END-TO-END PROCEDURE FOR SATELLITE ORBIT CATALOGUE FROM OPTICAL OBSERVATION

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ABSTRACT

The "End-To-End Procedure for satellite Orbit Catalogue from optical observation" (E2EPOC) project has been developed and completed through a collaborative research work between three organisations, including 6 Remote Observatories for Asteroid and Debris Searching (6ROADS), Astronomical Observatory of Adam Mickiewicz University (AO AMU) and ITTI Sp. z o.o. within ESA's Space Situational Awareness (SSA) program. The E2EPOC project was focused on the SST (Space Surveillance and Tracking) segment of the ESA SSA program. This segment aims mainly at creating and maintaining a catalogue of man-made space objects, detecting fragmentations (collisions or explosions) and supporting space missions.

The fundamental goal of the E2EPOC project was to develop, implement and validate the complete set of End-to-End procedures leading from planning satellite observations to the creation and maintenance of the catalogue comprising the orbits of these satellites.

Complete End-to-End procedures from selecting the objects to be observed to updating satellite orbits in the orbital catalogue were planned to be composed. Achieving these aims was possible through fulfilling the following tasks:

- Establishing an experimental (TRL-5) sensors network, which could simulate the future operational SST network. The observation campaigns were conducted without any major issues noted. The sensors network proved to be efficient and the workflow proposed for the observation campaigns was proceeding correctly.
- Defining and evaluating the End-to-End procedure of SST observations.
- Verifying the defined End-to-End procedure of SST observations.

The first step of a thorough and reliable verification of the proposed SST observations procedure was to compare the orbits, which were calculated based on the results obtained from the observation campaign, with the orbits obtained from external sources (NORAD catalogue, etc.). Subsequently, an assessment of the achieved orbit determination precision for selected classes of satellites was to be conducted. Following the adopted plan, the final phase was to verify the assessed precision by performing test observations with the use of ephemerides calculated on the base of catalogued orbits. The overall results of the End-to-End procedure evaluation can be considered successful. The amounts of data obtained during the observation campaigns proved to be sufficient for an adequate test of the procedure. The final product of this End-to-End procedure was a catalogue of satellite orbits. After undergoing a quality validation process, the obtained data was being processed by the software tools selected for the project and stored in three types of catalogues - the TLE Catalogue, the Keplerian Orbit Catalogue and the PV (position-velocity) Catalogue.

Keywords: orbit determination; optical observation; catalogue.

1. INTRODUCTION

One of the primary tasks of Space Situational Awareness (SSA) domain is to monitor the space and maintain an up-to-date orbital catalogue. The possibilities of determining the orbits of satellites based on only astrometric observations from a network of telescopes were presented by several research groups [2], [3], [5].

Designing and verifying the observation and orbit determination procedures dedicated to the Polish SST activities operations was the key goal of the project. Complete End-to-End procedures beginning from selecting the objects to be observed and ending with updating the orbit data in the orbital catalogue were planned to be composed.

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A set of procedures has been developed and the tools necessary for this process have been identified. Their usefulness was confirmed during 3 observation campaigns. During each campaign, about 20 satellites were observed in the orbits of MEO, GEO and HEO regimes. The result of the work was a catalogue of orbits maintained throughout the observation campaign.

2. BACKGROUND

2.1. Sensors network

The sensors network composed by 8 optical telescopes owned by 6ROADS and AO AMU with 0.3 - 0.7 m aperture was established for carrying out test observations and checking the operation of the developed procedures in reality. The geographical distribution of the telescopes is shown on the map in Fig. 1.

