closeap: GMV'S SOLUTION FOR COLLISION RISK ASSESSMENT

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ABSTRACT

In recent years, the Space Debris field has gained a lot of attention due to the growing population of uncontrolled objects orbiting the Earth, causing an increase in the risk of collision with operational satellites. A clear example of this interest is the European Space Situational Awareness (SSA) initiative.

As part of GMV's activities in this field, GMV has developed *closeap*, a tool for conjunction assessment, collision probability prediction and collision avoidance manoeuvre optimization integrated in *focusSuite*, GMV's commercial off-the-shelf (COTS), multi-mission, multi-satellite flight dynamics solution for satellite control. *closeap* is based on the already mentioned CRASS and ODIN tools and also on ESA´s **NAPEOS** software (Navigation Package for Earth Orbiting Satellites).

This paper presents *closeap* as a flight dynamics application to support satellite operations for collision risk assessment tasks. On the one hand, the paper focuses on its design and inheritance from other existing software packages, as well as on the performances obtained in real conjunction scenarios. On the other hand, an overview of the algorithms implemented in *closeap* is also carried out, even though most of them are described more in detail in the literature.

1. INTRODUCTION

The ever increasing population of space debris poses a major thread to operational satellites. Unfortunately, this has been proved recently by the collision between the operational satellite Iridium-33 and the already decommissioned satellite Cosmos-2251 in February 10th. This type of events are not only a serious problem for the owner of the satellite, but also for the rest of the satellite operators since more space debris is generated due to the collision in specially interesting orbital slots. Thus, it is important to have reliable and robust tools for collision risk assessment and avoidance manoeuvre optimization.

Within this area GMV participated in the development of ESA´s software for Orbit Determination and Collision Risk Assessment tools, **ODIN** and **CRASS**

respectively as explained in [1]. The Space Debris Office at ESOC operates these applications to forecast and mitigate collision risk probabilities of ESA´s ERS-2 and ENVISAT satellites as presented in [2]. **DISCOS,** ESA's Database and Information System Characterizing Objects in Space, used operationally together with **CRASS** and **ODIN**, was also developed and maintained by GMV. Currently, GMV´s major activities in the field of Space Debris include:

a) Development for ESA of **SSASIM** (SSA simulator), an Earth orbiting object catalogue maintenance simulator.

b) Study for ESA: "Identification and Analysis of **MEO** Observation Strategies for a future European Space Surveillance System"

On the other hand, GMV is a reputed satellite Flight Dynamics Systems (FDS) provider in Europe and USA. Some of the satellites or constellations for which GMV has successfully provided a FDS or is currently implementing it are:

− GEO operators: EUTELSAT, HISPASAT, HISDESAT, TELENOR, SCC, NILESAT, STARONE, ARTEMIS
− GALILEO and GLOBALSTAR constellations.
− CNES ATV cargo mission
− EPS-MetOp.
− Galileo GSTB-V2 (Giove B) FDS
− OCO/GLORY NASA missions.

Based on this vast experience on flight dynamics systems and space debris, GMV has implemented *closeap* in the frame of collision risk assessment operations. This application inherits the conjunction detection and collision probability algorithms from **CRASS** and makes profit of special algorithms for orbit determination in degraded tracking situations from **ODIN**.

Apart from the reuse of **CRASS** algorithms, its computational core is based on the well known and flight proven **NAPEOS** technology. Furthermore, it is integrated within *focusSuite*, GMV´s COTS infrastructure for FDS allowing fully automated operations and featuring an advanced user interface and graphical visualization tools.

2. *CLOSEAP* OVERVIEW

closeap is an application for:

- close conjunction detection
- collision risk prediction
- collision avoidance manoeuvre optimization

featuring (see Fig. 1):

- catalogue filtering, conjunction assessment and collision risk algorithms taken from **CRASS**
- orbit propagation library and computational core from **NAPEOS**
- the latest implementation of the Simplified General Perturbations (**SGP**) theory to compute space debris orbits based on publicly available Two Line Elements (TLE)
- full integration within *focusSuite*
- optimization of collision avoidance manoeuvres in case of high risk conjunction events

The capabilities of **NAPEOS** together with the specific algorithms from **CRASS** and **ODIN** have been essential for the successful implementation of *closeap*.

