/ESOC, Robert-Bosch-Str. 5, Darmstadt, Germany, Email: alexandru.mancas@esa.int*
[(2)]*GMV/ESAC, Camino Bajo de Castillo S/N, 28692, Villanueva de la Cañada, Spain, Email: beatriz.jilete@esa.int*
[(3)] *European Space Agency, Robert-Bosch-Str. 5, Darmstadt, Germany, Email: tim.flohrer@esa.int*

ABSTRACT

ESA's SSA programme aims to develop Space Debris Monitoring (SDmon) sensors and technology, and to support national as well as multi-national projects and international cooperation. The need for timely and accurate SDmon data is increasing, driven by the recent launches of large numbers of small satellites and the announcements of several large constellations.

There are several SDmon-capable optical telescopes (both already operational and planned) in Europe. SDmon data acquisition differs from 'traditional' astronomical observations, including much faster targets and very precise timekeeping. This paper proposes a standardised SDmon qualification procedure for optical telescopes.

As an example an ad-hoc qualification campaign was run with two optical telescopes (SHOT in the Czech Republic and SPADE in Italy) and the results analysed. The SDmon Expert Centre has its own more complex qualification procedures.

The approaches followed by ESA and the SDmon Expert Centre can serve as the basis for a European or international standard for SDmon telescope qualification, to be pursued under CEN/CENELEC or another body. A step-by-step qualification approach, to serve as the basis for a European standard, is proposed.

1 INTRODUCTION

Space Safety involves the exchange of observation data between various entities, including spacecraft operators, space agencies, catalogue producers, astronomical observatories, national authorities, etc. International standards are therefore needed not only to unambiguously exchange this data, but also to ensure that the data provided is of sufficient quality.

To facilitate data exchange, ESA established Expert Centres (ExpCen) for optical and Satellite Laser Ranging (SLR) observations. The ExpCen acts as a proxy between external data systems and assets and a Space Situational Awareness (SSA) system. The ExpCen manages observation requests and provides feedback about the quality of the received data. It can also deliver observations after a calibration process and support external sensors' validation and qualification for Space Debris Monitoring (SDmon) observations. The ExpCen has already demonstrated its capabilities for coordination and monitoring of sensors and data providers through several observation campaigns. Future activities will focus on developing new research functionalities, such as light curves exploitation, and performance demonstration through extensive observation campaigns.

ESA has recently (2016-2018) run a project that aimed to test and qualify two optical telescopes (SHOT - Sand Hill Optical Telescope and SPADE - SPAce DEbris telescope), and provide real data for end-to-end testing of SDmon software systems.

SHOT is a 0.43-m f/6.8 corrected Dall-Kirkham telescope (Planewave CDK17) with a precise German equatorial mount (10micron GM3000 HPS) and an Apogee Aspen CG9000 (3056 x 3056) CCD camera. SHOT is located in Teplice (Czech Republic), at the Teplice Observatory, which is part of the North-Bohemian Observatory and Planetarium.

SPADE is a 0.3-m f/2.8 Baker-Schmidt telescope with a German equatorial mount and a ProLine PL16803 CCD camera. During the project, the telescope was upgraded to an Officina Stellare RiFast 400 with a new German equatorial mount. SPADE is installed at the Centre for Space Geodesy (CGS) in Matera, and is owned by ASI (the Italian Space Agency) and operated by e-GEOS.

2 AD-HOC APPROACH FOR SHOT AND SPADE

The general approach for the SHOT and SPADE telescope was to run two campaigns: a qualification campaign, where object with precisely-known orbits are observed, and a "normal" data acquisition campaign, where space debris are observed. The consortium executing the project performed their own dedicated data analysis and ESA did a shadow engineering campaign that will be detailed in this section.

