POLISH SST SMALL TELESCOPE ASSESSMENT AND PROTOTYPED OPERATIONS

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ABSTRACT

POSST - Polish SST small telescope assessment and prototyped operations is a project carried out by Sybilla Technologies as the prime contractor founded by ESA (SSA P3-SST-XXII). Within the project we integrate over 30 sensors to test the possibilities of observing resident space objects (RSO) in LEO, MEO and GEO regimes. We examine new data formats and integration scenario of optical sensors within the stare and chase observation campaign. We present a new unifying format for requesting SST data, the Observation Scheduling Message (OSM). We evaluate the astrometric accuracy provided by the sensors. We also present the first results of the simulations and deployment, maintenance strategy for network of low-cost sensors (COTS) covering the GEO belt.

1 INTRODUCTION

The goal of the Space Surveillance and Tracking (SST) segment of the ESA Space Situational Awareness programme is the development, test and validation of technologies for detection, identification, cataloguing and tracking of space debris and satellites. To achieve that we need an effective way to schedule new observations in short and long term, monitor the execution of such observations, as well as receive and process the results. An efficient, automated network of cooperating sensors is an important part of the worldwide SST system. Integration of new and existing observing formats, interfaces and software is, however, a challenge for various SST networks.

Poland provides a significant contribution to the European SST domain in terms of passive and active optical sensors' network availability, capability to provide data, know-how, expertise, as well as a viable industry, academic environment strongly supported by Polish public administration.

In this contribution we present the current status of POSST, Polish SST small telescope assessment and prototyped operations project funded by and carried out for the European Space Agency (ESA SSA P3-SST-XXII, ESA Contract No. 4000129731, activity No. 1000025704). The project is being carried out by Sybilla Technologies as the prime contractor, together with Iguassu Software Systems, 6Roads, GMV Poland, Deimos Space UK Ltd., CBK and Ukrainian Space Center as subcontractors and partners.

Within the POSST project we integrate more than 30 sensors to test the possibilities of observing LEO, MEO and GEO regimes (Section 2). We examine new data formats and take the first glance at more complex integration scenario of passive and active optical sensors within the stare and chase observation campaign (Section 3).

The project's first goal is to integrate sensors, define and provide necessary interfaces, and validate this concept via observations campaigns. The important part of the project is the combination of the existing and new tools (e.g., ABOT, WebPlan or POLNOC system) [1], [2], [3], sensors, standards and software packages, and finally test them in real observing campaigns.

The new unifying format for requesting SST tracking and survey data, the Observation Scheduling Message (OSM) is presented in Section 4. We analyse OSM integration architecture with ESA SST Expert Centre and Polish SST National Operating Centre.

Sensors from Ukrainian network were also involved in POSST activity. For the first time they were used in ESA activity and therefore had to be calibrated in terms of evaluation of the accuracy of the provided data. The analysis is shown in Section 5.

In addition, we present the first results of the single sensor simulations and deployment strategy for network of low-cost sensors (COTS). The trade-offs of locations, various equipment for global network covering the GEO belt is presented in Section 6.

2 NETWORK OF SENSORS

Optical sensors, passive and active, from 6 different networks were involved in the activity (see the map on Fig. 1.). They were analysed considering sensors'

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properties and their geographical location. There were five passive optical networks involved:

- Panoptes-Solaris - 10 sensors
- 6ROADS - 7 sensors
- Deimos - 4 sensors
- SHOT - 1 sensor
- Ukraine - 10 sensors.

Together with these, the active optical LASBOR SLR station in Borowiec near Poznań, Poland, participated in tracking activities. The sensors are located on five continents on both hemispheres, with the majority in Europe [4].

