GMV COVARIANCE ESTIMATION, PROPAGATION AND ANALYSIS TOOLS

Francisco M. Martínez Fadrique, Isaac Juárez Villares, Diego Escobar Antón, Alberto Águeda Maté

GMV, Isaac Newton 11, 28760 Tres Cantos, Spain

E-mail: fmartinez@gmv.com, ijuarez@gmv.com, descobar@gmv.com, aagueda@gmv.com

ABSTRACT

The knowledge of the state vector covariance of any space object (either operational or space debris) is essential both for satellite operations and for space surveillance. The orbit determination process entails the estimation not only of the orbital state of the space object but also of its uncertainties, represented by their covariance. This covariance can be propagated to obtain a representation of the orbit evolution uncertainty with time.

In the frame of satellite operations, the covariance of the spacecraft state is needed for the assessment of collision risk with other objects. For Space Surveillance, it is used for the evaluation of the degradation of the knowledge of the state of the object being tracked, as additional tracking needs to be obtained for the objects suitable to be "lost" in order to update their state and uncertainties.

This paper describes the implementation details of the integration of components for orbit determination and its associated covariance analysis and handling, its actual and potential use in satellite operations and space surveillance environments and the foreseen enhancements in the attempt to obtain the already mentioned comprehensive covariance determination, propagation and analysis package.

1. INTRODUCTION

GMV has implemented a set of tools for covariance estimation, propagation and analysis based on different operational flight dynamics packages and the broad experience in satellite operations, orbit determination and data analysis acquainted during several years of activities in these fields. ESA's flight dynamics and navigation package NAPEOS (Navigation Package for Earth Orbiting Satellites) has been selected as core element for the implementation of the orbit determination algorithms and for the integration of all other tools required for the orbital motion analysis. The main target of this compilation of tools is the generation of a comprehensive package that can be used for the detection, catalogue and follow-up of objects, operational and debris, and the subsequent characterisation and analysis of their orbital motions. Some of the functionality integrated in this package is:

- Enhancement of the orbit propagator in NAPEOS to allow propagation of the covariance together with the state vector. This capability has also been included in the orbit determination modules (least squares and SRIF).
- Integration of specific tools for initial and degraded orbit determination to cope with situations where the amount and quality of tracking do not allow the estimation by standard methods. This functionality has been derived from ESA software CRASS and ODIN and integrated in the NAPEOS data and software structures.
- Tracking data correlator that allows the identification of objects with respect to an existing catalogue. Filtering and close event techniques have been derived from ESA's software CRASS (Collision Risk ASSessment Tool) to allow the efficient identification and correlation of objects

Proc. '5th European Conference on Space Debris', Darmstadt, Germany 30 March – 2 April 2009, (ESA SP-672, July 2009)

and to improve the object trajectory knowledge based on a sequential orbit determination algorithm.

- Improved support of TLE information, both through the use of the latest available SGP implementation and also through the use of adjustment techniques to improve the state propagation into the future.
- Support of standard CCSDS Navigation Data Messages (NDM) data formats for easy exchange of orbit information. In particular, CCSDS OPM (Orbit Parameter Message) and OEM (Orbit Ephemeris Message) are fully supported for both input and output; also the under development CCSDS ODM Pink Book is supported to allow exchange of covariance information.

