Five Years of SMARTnet: Data, Processing, and Improvements

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DLR: German Aerospace Center

ABSTRACT

SMARTnet, operated by the Astronomical Institute of the University of Bern (AIUB) and the German Aerospace Center (DLR), went online and became open to the public in 2017 with two telescope stations located in Zimmerwald, Switzerland, and Sutherland, South Africa. Over its five-year operational timespan, new Partners have joined while one Partner left, leaving telescope stations distributed today over Australia, South Africa, and Europe. All stations combined, 10 passive-optical telescopes are actively providing data to the network.

New contributors are currently in the applicant phase and will, together with further stations planned by DLR, enhance the network's capabilities. The retrieved data are used for research, collision warnings, catalogue maintenance, or for deriving data products, which can be sold to third parties. For the aforementioned points, the Backbone Catalogue of Relational Debris Information (BACARDI) was developed at DLR. BACARDI processes input data received from SMARTnet to data products such as ephemerides or orbit information for telescope observation planning, and attempts to detect new objects where an association of observations to already known objects is unsuccessful. To better operate the telescope stations, a dedicated software, called SMARTies, is under development as a joint project by AIUB and DLR. With this software, the telescope stations operations can be optimised to increase the daily data acquisition. It is planned to release SMARTies as Open Source software.

To avoid deteriorating accuracy of the orbital information, ephemerides forecasted by BACARDI are combined with the planning tool "Optimal Catalog Maintenance and Survey Tasking" (OMST), which will help to keep all resident space objects in the data base. Furthermore, OMST will allow to search for new objects in the vicinity of the telescopes' fields of view in so-called "dead-times".

1 INTRODUCTION

In the forthcoming ages of mega-constellations and the ensuing increase of resident space objects, it is mandatory that each possible collision shall be prevented. In order to prevent collisions, ephemeris data of both objects must be available. Nowadays, some companies gather sensor data of resident space objects and provide calculated ephemerides as a business model to satellite owners and operators. The approach of SMARTnet is different: every sensor operator can contribute to SMARTnet and retrieve all data collected within SMARTnet for free. The Astronomical Institute of the University of Bern (AIUB) and the German Aerospace Center (DLR) are operating SMARTnet and are using the data for research and satellite operations.

A short introduction to SMARTnet and its requirements is given, followed by some products retrieved from SMARTnet data. Also, the complete end-to-end chain from observations to processing, forecast, and its feedback loop to observations is presented. Lastly, selected observational campaigns of some of the telescopes are presented. As part of non-regular observations, supporting observations can be acquired in case of special events (e.g., Double Asteroid Redirection Test (DART) impact).

2 SMARTnet

SMARTnet, the Small Aperture Robotic Telescope Network, has been operational since 2017 [1]. It is an international platform for exchanging data of resident space objects. As of January 2023, five telescope stations from Switzerland, South Africa, Australia, Spain, and Slovakia are actively contributing with 10 passive-optical telescopes. The apertures range from 20cm to 80cm, allowing for survey and follow-up observations. DLR is preparing a new telescope station, which shall be deployed in South America by the end of 2023. Furthermore, other sensor operators are planning to join SMARTnet in the near future with telescopes located in Australia, USA, and Europe (see Figure 1). The concept of SMARTnet is that every sensor operator can contribute with their own data to the data pool of SMARTnet and can, in turn, retrieve all data from all other contributors free of charge. Then, each accepted Partner can, e.g., perform research, process the data to products and sell these or use them for own operations like the support of LEOP.

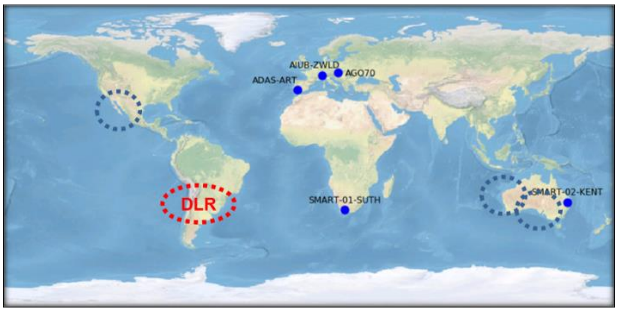

Figure 1. SMARTnet stations (filled dots) and future stations (dashed ellipses)

All data are exchanged via the Pick-up Point (see Section 3) and, are processed at DLR using BACARDI (see Section 4).

For transparency, every month, a bulletin is created stating basic statistics of the network's observations. These statistics include but are not limited to:

- Number of instruments per Partner
- Number of images, tracklets, and measurements
- Accumulated night length

The second part of the bulletin includes graphs concerning weather data, magnitude distributions of the measurements, and tracklet latency. The latter represents the time difference between a given observation and its upload. The faster tracklets are uploaded, the faster they can be handed over to the object association and orbit determination processes. Based on their results, a feedback loop can be created to acquire more observations from one sensor or to enable a hand-over to another station / Partner.

