PROCESSING OF OPTICAL TELESCOPE OBSERVATIONS WITH THE SPACE OBJECT CATALOGUE BACARDI

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Abstract:
In a joint project of the DLR Institute for Simulation and Software Technology and DLR Space Operations and Astronaut Training develop methods for space surveillance. The main objective of the project is to develop an orbital database for objects in Earth orbit – called the Backbone Catalogue of Relational Debris Information (BACARDI). The research topics are object identification form different sensor observations, orbit determination and orbit propagation including state vector and state uncertainty. Main applications of the orbital database will be close approach prediction for collision avoidance - further on re-entry prediction, detection of satellite manoeuvres and on-orbit fragmentations.
In this paper an introduction is given to the space object catalogue BACARDI. All information imported, processed and exported is stored within a relational database. A self-developed middleware provides the functionality for distributed computations on a scalable network of hardware devices. The data processing chain consists of a multi-staged algorithm of observation correlation and subsequent orbit determination. Results are presented for single processing steps by example of optical telescope observations of satellites in MEO and GEO.

Keywords: *space debris, space surveillance, space object catalogue, orbit database*

1. Introduction

Knowledge about the current and future space debris population is prerequisite to develop awareness for the risks and hazards space mission have to face. Statistical models on the object density help to design a mission, e.g. orbit selection and spacecraft shielding, and are a strong motivation for post-mission disposal. Many other safety measures are based on orbital information for specific objects, like collision avoidance for operational satellites, re-entry prediction or detection of orbit fragmentations. For the sake of risk mitigation, a data bank is required with the greatest possible completeness of space objects, the highest possible accuracy of orbital information, and object parameters like e. g. size. Reflecting the current situation, space surveillance in the future has to provide improved detection of small size objects and exchange of sensor data.

The Backbone Catalogue of Relational Debris Information (BACARDI) is an orbital database for the greatest number of known objects in Earth Orbit, both active satellites and space debris as the main share, and related information to create and maintain the orbit information [1]. A relational database is used for data storage and access. The data are structured in more than 100 tables, e.g. for space surveillance and tracking sensors, sensor observations, orbit information in the form of parameters sets for in different orbit dynamic models, object properties, on-orbit events like manoeuvres and fragmentation, and many other. Provenance data allow tracing back the sources of information for each data product. One example question to the relational database might be: Which sensor provided information that was used for orbit determination and prediction and subsequent generation of a close approach warning a satellite operator has to deal with. Past states of information can be reconstructed by evaluation of metadata and processing logs. Sharing of space surveillance data has a great potential under the assumption that different level of confidentiality are respected. Therefore, in BACARDI every data record is linked with configurable rights and definable user roles for data transfer in accordance to arbitrary given rules.

In addition to the relational database, BACARDI provides the hardware and software to create and maintain a space debris catalogue for a “large number” of objects. One can argue that all objects down to a size of approximately 1cm should be catalogued since spacecraft shielding is an efficient protection against objects of smaller size. Following statistical models like MASTER-2009 a “large number” of objects may easily translate to 1.000.000 in this case.

The computational effect is not a linear function with the number of objects. For some applications, like all vs. all close approach screening there is a quadratic dependency between the number of objects and computation steps. In the case of observation correlation for detection of new objects, hypotheses are tested that are formed as combinations of multiple un-associated tracks. There are $\binom{n}{k} = \frac{n!}{k! \cdot (n-k)!}$ ways to choose k elements for a set of n elements.

A self-developed middleware provides the functionality for distributed computations on a scalable network of hardware devices. Research topics are the development of computational efficient algorithms and high performance computing (HPC) methods like parallelization on CPU and GPU.