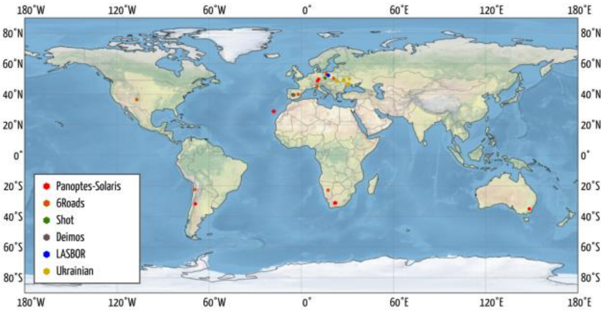

Figure 1: Optical sensors involved in POSST activity

For the purposes of the project, we are simulating the potential network setups, considering existing sites, infrastructure, costs of maintenance, weather, and light pollution. Taking in consideration all of these factors we hope to find optimal network for the future activities.

In total, there are over 500 astronomical observatories on Earth. This is an extremely heterogeneous group of places on all continents, including Antarctica. Fig. 2 shows most of the astronomical observatories on Earth divided according to the Bortle class [5]: blue for the areas with dark sky (class 1 and 2), green for the rural sky (class 3 and 4) and red for the high or very high light pollution in cities and suburban areas (class 5 and higher). The latter one is represented mostly by urban observatories, with a large historic value or set up by schools and amateurs as an outreach tool. Observatories located in the rural and suburban areas are often more modern, but are located in densely populated regions, like it is the case of most of Europe, where escaping light pollution is rarely possible. Luckily, for many SSA activities darkest sky possible is not as important as geographic distribution or technical capabilities and we assume this may be a decisive factor within the areas of interest and not the global network.

From this pool around 20-30 sites will be selected for more detailed simulations. A group of new potential sites should add value to the already existing network. It is expected that the simulations will show which factors are the most important, while planning such a network of optical sensors and how it relates to the operational know-how of contractors and partners.

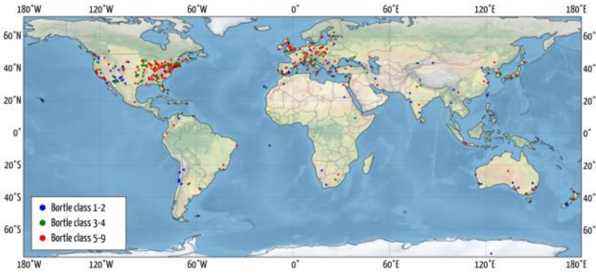

Figure 2: Astronomical observatories according to light pollution

3 TEST CAMPAIGN

A group of LEO, MEO and GEO targets was preselected to test the follow-up capability of sensors in real observing conditions. The expected result was the confirmation that the provided endpoints and links work as planned in the design. A test was considered successful if MEO and GEO targets were observed by optical passive sensors, and LEO and MEO by optical active SLR station. There were two modes scheduled: tracking for each sensor and survey for a selected group of sensors with enough large field of view.

To conduct the test campaign, we have prepared a mock of the ESA's SST Expert Centre [6] based on its architecture, including SFTP, file system, secure access to the data or visibility protecting users from seeing other data. This allowed the maximal compatibility with the SST Expert Centre possible. Nevertheless, the Key Performance Indicators (KPIs) definitions and procedures differ to some degree between POSST and SST Expert Centre.

KPIs measurement is based on SQL database and the telemetry streams provided by the sensors. Measured are the values related to the weather and performance, like night time available for observations, total off duration (in hours and percentage), off duration caused by bad weather, software issues, hardware issues, maintenance time, unknown issues. Also, measured is the number of OSM files (described below), valid TDMs produced by the sensors, correlation between TDMs and survey or tracking OSMs, average, minimal, and maximal time between measurement and TDM upload, as well as between OSM and TDM uploads.

Observations were carried out from October 2020 to January 2021. All selected sensors provided data, except SLR3 from Panoptes-Solaris network, due to camera repair. This had no effect on campaign results as backup sensors from the network were used. In total 608 survey TDMs were produced from 28 hours of observations and 1796 tracking tdms from 227 observing hours. The expected aim of the campaign was achieved successfully.