2.1 General approach

The shadow engineering qualification approach was simple and evolved a bit during the course of the project, with the final basic steps outlined in Fig.1:

Proc. 1st NEO and Debris Detection Conference, Darmstadt, Germany, 22-24 January 2019, published by the ESA Space Safety Programme Office
Ed. T. Flohrer, R. Jehn, F. Schmitz (http://neo-sst-conference.sdo.esoc.esa.int, January 2019)

- select targets for analysis; the focus was on GPS satellites with sufficient observations;
- apply annual aberration corrections; neither SHOT nor SPADE applied these, and the first attempt at the analysis showed the corrections are needed;
- determine the time bias, using all (or at least most) GPS satellites;
- compute the residuals in the observations relative the GPS sp3 orbit;
- perform a batch orbit determination (using the TLE as initial guess) and compare with the sp3 orbit.

The last step goes beyond simple telescope qualification, as the results of the OD depend on many other factors and will not be discussed in this paper.

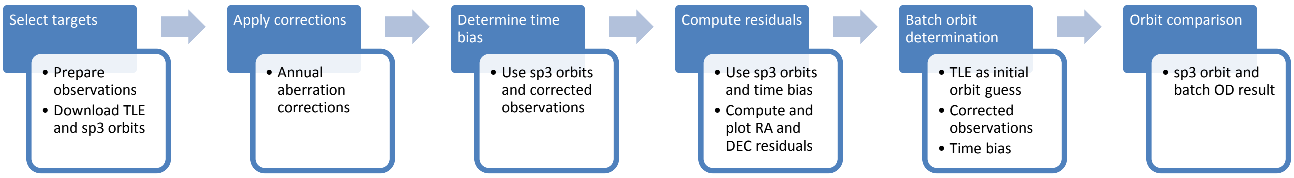

Figure 1 - Ad-hoc approach used for optical telescope qualification

2.2 SHOT results

The SHOT qualification campaign plan included observations of Cosmo-Skymed (LEO), Sentinel-1A/-1B (LEO), multiple GPS satellites (MEO), 2 BEIDOU satellites (GEO), and IRNSS 1F (GEO). Due to the lack of visible passes during the campaign, Sentinel-2A and -2B replaced Sentinel-1A and -1B. ESA analysed the GPS and Sentinel-2A/-2B observations.

2.2.1 GPS results

Fig. 2 shows the right ascension residuals for the SHOT observations of USA-132 (a GPS Block IIR satellite) acquired during October and November 2016. No corrections were applied to the observations and the residuals and the reference sp3 orbit from the International GNSS Service (IGS) was used [1]. The right ascension residual (multiplied by the cosine of declination) is plotted against right ascension. The sinusoidal signal with an amplitude of about 20 arcsec shows that annual aberration corrections need to be applied to the observations. After applying the annual aberration corrections the average residuals were non-zero, pointing to a time bias in the observations.

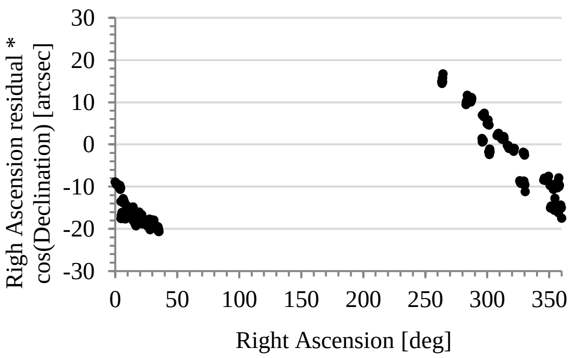

Figure 2 - Right ascension residuals for USA-132 from SHOT (before annual aberration correction)

For the next analysis attempt, estimating the time bias was inserted between applying the corrections and computing the residuals. Fig. 3 shows the same right ascension residuals, but for USA-145 (another GPS Block IIR satellite) observations from late May 2017. Since observations were taken at similar times each night, the whole right ascension range is not covered. The time bias was approximatively 55 ms. The residuals are much smaller (less than 4 arcsec) and the sinusoidal signal has been removed.