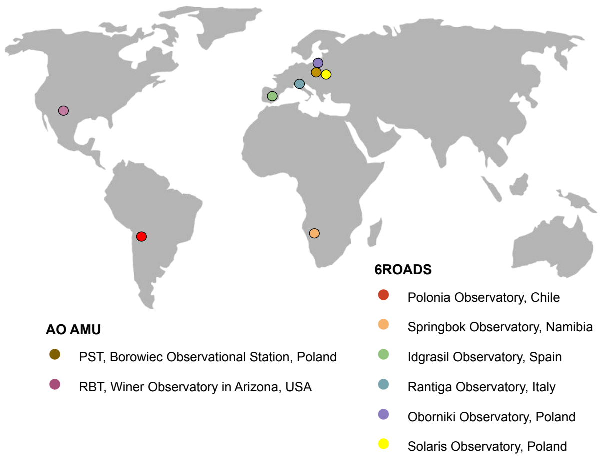


Figure 1. Location of telescopes around the globe.

A network of optical telescopes used in this projects was composed of remotely controlled and robotic sensors, equipped with different cameras and software systems. The sensor network was composed of 2 sensors of AO AMU:

- PST1 (MPC Code 187),
- RBT/PST2 (MPC Code 648),

and 6 sensors of 6ROADS:

- Rantiga (MPC Code D03),
- Oborniki (MPC Code K98),
- Idgrasil (MPC Code Z33),
- Solaris (MPC Code B63),
- Polonia (MPC Code W98),
- Springbok (MPC Code L80).

2.2. Software

Many different types of software are required to carry out the entire process of satellite catalogue creation and maintenance. The software chosen for the project is divided into the following packages:

- PSST Tasking - proprietary software of AO AMU,
- PSST Astrometry - proprietary software of AO AMU,
- ORBIT DETERMINATION - including GEODYN II - created by NASA Goddard Space Center [4] and software packages prepared by AO AMU to optimise the work related to GEODYN,
- ITTIOrbits - proprietary software of ITTI (based on the Orekit v.9.3. library).

The PSST Tasking software package is in-house software developed by AO AMU, dedicated to preparing observation tasks. Some of the functionalities of this package are downloading Satellite Catalogue from the Space-Track service [1], calculating the ephemerides for selected satellites and automatic planning of satellite observations for a single observatory.

To perform astrometric and photometric measurements on satellite tracking and survey images we used dedicated PSST Astrometry software package. The functionalities offered by the applications in this software package include detecting objects and determining their locations in FITS images regardless of its shape, identifying stars using the GAIA DR2 catalogue, identification of satellites, calculating satellite equatorial coordinates and magnitudes with uncertainties, generating output files in various formats and basic quality control of the astrometric results.

For precise orbit determination (OD) of the observed satellites we used the GEODYN II. Some extensions to the GEODYN software were developed by AO AMU in order to adjust it strictly to our needs.

It is also possible to use an alternative software for OD process such as ITTIOrbits. The results of orbit determination using the ITTIOrbits software were compared to the results obtained from the GEODYN software.

3. END TO END PROCEDURE

The fundamental goal of the E2EPOC project was the development, implementation and validation of the complete set of End-to-End procedures leading from the planning of the satellite observations to the creation and maintenance of the catalogue comprising the orbits of these satellites. Various stages of this procedure have been developed during the initial phase of the project and have been upgraded during the operational phase.

