EVOLUTION OF ESA'S SSA CONJUNCTION PREDICTION SERVICE

D. Escobar (1), A. Sancho (1), J. Tirado (1), A. Águeda (1), L. Martín (2), F. Luque (2),
E. Fletcher (3), V. Navarro (4)

(1) GMV S.A., Isaac Newton 11, Tres Cantos, Spain,
Emails: descobar@gmv.com, asancho@gmv.com, jtirado@gmv.com, aagueda@gmv.com
(2) GMV staff at the European Space Agency, ESAC, Villanueva de la Cañada, Spain,
Emails: luis.martin@esa.int, faluque@gmv.com
(3) European Space Agency, ESAC, Villanueva de la Cañada, Spain, Email: emmet.fletcher@esa.int
(4) European Space Agency, ESAC, Villanueva de la Cañada, Spain, Email: vicente.navarro@esa.int

ABSTRACT

This paper presents the recent evolution of ESA's SSA Conjunction Prediction Service (CPS) as a result of an on-going activity in the Space Surveillance and Tracking (SST) Segment of ESA's Space Situational Awareness (SSA) Programme. The CPS is one of a number of precursor services being developed as part of the SST segment. It has been implemented as a service to provide external users with web-based access to conjunction information and designed with a service-oriented architecture. The paper encompasses the following topics: service functionality enhancements, integration with a live objects catalogue, all vs. all analyses supporting an operational concept based on low and high fidelity screenings, and finally conjunction detection and probability algorithms.

1 INTRODUCTION

Over the last few years the space debris environment has gained a large attention due to the increasing amount of uncontrolled man-made objects orbiting the Earth. This population poses a significant and constantly growing threat to operational satellites, as proven by the collision of the satellite Iridium-33 with the decommissioned spacecraft Cosmos-2251. Major space organizations have developed their own systems to assess the collision risk and evaluate the need to manoeuvre their satellites in order to avoid collision events with other orbiting objects (see [1] , [2] and [3]).

In order to face this threat in an independent manner, the European Space Agency (ESA) launched, in 2008, an initiative for the development of a European Space Situational Awareness (SSA) programme. The precursor phase of this programme is partly dedicated to the development of precursor services of the three segments of ESA's SSA system, namely: the Space Surveillance and Tracking (SST) segment, the Space Weather (SWE) segment and the Near-Earth Objects (NEO) segment. The first of these segments, SST, is dedicated to the cataloguing of in-orbit debris and the analysis of the risks posed by these catalogued objects. As part of the SST segment, seven end-user services have been identified: 1) a catalogue service, providing access to the orbital information in the catalogue of space debris, 2) a conjunction prediction service, providing forecasts about upcoming satellite conjunctions based on the orbital information in the catalogue; 3) a re-entry prediction service, providing forecasts about satellite re-entries into the atmosphere, 4) a fragmentation analysis service, analysing the catalogue to detect possible in-orbit fragmentation events; 5) a manoeuvre characterization service, detecting manoeuvres of operational satellites; 6) a sub-catalogue characterisation service, characterising the object population below the minimum size detectable by the segment sensors in normal operation; 7) a special mission support, providing support to satellite missions during specific phases (e.g. launch and early operations phase).

As part of the programme, several SST precursor services are being developed and deployed at the Space Surveillance and Tracking Centre (SSTC) within the European Space Astronomy Centre (ESAC). These services are partially based on existing infrastructure, knowledge and software applications. One of these is the Conjunction Prediction Service (CPS). This service took, as starting point, ESA's Collision Risk Assessment Tool (CRASS) (see [21]), developed and used by the Space Debris Office at the European Space Operations Centre (ESOC). In a first phase of the service evolution, a web based front end was developed with the aim of providing users web access to the service. The system was named WBFE-CRASS [22]. The architecture of the system is presented in Figure 1. It consists of the following elements:

- *Application server*: this hosts the presentation and business layers of the system. It provides web access to the system via a web site, controls the executions of the analyses, etc. *Database server*: this is the node where the data layer of the system is located. It contains the orbital information uploaded by the users, and more importantly, all the information about the conjunctions detected in

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the analyses.

- *Web server*: this provides a single entry point to the system and is accessible from the external world via https.
- *CRASS system*: this is the node where the collision risk analysis is executed. Its inputs and outputs are transferred from and to the main application server.
- *Mail server*: this is in charge of sending the necessary notifications to the subscribed users in case a high risk conjunction is detected affecting one of the objects the user is subscribed to.