2.1 Optimal Catalog Maintenance and Survey Tasking (OMST)

Classical observation strategies divide into follow-up and survey observations. While survey observations may be scheduled without a priori knowledge and limited assumptions of the object population, follow-up observations rely on already determined orbits to calculate new ephemerides. Both strategies include a large number of telescope movements to the starting point of an observation series – called slewing.

Slewing is a limiting factor in terms of observation time. While a telescope is moving, it cannot be used to acquire images. With the reduction of different pointing directions and therefore slewing, the time for observations is increased. The Optimal Catalog Maintenance and Survey Tasking (OMST) algorithm performs an optimisation process to minimise the number of pointing directions while maximising the number of scheduled objects over the night. Those objects may stem from an internal data base or publicly available catalogues, respectively.

The OMST algorithm was initially proposed in [2, 3] and has been developed further since then [4-10]. Details about the algorithm and its implementation may be found in the given literature. A test campaign was carried out in 2022 using SMARTnet's telescope stations SMART-01-SUTH (in South Africa) and SMART-02-KENT (in Australia). The results may be found in [11].

2.2 SMARTies

The observation software currently used at DLR's telescope stations was developed to accommodate AIUB's ZIMLAT telescope for alternating SLR and passive-optical observations [12]. With adaptations, this software is also used by the other telescopes at the Zimmerwald observatory. With its inception, SMARTnet was allowed to also use the observation software for its telescopes.

Unfortunately, it represents a third-party product for SMARTnet, which cannot be modified nor adapted to the requirements by SMARTnet. Therefore, the decision was made in favour of developing a new software package, called SMARTies (SMARTnet Instrument Enhancing Software).

This software package is highly modularised for easy maintenance. It does not depend on the currently used hardware, but is kept general to enable the inclusion of

other hardware components in the future. The core function calls are kept and only the respective hardware server must be coded when using a different hardware component. Hence, the main source code will not have to be changed when replacing hardware, only the initialisation files will have to be adjusted to use the new server code. Command structure and responses will stay the same. This will decrease the workload in testing phases (e.g., for cameras CCD ↔ sCMOS) and alleviate operations for anyone using this software with different hardware components.
SMARTies also supports simultaneous observations with several sensors as long as their optics are serviced by the same telescope mount.

The software itself will be open source and cost-free, and may be implemented by anyone at their own telescope station. It is part of an on-going improvement of remote telescope stations, and their hardware and software [13].

3 PICK-UP POINT

SMARTnet's policy includes a cost-free exchange platform for tracklets. Each Partner has the possibility to store their data and retrieve data from all Partners. Tracklets may be uploaded at any time, thus accommodating for different time zones and eliminating delays after the end of observations. All tracklets undergo a format check, assuring they comply with the CCSDS TDM standard [14].

Each Partner receives an individual access to DLR's sftp-server and is given the folder structure for uploading as well as for downloading. Due to DLR's security policy, each Partner only has access to their own folder structure, and no read nor write permissions for any other folder.

Furthermore, with results being obtained faster, other products can be calculated. As of 2023, observations were used to improve orbits in the Launch and Early Operations Phase [15] and to develop a manoeuvre detection and estimation method (see Section 4.3).

4 BACARDI

The Backbone Catalogue of Relational Debris Information (BACARDI) provides both a data base and a processing framework for observation data generated by SMARTnet contributors. BACARDI fully automates and parallelizes the download, storage, and processing of observations to data products such as improved orbit records and ephemerides. Multiple data formats are available both for import and export. The basic functionalities of BACARDI may be found in [16] and are not repeated here. Newly developed methods include tracklet-object correlation calculated with pseudo-probabilities, cluster-graph methods for identifying new resident space objects, and manoeuvre detection and estimation algorithms. Manoeuvre detection has already reached the status of a prototype, but is not yet fully implemented in the operational version of BACARDI.

In the near future, it is planned to implement close approach screening, followed by analyses of the close approaches and creation of collision data messages (CDMs) for satellite operations at the German Space Operations Center (GSOC).

4.1 Pseudo-Probability Correlation

All provided data are fetched from the pick-up point and associated to already known objects and their orbit representations. The novel method currently applied for the association uses so-called pseudo-probabilities and a corresponding publication is currently in preparation. In this method, a set of similarity metrics are created for the observations and each candidate object orbit, which are then transformed to a vector space. By normalising the values, a pseudo-probability can be provided for each observation/object pair.

Subsequently, the associated observations are used to improve the orbits stored in the data base by means of a batch least-squares method.

4.2 Cluster-Graph Method

In order to identify new resident space objects from observations like tracklets, we perform a graph-based clustering analysis. Cluster analysis is a commonly used unsupervised machine learning technique for grouping objects.

