SSASIM: AN EARTH-ORBITING OBJECTS CATALOGUE MAINTENANCE SIMULATOR

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ABSTRACT

The comprehensive knowledge of the population of man-made space objects is one of the main aims of the Space Situational Awareness (SSA). This knowledge is achieved through the execution of Space Surveillance operations aimed to detect, correlate and characterize these objects as well as to assess their orbital evolution. The information gathered and computed for the detected space objects needs to be catalogued, maintained and regularly updated.
GMV has developed SSASIM for prototyping the orbit evolution cataloguing activities as a precursor of the envisaged operational Tracking & Survey Data Centre part of the future European Space Situational Awareness System.
Exhaustive reuse of well-known and proven ESOC software (ODIN and NAPEOS) and of the *focusSuite* framework has been performed in order to maximize its reliability, robustness and expandability.
This paper describes the catalogue maintenance process performed by SSASIM.

1. ORBITING OBJECTS CATALOGUING

The comprehensive knowledge of the population of man-made space objects (both operational and space debris) is one of the main aims of the Space Situational Awareness (SSA). This knowledge is achieved through the execution of Space Surveillance operations aimed to detect, correlate and characterize these objects as well as to assess their orbital evolution.
The detections are performed by tracking network formed by a set of sensors both ground and space-based. On one hand, ground based sensors accomplish different types of both radar and optical. The former illuminate actively the object to observe (which limits the range of applicability) while the latter requires the necessary Sun illumination on the object to be observed (which limits the time of availability). On the other hand, space-based telescopes may be used to reach levels of detection which cannot be achieved with sensors on ground.
The information gathered and computed for the detected space objects needs to be catalogued, maintained and regularly updated. For this purpose, the measurements from the tracking network must be continuously collected and processed. These measurements must be firstly correlated with respect to existing catalogued objects, then combined with earlier data (in case the correlation is successfully achieved) and finally the orbital evolution of the object is updated. The system must also consider uncorrelated objects to be inserted in the catalogue.
In addition, the catalogue has to be regularly inspected and post-processed to search for events such as manoeuvres, fragmentations (explosions or collisions), re-entries and new launches. These events must be also stored in the history of the catalogued objects.

2. SSASIM

GMV has developed SSASIM for prototyping the catalogue maintenance operations for any kind of man-made Earth orbiting object. SSASIM is intended to become a precursor of the Tracking & Survey Data Centre envisaged within the future European SSA System. The implementation of this simulator has been performed in the frame of a Space Situational Awareness study for ESA.
SSASIM is based in well-known and proven technologies developed by GMV for ESOC: ODIN (Orbit Determination by Improved Normal equations, [7]) and NAPEOS (Navigation Package for Earth Orbiting Satellites, [6]). The re-usability of existing tools has been maximized to ensure the reliability of the simulator: ODIN for the preliminary orbit determination of new objects and NAPEOS for the final operational orbit determination of catalogued objects.
The reuse of generic orbit determination tools enables SSASIM to process a considerable wide range of types of measurements (from mono-static and bi-static radar, SLR and telescopes both on-ground and space based, including range, range-rate and angles) and to cope with any type of orbit around the Earth. This software packages implement state-of-the-art models for orbit propagation and measurements reconstruction what ensures the achievement of accurate orbital solutions.
Additionally, this exhaustive reuse leads to reliable, robust, expandable and portable solutions as it is based on elements that share these properties, which places SSASIM in an excellent position for becoming a real prototype for a future operational system
SSASIM stores and maintains the catalogued data in a SQL Relational Database accessed through a standard RDB Management System, guarantying quick data

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access, indexing services and safe storage and handling of data. This catalogue is post-processed to detect manoeuvre and fragmentation events and to identify objects re-entries and launches (not yet implemented). In addition, the catalogue is analysed to obtain figures of merit of the performances achieved during the catalogue maintenance process. All these catalogue post-processing and analysis activities can be easily automated through the use of simple SQL queries, making the system independent of them.

SSASIM has been fully integrated with PROOF (Program for Radar and Optical Observation Forecasting), ESOC's SW for sensors modelling. PROOF has been enhanced to simulate a configurable Space Surveillance Network, providing SSASIM with measurements from mono-static and bi-static radars and for ground-based and space-based telescopes. The measurements pre-processing interface in SSASIM has been implemented to allow the future integration of SSASIM with a real Space Surveillance Network.

This interface has also been enhanced to allow the possibility to take advantage of the original proven detection capabilities of PROOF and the measurements simulation capabilities in NAPEOS. The measurements from PROOF can be re-simulated according to the detailed measurements reconstruction models including state-of-the-art correction models for the sensors detections identified by PROOF.