The development of **NAPEOS** started at the end of 1995 and since then GMV has remained the main contributor to its development for ESA. GMV has also taken the lead in its use for the implementation of operational flight dynamics facilities and precise orbit determination systems. The highly accurate orbit propagation library of the **NAPEOS** package has been fully reused in the development of *closeap*, ensuring operational robustness, compatibility of all applications and minimizing the software development and maintenance efforts. Regarding orbit determination tasks, *closeap* is used together with the **NAPEOS** orbit determination elements which were enhanced with the specific algorithms from **ODIN** that allow accurate orbital fits in degraded tracking situations. This is particularly useful if dedicated tracking campaigns are carried out on a specific space debris object with which a high collision risk has been previously predicted.

Aside from the reuse of the orbit propagation and determination modules from **NAPEOS**, the software developed for *closeap* is fully based on GMV´s experience in the Space Debris field. The so-called *Smart Sieve* from [3] for catalogue filtering and close conjunction assessment as well as the collision probability algorithms, initially developed for **CRASS** and optimal in terms of computational efficiency, have been reengineered for *closeap*.

The implementation of *closeap* has also allowed the revision of the TLE implementation used in **NAPEOS**, based on the SGP theory firstly described in [4]. This

theory plays a central role in *closeap*, and in any other similar application (e.g. **CRASS**), since the orbits of the space debris objects are computed based on such TLE sets and the **SGP** theory. Reference [5] shows that several deficiencies exist in former implementations of the **SGP** equations that are corrected in a new fully tested implementation developed in the frame of that study. This new implementation is reused for *closeap* and thus it features the most up to date and tested TLE propagation library.

Finally, algorithms for collision avoidance manoeuvre optimization taken from [6] have been implemented in *closeap*. In case of a high risk conjunction event, the application can provide a collision avoidance manoeuvre optimized in terms of risk mitigation and also in terms of mass fuel consumption.
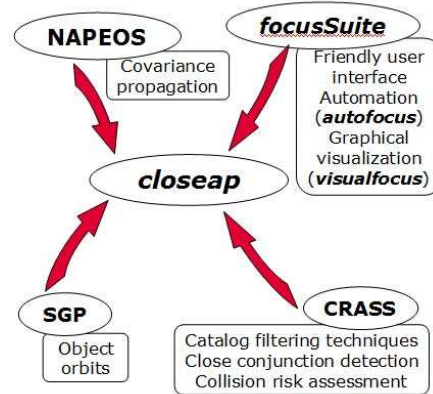

Figure 1: Schematic of closeap inheritance

3. *CLOSEAP* INHERITANCE

3.1. Benefits from NAPEOS core elements

closeap is built on top of **NAPEOS** core elements for orbit propagation featuring:

- IERS 2003 conventions
- Support of GNSS, SLR, DORIS, radar, optical,... measurements.
- Very high precision orbit propagation and determination for any type of orbit (LEO, MEO, GEO, near circular or highly eccentric orbits, ...)

This precise orbit propagator is used:

- to propagate with high accuracy the orbit of the operational satellites under consideration
- to propagate the state covariance of both the chaser object and the target satellite. The initial state covariance of the target satellite is taken from its routine orbit determination while the initial covariance of the object is taken from a look-up table with typical covariance matrices of space debris objects

Thanks to the full compatibility with the rest of the elements, it is possible to carry out more detailed analyses of high risk conjunctions detected with *closeap*. In particular, if the collision probability is too high and a dedicated tracking campaign is contracted to obtain more precise tracking measurements of the colliding object, those measurements can be processed to do an orbit determination of the object. For the latter task, an enhanced Levenberg-Marquardt strategy for degraded tracking situations has been reused from **ODIN** and implemented in the batch least squares orbit determination module. This algorithm has already been tested with real data in real collision avoidance scenarios and is well suited for operational integration. The resulting object's orbit can be input to *closeap* together with its state covariance matrix. The improved orbital knowledge of the chaser object allows refining the collision probability computations. If the new risk estimate is still too high, then a collision avoidance manoeuvre can be performed based on the optimization carried out by *closeap*. In this manner, the whole loop of satellite operations for collision risk assessment and mitigation, as presented in [7], – detection, evaluation, refinement and avoidance – is supported by *closeap* and the surrounding elements.