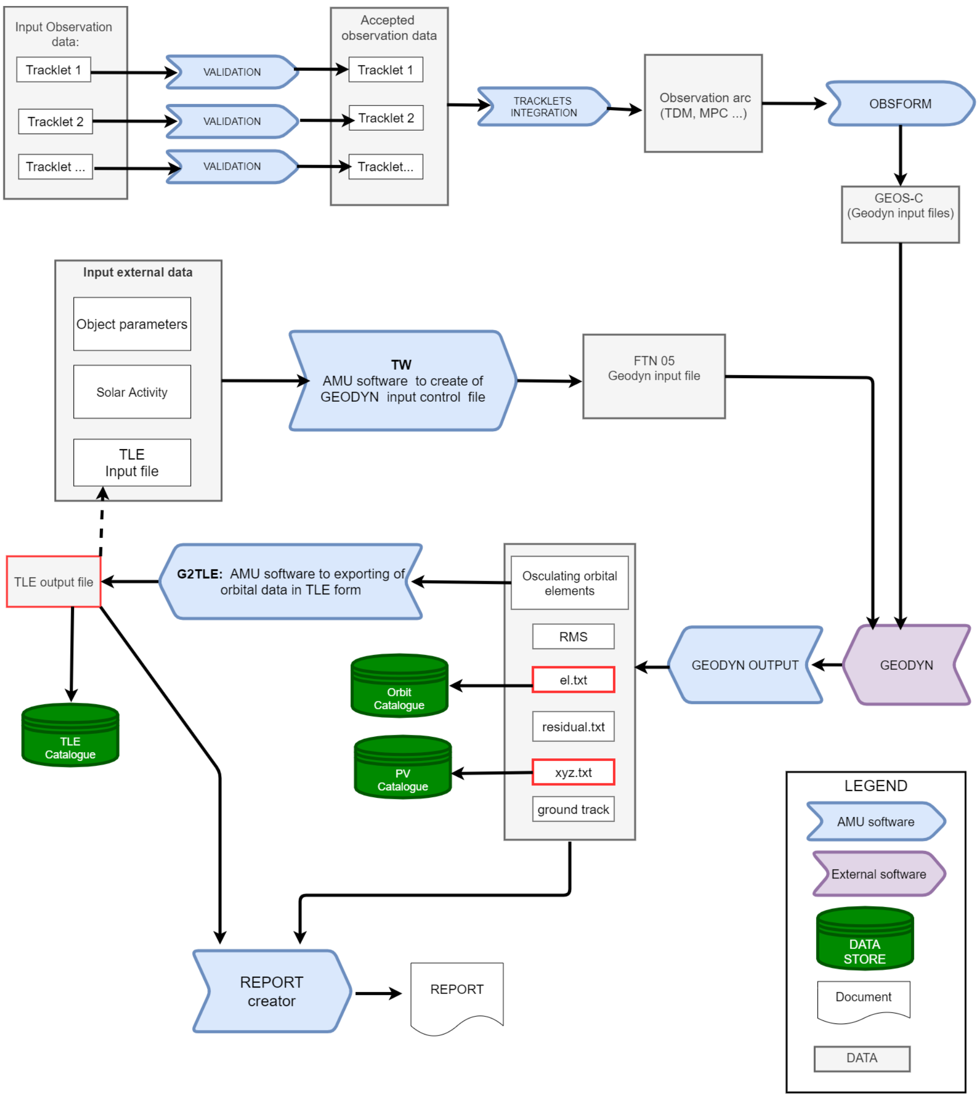


Figure 2. E2E procedure - "astrometry to catalogue" scheme.

Two main parts have been separated throughout the process: from planning observations to astrometry and from astrometry to the catalog. The first involves planning observations, distributing observation plans, performing observations, reducing images, and delivering astrometric measurements of selected targets. This part requires communication between the operations center and the sensor operators. The input data for the second part of the process are measurements (eg. TDM files), which are validated, combined into observational arcs and on their basis orbits are corrected, correlated and cataloged. A diagram of this part of the process is shown in Fig. 2.

3.1. Observations planning

A central observation scheduling system has been created for all sensors participating in each campaign. It is based on PSST Tasking - a collection of AO AMU satellite observation planning and observation analysis programs. It automatically analysed observations and orbit determinations to assign a priority to each target for the next night. Subsequently, it combined own, recently determined orbits with orbits from Space-Track for targets without orbit determined less than 5 days ago. Finally it automatically created an observation plan and a command list for each telescope taking into account various restrictions and parameters such as: geographic location, target priority, observing altitude limits, meridian flips, star field density, telescope slewing time etc. The observing plan for the following night were distributed via Secure Copy Protocol (SCP) and through email.

3.2. Observations

During the course pf the project three observing campaigns have been conducted in 2019, each lasting from

3 to 4 weeks. Prior to each campaign a simulation was carried out to select targets from three orbital regimes: MEO, GEO and HEO. Half of the targets were selected among objects with the highest number of passes over the highest number of sensors to test our procedures in the easiest possible situation with a wealth of observing data. The second half was selected among objects with median amount of passes to represent a more typical observing scenario.