4 OBSERVATION SCHEDULING MESSAGE

The Observation Scheduling Message (OSM) is the scheduling data format to be used in the exchange between Expert Centre and the sensors used in the POSST activity. The focus is on passive optical sensors, but SLR are supported as well. The message facilitates the interoperability between different sensors and networks. It also supports the automation of the data acquisition processes. The follow-up and survey strategies are included. The main purpose of the OSM is to schedule observations to get information about the observed object at specific time. For passive optical sensors, this information is the sky position and brightness. For SLR, the ranging measurements are obtained. OSM does not specify the observation method, but rather defines an interval in which a certain task shall be completed. The task can be an object to be followed or a survey region to be covered. In both cases it is the sensor responsibility to plan the observation details. The outputs shall be measurements in the TDM format.

The OSM content was designed in the similar way as Consultative Committee for Space Data Systems (CCSDS) Navigation Data Messages (NDM) and re-uses types developed by the CCSDS Navigation Working Group. The XML format was adopted, and associated schema was created following the CCSDS approach. Each OSM shall consist of a <header> and a <body>. They follow the CCSDS NDM/XML basic structure. The OSM body shall consist of one or more <segment> constructs. The OSM <segment> shall consist of a <metadata>/<data> pair, as shown on Fig. 3.

```
<osm>
  <header>
  </header>
  <body>
    <segment>
      <metadata>
      </metadata>
      <data>
      </data>
    </segment>
    <segment>
      <metadata>
      </metadata>
      <data>
      </data>
    </segment>
  </body>
</osm>
```

Figure 3: OSM XML basic structure

The metadata section shall be set off by the <metadata></metadata> tag combination. It specifies the observation strategy (follow-up, survey), time system and the time interval covered by the data section.

The data section shall follow the metadata section and shall be set off by the <data></data> tag combination. Based on the observation strategy defined in the metadata section, the data section shall contain one or more:

- *trackingRequest* sections (if observation strategy is follow-up) represented by the <trackingRequest></trackingRequest> tag combinations within the data section, or
- *surveyRequest* sections (if observation strategy is survey) represented by the <surveyRequest></surveyRequest> tag combinations within the data section.

Follow-up object is specified by the set of TLE parameters. It can use only NORAD ID for the object identification. In that case the sensor is responsible to download the related ephemeris. CPF ephemerides can be used to schedule SLR observations.

```
<data>
  <trackingRequest>
    <target>
      <ephemerides>
        <meanElements>
        </meanElements>
        <tleParameters>
        </tleParameters>
      </ephemerides>
    </target>
    <observation>
    </observation>
  </trackingRequest>
</data>
```

Figure 4: Tracking request structure for follow-up observations

```
<ephemerides>
  <EPHEMERIDES_TYPE>TLE
</EPHEMERIDES_TYPE>
  <tleParameters>
    <NORAD_CAT_ID>36868
</NORAD_CAT_ID>
  </tleParameters>
</ephemerides>
```

Figure 5: TLE ephemerides for follow-up using only NORAD ID

Surveys are defined using horizontal or vertical stripes. The angular separation between survey fields can be specified as well.

```
<data>
  <surveyRequest>
    <surveyStrategy>
    </surveyStrategy>
    <observation>
    </observation>
  </surveyRequest>
</data>
```

Figure 6: Survey request structure for survey observations

```
<surveyStrategy>
  <STRIP_DIRECTION>1
</STRIP_DIRECTION>
  <SURVEY_UNITS_HOR>HA
</SURVEY_UNITS_HOR>
  <FIELDS_PER_STRIP>3
</FIELDS_PER_STRIP>
  <NUMBER_OF_STRIPS>2
</NUMBER_OF_STRIPS>
  <INITIAL_HOR>15</INITIAL_HOR>
  <INITIAL_DEC>-5</INITIAL_DEC>
  <DELTA_HOR_FIELD>0.7
</DELTA_HOR_FIELD>
  <DELTA_HOR_STRIP>3.5
</DELTA_HOR_STRIP>
</surveyStrategy>
```