We start with the results of a pairwise correlation of tracklets, which estimates whether a pair of tracklets might belong to the same resident space object (tracklet-tracklet correlation) [17]. From this we construct a graph. A graph $G = (V, E)$ is an abstract structure composed of a finite number of edges E, which connect two vertices V, also called nodes. In our specific graphs two vertices are connected via an edge, if the tracklet pair is identified to possibly belong to the same object by the tracklet-tracklet correlation.

A subsequent orbit determination has to be performed for every identified cluster to confirm the object. The whole process is realised within BACARDI.

In order to find the correct parameters of the clustering algorithm, mainly Markov Clustering, we developed evaluation techniques that are suited for our task. Classical evaluation techniques often do not fulfil our requirements, because tracklets of the same object may coexist in more than one connected component of the graph that is clustered. For training and testing, we use a large observation data set created by SMARTnet, which was split into subsets.

Our training resulted in a successful clustering for diverse test datasets. Thus, the object identification is improved by increasing the number of associated tracklets, reducing the number of false associations, and obtaining a speed-up by decreasing the number of subsequent orbit determination processes. More details may also be found in [18].

By adding the possibility to identify objects that are not tracked in publicly available catalogues, BACARDI builds and maintains an extensive data base of resident space objects.

4.3 Manoeuvre Detection

Every time a new tracklet is added to the data base and is successfully associated to an existing object, a manoeuvre detection algorithm is triggered. This algorithm uses a non-linear Kalman filter to find unexpected deviations in the measurement residuals from the predicted orbit [19, 20].

If reasonably accurate orbit estimates are available before and after a suspected manoeuvre, the manoeuvre epoch and Δv-components may be estimated in a subsequent step. This in turn can significantly improve the orbit solution or even impact the tracklet-to-object association. Once a given object is known to have performed a manoeuvre, it is flagged as capable of manoeuvring in the data base.

While this method has so far only been tested on passive-optical SMARTnet observations, it is also applicable to other measurement techniques with minor adaptations. We aim to fully automate this process and to have it incorporated into the operational version of BACARDI within the next year.

4.4 Provenance

Since data generated by BACARDI can and will be used for critical decisions in satellite operations, the quality and reliability of these data products play an important role [21]. Therefore, a provenance model was developed for BACARDI [22].

Provenance is defined as information about entities, activities, and people that are involved in producing a piece of data. This might include all relevant activities, such as data processing, data storage operations, and exporting data products as well as importing data products.

This provenance information is stored in a separate graph-based provenance store, allowing for efficient querying. As a result, it is possible to make statements about the quality and reliability of both data products and processes. Since the actors involved in the creation of inputs, outputs, and every step in between are recorded, provenance facilitates following privacy, confidentiality, and legal requirements that may be set by the involved parties or sources of any data used.

An application including the provenance model tailored to BACARDI is currently in the process of implementation.

5 INTERFACES

BACARDI can provide its data products via a set of interfaces like a ReST-API or direct export via an FTP-API. This way, data products of multiple formats can be supplied for several use cases: for example, ephemerides created by BACARDI can be used for observation planning, catalogue maintenance, and tracking. A record of all current orbit records can be provided for real-time visualisation, which is then exposed to the public via, e.g., the BACARDI website. Research is facilitated by the provision of historic observation data, which can be requested by internal users via the ReST-API. BACARDI's data base software provides a powerful set of filters, which allow for an efficient pre-filtering of requested data.

6 SMARTnet IN FIVE YEARS

In the next five years, it is envisaged to set up a global network with Partners and more stations operated and owned by DLR. The main goal is to achieve full coverage of the geostationary regime and everything orbiting Earth at an altitude of 6000km or higher. Furthermore, it is foreseen to include more sensor types like, e.g., radars or sensors operated by Laser. BACARDI is already set up to process such data. Finally, the maintenance of an almost complete catalogue is the final goal to support satellite owner / operators and intensify research.

7 REFERENCES

[1] Fiedler, H., Herzog, J., Ploner, M., Prohaska, M., Schildknecht, T., Weigel, M. & Klabl, M. (2017). SMARTnet™ - First Results of the Telescope Network. In *Proc. of the 7th European Conference on Space Debris*, Darmstadt, Germany.

[2] Frueh, C., Fiedler, H. & Herzog, J. (2018). Heuristic and Optimized Sensor Tasking Observation Strategies with Exemplification for Geosynchronous Objects. *Journal of Guidance, Control and Dynamics*, **41**(5), 1036-1048.

[3] Frueh, C. (2017). Sensor Tasking for Multi-Sensor Space Object Surveillance. In *Proc. of the 7th European Conference on Space Debris*, Darmstadt, Germany.

[4] Frueh, C. (2017). Fusing Survey and Follow-up for SSA Sensor Tasking. In *Proc. of the AAS/AIAA Astrodynamics Specialist Conference*, Columbia River Gorge, WA, USA.