Every night, if weather and technical conditions allowed it, astrometric observations of the satellites were made through all telescopes in the network. Observations made in tracking mode are effective and easy to perform for satellites in orbits higher than LEO. The effectiveness of the observation is high. Statistically, more than 50% of the exposures made allow for accurate astrometry.

Overall during the three campaigns we collected 7883 tracklets for 28 satellites, 1538 tracklets for 21 satellites and 11561 tracklets for 25 satellites.

3.3. Astrometry

A fully automatic, central system for imaging data analysis has been created for each sensor in the network. Within its pipeline, it combined image extraction, field identification, astrometric transformation, photometric analysis, error estimation, target identification and basic quality control. The astrometric results were saved in multiple formats, including Tracking Data Message (TDM) and Modified Minor Planet Center format (MPCMOD) which were used for orbital analysis.

The analysis of astrometric observations included also time bias and accuracy determination as a sensor calibration routine. By using GNSS accurate ephemeris in SP3 format and ILRS ephemeris in CPF format we calculated the differences between observed and ephemeris positions of selected calibration satellites. The deviations along satellite trajectory were interpreted as time bias measurements, while deviations across satellite trajectory as astrometric measurement errors. An example of calcualted time bias is presented in Fig. 3 for RBT/PST2 and Idgrasil telescopes.

3.4. Observational data validation

The first step performed in the process of orbital determination (observational data validation) consists in removing accidental, erroneous observations from the observational data set. In the process of automatic, robotic execution and processing of observations and automatic determination of astrometric positions, accidental errors may occur, e.g. incorrect identification of reference stars. Such observations cannot be used for orbit determination and should be removed before the proper orbit determination process begins. The schematic procedure for validating the observation data is shown in the Fig. 5.