3.2. Latest SGP implementation

In order to evaluate the collision risk of a given operational satellite with any space debris, a very efficient way to compute the orbit of all the objects is needed. The only orbital information publicly available is provided by USSTRATCOM in the form of TLE sets. Thus *closeap* makes use of the **SGP** theory to propagate those TLE sets in a very efficient way.

Vallado et al. reviewed in [5] the implementation of the **SGP** theory. The original source code, made available to the public in [4], was used as starting point. In a first stage, several corrections from different reliable sources were implemented and validated. Later on, the source code was completely reengineered with modern programming techniques and tested with many different real TLE sets known to cause problems with the original implementation. The resulting implementation is believed to be the closest one to the true implementation used by USSTRATCOM to generate the TLEs from radar and telescope measurements.

Fig. 2, 3 and 4 show some examples of the different results obtained with the original SGP implementation from [4] and the new one by Vallado et al. Based on these figures, it is clear that the use of the original version can lead to unacceptable errors in an operational environment.
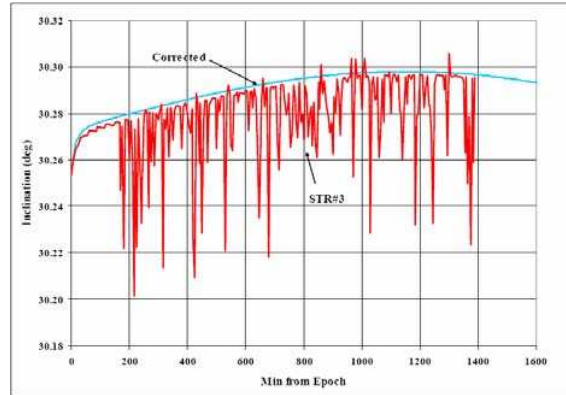

Figure 2: Comparison of inclination evolution for satellite 23333 obtained with the original and the latest SGP implementations (figure from [5])
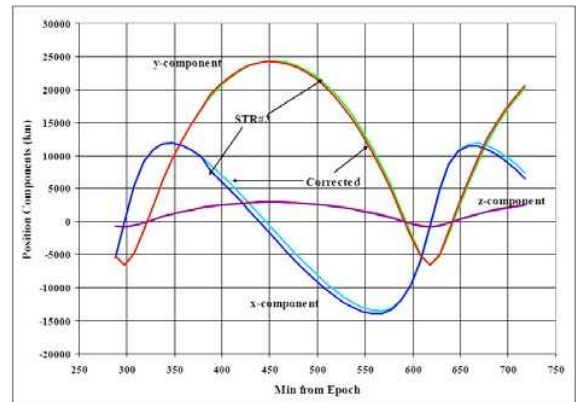

Figure 3: Comparison of position components evolution for satellite 23599 obtained with the original and the latest SGP implementations (figure from [5])
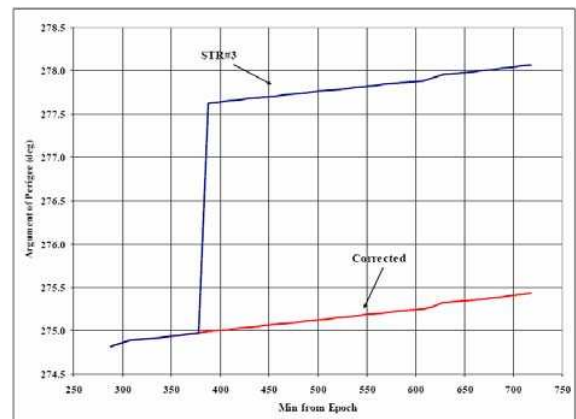