SSASIM has been integrated in the *focusSuite* infrastructure ([4]) which provides SSASIM with an off-the-shelf flight proven robust framework to facilitate its configurability and usability.

2.1. Functional overview

As mentioned above, SSASIM is integrated in the *focusSuite* framework. This framework provides SSASIM with a easy to use and configure system.

The whole process is driven in an automatic mode by a Java-based process manager. This manager is in charge of performing all the automatic operations, following a certain predefined working sequence and also of managing the SBL DB catalogue and all the interfaces of each element in the system with this catalogue.

An overview of the main elements in the SSASIM catalogue maintenance simulator can be found in Fig. 1.

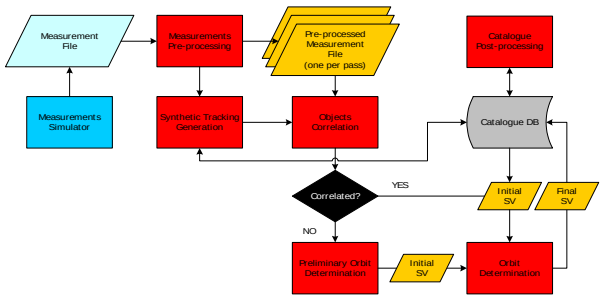

Figure 1. SSASIM Functional Overview

This process is run over a set of measurements that are collected from a certain pre-defined tracking network.

As a summary, the system is composed by the following individual elements:

- A measurements pre-processor, in charge of accommodating the input data from the sources supported to the internal measurements format and scheme. SSASIM implements several pre-processors supporting the measurements data simulated by PROOF and by the NAPEOS tracking simulator for the detections performed by PROOF.
- A synthetic measurements generator (based in the NAPEOS tracking simulator) which generates the synthetic tracking for the available sensors and the last available propagated orbital state of the objects in the catalogued. As part of the same process, the existing updated information of the catalogued objects is propagated to reduce the required processing time.
- An objects correlator taking the synthetic tracking generated and performing object correlation with the input real pre-processed measurements in the domain of the available measurements types.
- A preliminary orbit determination tool from ODIN obtaining initial orbital solution and associated covariance for angles-only sets (implementing not only the Gauss and Laplace method but also the Baker-Jacobi with no coplanar singularities) as well as for range and angles sets (Herrick-Gibbs method).
- A sequential orbit determination tool from NAPEOS performing a SRIF filter with numerical orbit propagation and implementing state-of-the-art dynamical models and measurements reconstruction patterns.
- A catalogue post-processing component finding for events in the catalogue (manoeuvres, fragmentations, etc.) which at the time this paper is being written is still TBD.

Each of these elements can work in a stand-alone mode or can be integrated in order to perform the whole catalogue maintenance process. This is an extraordinary advantage for testing purposes on the different elements of the system.

2.2. Reuse and reliability

SSASIM has been conceived to become a precursor of an operational system. Therefore, the operational constraints and implications have been carefully taken into account for the design of the simulator.

The required reliability has been inherited from the exhaustive reuse of well-known and proven under operational conditions ESOC software (ODIN and NAPEOS). In addition, the *focusSuite* flight proven framework has been selected for the sake of robustness.

Additionally, this new extension of the multiple reuses of the NAPEOS SW (broadly used for flight dynamics, navigation, simulation and beyond) ensures the future expandability of the system.
Another ESA tool has been reused for the generation of the measurements test data for SSASIM: PROOF. The use of PROOF as a measurements simulator ensures the independence of the sources of the algorithms for the generation of data for the simulator and its processing, adding an additional level of reliability on the results and conclusions obtained in the end-to-end simulations

2.3. Measurements

SSASIM is able to manage at all levels of the processing survey and tracking data from the following types of sensors:

- Ground-based monostatic radar.
- Ground-based bistatic radar (including beam-park experiments).
- Ground-based telescope (including SLR for non-cooperative objects).
- Space-based telescope.

The measurement types supported for a ground-based sensor are the following:

- Two-way range.
- Two-way range-rate (Doppler).
- Fixed angles (right ascension and declination).
- Topocentric angles (azimuth and elevation).

While those for a space-based (optical) sensor only fixed angles (right ascension and declination) are necessary to be supported.
The use of state-of-the-art measurements reconstruction modelling and of accurate corrections has been ensured by the full reuse of the measurements generation capabilities in the NAPEOS SW.
Adequate reconstruction models for the presented types of observations are the defined in order to optimize the accuracy of the orbital solutions and predictions obtained to support the success of the correlation process. Ground station position and reference system transformations are fully compliant with IERS 2003 standards.