A second phase of the evolution process of the CPS was started at the end of 2011 as part of the CO-VIII activity within ESA's SSA programme. This second evolution phase is the subject of this paper. The objectives of this second upgrade can be summarized as:

- Enhance the current infrastructure based on the CRASS analysis approach.
- Read orbit information from a database (a named objects catalogue)
- Perform all-on-all conjunction predictions, as well as analysis on specific objects to be performed through individual calculations
- Allow parallel processing techniques to be employed on large input datasets
- Ensure automated operation and output
- Provide output to an SQL database
- Enhance web-based operations
- Provide a stand-alone Human-Machine Interface with complete access to the system for its operators
- Enable integration to the service oriented infrastructure of the SST segment

The following aspects are described in this paper:

1. Service functionality enhancements: several additional capabilities have been added to the Conjunction Prediction Service both in terms of external user access and operator usability. Two types of analyses are now available: low fidelity screenings, based on regular all vs. all analyses, and high fidelity screenings, based on specific one vs. one analyses of previously detected high risk conjunctions. Special focus has been paid to the adoption of international standards such as CCSDS for both input and output.

2. Integration with a catalogue of objects. One of the major upgrades of the system is the integration of the system with a catalogue of objects. Practically speaking this implies interacting with a database of objects and object-specific orbital information represented as a time-tagged sequence of state vectors and covariances.

3. The possibility to perform all vs. all analyses in an efficient manner has been added to the service. This will be briefly summarized in the paper. Special focus will be paid to the validation activities carried out during the activity.

4. As part of the service evolution a thorough review of the existing algorithms for collision probability has been carried out, covering both low and high velocity encounters.

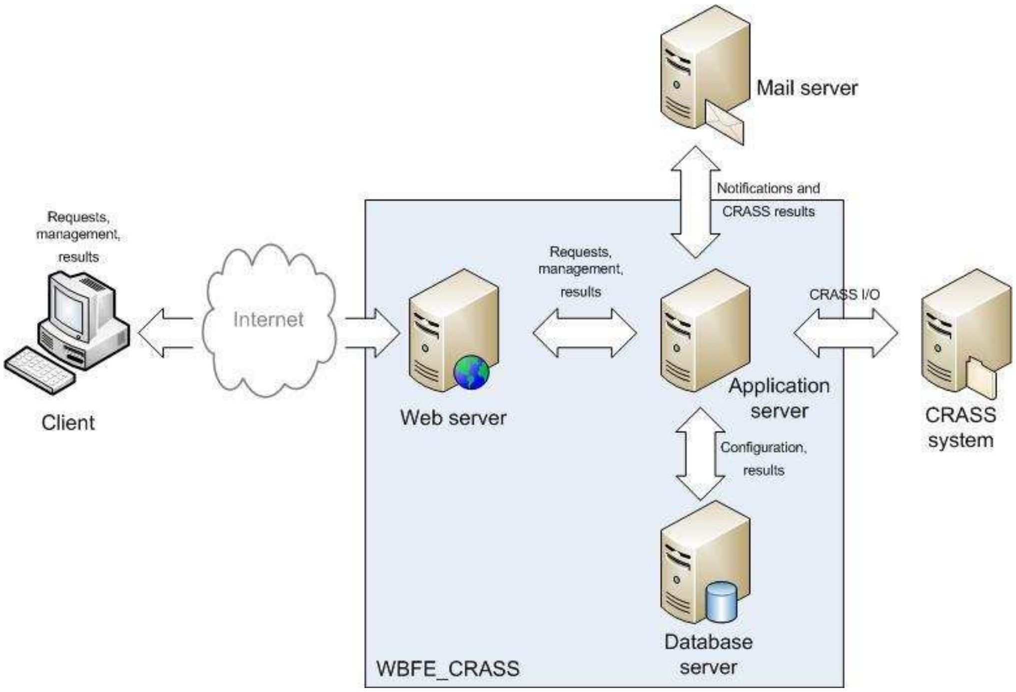


Figure 1: WBFE-CRASS system architecture

2 OPERATIONAL CONCEPT - LOW AND HIGH FIDELITY SCREENINGS

Apart from the main objectives defined in the previous section, the design of the enhanced system has taken into account the way the CPS is intended to be operated. To this respect, ESA has defined two levels of analyses or fidelity screenings:

- Low fidelity screening: detection of all conjunctions and identification of those of high risk (i.e. above a certain probability threshold)
- High fidelity screening: refined analyses of the high risk conjunctions detected as part of the low fidelity screening.