Figure 4: Comparison of argument of perigee evolution obtained for satellite 23599 with the original and the latest SGP implementations (figure from [5])
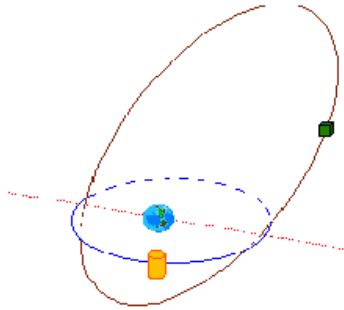
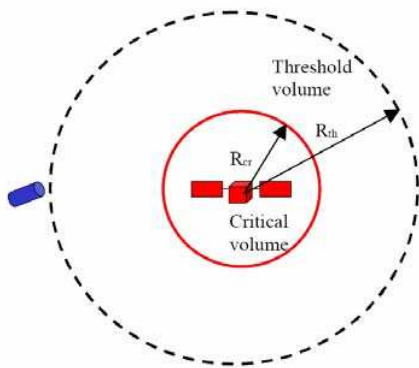*Figure 5: Schematic of the apogee-perigee filter*

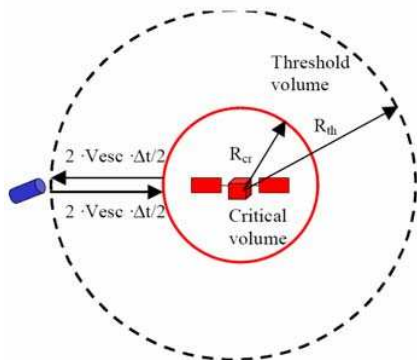*Figure 6: Schematic of the sieve concept*

Figure 7: Schematic of escape velocity threshold volume

4. CATALOG FILTERING TECHNIQUES

Due to the large amount of space debris in space, the propagation of all objects along a period of time on the order of several days is a computationally intensive task. Therefore, those objects whose orbital properties make it impossible for them to collide with the target satellite are filtered out. In this manner, only the covariance of the remaining objects has to be propagated and the computational cost is reduced. In first place, an epoch filter removes those objects whose TLE data sets have a generation epoch too old with respect to the starting time of the analysis. Besides, objects considered as decayed according to the TLE sets are also removed from the analysis because they do not pose any thread. Once these preliminary filters have been applied, three different consecutive filters based on the relative position and velocity of target and chaser are used: a) the classical apogee-perigee filter, b) the so called *Smart Sieve* and c) a fine conjunction detection. The *Smart Sieve* technique consists of a series of filters based on very simple astrodynamics principles and is designed to minimize the computational cost in a safe and conservative manner. Several different steps of filters constitute the *Smart Sieve*, but all of them are based on the relative position and velocity of the chaser object with respect to the target satellite. All three steps are described next:

  - **apogee-perigee filter**: this filter allows discarding target-chaser pairs based on the difference between the apogee and the perigee radii of both objects. If the difference is higher than a specified threshold, then the pair is rejected for the whole time interval under consideration (Fig. 5). This is the most efficient classical filter and thus it is used in the first place to reject pairs whose altitude belts do not cross each other.

  - **smart sieve techniques**: in sieve methods, the time interval under analysis is sampled at given time steps. The state vectors of all satellites and objects are computed at each time step. Then, if the distance between a target-chaser pair is higher than given thresholds, the pair is rejected in the current time step (Fig. 6). Those thresholds are defined based on two simple astrodynamics concepts: a) the speed of an object orbiting the Earth can never exceed the escape velocity; b) its maximum possible acceleration is the standard free fall acceleration at sea level.

  - **fine conjunction detection**: those pairs which pass all previous filters and sieves for a given time step go through a conjunction detection process. A numerical root finder algorithm is used to accurately estimate the time of closest approach and the corresponding miss distance which are used later on to evaluate the collision risk probability.