2.4. Objects correlation

As mentioned above, the objects correlation in SSASIM is fully performed in the domain of the available measurements types.
Synthetic tracking is generated for all the sensors in the used network and all the catalogued objects. Pseudo-measurements are generated from the real measurements in order to synchronize the data and then be able to perform a direct match between the set of real pseudo-measurements and each set of synthetic measurements. Several thresholds and weighted correlation quality factors and indexes have been implemented in order not to miss any possible correlation. See an illustration of the matching process in Fig. 2.
This method, though not quite sophisticated, has been found to be remarkably efficient in terms of computation time and very effective for correlation.

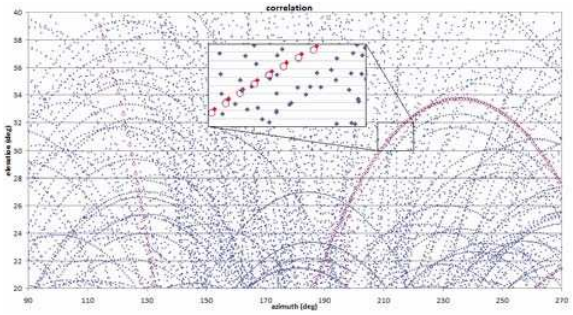

Figure 2. Measurements Matching for Correlation

2.5. Orbit determination and propagation

SSASIM uses the POD-capable wide range of state-of-the-art dynamical models implemented in the NAPEOS SW and is compliant with the latest IERS 2003 conventions reference frames handling.
The orbit propagation is performed following a Runge-Kutta predictor-corrector integrator with a fully configurable dynamical model. Not only the orbit is propagated along time but also the associated covariance is numerically propagated taking advantage of the integration of the variational partial derivatives.
The orbit determination is based in the SRIF filter implemented in NAPEOS which has been extensively described in [1] and [2]. A considerable set of solve-for parameters can be established, though for the space surveillance issue, this functionality has been restricted to the use of drag coefficient and solar radiation pressure for each object.
All the orbit propagation and determination processes interface following the CCSDS OPM standard format ([5]) storing not only orbital information but also the associated covariance. The drag and solar radiation pressure coefficients considered are also incorporated into the OPM in order to allow more precise propagation from the information contained in the OPM. This ensures the continuity of the sequential operations and the consistent exchange of information with other entities.

2.6. Preliminary orbit determination

The preliminary orbit determination module in SSASIM has been reduced from the ESOC's ODIN (Orbit Determination via Improved Normal Equations) SW.
It implements classical well known algorithms that have been proven to solve this problem in a competent way.

The main algorithms under use are the following:

- Herrick-Gibbs algorithm for radar range + angles measurements.
- Gauss/Laplace method for telescope angles only measurements.
- Baker-Jacoby new implementation (having no co-planar singularity) for telescope angles only measurements.

See in Fig. 3 a representation of the automatic for the statistical selection of the best candidate solution for angles-only problems.

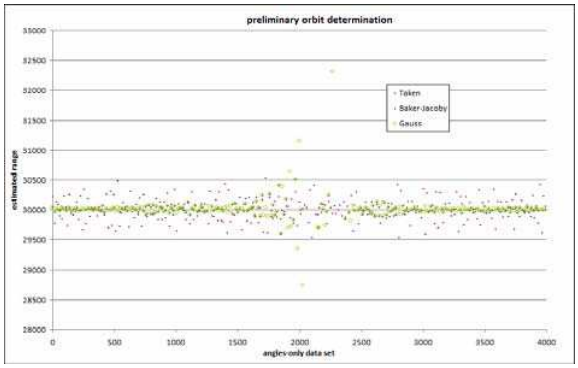

Figure 3. Angles-only Preliminary Orbit Determination

Other algorithms are being analysed as this is one of the key issues in the space surveillance domain. Several algorithms have been proposed by the experts and are intended to be evaluated within SSASIM.

Also covariance information is computed at the start of the acquisition measurements pass. This information is stored in CCSDS OPM format for later use as for the rest of the orbit determination process (whose initial estimate is provided by this module in this OPM file).

2.7. Catalogue management

All the information that requires being stored in order to analyse the performances achieved and the status of the processing is maintained in the catalogue database. The integrity and safe storage of this data is crucial for the process.

SSASIM implements a Java-based fully automated process manager and catalogue manager. The process manager is in charge of running the sequence of sub-processes for the build-up and maintenance of the catalogue. This manager accesses the data in the catalogue through a single database manager in order to collect it as input for the processing of a function in the system or to update it as a result of that processing.

The catalogued data is stored and maintained in a SQL Relational Database accessed through a standard RDB Management System, guarantying quick data access, indexing services and safe storage and handling of data.