[5] Little, B. & Frueh, C. (2017). Comparison of Optimizers for Ground Based and Space Based Survey Sensors. In *Proc. of the AAS/AIAA Astrodynamics Specialist Conference*, Columbia River Gorge, WA, USA.

[6] Little, B. & Frueh, C. (2020). SSA Sensor Tasking: Comparison of Machine Learning with Classical Optimization Methods. *Journal of Guidance, Control and Dynamics*, **43**(2), 262-273.

[7] Little, B. & Frueh, C. (2020). Multiple Heterogeneous Sensor Tasking Optimization in the Absence of Measurement Feedback. *Journal of Astronautical Sciences*, **67**(4), 1678-1707.

[8] Paul, S.N., Little, B. & Frueh, C. (2022). Detection of Unknown Space Objects Based on Optimal Sensor Tasking and Hypothesis Surfaces Using Variational Equations. *Journal of Astronautical Sciences*, **69**(4), 1179-1215.

[9] Rose, M. & Frueh, C. (2020). Elevation Constraint vs Probability of Detection in an Optical Sensor Network Designed for Complete GEO Coverage. In *Proc. of the AAS/AIAA Astrodynamics Specialist Conference*, virtual edition.

[10] Rose, M. & Frueh, C. (2021). Sensor Tasking Analysis for an Optical Sensor Network Designed for Complete GEO Coverage. In *Proc. of the 8th European Conference on Space Debris*, virtual edition.

[11] Herzog, J., Fiedler, H., Prohaska, M. & Schildknecht, T. (2022). Application of the Optimal Maintenance and Survey Tasking (OMST) strategy at the Telescope Network SMARTnet. In *Proc. of the 73rd International Astronautical Congress*, Paris, France.

[12] Gurtner, W. & Ploner, M. (2006). CCD and SLR Dual-Use of the Zimmerwald Tracking System. In *Proc. of the 15th International Workshop on Laser Ranging*, Canberra, Australia.

[13] Herzog, J., Hofmann, B., Fiedler, H., Prohaska, M. & Schildknecht, T. (2021). Software and Hardware to Improve a Remote Telescope Station. In *Proc. of the 8th European Conference on Space Debris*, virtual edition.

[14] The Consultative Committee for Space Data Systems (2020). *Tracking Data Message (Blue Book)*, https://public.ccsds.org/Pubs/503x0b2c1.pdf.

[15] Hackel, S., Herzog, J., Spiridonova, S., Meissner, F., Kirschner, M., Fiedler, H. & Kahle, R. (2021). Orbit Determination using Ground-Based Optical Observations in Launch and Early Operations Phase of EDRS-C. In *Proc. of the 72nd International Astronautical Congress*, Dubai, UAE.

[16] Fiedler, H., Herzog, J., Hofmann, B., Kahle, R., Meinel, M., Prohaska, M., Rack, K., Schildknecht, T., Siggel, M., Stoffers, M., Kurnatowski, L., Wasser, Y. & Weigel, M. (2019). SMARTnet™ and BACARDI. In *Proc. of the 70th International Astronautical Congress*, Washington, DC, USA.

[17] Siminski, J., Montenbruck, O., Fiedler, H. & Schildknecht, T. (2014). Short-arc tracklet association for geostationary objects. *Advances in Space Research*, **53**(8), 1184-1194.

[18] Griese, F., Rack, K., Schmitz, S., Fiedler, H., Hofmann, B., Schmidt, M., Schmidt, D. & Schildknecht, T. (2022). Applying Graph-based Clustering to Tracklet-Tracklet Correlation. In *Proc. of the 73rd International Astronautical Congress*, Paris, France.

[19] Bergmann, C., Zollo, A., Herzog, J. & Schildknecht, T. (2021). Integrated Manoeuvre Detection and Estimation Using Nonlinear Kalman Filters During Orbit Determination of Satellites. In *Proc. of the 8th European Conference on Space Debris*, virtual edition.

[20] Bergmann, C., Zollo, A., Herzog, J., Fiedler, H. & Schildknecht, T. (2022). Detection of Satellite Manoeuvres Using Non-Linear Kalman Filters on Passive-Optical Measurements. In *Proc. of the 73rd International Astronautical Congress*, Paris, France.

[21] Stoffers, M., Meinel, M., Hofmann, B. & Schreiber, A. (2022). Integrating Provenance-Awareness into the Space Debris Processing System BACARDI. In *2022 IEEE Aerospace Conference*, AERO 2022, Big Sky, MT, USA

[22] Stoffers, M., Meinel, M., Hofmann, B. & Fiedler, H. (2022). A use case study on provenance-based data assessments for mission critical software systems. In *Proc. of the 73rd International Astronautical Congress*, Paris, France.