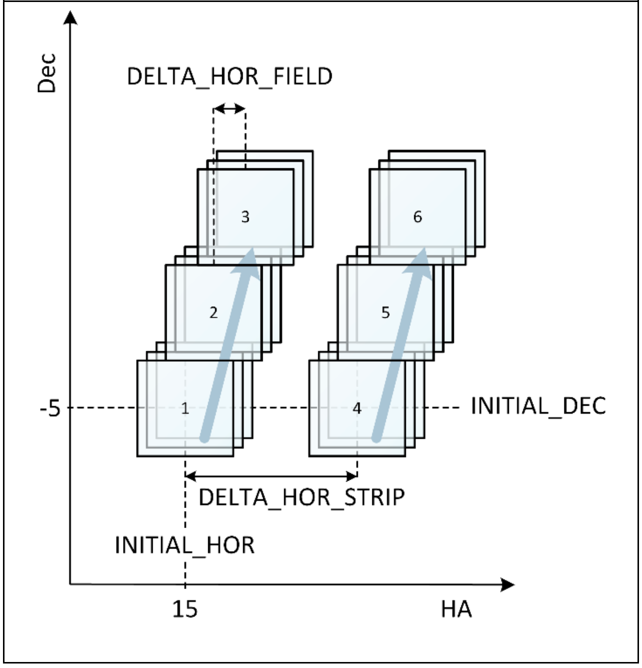

Figure 7: Survey strategy example with predefined offsets between fields and stripes (vertical stripes). For the illustration it is assumed that the FoV is 2 degrees.

The observation timing is given as an interval in which the follow-up or survey shall be performed. It is the sensor's responsibility to schedule individual observation within the observation interval in order to get the tracklets.

```
<observation>
  <DATE_TIME_START>2020-05-
03T21:00:00.00</DATE_TIME_START>
  <DATE_TIME_END>2020-05-
03T21:15:00.00</DATE_TIME_END>
</observation>
```

Figure 8: Observation interval

5 UKRAINIAN SENSORS' DATA CALIBRATION

Data from two Ukrainian sensors, ODESSA (Odessa City) and QOS-Zonnefeld (located at Center of Special Information Reception and Processing, CSIRP and Navigating Field Control, NFC) were used to evaluate the accuracy of the provided data from telescopes involved in POSST activity. The evaluation of the astrometric accuracy was done by GMV Poland, based on the tracking TDMs with over 68 thousand measurements for 14 LEO, MEO and GEO objects.

The sensors' owner provided information on telescopes regarding optical design, mount, parameters of CCD, measurement format, and measurement accuracy. The last one was compared to the values derived from the analysis of the delivered data.

From the data provided only those were chosen for analysis that have data for objects with the trusted orbital information that could be used as a reference in calibration process. The observed objects and those chosen for analysis are shown in Tab. 1.

Analysed Ukrainian sensors did not apply the annual aberration correction, hence data had to be corrected by annual aberration. Then the time bias was calculated. Observations with high value of residuals were rejected during the analysis. The process used to reject observations, in the calibration, is the standard 4-sigma filtering. It focuses on rejecting measurements with residuals higher than specified multiple of the RMS of the population of residuals. Residuals in analysed data were differences between observed values (measurements) and the measurements computed during the orbit determination process.

The calculated astrometric accuracy for QOS-Zonnefeld, less than 1", turned out to be below declared value, 2-5". The evaluated time bias for this sensor was around 8 milliseconds, which was also below declared value (15-20 msec). Only 2.1% of measurements with too high residuals were rejected from the calibration. Since the number of rejected data points was quite low, the observations were performed with good accuracy and without mistakes in objects identification.

NORAD ID	Name	Type of orbit	Classification
16908	EGS (AJISAI)	LEO	Geodetic
39452	SWARM A	LEO	Science ESA
33105	JASON 2	LEO	Earth resources
41240	JASON 3	LEO	Geodetic and Science US
41384	IRNSS 1F	GEO	IRNSS (Indian Regional Nav Sat System)
40315	COSMOS 2501 (GLONASS)	MEO	GNSS
37948	BEIDOU IGSO 5	IGSO	GNSS
36582	COMSATBW-2	GEO	GEO, Military
32711	NAVSTAR 62 (USA 201)	MEO	GNSS
19751	COSMOS 1989 (ETALON 1)	MEO	GNSS
15264	SL-12 R/B(2)	MEO	Rocket body
14977	COSMOS 1554 (GLONASS)	MEO	GNSS
35943	COMSATBW-1	GEO	GEO, Military
40128	GALILEO 5 (261)	MEO	GNSS

Table 1: Observed objects, measurements for objects marked in grey were used to calculate the time bias

In case of the ODESSA sensor the calculated astrometric accuracy around 5” was quite large (declared value was 2”). However, the number of rejected data points was surprisingly small, around 0.1%. The evaluated time bias for this sensor was around 1 millisecond. The example of non-rejected residuals for one observed object (SWARM A) is shown on Fig. 9.