The main advantages of this handling are that all the catalogue post-processing (deletion of re-entry objects, merge between not correlated and duplicated objects, addition of additional objects from external sources, etc) and analysis activities can be easily automated through the use of simple SQL queries, making the system independent of them. In addition, the reporting activities from the status of the catalogue can be easily implemented and enhanced through the use of these queries. Last but not least, the safe existence of multiple catalogues is also ensured by this managing system.

The main information stored is the orbit and covariance information for the catalogued objects. In addition, other information such as the "context" information necessary for running the sequential orbit determination process (in case of revisit), the history of the measurement passes processed and the history of the correlation processes performed (including results of the correlation process and computed quality factors) must also be maintained,

2.8. Configurability

As a multi-purpose SW package for satellite navigation, flight dynamics, scenario simulation, and beyond, the level of configurability allowed for the tools in NAPEOS is outstandingly high. The SSASIM allowed configuration has been established according to a trade-off between the simplicity of use and the flexibility, specially for the orbit determination function.. Tuning the filter for obtaining optimal performances for space surveillance operations has considerably reduced the original level of complexity of the system, coming to a compact set of main configurable items.

2.9. Robustness

Sequential estimation is a known problem and the SRIF algorithm has been used for orbit determination purposes in several other cases. The main difference in the SSASIM context is that the system must work autonomously for long periods of time and therefore SSASIM itself and its configuration must be robust enough to react properly when receiving anomalous data and under degraded scenarios.

Additionally, the level of sensitivity of the preliminary orbit determination algorithms to the amount and quality of data during an acquisition is a well known issue. Proper handling of wrong data during this phase for the estimation of an initial state is very relevant.

Configurable thresholds for edition of bad data (culling) are available in SSASIM for both preliminary and final orbit determination. Observation outliers are detected and automatically removed from the process.

One more key point for the establishment of the robustness of the system is the handling of the catalogue. SSASIM stores all the necessary catalogued information in a relational database accessed through simple SQL queries. This ensures the data integrity and, as a result, the robustness of the process.

2.10. Continuity

The continuity between consecutive sequential executions of the orbit determination process (each time an object is re-visited) is guaranteed through the so-called "context". After each execution, the whole status of the SRIF procedure is stored in a "context". The successive run will start from the status of the previous one by restoring this "context" before the next step in the estimation process is performed. Thus, the sequential process can be stopped and re-started at any point in time.

This also applies to the whole SSASIM process, where the situation of the system under analysis is stored in the catalogue and therefore the process status can be inspected for analysis purposes at whichever state of the processing.

3. RESULTS

Very limited consolidated results have been obtained by the time this paper has been written. Exhaustive testing of the proposed sensors architectures for the future European Space Surveillance system are to be performed very soon with this simulator in order to evaluate the actual objects cataloguing performances and capabilities by this future network

4. FUTURE ENHANCEMENTS

A considerably large number of enhancements have been already been addressed. The extraordinary reusability and expandability makes easy the incorporation of new functionalities in the existing SW.

The main enhancements envisaged are listed below:

- Reporting enhancement: More detailed information, including automatic generation and provision of statistics and graphics.
- SRIF robustness enhancement: Implementation of more safeguards.
- Further research and analysis on existing preliminary OD algorithms.
- Catalogue post-processing implementation (manoeuvres, fragmentations …).
- Interface with real sensors (telescopes, radars and SLR).
- Catalogue initialisation with a-priori available information from external catalogue, i.e. TLE catalogue, DISCOS, etc.
- Interface with *closeap*, GMV's collision risk assessment and mitigation tools. Provision of accurate catalogued orbital data (including covariance) to compute conjunction probability.
- Interface with *Visualfocus* visualization tool, capable to support space surveillance scenarios.
- Support for NEOs measurements and orbits (precursor of a NEO Data Centre).

5. CONCLUSIONS

GMV has developed SSASIM, a catalogue maintenance simulator conceived as a prototype and precursor of the Tracking & Data Centre envisaged in the future European Space Situational Awareness System. It will be used to evaluate the cataloguing performances and capabilities of the sensors network forming the European Surveillance Network.

It has been designed to maximize its reliability, robustness, expandability, portability and robustness by reusing of well-known proven ESA SW such us NAPEOS and ODIN using state-of-the-art detailed models for orbit propagation, measurements reconstruction and orbit determination.

The interface with PROOF has been implemented to generate an end-to-end simulator.

The system has been integrated in the GMV's flight proven multi-purpose *focusSuite* framework.

A Java-based management of the automatic catalogue maintenance process has been built-in. The catalogue is stored in an Relational Database which is accessed through SQL simple queries.

The use of standard information exchange formats has been taken into account by the implementation of the CCSDS OPM format for the storage, interface and exchange of orbital data, including covariance.

6. ACKNOWLEDGEMENTS

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