The first sensor network contributing observation data to BACARDI is the Small Aperture Robotic Telescope Network (SMARTnet) [2], [3]. The network is used for monitoring the geostationary Earth region and is subject to a proposed second presentation at ISSFD 2015 [4]. Since August 2014 a robotic telescope is tested at the Zimmerwald Observatory of the Astronomical Institute of the University of Bern. Once testing is finished, the telescope will be deployed at the Sutherland Observatory in South Africa. Optical observation of GEO and MEO objects where gathered since the beginning of the test campaign. Thereby, it is possible to present the first results of BACARDI processing algorithms based on real measurements. The core steps of the processing chain will be demonstrated for passive optical observations that provide short series of line of sight measurements from geostationary objects.

2. Backbone Catalogue of Relational Debris Information (BACARDI)

The information system BACARDI consists of three main components. First, interfaces to transfer data between BACARDI and external information sources and receivers. Second component is middleware software providing the required processing functions on a scalable network for distributed computations. And third, a relational database is used to store and access all information.

2.1 External Information Sources and Recipient

The completeness and accuracy of the orbital database is driven by the available observation measurements from a global sensor network. There are a number of long existing sensor for satellite or single debris object tracking like transponder ranging, on-board GNSS receiver, satellite laser ranging and the Tracking and Imaging Radar (TIRA). The robotic telescope of SMARTnet will be the first surveillance sensor accessible to GSOC. A laser tracking station with ranging capability to LEO object without laser retro-reflector is currently build up by the DLR Institute of Technical Physics [5], [6]. The station is also capable of passive optical surveillance and tracking and will be connected to BACARDI. A second ongoing sensor development is the German Experimental Space Surveillance Radar (GESTRA) which will provide observations to German research institutes and shall be the baseline for future operational surveillance system. Finally BACARDI supports sharing of sensor data, a key for space surveillance of the future.

Sources for externally generated orbit information are the Joint Space Operation Center (JSpOC) providing the Two-Line Element (TLE) catalogue, the International Laser Ranging Service (ILRS), the Astronomical Institute of the University of Bern (AIUB) and providing orbits of GEO and HEO objects and other sources like e. g. satellite operators for active satellites. For objects with orbit information from multiple sources, the one with highest confidence and accuracy is selected. Fusion of different orbits relies on correct orbit uncertainties and orbit determination based on combined sensor observations should be preferred.

Additional data required for orbit propagation and orbit determination are solar flux values, Earth rotation parameter, and object properties like mass and cross-section which are regularly imported by BACARDI.

External user query trigger the transfer of matching database records in accordance to the data rights of the user. This include among many other: sensor observations, orbit and uncertainty information, conjunction warnings and re-entry prediction.

2.2 Middleware for Distributed Computations

Middleware software was developed as a customized framework for distributed applications on a scalable network of different hardware devices. A processing master creates tasks and puts them on a processing queue. For each network device a configurable number of processing workers requests tasks from a processing queue and puts back the results once processing is finished. Parallel workers are possible for all steps of the processing chain like orbit prediction, observation correlation and orbit determination as well as generation of addition products like close approach prediction, manoeuvre detection, fragmentation detection, re-entry prediction, etc. More details on the software architecture can be found in [7].

BACARDI is both an event based and a time based system. Some interfaces are polled and other pushed. As an example of event based action, the observation data of SMARTnet are imported by a pushing interface and are immediately handed over to the processing chain of observation correlation and orbit determination. Once the orbit information of an object is refined, all derived products like close approach analysis results are updated. An example of a typical time based task is the regular import of solar flux data by a polling interface.

2.3 Relational Database

More than 100 relational database tables have been defined with an uncounted number of data links. Emphasis has been put on further provenance and log data. It is therefore possible to retrace information flow and reconstruct processing steps. For illustration, BACARDI can answer questions like:

- With measurement corrections were applied for a specific sensor?
- With observation data where used for the creation of an orbit information?
- What were the settings for orbit estimation, e.g. gravity field, atmospheric density model, third bodies, numeric integrator?
- What is the origin and import date of a specific data record?
- What is known about an object, e.g. mass, size, laser reflector, manoeuvrable, debris?
- What is the object history, e.g. launcher, fragmentation parent object, re-entry?
- When was a close approach event first known and how did assessment results evolve?
- What are the error statistic of observations and orbit information from different sources?
- Which entities are allowed to receive a specific data record and which did so fare?