To support these fidelity levels, the following processes or scenarios have been identified as necessary:

a) All vs. all routine analyses: automated conjunction prediction analysis among all the objects contained in the objects catalogue to be performed in a regular basis (i.e. once a day) with a forecast time span of one week typically. This scenario covers the low-fidelity screening concept described above. The intervention of the operator is limited to the verification of the correct operation, investigation and resolution of anomalies and the preliminary analysis of results as applicable. This process includes the submission of notifications to the required users when user-specific thresholds are exceeded.

b) Contingency scenario after the detection of a high risk collision: this scenario is triggered if the low fidelity screening identifies an event where the collision probability between two objects exceeds a system-wise threshold. The automated process consists of:

- Request for additional tracking: in order to improve the collision risk estimation the system may request more accurate ephemerides of the objects involved in a high-risk collision. As soon as these ephemerides are updated in the objects catalogue, the CPS automatically reanalyses the risk of collision with a one vs. one process to compute an update of the conjunction geometry collision and collision probability.

- Upload of new satellite orbital data by the satellite operator(s) (if available): this is assumed applicable to those cases when external orbital information for one of the objects (in case this is an active satellite) is provided by an external entity accounting for future manoeuvres. After the update of the ephemerides in the objects catalogue, a reassessment of the conjunction is carried out. In particular, this supports the analysis of collision avoidance manoeuvres since their effect can be evaluated with the new orbital information

3 SERVICE FUNCTIONALITY ENHANCEMENTS

So far a description of the initial state of the Conjunction Prediction Service has been carried out together with the aspects to be enhanced and the operational concept to follow. Next a description of the enhancements designed and implemented in the CPS to accomplish the aforementioned goals is presented.

3.1 System architecture

First of all, it is important to note that the CPS is one of the various systems composing the SST segment. Other these systems include: the Data Processing Chain (DPC), whose main task is maintaining the objects catalogue by requesting tracking and survey activities to a network of sensors and by processing the data obtained by them; the Sensor Planning System (SPS), whose main task is the reception of the requests for tracking and surveys from other systems and the generation of an optimized observation plan for the network of available sensors.

Based on the descriptions above, the interactions of the CPS with other systems of the SST segment are: 1) access to orbital information contained in the objects catalogue; 2) submission of tracking requests to the SPS for high-risk conjunctions as part of the high-fidelity screening. This concept is shown in Figure 2. Note that the figure considers a sensor simulator, which is intended to simulate the behaviour of the SST sensors in terms of inputs (observation requests) and outputs (observations or tracklets) as long as the real SST sensors are not available.

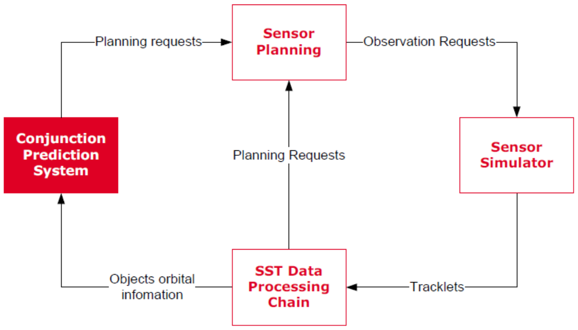


Figure 2: Interaction of the CPS with other SST systems

The design of the enhanced CPS system shares many commonalities with its predecessor. The architectural design is presented in Figure 3. Aside from the CPS, another service is being developed as part of the CO-VIII activity. This is the Re-entry Prediction Service (RPS), in charge of analysing re-entry events and provides estimates of possible areas on the Earth ground affected by the re-entry. A design similar to the CPS has been considered for the RPS.