2. AREAS OF ANALYSIS

2.1. Orbit Propagator

The first and main task in the compilation of tools is the definition and implementation of the orbit propagator. It should be generic enough to cover all types of orbits (LEO, MEO and GEO, circular, highly eccentric …) and should provide a clear interface for the integration into all other tools of the suite. Furthermore, in order to propagate thousands of objects within a reasonable amount of time it should be very computationally efficient with dynamic models of moderate accuracy while allowing very accurate dynamics for its use in precise orbit determination. Thus, the dynamical should be user configurable to provide flexibility. Within the field of orbit determination, propagators do not only have to propagate state vectors, but also the partial derivatives with respect to all dynamical parameters by integrating the variational equations of motion. This, in turn, allows propagating the covariance based on the initial uncertainty of the state vector and any dynamical parameter under consideration. And finally, since it is to be used as part of many other applications, modern programming techniques (e.g., data orientation and encapsulation) are to be employed to ease the interfaces with the rest of elements. Because of all this, GMV has reused NAPEOS propagator which fulfils most of all the previous requirements and improved it to output the state covariance matrix based on the propagation of the transition and sensitivity matrices which where already in place. This propagator features user configurable very precise dynamical models that allow the modelling from a simple Keplerian orbit to the most detailed model for precise orbit determination. All these models have been validated and tested at ESOC against other state-of-the-art software packages and through operations of precise orbit determination systems. Currently, it is used at ESOC/OPS-GN, among other projects, for ESA's own precise orbit determination systems (ENVISAT and ERS-1/2) and ESA's contributions to the IGS (International GNSS Service), the ILRS (International Laser Ranging Service) and the IDS (International Doris Service).

2.2. Initial Orbit Determination

Initial orbit determination is a key step in all space surveillance system when initialising and maintaining a catalogue of object in space. The literature provides a large number of techniques and algorithms for initial orbit determination, however, several are theoretical, or have not been tested in sufficiently different scenarios or the available software implementations are not adequate for operational usage.

The space surveillance scenario essentially relies on two sources of data suitable for initial orbit determination: radars and telescopes. Whereas radars provide information on range, range-rate and line of sight angles that can be easily turned into position and velocity, telescopes provide just the line of sight angles. Initial orbit determination from angles only represents a more difficult problem as the most commonly used algorithms (e.g. Gauss and Laplace) present singularities that make them unsuitable for implementation in operational systems. GMV has enhanced the implementations available in ODIN and the classical algorithms with other approaches (e.g. Baker and Jacoby) in a single preliminary orbit determination tool that is robust when facing poorly conditioned scenarios. Additionally statistical reductions are applied to refine the state obtained vector when the number of observations is large enough. Also in this case an estimate of the covariance can be obtained analysing the statistics of the state vectors retrieved at the different observation epochs with respect to the best fit.

The problem of the initial orbit determination still persists even after an initial guess of the state vector has been obtained. Orbit determination when few observations are available and the accuracy of the initial state vector is limited presents a convergence problem. This problem was already addressed by ODIN that implements a least squares algorithm enhanced with a Levenberg-Marquardt strategy. This ODIN algorithm has already been tested with real data in real collision avoidance scenarios and is well suited for operational integration.

2.3. TLE Support

Traditionally two-line element (TLE) sets have been used to support general orbit modelling particularly in the space debris scenario. Two main difficulties have always been linked to the use of TLE sets: lack of definition in the models used for the generation of the sets and impossibility to associate to them an accurate covariance. Both difficulties limit the analysis of orbits based on TLE sets, in particular the lack of covariance prevents the accurate analysis of collision avoidance scenarios and forces either the arbitrary assignment of covariance as function of the orbit type or the implementation of techniques to compute the covariance whose results not always can be properly verified.

The first step undertaken in the support to TLE sets has been to update the SGP model to the latest and most accurate implementation (Revisiting Space-track Report #3, Vallado et al.).

2.4. Support to Standard Data Formats

Standardisation of interfaces is one of the key aspects in ground systems today. This of course includes the ground data systems associated to space surveillance, where the data exchange is not much different from other satellite control systems. Of particular interest in our case is the exchange of orbit data required for the initialization and maintenance of the space objects catalogue and also for the ingestion and export of orbit data required for the interaction within and outside the space surveillance system.