3. Processing Cain

The data processing chain consists of a multi-staged algorithm of observation correlation and subsequent orbit determination, see Fig.1. In a first correlation step new measurements are compared against existing orbital information of already known objects, for example previously generated or imported database records. In case of an unambiguously and reliable correlation result the orbit records is updated by the new observations. The remaining uncorrelated measurements are passed to an object identification algorithm that filters out multiple observations that are connected by an elliptical Earth orbit. In this way new candidate objects are discovered and initial orbits are determined. The association of further observations increases the orbit accuracy and may leads to an object candidate confirmation and generation of a new catalogue record.

The correlation of observations is generally divided into a comparison of sensor observations with orbit data of a catalogued object or candidate object or into a comparison of two or more sensor observations. In observation correlation with orbit data, modelled observations are computed in a first step. For ground based observation this requires object position and velocity with respect to the sensor station, and for space based observations the state vector of the object and potentially secondary satellite hosting a sensor payload. For this purpose, any orbit propagators with different dynamic models can be used. The distance k is a measure how close the real observation z and modelled observation $\hat{z}$ match each other:

$$k = (z - \hat{z})^T (P_z - P_{\hat{z}})^{-1} (z - \hat{z}) \tag{1}$$

It is important to note, that the distance k incorporates the error matrix of the observations P_z and error matrix of the modelled observation $P_{\hat{z}}$, which is derived from orbit uncertainties and models on addition error sources like measurement noise and bias.

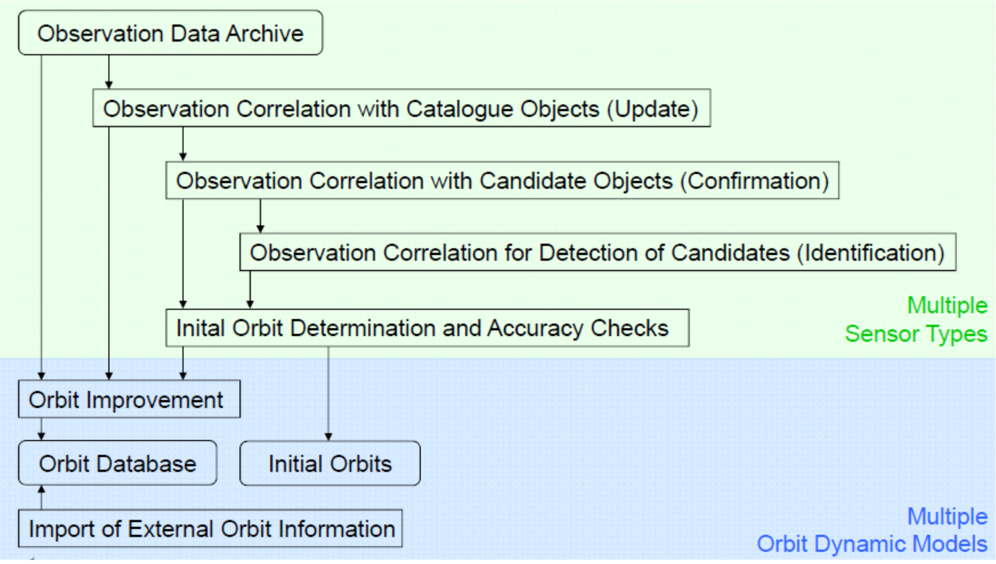

Figure 1: Processing Chain

Observation correlation is performed on a track-by-track basis. In the case of ground-based observations of low Earth orbit (LEO) a station pass lasts up to ten minutes or more, depending on minimum and maximum elevation. In case of optical telescope observations in MEO and GEO, multiple exposures are taken successively. Like for most sensor types, a short time series of measurements is generated inherently associated to the same object and that is called track or tracklet. The observation vector z , and correspondingly the modelled observation vector $\hat{z}$ should gather all quantities that are measureable during a typical track of a specific sensor type. The vector is called attributable vector if it contains parameter that not part of a single sensor measurement, like measurement time derivatives.
For the purpose of object identification the correlation of two or more observations has to be tested. The computation of an initial orbit is required that allows to form the attributable vector at different observation times. For the purpose of object identification, a dedicated initial orbit determination algorithm has to be available for every combination of observations with different sensor type. For the purpose of orbit confirmation and update, observations are compared with orbit data and the correlation algorithm has to be specific for each sensor type.