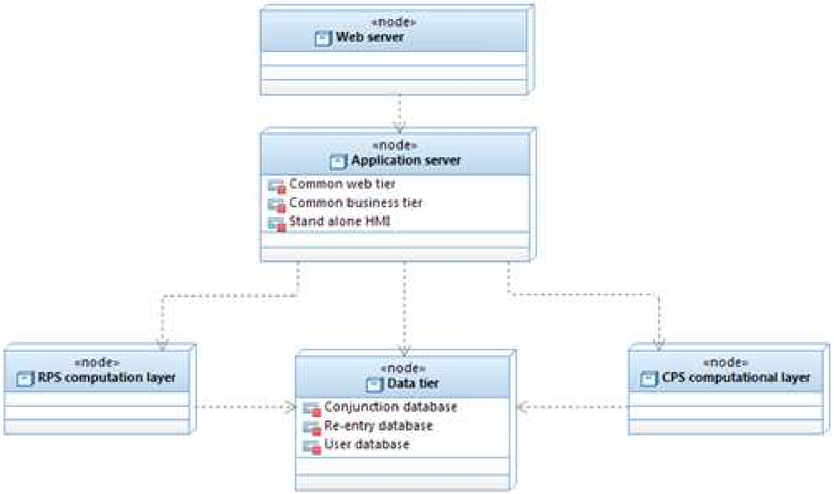


Figure 3: Overall deployment diagram for the CPS and the RPS

The main differences between the deployment diagram of Figure 3 and Figure 1 are: the presence of a node for the CPS computational node, improving upon the original CRASS implementation and hosting the conjunction analysis subsystem; and the RPS computational node, playing a similar role for the RPS. Note that the application server, the database server and the web server are shared by the CPS and the RPS. The complete system forms the so-called SST web portal, which provides access to the conjunction and re-entry information computed by the CPS and RPS of the SST segment.

3.2 Integration with the objects catalogue

An important aspect to take into account while designing the work flow of the CPS is the size of the orbital information needed for the conjunction analyses. For a typical catalogue of 15000 objects and ephemerides with a time span of 7 days and a time step of 60 seconds for the state vector and 300 seconds for the covariance evolutions, the size of the complete orbital information amounts to more than 10 Gigabytes.

On the other hand, a stringent performance requirement is imposed on the CPS for the all vs. all analysis. It is required to carry out an all vs. all with a catalogue of 10000 objects in less than 30 minutes, including the time to retrieve the orbital information from the catalogue and store the conjunction information in the database storage.

In order to avoid the transfer of many Gigabytes of data over the network, from the node hosting catalogue to the node running the CPS, it has been decided to store the latest orbital information within the CPS node and keep it synchronised with the objects catalogue.

This means that every time there is a new ephemeris for an object in the catalogue, the information is transferred automatically to the CPS and stored for later use in the conjunction analyses. This design avoids transferring all the orbital information at once at the beginning of each conjunction analysis whilst ensuring that the latest up-to-date orbital information is used.

The DPC and CPS are separate systems exchanging orbital information and the interface between them implements CCSDS standards. Orbit Ephemeris Messages (OEM) and Orbit Parameter Messages (OPM) in XML format (see [18] and [19]) are provided by the objects catalogue to the CPS as part of the synchronization process.

A direct consequence of the use of full ephemerides is the need to interpolate the orbital information to the required point in time for the conjunction analysis. While this is a common operation for the state vector information, the interpolation of covariance matrices introduces an added difficulty (see [17]). In this case, and after an evaluation of different possible approaches, it has been decided to carry out the interpolation of covariance matrices expressed in orbital frame, where the evolution of the covariance is smoother.

For the development and initial operation of the CPS and RPS, a mock-up of the catalogue has been implemented. This element generates orbital information based on up-to-date Two Line Elements (TLEs) by using the Simplified General Perturbation (SGP) theory (see [14]) and sends the resulting OEMs and OPMs in XML format to the CPS.

3.3 Conjunction analysis

As described above, the computational and algorithmic core of the CPS is located in a dedicated node. This node executes the following sequence of tasks:

- Retrieval of orbital information
- Conjunction detection
- Collision probability computation
- Storage of conjunction information

The main functionality added to this component is the ability to carry out all vs. all analyses (see [4]) using parallelization techniques to speed up the computations. Details on the algorithms implemented for the conjunction detection process and the collision probability computation can be found in sections below.

A very important difference with respect to its predecessor is the interaction with the database server. The CRASS-based system provided the output conjunction information in the form of files that were parsed by the business layer, running in the application server and stored in the database server. In order to avoid files-based interfaces and bottle necks, direct storage of the information in the database is carried out by the conjunction analysis subsystem.