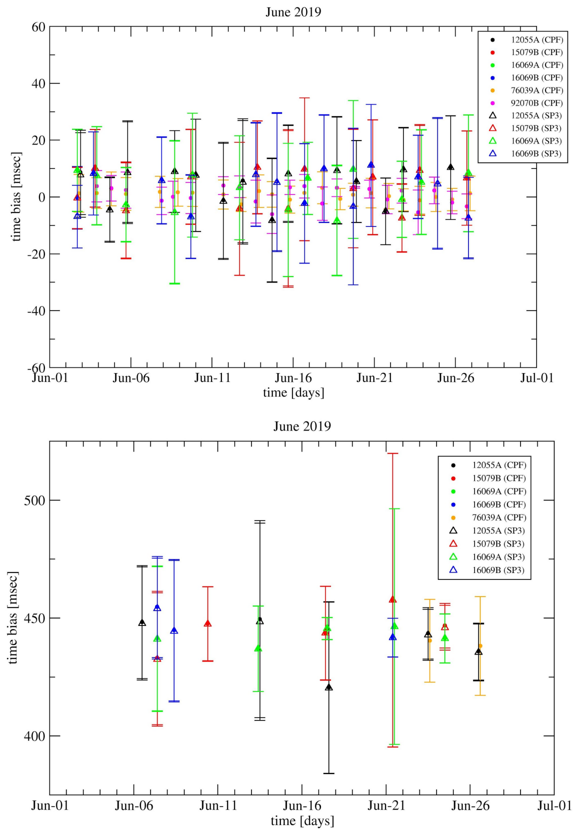


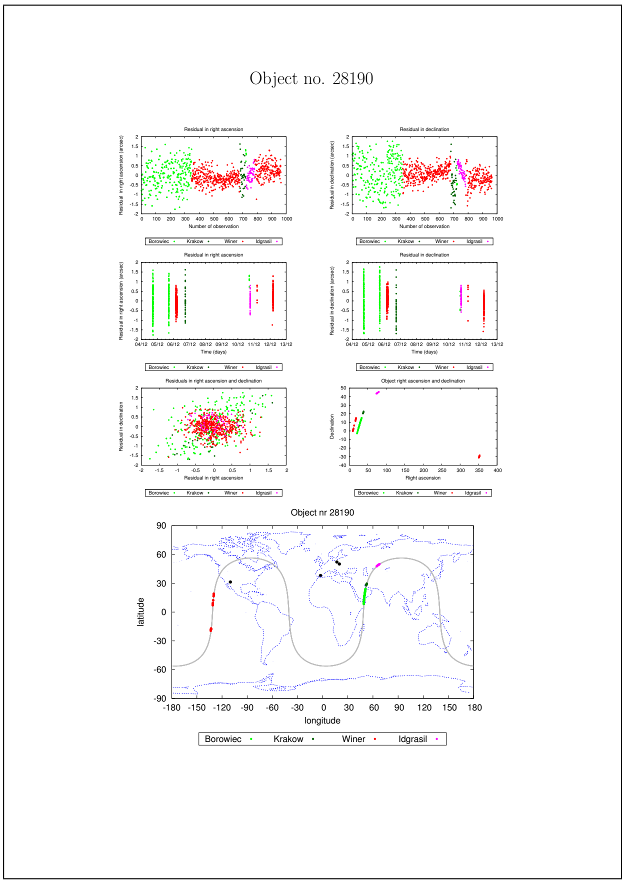
Figure 3. Time bias measurements for RBT/PST2 (top) and Idgrasil (bottom) telescopes during the first observation campaign in 2019. The differences arise from the fact that RBT/PST2 is using an electronic shutter Andor iXon camera while Idgrasil is using FLI CCD camera. Both telescopes showed constant time bias and reliable image timing during the whole campaign.

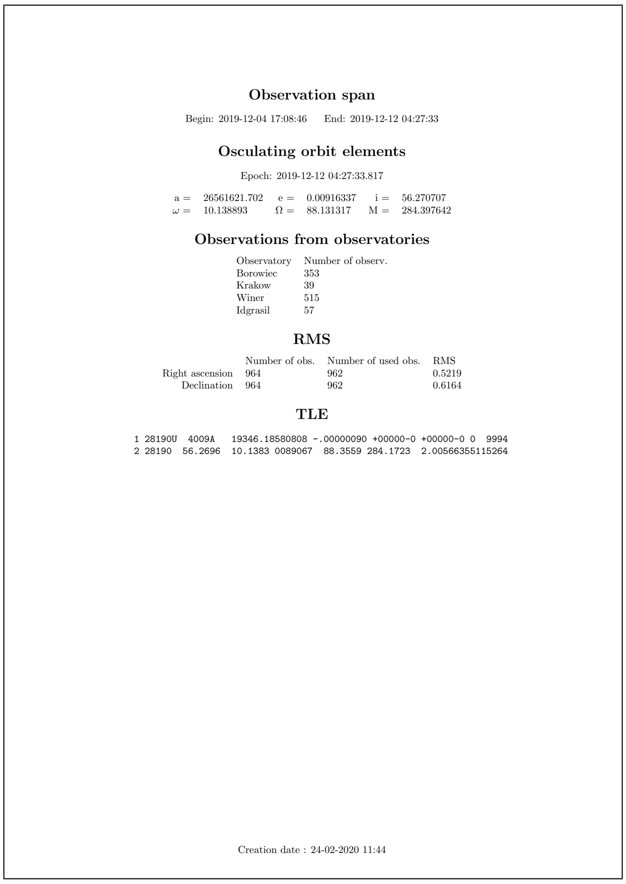
Data validation process is based on orbit determination, but only a provisional orbit is calculated in this step and outlier observations are deleted. This approach guarantees consistency of observational data.