Once a new observation is assigned to an object or candidate object, the database orbit information is updated. If batch least squares estimation is applied, previous observations of the same object within a certain time interval have to be retrieved from the database and are jointly processed with the new observations. If a Kalman filter is used the last filter state is read from the database, propagated till the observation epoch and updated by the new measurements. A different parameter sets has to be estimated for each orbit dynamic model supported for orbit determination. For the import of extern orbit information the specific orbit propagator is needed.

3. Results

The first SMARTnet telescope is currently tested at the Zimmerwald Observatory of the Astronomical Institute of the University of Bern. The results of the core processing steps are presented in the following subsections.

3.1 Observation Correlation for Object Identification

The association of tracklet pairs is tested using the boundary-value optimization method developed by Simiski [8], [9], [10]. The attributable vector contains the astronomical angles right-ascension α and declination δ and their first time derivate. A least-squares fit has been applied to the single line of sight measurements of each short series of image exposures to compute the attributable vector for the series mean time. The attributable vector z together with the error matrix P_z reads as:

$$z = \begin{pmatrix} \alpha \\ \delta \\ \dot{\alpha} \\ \dot{\delta} \end{pmatrix}, \qquad P_z = \begin{pmatrix} \sigma_\alpha^2 & 0 & 0 & 0 \\ 0 & \sigma_\delta^2 & 0 & 0 \\ 0 & 0 & \sigma_{\dot{\alpha}}^2 & 0 \\ 0 & 0 & 0 & \sigma_{\dot{\delta}}^2 \end{pmatrix} \tag{2}$$

Adding a possible range value to the mean line of sight measurement allows calculating a position with respect to the sensor coordinates, and further on with respect to the inertial coordinate system in use. By solving the Lambert problem a Keplerian orbit is obtained that connects two position vectors within the time difference of two tracklet observations. The boundary-value optimization method finds the optimal range values with respect to a loss function according to the distance defined in equation 1. The measurement vector z contains the first time derivate of right-ascension and declination at both observation epochs. The modelled measurements follow form the lambert solution found. Multiple solutions are possible depending on the number of half revolutions in the time between both observation epochs. By suitable selection of the initial range values all solutions can be found.