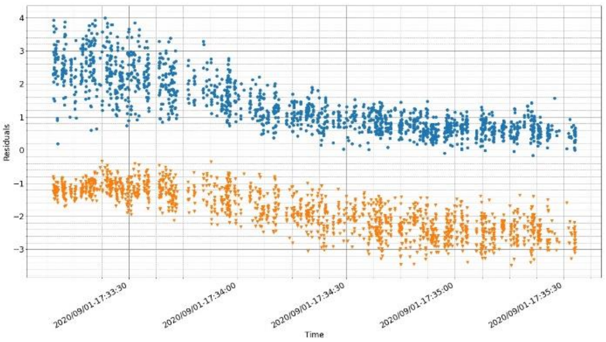

Figure 9: Non-rejected residuals for SWARM A observed by Odessa sensor

In general, the performed calibration for Odessa and QOS-Zonnefeld sensors gives respectively small value of time bias under 10 ms that is normal error produced in the hardware of the telescopes.

6 FIRST RESULTS FROM SENSOR SIMULATIONS

The aim of simulations was to propose the best COTS hardware configuration and optimal geographical distribution of selected units to provide full GEO coverage to the required limits, like depth of the survey, search rate, number of tracked objects, budget, sensitivity.

For a single sensor simulation of different setups, Deimos used an in-house SST simulator, AS4. This tool can evaluate a system's capacity from a cataloguing perspective. It uses two main modules, Population Generation and the Measurement Generation, which provide flexibility regarding the objects in space and the sensor configuration (number, types, and performance).

The Population module generates catalogues which contain the orbital information corresponding to the population of potentially observed objects or detected by the sensors simulated afterwards. The tool then converts the catalogue files to a format required for the simulator. This format includes the Cartesian state vector of every object in the catalogue and orbital elements. For this project, as input for this module, Deimos used Two Line Elements (TLE) plus information on estimated mass and area for every object (as listed in SATCAT from CelesTrak). TLE contains mean orbital element sets generated by fitting observations to a trajectory based upon the SGP4/SDP4 orbital model. SGP4 is applied to objects with an orbital period of less than 225 minutes (Near-Earth objects in NORAD classification), while SDP4 is used for orbital periods greater than 225 minutes (deep space objects).

The Measurement Generation module is one of the core elements of the software. The tool allows a flexible definition of the architecture and observation strategies to be analysed. Architecture definition includes the number and location of observation sites, the number of telescopes per site, and each telescope's independent features. The observation strategy can be defined independently for every simulated telescope in a very flexible way. The user may define outages due to maintenance or bad weather conditions (which may last complete or partial nights). These outages can be entered in a deterministic or random way depending on the simulated sites' typical weather conditions.

The simulated measurements are generated by determining if a body within the catalogue is visible from a telescope and, if so, evaluating the azimuth, elevation, etc. For each body, visibility determination is accomplished in several steps, with different filters and discarding criteria:

- Feasibility criteria are applied to discard bodies that will not be visible from the telescope at any time.
- Trajectory propagation for those bodies identified as feasible.
- Visibility criteria are applied at different observation times using trajectory propagation data for feasible bodies. These are criteria applied at a lower level than the feasibility criteria, which discard bodies from a catalogue but only during a specific time, i.e., 1 day for optical telescopes. So, after that characteristic period, the body is rechecked.

Furthermore, pre-filters are also used for observation feasibility analysis. They are applied to each body and are based on geometrical & physical considerations:

- Debris apogee altitude vs. minimum altitude observable from a telescope.
- SNR at apogee vs minimum SNR value of the probability, where the user introduces SNR function into the input file.

These pre-filters work as preliminary filter to skip debris bodies out of the observation site's scope.