One of the main disadvantages of the use of TLE is its inability to support detail information about the orbit characteristics, to incorporate covariance information to the orbital states and to adapt to different data exchange configurations. The CCSDS proposes a collection of standard messages for the exchange of orbit information. The Orbit Parameter Message (OPM), Orbit Ephemeris Message (OEM) and Orbit Mean-elements Message (OMM) provide a wide variety of mechanisms for the exchange of orbital data in osculating or mean representation with the possibility to include covariance information. In addition, the OMM can support TLE like information allowing continuity with the systems that are implemented on its basis. In addition there is a representation in XML of the navigation messages that the permits the natural evolution to modern ground systems with validation mechanisms and standard handling tools.

3. IMPLEMENTATION

3.1. Orbit Propagator

The reference orbit propagator of the suite is the one from NAPEOS enhanced with full covariance propagation capabilities. It has been incorporated to four elements within the suite:

- PROPAG: this is the original propagator from NAPEOS that now can ingest a covariance qualified state vector and propagate it to any future or past epoch.
- BAHN: benefits directly from the previous implementation. Although the effect in the batch orbit determination is limited, it can be used for validation and orbit determination analysis.
- SRIF: this is the sequential estimator where the propagation of covariance is essential. Although SRIF provides its own mechanism for covariance handling and propagation, its use in combination with the new propagator provide benefits in flexibility of use and initialisation (combined with the use of standard formats as described below).
- ODIN: the main advantage of the combination of ODIN and the new propagator comes from the improved orbit determination capabilities of ODIN together with the improved dynamic models and reference models in the propagator. The main reason to incorporate the propagator here is to have a complete suite that relies exactly in the same representation of dynamics and reference frame.

3.2. Initial Orbit Determination

Two algorithms have been implemented for initial orbit determination, one based on orbit fixes from range and angles based on the Gibbs and Herrick-Gibbs methods and a combined algorithm for the angles only scenario where the Gauss and Baker-Jacoby algorithms are combined. The combined approach for the angles only scenario targets to remove the coplanar singularity that appears in the Gauss method.

In addition it is very relevant to be able to derive a covariance estimate for the computed state vector.

The high level algorithm is common to both scenarios as both provide in the end state vectors with higher or lower accuracy depending on the input data quality. The process combines sets of three or four observations to produce a population of state vectors to which a preliminary reduced dynamics orbit is adjusted in a least squares process. The output state vector is computed at the desired epoch from this adjusted orbit. The covariance of the estimation process is also computed as a function of the residuals of the individual state vectors with respect to the adjusted orbit in the least squares process used.

In the cases where the total number of measurements is too low to permit look up tables are used to provide a conservative initial value of the covariance. The mechanism for this orbit characterisation is similar as the one used in CRASS.

3.3. TLE Support

A number of tools have been implemented to support the handling of TLE sets. All of them rely in the latest available SGP model (Vallado et al.) integrated in the core library. It is to be noted that this implementation relies on some assumptions like the accuracy of the information available for the SGP model and that the reference frame of the commonly distributed TLE sets is the True-Equator Mean-Equinox (TEME) what may be questionable is some cases.

- TLE propagator: to turn a TLE set into orbit ephemeris in the selected reference frame and output according to a selectable variety of formats
- TLE estimator: to compute a TLE set in the TEME reference frame from a list of orbit ephemeris using

a least squares process. The estimation process also provides an initial estimate of the covariance based on the residuals of the TLE positions with respect to the adjusted orbit.

- Improved TLE propagator: essentially adjusts a numerical orbit to the input TLE set and predicts the future trajectory using the numerical integrator. This approach was already successfully applied for GEO satellites (Martin-Polo et al.) and it now extended to generic orbits benefiting from the performant orbit propagator.

3.4. Support to Standard Data Formats

This is considered one of the key aspects in the implementation of the suite. Whereas the algorithms and data handling mechanisms provide the adequate level of accuracy and information, the implementation of the standards for interfaces and internal data handling provides the adequate level of integration if when the software is to be used in operational environments.

The CCSDS navigation standards are implemented at two levels, which are essentially linked to the interface and internal data use levels.