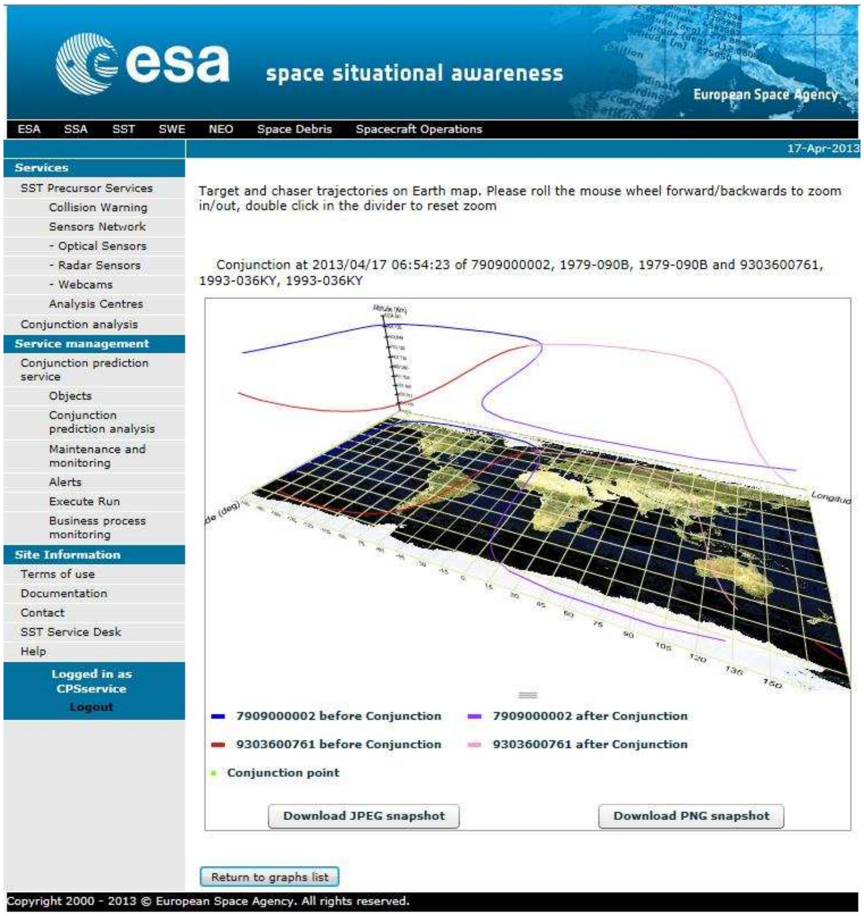
3.4 New functionality in Web Based Interface

From an external user point of view, the web-based interface provides access to the following features:

- Conjunction results obtained during the last 7 days, (either in automated runs or in user executions) affecting the objects for which the user is registered.
- Historical conjunction results affecting the objects for which the user is registered.
- User executions with orbital information uploaded by the user. This allows taking into account manoeuvre information not included in the objects catalogue. This is intended for collision avoidance manoeuvre analysis.

Based on the available functionality, the following work flow is available to the user:

- Routine reception of notifications of high-risk conjunctions affecting user-registered objects
- Access to the web site to analyse the information in case of a high-risk conjunction.
- Execution with user-uploaded ephemerides for the evaluation of the effects of a possible collision avoidance manoeuvre.



Target and chaser trajectories on Earth map. Please roll the mouse wheel forward/backwards to zoom in/out, double click in the divider to reset zoom

Conjunction at 2013/04/17 06:54:23 of 7909000002, 1979-090B, 1979-090B and 9303600761, 1993-036KY, 1993-036KY

Figure 4: Screenshot of the web interface for operators. Detail of the 2D geometry of the conjunction

As part of the evolution of the CPS, the web interface provided to external users has been enhanced with the following features:

- Access to results affecting registered objects computed in the low and high fidelity screenings. A major change in the web application has been necessary since it was originally designed only for one vs. all analyses.
- Conjunction information provided in the form of CCSDS Conjunction Data Message (CDM), either in ASCII or XML format, apart from the pre-existing reports
- Download of the plots visualized in the web in the form of png or jpeg files
- Upload of user-specific orbital information in the form of OPM and OEM compliant files, both in ASCII and XML formats.
- Executions using the orbital information uploaded by the user. This orbital information is only available to the user who uploads it and it is not considered in automated runs of the system, only in user analyses.
- Integration with ESA's SSA Technical Web Portal for the provisioning of identity management services (Single-Sign-On feature provided by openAM).

