TOOLS AND TECHNIQUES SUPPORTING THE OPERATIONAL COLLISION AVOIDANCE PROCESS AT ESOC

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ABSTRACT

ESA's Space Debris Office provides a service to support operational collision avoidance activities. This support currently covers ESA's missions Cryosat-2, Sentinel-1A, Sentinel-2A, Sentinel-3A, and the constellation of Swarm-A/B/C in low-Earth orbit (LEO). The support process is provided to third party customers, too.

We provide an overview on tools used in the mission design phase and during the operational phase. In addition, we briefly introduce the process control and data handling in the ESA process.

During the mission design phase collision avoidance is studied. Here the focus is at the effect of warning thresholds on the risk reduction and manoeuvre rates. For such analysis ESA's DRAMA tool suite with the module ARES is available.

During operations collision avoidance needs to address conjunction event detection, collision risk assessment, orbit determination, orbit and covariance propagation. ESA's process based on the central tools Collision Risk Assessment Software (CRASS) and Collision Risk Assessment and Avoidance Manoeuvres computation (CORAM) are implemented following a database-centric approach through a temporary local "mini-catalogue". This catalogue is based on Conjunction Data messages (CDM) and own operational orbits. Each forecasted conjunction event is analysed in an automated way, returning the approach details and an estimate of the associated collision probability. A wide range of contemporary collision risk estimation algorithms with covariance scaling is supported. Identified high-risk conjunction events are further assessed and mission-specific processes are in place for decision-taking and manoeuvre recommendation. CORAM is able to assess optimised manoeuvres considering various constraints.

The database is also used as the backbone for a web-based tool (SCARF), which consists of a visualisation component and a collaboration tool that facilitates both, the status monitoring and task allocation within the support team, as well as the communication with the control team. The web-based solution optimally meets the needs for a concise and easy-to-use way to obtain a situation picture in very short time, and the support of third party missions not operated from ESOC.

Index Terms— Collision Avoidance, Spacecraft Operations, Mission planning, Manoeuvre planning, Web-based tools

1. INTRODUCTION

ESA's Space Debris Office provides operational and contingency support as a service to ESA and third party missions during all mission phases. The collision avoidance and re-entry predictions and analyses are supported by acquiring and processing dedicated measurements from different sensors (e.g. ESA's OGS telescope, TIRA by Fraunhofer FHR, Zimmerwald telescopes of the University of Bern, Switzerland). Today, the collision avoidance support covers Cryosat-2, Sentinel-1A, Sentinel-2A, Sentinel-3A, and the constellation of Swarm-A/B/C in low-Earth orbit (LEO), as well as the Blackbridge-operated RapidEye constellation as a third party customer ([2], [3]). Table 1 gives a current overview on the covered missions.

Table 1: Supported ESA and third-party missions and services provided, updated to March 2016 from [1].

Satellite	Comment
ERS-2	Manoeuvre/TLE screening, CDM processing, including de-orbiting phase in 2011
Envisat	Manoeuvre/TLE screening, CDM processing, up to failure in 2012
Cryosat-2	Manoeuvre/MiniCat screening, CDM processing, since launch
Swarm-A, B, C	Manoeuvre/MiniCat screening, CDM processing, since launch
Sentinel-1A	Manoeuvre/MiniCat screening, CDM processing, since launch

Sentinel-2A	Manoeuvre/MiniCat screening, CDM processing, since launch
Sentinel-3A	Manoeuvre/MiniCat screening, CDM processing, since launch
Proba 1	Only review of JSpOC alerts
Proba 2	Only review of JSpOC alerts, support of thruster testing
Proba V	Only review of JSpOC alerts
RapidEye 1-5	Manoeuvre/MiniCat screening, CDM processing, since 2012
Cluster-II 1-4	Manoeuvre/TLE screening, during GEO passages
XMM	Manoeuvre/TLE screening, during GEO passages and LEO passages
Galileo/Giove, MetOp-A/B, MSG-3/4	JSpOC alerts received for a limited period of time
Artemis	CSM/JSpOC alert received until operations handed over, Now only case-by-case support

2. TOOLS IN THE COLLISION AVOIDANCE

ESA's Space Debris Office is responsible for the development and the maintenance of an infrastructure in support of ESA's commitment on space debris mitigation and risk reduction. We therefore also address debris environment and risk analysis tools relevant for the collision avoidance support in this section.

Distinguishing the tools available for the mission design phase from the tools for the operational phase is obviously necessary. In particular interesting is the module of ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) tool suite for the Assessment of Risk Event Statistics (ARES). DRAMA/ARES uses ESA's Meteoroid And Space debris Terrestrial Environment Reference (MASTER) model for the prediction of the space debris flux, spatial density, and evolution. After discussing DRAMA/ARES we describe the tools and techniques in use during mission operations.

It is important to recall that surveillance data from non-European (mainly US) sources are essential input for many tools and techniques in the collision avoidance process. Before 2010 ESA only had access to low accuracy TLE data, which comes without information on accuracy. With the availability of better data for conjunction events from the US provided through JSpOC after 2010 this situation improved considerably. This more accurate data comes with accuracy information. A data sharing agreement between USSTRATCOM and ESA was signed on October 30th, 2014.

2.1. Mission design phase

Today, space debris issues, such as collision avoidance and compliance with space debris mitigation rules, are addressed early in the mission design phase. Operational collision avoidance in LEO requires a careful planning of the resources available on-board (such as manoeuver capabilities and fuel budget) and in the ground segment (collision avoidance process implementation and needs).