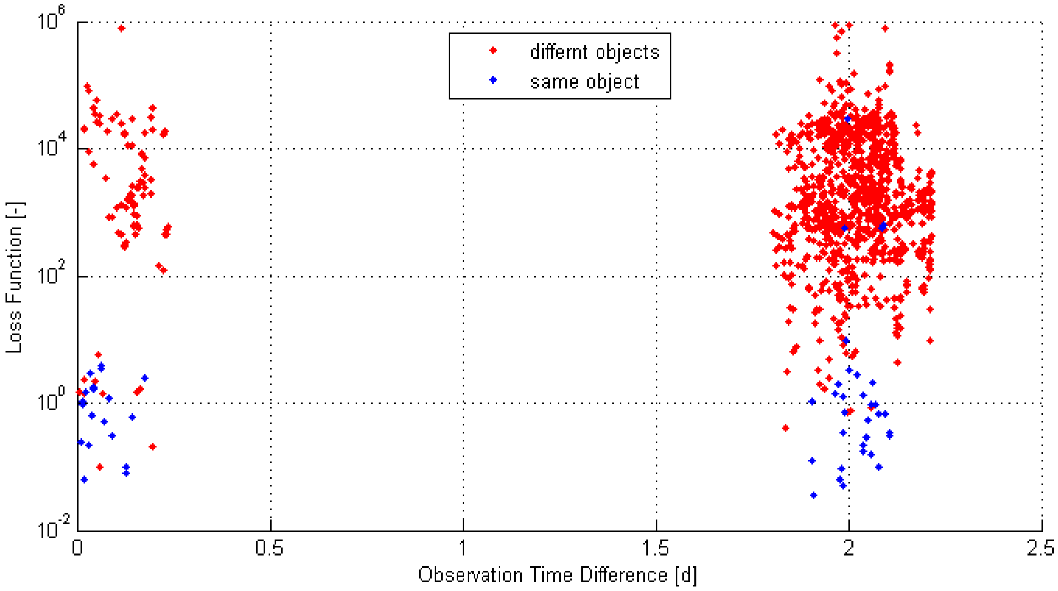

Figure 2: Short-Arc Observation Correlation for Object Identification

Tracklet association has been tested for all pairs of observations from two observation night, 2014/08/22 to 2014/08/23 and 2014/08/24 to 2014/08/25. The loss function after final optimization step is shown in Fig. 2, the lambert solutions with lowest loss function is considered for each tracklet pair. Depending on the time difference there are two clouds of tracklet pairs, the left cloud contains tracklet pairs within the same observation night, the right cloud represents tracklet pairs from different observation nights. For every tracklet, correlation with the TLE catalogue has been performed. Pairs of tracklets belonging to the same TLE object are shown in blue; pairs of tracklets belong to different TLE objects are shown in red. True pairs can be filtered out by setting a threshold for the maximum loss function value. The filter rate follows a chi-squared distribution and depends on the time difference and angular distance between both short arc observations.

3.2 Correlation of Observations and Orbit Data

The correlation of sensor observations and orbit data has to deal with challenging situations when many objects move on similar orbits. Example cases are on-orbit fragmentations, like on-orbit explosions and collisions, or satellite close-formations and co-located satellites. Cluster of co-located geostationary satellites were repeatedly observed during two successive nights, 2014/09/25 to 2014/09/26 and 2014/09/26 to 2014/09/27.

The distance between real observations and modelled observations based on the TLE catalogue is computed according to Equation 1 and 2. Since TLEs do not hold any information on orbit uncertainty, the error matrix of modelled observations is set constant for all TLE objects. Every tracklet is associated to the TLE object with the lowest k value. All tracklets associated to a single object handed over to batch-least-squares orbit determination. Outliers are rejected tracklet by tracklet until all residuals do not exceed a certain threshold. In the following a threshold of 1" is applied. Association of all tracklets, rejected or not, and update of all orbits repeats until all tracklet associations stay unchanged.

Observation correlation results for the cluster of three satellites EUTELSAT HOT BIRD 13B, 13C and 13D are shown in Fig. 3. The distribution of a total number of 111 tracklets gathered is shown in the top left subfigure. Based on TLE data, the projected movement of the three satellites between the start of the first night and end of the second night is added in the subfigure on the top right. False associations emerge for a large number of tracklets at the centre of the cluster. A single tracklet is associated to the TLE orbit of satellite with COSPAR ID 2006-032-A (green dashed line). This demonstrates the algorithms ability to balance difference in line of sight and difference in apparent movement. Orbit improvement is started for the tracklet sets initially associated to the TLE orbit for object 2008-065-A (red dashed line) and 2009-008-B (blue dashed line), and not to the single tracklet of object 2006-032-A. After the first iteration step the tracklet association slightly improves, see bottom left subfigure. There are false association for a lot of tracklets at the centre of the cluster. The TLE orbit of object 2006-032-A (green dashed line) is still used, since it was not updated in the first iteration step. Two tracklets get associated to this object and a batch-least-squares orbit determination is possible for all three satellites in the second iteration step. The updated orbit for object 2006-032-A is not very precise, but leads to association of even more tracklets in the third and final iteration step. The final solution is shown in the bottom right subfigure. All 111 tracklets are associated to one of the three satellites