3.5. Orbit Determination

Precise orbit determination of satellites has to be performed with the use of a set of software tools for satellite orbit determination from astrometric observations. These tools include NASA's GEODYN II as a main orbital program and a number of additional programs based on the STOP software developed in the AO AMU [6]. The GEODYN II has been used for precise orbit determination from astrometric observations (right ascension and declination) obtained by telescopes participating in the E2EPOC project. The following force model has been taken into account:

- Earth gravity field: GRACE Gravity Model 03 (GGM03) up to 80 x 80 degree and order,





Observation span

Begin: 2019-12-04 17:08:46 End: 2019-12-12 04:27:33

Osculating orbit elements

Epoch: 2019-12-12 04:27:33.817

a =	26561621.702	e =	0.00916337	i =	56.270707
ω =	10.138893	Ω =	88.131317	M =	284.397642

Observations from observatories

Observatory	Number of observ.
Borowiec	353
Krakow	39
Winer	515
Idgrasil	57

RMS

	Number of obs.	Number of used obs.	RMS
Right ascension	964	962	0.5219
Declination	964	962	0.6164

TLE

```
1 28190U  4009A   19346.18580808 -.00000090 +00000-0 +00000-0 0  9994
2 28190  56.2696  10.1383 0089067  88.3559 284.1723  2.00566355115264
```

Creation date : 24-02-2020 11:44

Figure 4. Sample report generated during OD calculations

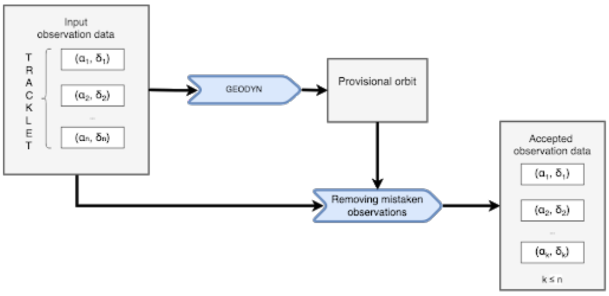


Figure 5. Validation process scheme.

- Third body gravity: Moon, Sun and all planets with the use of DE403 JPL Ephemerides,
- Atmospheric drag with MSIS empirical drag model of the Earth's atmosphere,
- Earth and ocean tides,
- Solar radiation pressure, including the Earth's shadow effects.

During the project implementation, it turned out that for the selected orbital regimes, the OD process gives the best results, if the observations from the last 5 days are taken into account for the calculations. To optimise the work with the GEODYN II a number of software packages were created:

- OBSFORM - program for conversion from the observation measurement format to GEOS-C data format (GEODYN II observation input files),
- TW - a program to create the GEODYN ftn05 file, including control cards, detailed specification of the problem to be solved by GEODYN II,
- GEODYN_OUTPUT - software packages to export GEODYN II output data to formats required by the user: ORBIT, PV DATA, RESIDUALS.

In successive iterations, in the differential orbit improvement process, applying all the observations, the best orbital parameters were estimated. Using these parameters, values of residuum O-C in right ascension - α and declination – δ and RMS were calculated. After each calculation a report file was generated automatically, containing most important information. Report contains several diagrams which present the residuals in right ascension and declination, a drawing which presents the parts of the orbital arc covered with observations, the time interval including the observations used for a given orbit determination, the statistics of this observation, RMS values in right

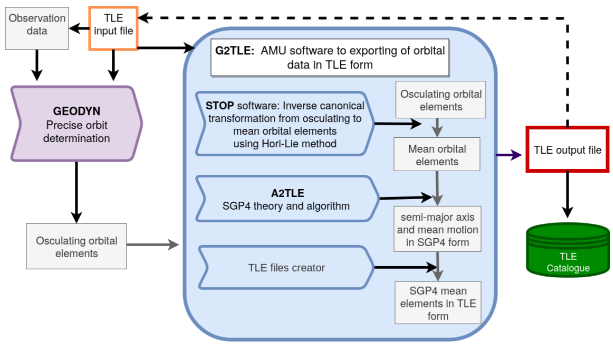


Figure 6. Procedure of exporting orbital data to the TLE format.

ascension and declination, osculating orbit elements and TLE elements. Sample report is presented on Fig. 4.