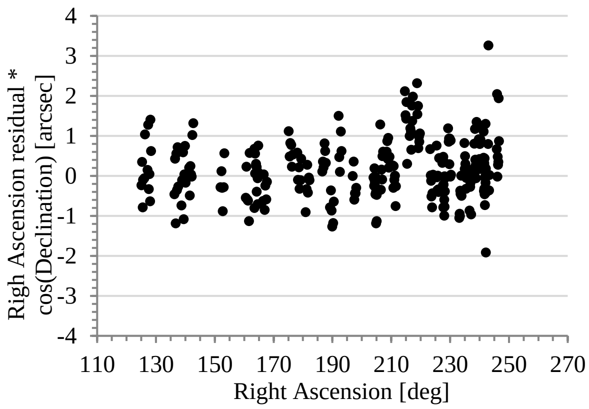

Figure 3 - Right ascension residuals for USA-145 from SHOT (after annual aberration and time bias correction)

2.2.2 LEO results

Time biases (relative to high accuracy orbits computed by the Navigation Support Office at ESOC) were computed for both Sentinel-2A and Sentinel-2B. Both satellites were used for the time bias, as this increases the sample size. The time bias was approximatively 57 ms.

The right ascension residuals (multiplied by the cosine of declination) against right ascension and declination residuals against declination can be seen in Fig. 4 and 5 respectively. The residuals are slightly higher than for USA-145, with more outliers:

- 6 right ascension measurements with residuals between -5 and -15 arcsec;
- 2 right ascension measurements over 5 arcsec;
- declination shows a bias in the -5 to -10 arcsec range.

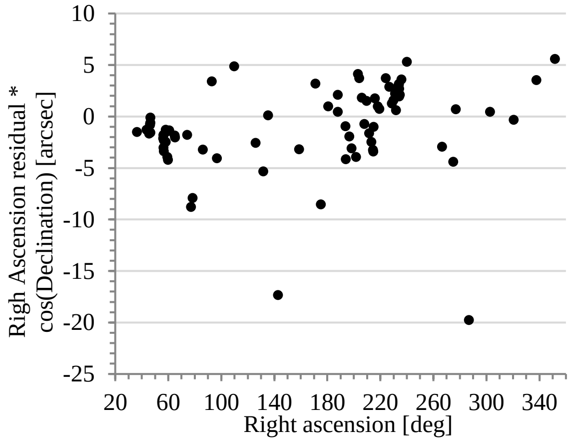

Figure 4 - Sentinel-2A right ascension residual (multiplied by the cosine of declination) against right ascension

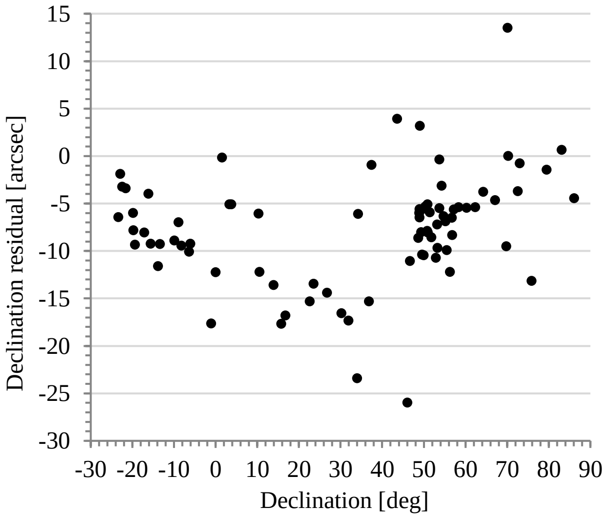

Figure 5 - Sentinel-2A declination residuals against declination

2.3 SPADE results

The SPADE data was analysed after SHOT; due to the differences in the amount of data and residuals, different plots were produced. The SPADE qualification campaign plan included observations of Cosmo-Skymed (LEO), Sentinel-1A/-1B (LEO), multiple GPS satellites (MEO), 2 BEIDOU satellites (GEO), and IRNSS 1F (GEO). ESA analysed the GPS observations, as they were the only ones with publicly available high-accuracy orbits.