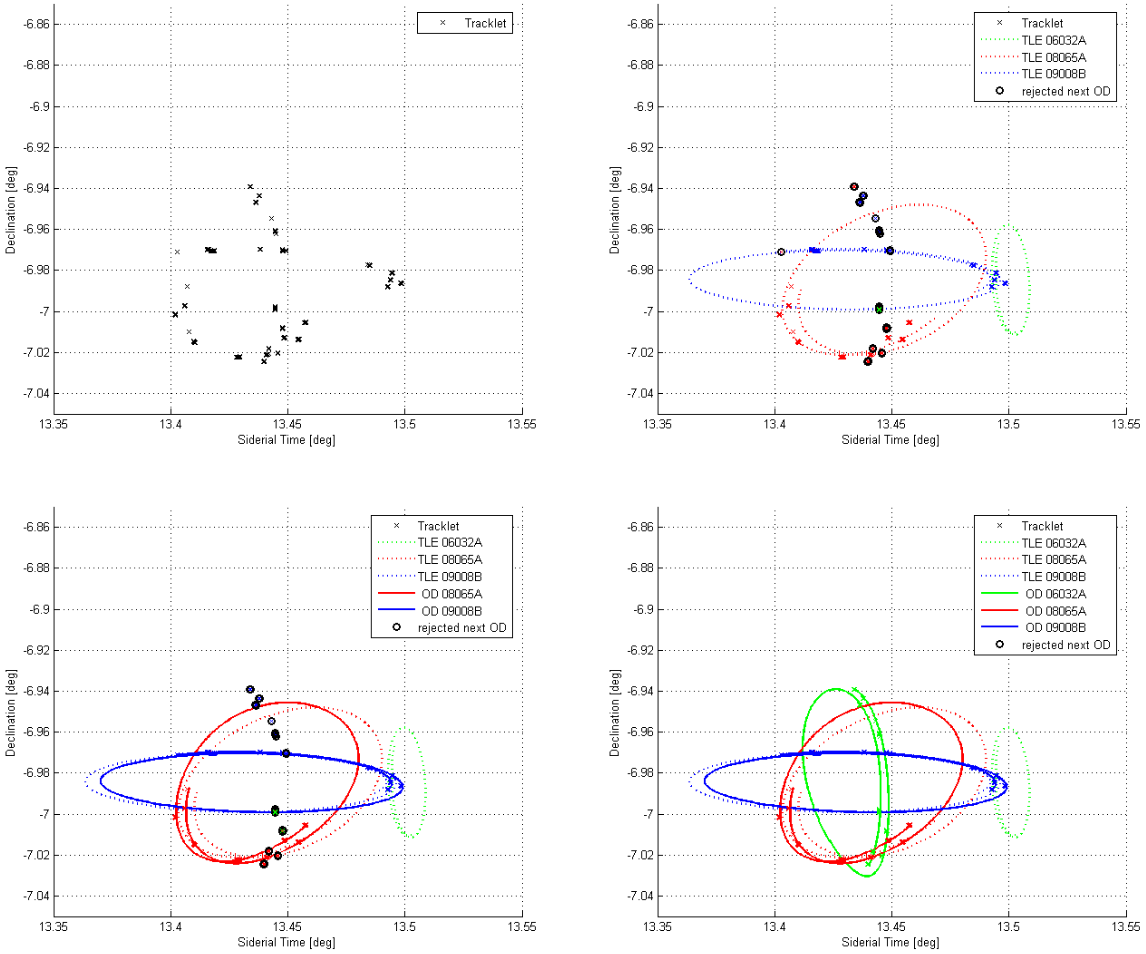

Figure 3: Observation Correlation for Geostationary Satellite Cluster (top left: un-associated tracklets from two observation nights, top right: correlation results with TLE catalogue, bottom left: correlation results after first iteration step, bottom right: correlation results after third and final iteration step)

with high confidence, according to the residual statistics: 2006-032-A RMS α=0.25” δ=0.35”, 2008-065-A RMS α=0.30” δ=0.34” and 2009-008-B RMS α=0.29” δ=0.34”.