- A generic C++ application based on SAX (Simple API for XML) and the standard Xerces-C from Apache. This is a generic purpose library and application that can handle both XML and plain text navigation messages. The implementation allows the validation of files through the associated XML schemas and the conversion of types. This library is derived from CCSDS official XML to text NDM conversion tool.
- A dedicated Fortran 95 library for direct use in flight dynamics applications. This library is mainly intended for the export data in the CCSDS standard and also allows the ingestion of the in the plain text format of the standard. Unlike the C++ library, this is a lightweight implementation for those cases when the full fledged functionality is not required.

The use of the CCSDS NDM has become interesting once they are capable to support representation of covariance for sing state vectors and for orbital ephemeris. The OPM and OMM become then comprehensive in terms of data required for catalogue maintenance and simplify the data exchange mechanisms and storage while remaining standard when the exchange is in an external interface.

This implementation has been successfully applied for the implementation of the SSA simulator for ESA.

4. OTHER TOOLS

Although not directly linked to the estimation and handling of covariance there are a number of tools that have also been included in the suite as they are very relevant for the processing of space debris related scenarios. They are described in detail in the SSA simulator documentation but it is worth mentioning the briefly here.

4.1. Tracking Data Correlator

Perform the identification of predicted tracking from Earth or space based sensors on catalogued objects with respect to real input data. It provides the input to the preliminary orbit determination when input objects do not correlate with the catalogued ones.

The software relies on three main components:

- Tracking data pre-processor, that ingests the tracking data and formats for efficient input/output and generates a list of sensors and visibility periods for later processing. The current implementation is PROOF compliant.
- Synthetic data generator, that from the list sensors given by the pre-processor produces a collection of

synthetic data for the catalogued objects using the visibilities and orbital information from OPM sets stored in the catalogue. The data is also formatted for efficient input/output

- The correlator itself, that combines the synthetic data and the real data to produced for each object a weighted correlation index. The best correlation are used to identify the object that bets adjusts to the input real data and the second best correlation (together with the best) to assess the quality of the correlation. Absolute correlation thresholds per data type are also considered in the process.

4.2. PROOF Data Tuner

This tools benefits from the capabilities of PROOF (ESA tool for space environment modelling) and the high tracking simulation performance of NAPEOS. The approach is essentially to fill the visibility periods defined by PROOF with tracking data produced by NAPEOS tailored for a specific purpose (improved accuracy, intentional data degradation, re-sampling, etc.). The implementation preserves the format what permits feeding any system that already ingests PROOF data.

4.3. CRASS Evolution

CRASS is the Collision Risk Assessment Software System developed by GMV for ESA targeting to the operational routine monitoring of conjunction events of ESA satellites with space debris. CRASS has proven efficiency and robustness over the several years of operations and is the best candidate for a generic solution for collision risk mitigation. CRASS implements the smart sieve algorithm that can efficiently cope with a variety of close conjunction scenarios. CRASS is the final main consumer of covariance provide by all other tools. Indeed, the assessment of collision probability is performed is based on the provided input trajectories and their associated covariances.

5. CONCLUSION

GMV has identified the necessity to consolidate the algorithms and software used in the monitoring of space debris and the associated data handling. Of course there are several possible solutions; this paper has presented a possible alternative based on already available operational software components developed in the frame of other flight dynamics applications. Necessarily the specificities of the space debris scenario require additional elements to complete the demand of data processing and accuracy. This can be easily achieved if the software kernel provides adequate generic interfaces and the interfaces elements are supported by actual standards. A possible approach has been described here that relies essentially in software components developed in the ESA context, then complemented with those elements specific to the space debris environment. Being the solution of the problem definitely not unique, hopefully the outcome of this paper highlights the need to focus on an operational approach. The many interesting initiatives around algorithms and strategies should become operational solutions well proven, robust, suitable for automation and accurate enough to give agencies and operators a solution for the mitigation of collision risk for satellites in operation.