The simulation also depends on sensor capabilities, especially on optical tube and camera features. It is possible to evaluate typical sensor performances regarding reachable FoV and visual magnitude.

Signals received by CCD or sCMOS cameras are evaluated as the total amount of energy received from space object during the integration time. It is not the energy received by a single pixel, but the total energy received by the set of pixels contained in the camera. The signal received from the observed body consists of light from the Sun reflected by the object and observed by the telescope. The phase angle represents the critical parameter to define the observation condition and is considered for observing each object. The flux of energy from the body is inversely proportional to the square of the distance and directly proportional to the debris body's characteristic area. Total energy is derived from this flux by integrating the flux along the integration time and over the telescope aperture area, and considering several losses sources; e.g., atmospheric transmission efficiency, telescope optical efficiency and camera's quantum efficiency. The following main parameters are considered when evaluating the performance of a sensor (in addition to considering the location of the sensor and the observed objects):

- Aperture diameter (m)
- Pixel size in arcsec
- Field of view of telescope (deg)
- Integration time (seconds)
- PSF size (arcsec)
- Mean atmospheric transmission
- Mean optical transmission
- Mean quantum efficiency
- Sky background magnitude
- Camera readout noise (e/pixel)
- Dark current (e/pixel/sec)
- Minimum snr ratio for detection
- Number of images in survey
- Reference flux (photons/s/m2)
- Reference diameter (m) for reference magnitude at albedo (0.1)
- Reference magnitude corresponding to reflux
- Telescope 1-sigma error in pointing (arcsec).

For each sensor to be analysed, these main parameters need to be defined, and then simulations for observation capability can be executed.

In the first iteration, the RASA 11", QHY268M setups were tested, placed at the location of Deimos Sky Survey in Puertollano. The GEO surveillance declination strip strategy was simulated for one day with 3 images and an exposure time of 6 seconds, 2 seconds between each image, and no SNR filter applied. Considering the public TLE catalogue of objects, 192 objects were found to be observable with the given setup on the night of 10-11 December 2019. The observable objects ranged in diameter from 0.65 m to 10.43 m and visual magnitude from 10.4 and 16.4 (see Fig. 10). The figure demonstrates the connection between magnitude and size. In further tests and for different setups, the SNR filter will be applied. With a campaign of simulations, with varied input parameters (i.e., the observation time), it will be possible to extract the realistic limits of a given setup.

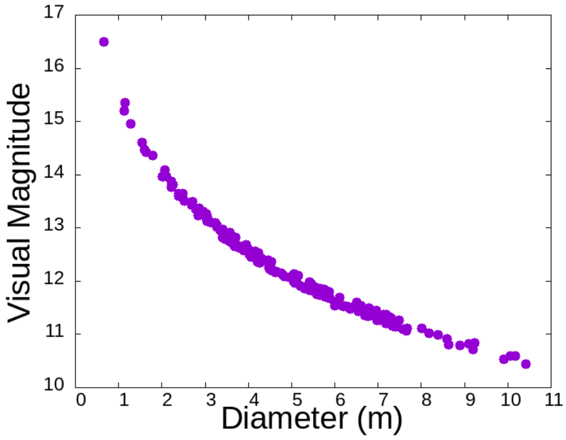

Figure 10: Observable objects with the first setup on 10-11 December 2019

7 SUMMARY

There were over 30 sensor located on 5 continents involved in POSST project. We have conducted test campaign with those sensors to test them in real observing conditions. The aim of the campaign was to confirm that the provided endpoints and links work as planned in the design. To test it, a mock of the ESA's SST Expert Centre was created based on its architecture, SFTP, file system, and secure access to the data. We used new unifying scheduling data format, OSM, for requesting SST tracking and survey data in the exchange between Expert Centre and the sensors working in the POSST activity. For the first time Ukrainian sensors were used in ESA activity. Their astrometric accuracy was confirmed in a sensor calibration. We have also conduct single sensor simulations to propose the best COTS hardware configuration and optimal geographical distribution of sensors to provide full GEO coverage to the required limits. During the project the stare & chase campaign will also be performed.

8 REFERENCES

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