The determined orbits differ from the latest TLE data the end of the second observation night by magnitude of several kilometres for object 2008-065-A and 2009-008-B and up to 100km for object 2006-032-A. A possible explanation may be an East-West station keeping manoeuvre not known to the United States Strategic Command and not part of TLE and simplified general perturbations models.

3.3 Orbit Determination

Batched least squares estimation is a standard method for orbit determination and is not explained here. Further on, the analysed observation data set is not suited for a statistical orbit determination error analysis. As a show case for the orbit determination (OD) step of the BACARDI processing chain, two example results are presented.

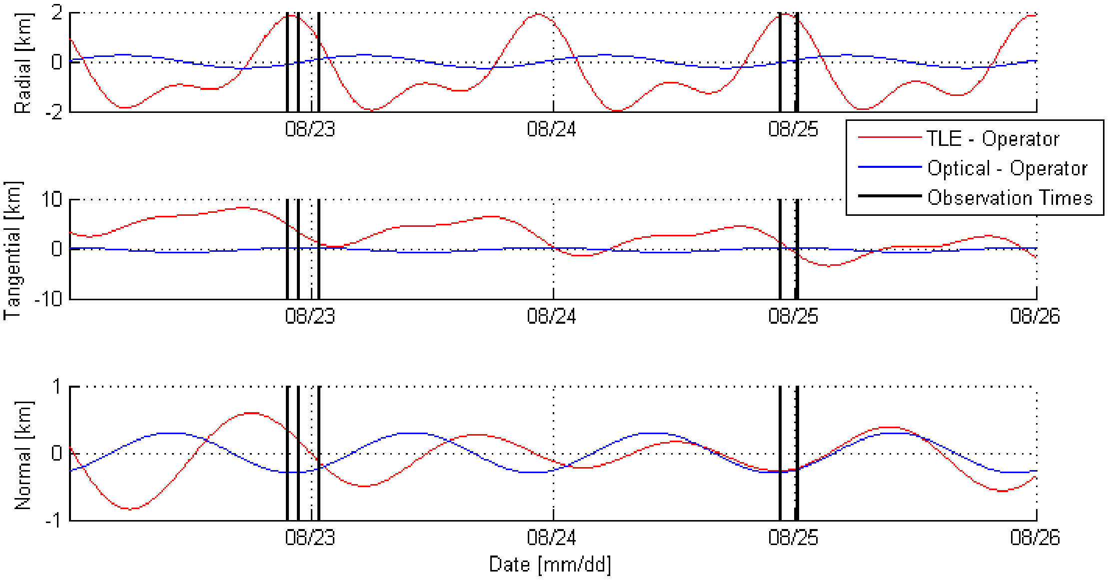

Figure 4: Example case GEO – Position Difference for OD of METEOSAT 8

In the first example orbit determination of the geostationary satellite METEOSAT 8 (COSPAR ID 200-040-B) is performed based on six tracklets obtained within two observation nights. The time span between first and last observation is 2.11 days and the angular separation of the entire observation arc covers less than 12% of the orbit. METEOSAT orbital parameters including manoeuvre data are published at EUMETSAT webpage. State vector including solar radiation pressure coefficient are regularly updated. Without secured information on spacecraft cross section and force models applied for parameter estimation, the obtained state vector was propagated to obtain a reference orbit from satellite operator data.
In Fig. 4 position differences with respect to the reference orbit are shown for the latest TLE at the time of the last observation ("TLE-Operator" in red) and for the estimated orbit from telescope observations ("Optical-Operator" in blue). The TLE orbit differs from both of the other solutions by up to ten kilometres, most severe in along-track direction. The estimated orbit from telescope observations and the orbit including operator data show maximum discrepancy of 260m in radial direction, 750m in along-track direction and 300m in cross-track direction, during the time interval between first and last observation. Since the accuracy of the reference orbit is unsure, the conclusion is that the real OD position error stays well below one kilometre in this particular OD case with few observation data.