Observations from 6 GPS satellites between 16 July and 9 August 2017 were used for the time bias estimation: USA-151, USA-201, USA-206, USA-248, USA-256 and USA-258. The time bias was approximatively 240 ms.

Fig. 6 and 7 show the SPADE right ascension (multiplied by the cosine of declination) and declination residuals against time for all GPS satellites observed and with large outliers removed. The residuals are larger than for SHOT (on the order of tens of seconds). Between 19 July and 25 July the SPADE operators performed some configuration changes, and this can be seen in the much smaller residuals (typically below 20 arcsec).

After these observations were acquired and processed by ESA, the SPADE data acquisition process was improved: shorter exposure time, a more accurate star catalogue, and improved track centre computation precision

3 EXPCEN APPROACH

The ExpCen has procedures [2] defined for two activities that overlap with the ad-hoc qualification described in section 2:

- evaluate and calibrate data sources and provide the evaluated data to an SSA/SDmon system;
- validate and qualify other sensors.

The following high-level procedure has been defined for the evaluation and calibration of data sources:

1. receive the observations via the agreed interface;
2. convert the observations to the Tracking Data Message (TDM) format, if they have not been already delivered as TDMs;
3. further processing of the observations depending on the type of observation:
    a. tracking observations: a correlation step is performed to remove mis-correlated observations from the data set;
    b. survey observations: a show/no-show procedure is performed to evaluate the survey efficiency;
    c. calibration observations: the observations for calibration objects (eg GPS) are processed and the time and astrometric biases are estimated; once they are computed they are applied to the other objects.

Validation and qualification are successive activities, ie a telescope is first validated, then qualified. Validation aims to test the following through an observation campaign:

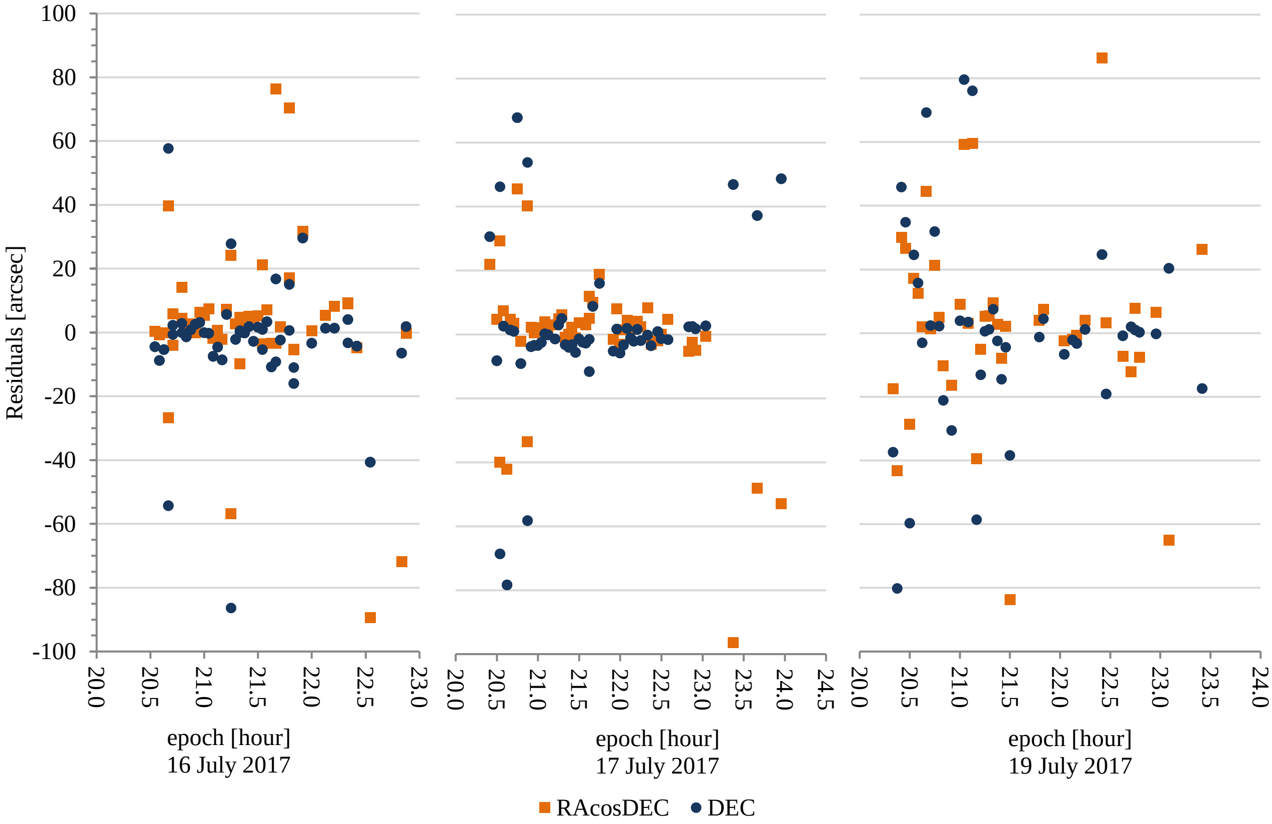

Figure 6 - SPADE GPS residuals (16-19 July)

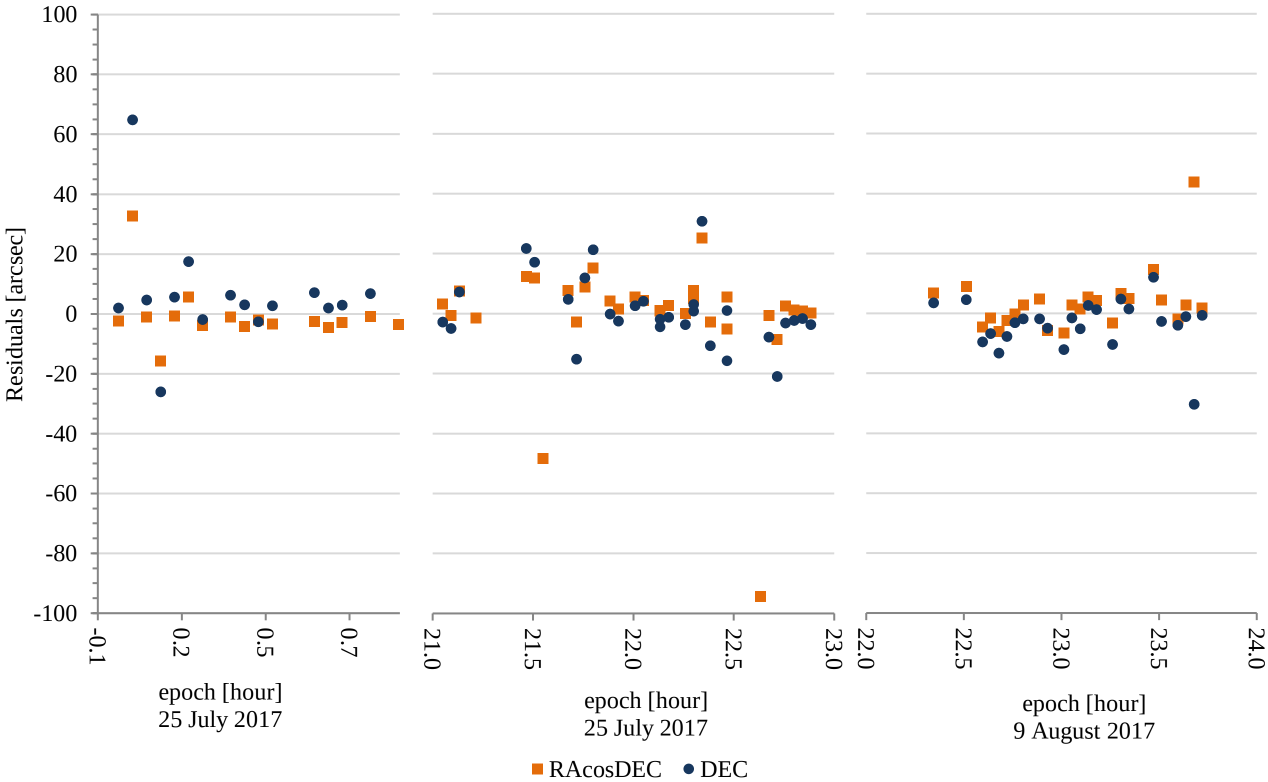

Figure 7 - SPADE GPS residuals (25 July and 9 August)

- information exchange between the scheduling entity and the telescope operator;
- receiving planning data correctly;
- correctly processed and delivered observations;
- validate the observations.