5. COLLISION RISK PREDICTION

Once all close conjunctions have been detected and the corresponding times of closest approach and miss distances computed, it is possible to estimate the collision probability associated to the conjunction events. Several collision risk algorithms are proposed in the literature, but, after several analyses performed in the frame of the **CRASS** development, it became clear the most appropriate is the one from Alfriend and Akella presented in [8]. This algorithm requires computing the covariance of both the satellite and the object at the time of closest approach. The combined position covariance is then projected onto the B-plane, a plane perpendicular to the relative approach velocity. The collision probability is computed numerically as an integral of the probability density distribution function.
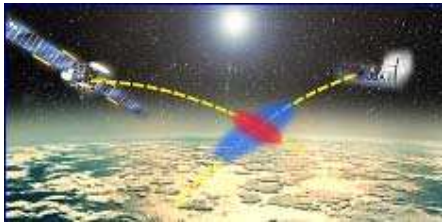

Figure 8: Schematic of satellite and object ellipsoid at time of closest approach

6. COLLISION AVOIDANCE MANOEUVRE

The last step of the collision risk mitigation process is computing the required avoidance manoeuvre in case a close conjunction with an unacceptably high collision risk is found. In this step, both the conjunction geometry and the combined uncertainty in position are taken into account to compute an optimal collision avoidance manoeuvre.

For a specified manoeuvre time, *closeap* computes the manoeuvre size and direction allowing the satellite to move along the steepest descent in the collision probability 3D field and targeting an acceptable final risk. A schematic of the concept is depicted in Fig. 9. The exact algorithm was first presented by Patera et al. in [6].
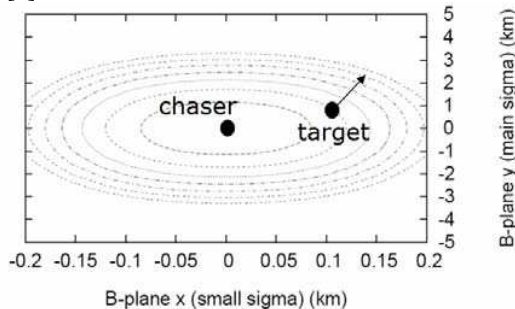

Figure 9: Schematic of steepest descent in collision probability 3D field projected onto the B-plane

7. RESULTS FOR REAL SCENARIOS

This section is intended to show the performances of *closeap* in real conjunctions scenarios. ESA´s ERS-2 and ENVISAT satellites are two good choices since real close approaches are described in detail in [1] for those satellites based on results obtained with **CRASS**. Besides, precise orbit determination is possible for those two satellites through the use of laser measurements available at the ILRS ftp server (International Laser Ranging Service). Thus, these events can be analyzed in an operational-like situation with *closeap* for validation purposes.

The following conjunctions have been analyzed:
- ENVISAT vs. COSMOS-1269 (2004/09/02)
- ENVISAT vs. ZENITH-2 (2004/10/22)
- ERS-2 vs. COSMOS-3M (2004/03/06)
- IRIDIUM-33 vs. COSMOS-2251 (2009/02/11)

Tab. 1 shows the miss distance and collision probability obtained for each one of the conjunctions listed above. The agreement with the values presented in [1] is good if one takes into account that: a) the satellite orbit prediction is generated based on an orbit determination from laser measurements while the actual operational orbit, used in [1], was generated by other means; b) the TLE used to compute the object's orbit is the latest one available before the conjunction. In the case of the Iridium-33 and Cosmos-2251 no accurate tracking is publicly available and thus TLE sets have been used for both objects. Even if these inaccurate orbits are used, the miss distance is 700 metres, which is within the uncertainty of the **SGP** theory. Note that the corresponding collision probability is of the same order of magnitude than other conjunction events for ERS'2 and ENVISAT.

Conjunction event	Miss distance (km)	Collision probability
ENVISAT vs. COSMOS 1269	1.38	1.66e-05
ENVISAT vs. ZENITH-2	0.26	1.66e-04
ENVISAT* vs. ZENITH-2	0.38	3.48e-05
ERS-2 vs. COSMOS-3M	0.14	1.07e-04
IRIDIUM-33 vs. COSMOS-2251	0.70	1.64e-05

(* with true collision avoidance manoeuvre)
Table 1: Miss distance and collision probability computed by closeap in real conjunction scenarios

Fig. 10, 11, 12, 13 and 14 show images obtained with *visualfocus* for the different conjunctions analyzed. Flexibility of analysis and interpretation of the conjunction scenarios is gained by using such visualization capabilities.