The second example is an orbit determination of GPS IIR-5 satellite. Moderately improved observation data are available, compared to the OD example for METEOSAT 8. The observation arc contains a total number of 29 tracklets, spanning a maximum time interval of 3.16 days and covering around 17% of the orbit. The estimated orbit can be compared against a well-defined reference orbit retrieved from the Center of Orbit Determination in Europe (CODE). For GNSS satellites the reference orbit errors are magnitudes of orders smaller than expected OD errors from ground base optical observations. Therefore the results shown in Fig. 5 reflect the real OD errors for the second example case. The maximum positon errors during the first and last

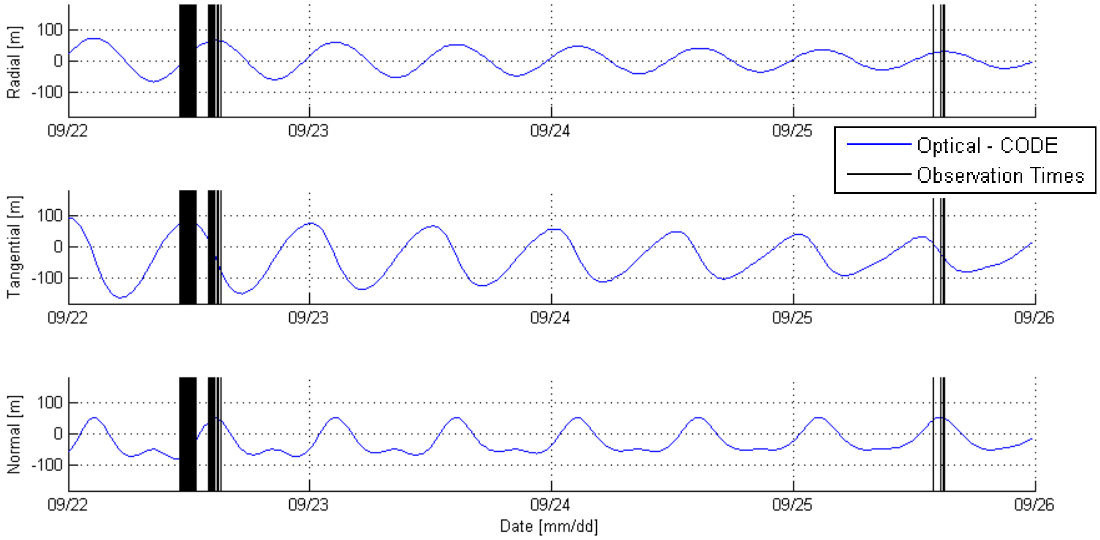

Figure 5: Example case MEO – Position Errors for OD of GPS IIR-5

observations are 71m in radial direction, 161m in along-track direction and 78m in cross-track direction. The positon errors are small than in the GEO example. One reason is the reduced observation range, connected to smaller position error at constant angular resolution of the telescope. The second reason for smaller OD errors may be the improved quantity and distribution of observations.

4. Conclusions

The Backbone Catalogue of Relational Debris Information (BACARDI) being developed at GSOC is a space object catalogue system with the goal to provide most complete and accurate orbit data and related products for safe space operations. The system challenges and design solutions have been presented. The next major step will be catalogue creation and maintenance for GEO objects monitored by the Small Aperture Robotic Telescope Network (SMARTnet). During the on-going test campaigns observations have been gathered from many observation nights. Tracklets have been successfully processed for each step of the processing chain with the presented results.

5. Acknowledgments

AIUB carried out installation of the SMART-01 telescope and commissioning at the Zimmerwald Observatory, Switzerland. The night observers on-site supported the test campaign.

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