Qualification campaigns are run to test and/or assess:

- efficiency (what percentage of the planned objects are observed);
- data provision latency;
- epoch bias (tested during validation as well);
- astrometric accuracy (tested during validation as well);
- miss-correlation (tested during validation as well).

The following steps are followed for validating an optical telescope:

- set up and test a basic information exchange process; the process is flexible and can be adapted on a case-by-case basis;
- send observation planning data to the sensor;
- receive the observations from the sensor;
- observation validation:
    - determine epoch bias from GNSS observations;
    - estimate astrometric accuracy;
    - determine the miss-correlation rate.

An optical sensor needs to meet the following criteria for qualification as an SDmon capable sensor:

1. be a validated sensor;
2. run 3 1-night observation campaigns, with less than 72 hours between successive campaigns;
3. have an efficiency over 75 % for each campaign;
4. data latency below 12 hours for 75 % of the observations;
5. stable time bias (below 50 ms for 75 % of the observations);
6. astrometric accuracy better than 1 arcsec for 75 % of observations;
7. miss-correlation for less than 10 % of observations.

There are some additional requirements for survey observations: observing for more than 50 % of the planned survey time and provide astrometric data for more than 50 % of the catalogued objects observable during the survey.

4 PROPOSED STANDARD APPROACH

Due to the complex, multi-stakeholder nature of the SDmon landscape in Europe (EU and ESA SSA activities, national and commercial activities), a standard approach should be taken for the validation and qualification of SDmon optical sensors. As the EU-endorsed standardisation bodies, the European Committee for Standardization (CEN), and European Committee for Electrotechnical Standardization (CENELEC) are the ideal bodies to standardise the optical sensor validation/qualification process. CEN/CENELEC have an SSA Working Group as part of Technical Committee 5 'Space' (TC5/WG2) [3].

A standardised approach for the validation and qualification of optical sensors for SDmon should meet the following high-level requirements:

- provide a quantitative estimate of the time bias, astrometric accuracy, and miss-correlation;
- define a minimum number of 'test' targets to be observed a minimum number of observations to be acquired;
- provide quantitative requirements on time bias stability, astrometric accuracy, efficiency, etc that should be met by qualified sensors;
- do not be over-specific on the data exchange methods or formats (with the exception of the TDM as output format), as these can be decided on a case-by-case basis.

The following process should serve as a guideline in drafting the standard (the exact quantitative specifications will be decided during the standardisation process):

2. Sensor validation: aims to test data exchange and get a quick estimate of time bias, astrometric accuracy, and miss-correlation.
    a. Establish a data exchange process to/from the sensor. This can be something as simple as request observations of a catalogued object by email and receive the TDMs via FTP. There should be no technical requirements on this process in the standard.
    b. Select at least 4 [TBC] GNSS satellites for the observation campaigns.
    c. The sensor should acquire at least 30 [TBC] observations of each selected target over a span of 3 days.
    d. The validating authority will process the observations to determine the time bias (both overall and per-tracklet), astrometric accuracy, and miss-correlation rate.
    e. The sensor is declared 'validated for SDmon' if:
        i. The time bias difference between different tracks is less than 10 [TBC] ms.
        ii. The mean residuals in right ascension and declination are both below 0.8 [TBC] arcsec.

        iii. The RMS of the right ascension and declination residuals are both below 4 [TBC] arcsec.
        iv. Each target has fewer than 2 miss-correlated observations overall, on 1 per observation night.