3.5 Stand-alone Human-Machine-Interface

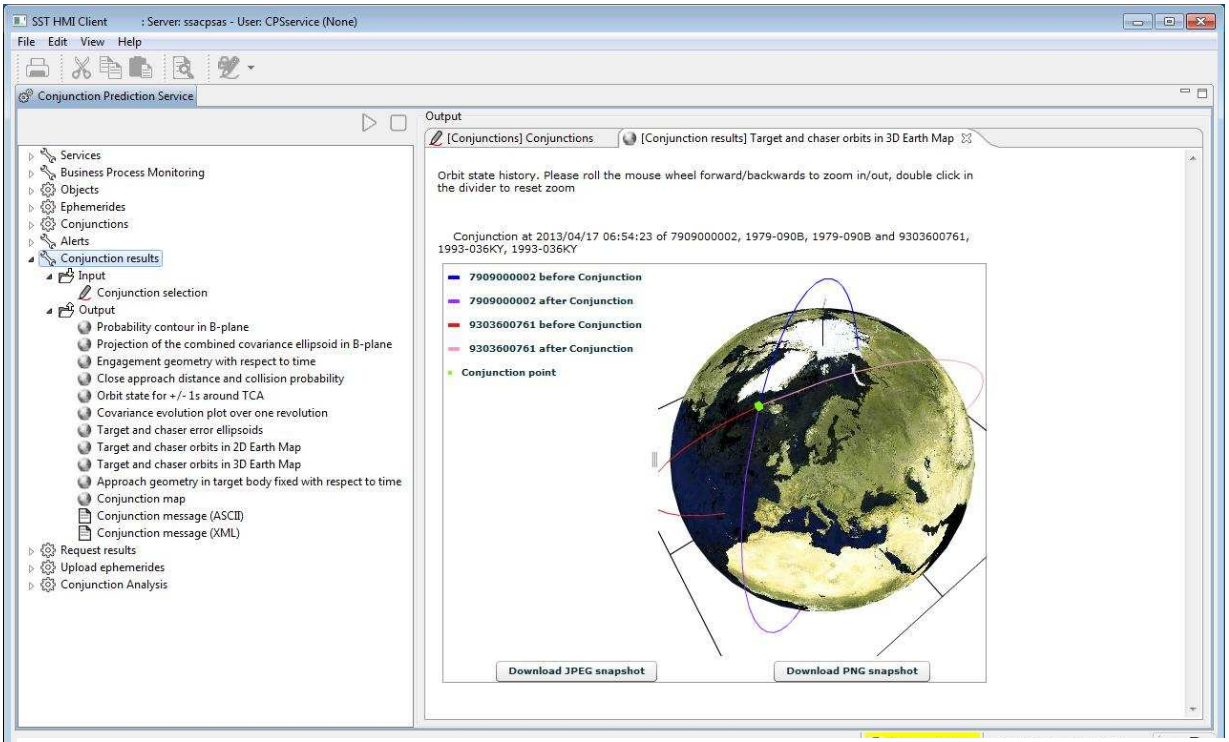
Another upgrade of the CPS is the implementation of a stand-alone Human Machine Interface (HMI) intended to provide full visibility of the state of the system to operators. While the web interface allows connection from the outside world through the Internet, this HMI is designed to connect to the CPS only from the Operational Back End Network of the SST segment.

The HMI is based on GMV's product ***focus client***. This product is implemented using the Eclipse RCP framework for rapid user interface development. It has been specifically adapted to interface with the application server of the SST web portal following the restrictions imposed by the network setup.

The communications between the application server and this client application are carried out by means of a series of web services exposed in the application server.

Similarly to the web interface, the stand-alone HMI uses openAM as identity provider for user authentication purposes. opeanAM also secures the web services exposed by the server and thus the HMI must include an authenticated token in every request to the server.

Another interesting aspect in the integration of this HMI has been the reuse of the internal web browser of Eclipse to display the very same interactive plots accessible via web, based on the jQplot library and Adobe Flash (see Figure 6)



Orbit state history. Please roll the mouse wheel forward/backwards to zoom in/out, double click in the divider to reset zoom

Conjunction at 2013/04/17 06:54:23 of 7909000002, 1979-090B, 1979-090B and 9303600761, 1993-036KY, 1993-036KY

Figure 5: Screenshot of the stand-alone human machine interface for operators. Detail of the 3D geometry of the conjunction

4 CONJUNCTION DETECTION

One of the main algorithms to be implemented in any conjunction analysis software is the one dedicated to conjunction detection. These algorithms need to be computationally efficient at filtering pairs of objects that cannot collide in a given time interval, in order to have a reasonable performance, and at the same time, real potentially colliding pairs cannot be filtered out incorrectly. These are the main drivers for the selection of the conjunction detection algorithms. Moreover, given the delicate nature of the conjunction detection filtering process, an independent validation has been carried out. This is also described below.