8. CONCLUSIONS

closeap, GMV´s solution for collision risk assessment and mitigation was presented focusing on its design, its inheritance and algorithms and its performances in real conjunction scenarios. The reuse of validated software libraries and the implementation of algorithms from current operational system was highlighted and the main benefits from the combined used were summarized. Finally, results for real events agree well with published information.

9. ACKNOWLEDGEMENTS

10. REFERENCES

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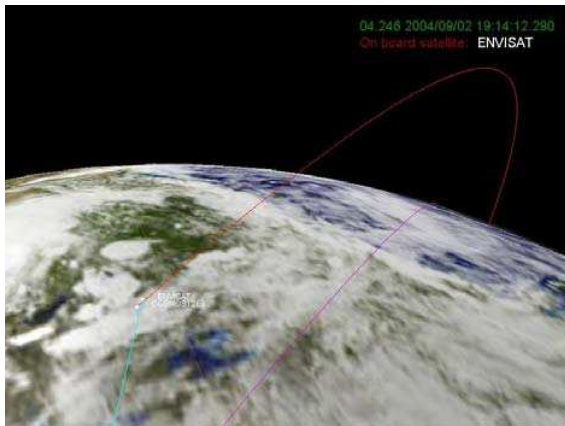
Figure 10: 3D plot extracted from visualfocus *for the ENVISAT vs. COSMOS-1269 conjunction event*
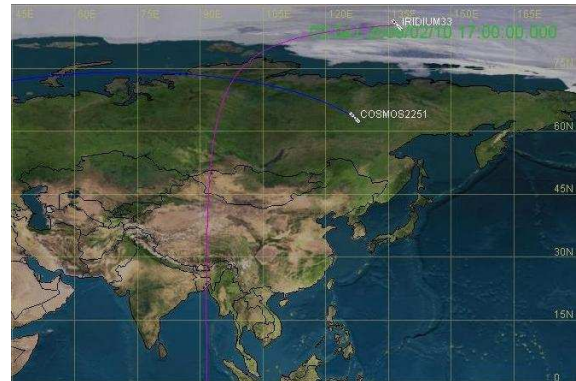

Figure 13: Groundtracks extracted from visualfocus *for the IRIDIUM-33 vs. COSMOS-2251 conjunction event*

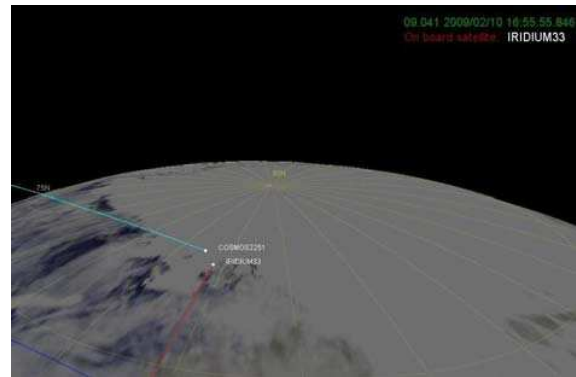*Figure 11: Groundtracks extracted from* visualfocus *for the ENVISAT vs. ZENITH-2 conjunction event*

Figure 14: 3D plot extracted from visualfocus *for the IRIDIUM-33 vs. COSMOS-2251 conjunction event*
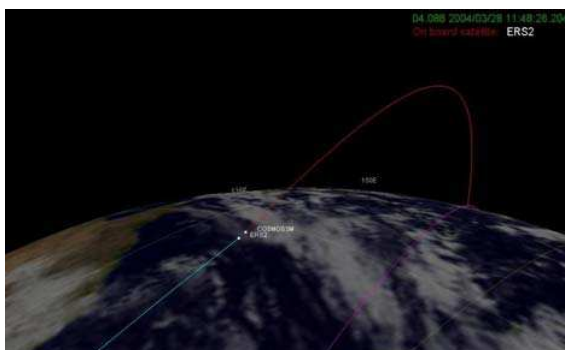

Figure 12: 3D plot extracted from visualfocus *for the ERS-2 vs. COSMOS-3M conjunction event*