During the E2EPOC project, it was noticed that one of the most significant parameter in the orbit determination process is the value of the area to mass ratio A/m. An incorrect value of this parameter can degrade the results of the orbit determination process. Orbit determination requires using the area to mass ratio value as close to the actual one as possible. If these values are unknown or uncertain, it is necessary to carry out the process of estimating them. The area to mass ratio estimation procedure has also been implemented.

3.6. Calculation of the mean elements in the TLE format

Osculating orbital elements obtained from GEODYN are transformed to mean elements (according to the SGP4 definition) and are saved in a file in the TLE format. The G2TLE software tool has been used to create TLE files. In the first step, the osculating orbital elements are transformed by STOP software to mean elements according to the algorithm of inverse canonical transformation from osculating to mean orbital elements using the Hori-Lie method. Next, the new semi-major axis and mean motion values are obtained according to the SGP4 algorithm (using A2TLE program). Finally, the results are written in the TLE format by using “TLE files creator”.

The diagram 6 shows the procedure of the transformation from osculating orbital elements to the SGP4 mean orbital elements written in the TLE format.

It was necessary to develop a procedure for determining TLE elements due to the fact that the programs controlling the telescopes used in the project use this format. As a result, it was possible to reobserve the tracked objects based on our own catalogue and close the process loop.

3.7. Orbit Catalogue

The final product of this End-to-End procedure is a catalogue of satellite orbits. The process of building the catalogue is carried out once a day. New observations must be taken into account. During the process, applying new observations, a new orbit for each satellite object is calculated and saved in the catalogue file. There are three formats in which the catalogue is produced:

- osculating Keplerian elements catalogue,
- osculating position-velocity (PV) elements catalogue,
- TLE format catalogue.

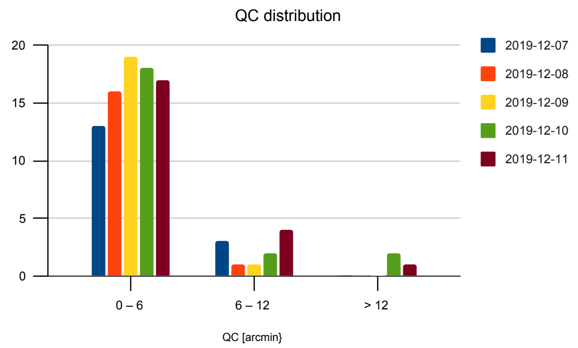


Figure 7. Distribution of QC parameter over the period of 5 days.

The quality of the determined orbital elements was checked by comparison with the NORAD catalogue [1]. The comparison was based on the prediction of the orbit from NORAD and determined from our own observations for a period of 24 hours and calculating the difference in position on the sphere between them. The parameter that describes this difference is labeled QC. Fig. 7 shows the distribution of these differences for 5 consecutive days, taking into account two thresholds: 6 arcmin and 12 arcmin.

3.8. Automation of the process

Process automation is an essential aspect of the entire system. Due to the large amount of data, it is impossible to perform all calculations manually. The presented procedure assumes the automation of most processes with appropriate operator supervision. Additional programs and control scripts were used for automation. The operator follows the instructions to implement the procedure in an appropriate manner. An even higher level of process automation is possible for larger amounts of data. The program, in such a case, should automatically perform the relevant parts of the process controlling the flow of data, but then a much more advanced system is needed to monitor the process and inform about possible failures or problems. Operator's supervision during the performance of individual procedures allows to quickly notice errors such as incorrect marking of observed objects or poorly performed astrometry. In the event of problems with the process or unusual situations at any stage, a given task is redirected to an analyst who is able to analyze the situation and indicate appropriate further procedures. Despite the automation of most of the process, human surveillance is essential.

4. SUMMARY

The paper presents the End-To-End procedure for satellite orbit catalogue from optical observations. The described procedure has been developed and implemented. During the three observation campaigns, a catalogue of the orbits of the MEO, HEO and GEO satellites was maintained using observations from a telescope network and data processing in a highly automated manner. The quality of the catalogue was confirmed by comparing it with the NORAD catalogue and by reobserving the objects on the basis of the own catalogue.

ACKNOWLEDGMENTS

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