4.1 Algorithm selection

Given the experience gained with the Smart-Sieve in the development of CRASS and the dramatic speed-up improvements with ***closeap*** (see [4]), the same conjunction detection algorithm has been used for the CPS. The algorithm has been parallelized with OpenMP to profit from the multi-core processors of the operational servers used for the analyses.

4.2 Validation

In order to independently validate the conjunction detection implementation of the CPS, two comparisons have been used:

- Comparisons against the results obtained with ARC (see [15]) by Atos Origin independently for the very same input ephemerides.
- Comparisons against results obtained with a brute-force method. This brute force method consists in searching for conjunctions in an all vs. all scenario with a rather small time step (1 second) and no filters at all.

4.3 Advanced concepts

Parallel to the development activities of the enhancements of the CPS, advanced methods for conjunction detection have been analysed and prototyped. Two separate paths have been considered here: 1) combination of the Smart-Sieve with the method of spatial bins proposed in [5] and 2) use of a double Smart-Sieve approach with different time steps for each of the smart-sieve layers. This method resembles the concept of multi-grid methods of numerical fluid dynamics

The details of the both methods can be found in [16]. Prototype implementations of them show a speed-up larger than 60% of the conjunction detection process with respect to the original Smart-sieve implementation of the CPS, which is already rather optimized. Currently, it is under evaluation whether these methods are implemented in the CPS for improved performance.

5 COLLISION RISK ESTIMATION

Being one of the most relevant figures to evaluate the risk posed by a conjunction, the probability of collision is computed by the CPS for any close conjunction event detected. To this respect, it has become common to distinguish between low and high velocity encounters, also named, short and long duration conjunctions respectively. A thorough review and trade-off of the available algorithms has been carried out. This is described next. Aside from the algorithm selection, the methodology used for the validation of the algorithms implemented is also presented below.

5.1 Algorithm evaluation and selection

In the case of high velocity encounters, even though there are several methods (see [7]), given the positive experience with CRASS, it has been decided to implement the same method based on Akella and Alfriend’s formulation (see [6]). In any case, all of them are based on the same two-dimensional hypothesis.

For low velocity encounters, after an evaluation of several methods (see [7], [8], [9], [10], [11], [12] and [13]), the selected method was the method of McKinley (see [13]) due to its simplicity and expected low computational requirements. The threshold to start using the low velocity method is above 10 m/s, which is a commonly accepted value (see [20]) for non-linear effects to start playing a role in the probability computation.

5.2 Validation

In order to validate the collision probability algorithms, the following independent comparisons and cross-checks have been carried out:

- Comparison of collision probabilities for high velocity encounters against results computed by ARC
- Comparison of collision probabilities for low velocity encounters described in detail in the literature by McKinley (see [13]) and Alfano (see [9])
- Comparison of collision probabilities against results obtained with Monte-Carlo analyses as explained below.

In all cases the results of the comparison were acceptable, except for encounters below a relative velocity in the order of 10 cm/s. It is believed this is due to the selected algorithm for conjunction detection, but is not considered an issue due to the very low relative velocity.

5.3 Advanced concepts

One of the challenges of the Monte-Carlo analyses carried out as part of the validation has been the speed-up of the computations. In this type of analyses, one of the main elements driving analysis time is the propagation of the perturbed state of the objects to compute the new conjunction conditions. To reduce the amount of computations required, a new method has been used for the generation of the perturbed orbits of the Monte-Carlo trials. It is based on the use of the transition matrix to compute the perturbed orbits by linear Taylor expansion with respect to the reference orbit. Comparisons show an agreement in the order of 5% against results obtained with Monte-Carlo analyses based on full propagations of the perturbed state.

6 CONCLUSIONS

This paper has described the latest enhancements introduced in ESA's SSA Conjunction Prediction System. It has provided insight into the system evolution from an architectural design point of view, added functionality available to the end-users and the operators and the selected algorithms for conjunction detection and collision probability computation.

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