3. Tracking sensor qualification: aims to test astrometric accuracy, time bias, and miss-correlation with a larger sample size and stricter performance requirements. The efficiency and data latency of the sensor are also estimated.
    a. All the sensors to be qualified shall already be validated.
    b. Select target objects for the qualification campaign. All targets should have high-accuracy orbits available to the qualification authority:
        i. At least 4 [TBC] objects in LEO, only if the sensor should be qualified for LEO observations as well;
        ii. At least 16 [TBC] objects in MEO;
        iii. At least 2 [TBC] object in GEO.
    c. The sensor should acquire at least:
        i. 50 [TBC] observations (at least 2 tracks) of each LEO object;
        ii. 100 [TBC] observations (at least 4 tracks) of each MEO object;
        iii. 500 [TBC] observations (at least 8 tracks) for each GEO object.
    d. The qualification campaign should be spread out over at least 14 [TBC] nights.
    e. The qualification authority will process the observations to determine:
        i. The time bias: per-track, per-object, per-orbital regime, per-night, overall;
        ii. The astrometric accuracy;
        iii. The miss-correlation rate;
        iv. The data latency (time gap between 'observations acquired' and 'observations delivered');
        v. The efficiency (what percentage of the planned tracks were observed);
        vi. The miss-correlation rate.
    f. The sensor is declared 'qualified for SDmon tracking' if:
        i. Time bias:
            1. The 'overall' time bias (for all observations) is below ± 10 ms [TBC] (ie the observations are corrected for "ground delays");
            2. The difference between the overall time bias any per-track, object, orbital regime, and night bias is less than 10 ms [TBC] (ie the time bias is stable from night to night).
        ii. Astrometric accuracy:
            1. LEO: mean right ascension and declination residuals below 1 arcsec [TBC], RMS below 7 arcsec [TBC], 75% of observations below 5 arcsec [TBC];
            2. MEO and GEO: mean right ascension and declination residuals below 0.1 arcsec [TBC], RMS below 4 arcsec [TBC], 75 % of observations below 2 arcsec [TBC];
        iii. Miss-correlation rate: below 0.5 % [TBC] for each orbital regime;
        iv. Data latency: depending on agreed exchange method; less than 10 hours [TBC], but 'automated' exchange should be below 1 hour [TBC];
        v. Efficiency: over 75 %;

4. Survey sensor qualification: aims to test solely survey-related performance.
    a. The sensor shall already be qualified as a tracking sensor.
    b. A survey period and scan pattern shall be agreed by the sensor and the qualification authority. The survey period shall be at least 20 hours [TBC], spread over at least 4 nights [TBC], with no less than 2 hours [TBC] each night.
    c. The sensor shall execute the survey and deliver the data to the qualification authority.
    d. The qualification authority will:
        i. Determine which catalogued objects were in the FoV of the sensor during the survey and how many were observable (ie bright enough for the sensor).
        ii. Determine which of the observable objects were indeed observed during the survey. The qualification authority may need to correlate the observations with the survey.
        iii. Determine the total survey time of the sensor.
    e. The sensor is declared 'qualified for SDmon surveys' if:
        i. The sensor observed at least 50 % [TBC] of the observable objects.
        ii. The sensor surveyed for at least 75 % of the planned survey time.

5 SUMMARY AND CONCLUSIONS

Validation and qualification of SDmon optical sensors are active fields and ESA is running multiple activities in these topics. The ExpCen has procedures defined for both and can support telescopes in becoming qualified for SDmon observations. To facilitate these processes, a standardised approach (through CEN/CENELEC or another standardisation body) can be developed.

6 REFERENCES

1. "IGS Products Information". International GNSS Service. http://www.igs.org/products/information
2. "Expert Centre Procedures". Issue 1.1. Revision 3. European Space Agency. September 2017.
3. European Committee for Standardization (CEN) and European Committee for Electrotechnical Standardization (CENELEC) European standards for the space industry website: https://www.cencenelec.eu/standards/Sectors/AirSpace/Space/Pages/default.aspx