DRAMA/ARES is available worldwide through the Space Debris Office's web portal https://sdup.esoc.esa.int [4] after registration. DRAMA/ARES aims at supporting mission planners in estimating the expected number of annual collision avoidance manoeuvres based on a risk threshold the mission is willing to accept. The annual collision probability can be analysed in more detail as a function of the quality of the orbital information of the secondary (chasing) object. The quality of the catalogue data can be selected to reflect different options for data provision. In general, smaller uncertainties significantly reduce the risk, and thus lead to a lower number of required collision avoidance manoeuvres. For example, Flohrer et al. [1] reported that in a specific case and for a very typical reaction threshold of 10^{-4} a total of 28 manoeuvres per year for a TLE-based approach would have been required, while only 4 manoeuvres would be required using in the assessment today's standard, Conjunction Data Messages (CDM) provided by JSpOC. These CDMs are based on Special Perturbation (SP) data that is far more accurate.

Management decisions on defining a reaction threshold can be supported by DRAMA/ARES through statistics related to the collision risks and estimating how much risk would be acceptable for a given mission design (such as, e.g., to cover 95% of the known and avoidable risk). Correspondingly, this analysis quantifies the risk of a mission loss due to a collision and how much risk reduction can be achieved for a given catalogue source and reaction scenario. Figure 1 gives a typical example for a possible analysis with DRAMA/ARES. The expected manoeuvre frequency for the selected reaction threshold and orbit uncertainties can be estimated as well. That result (for example 1.5 manoeuvres/year for a typical LEO satellite) can then be used for discussion with the project and the payload operators, as usually such a manoeuvre interrupts the data collection. The final set of output from DRAMA/ARES then combines the estimated manoeuvre rate as a function of accepted collision probability level and the corresponding false alarm rates, the estimated ΔV budget and propellant mass to perform collision avoidance manoeuvres, the achievable risk reduction, and an estimate of the residual and remaining collision risk.

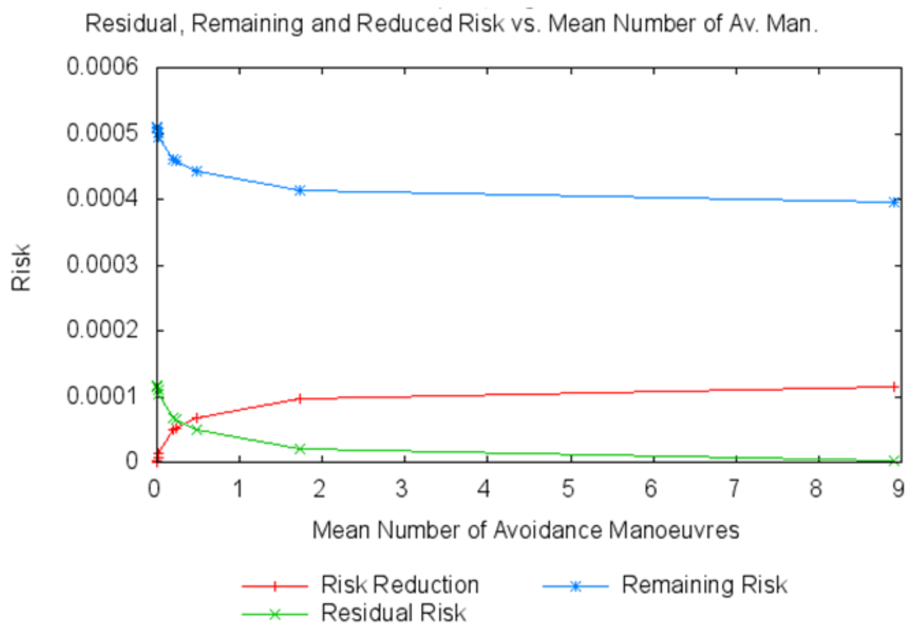

Figure 1 Residual, remaining and risk reduction as a function of the mean number of collision avoidance manoeuvres for a given example mission scenario analysed in DRAMA/ARES

A comparison with actual manoeuvre rates can be used to validate the corresponding DRAMA/ARES predictions. Recent analyses ([1], [5]) show a good agreement between predicted and performed collision avoidance manoeuvres. Changes in the underlying process and decision criteria need, however, to be considered as a limiting factor to the accuracy of such comparisons.

2.2. Operational phase

The current operational collision avoidance has been presented in detail recently [1]. That work also reviewed the process evolution, operational at ESA since 2006.

Significant upgrades have been applied reflecting the evolution and the growing maturity of the process. Drivers for the process upgrades have been the increasing number of covered missions, the increase of close conjunction events due to a general increase of the space debris population due to fragmentation events, and, finally, the need for automation and seamless proactive result provision to the missions. We observe that the effective number of received CDMs has been increasing continuously during the last years, which can be explained by the exploitation of owners and/or operators (O/O) orbit information in the process, and an enlargement of the forecast volume (both, temporal and spatial).

2.*2.1 ESOC process*

The currently followed process (as presented by [1]) is outlined in Figure 2. The process is widely automated now, and can be characterised by a central database. An important tool is the well-established CRASS (Collision Risk Assessment Software), which is used to assess the associated collision probability based on orbit and covariance information for the objects involved in a conjunction. In the ESA process all received CDMs together with the results from the CRASS risk analysis remain available in the database.

CRASS, is being complemented by CORAM (Collision Risk Assessment and Avoidance Manoeuvre) [7] that actually is a combination of CORCOS (COllision Risk COmputation Software) and CAMOS (Collision Avoidance Manoeuvre Optimization Software). CORCOS provides a wide set of algorithms for the evaluation of the collision risk (for the complete list see [1]) and is configured to generate a new CDM with risk figures, which is then again inserted in the database. CAMOS supports the planning of avoidance manoeuvres by optimisation strategies, such as by minimising the risk or the needed Δv, or maximising (radial) separation by varying size, direction and epoch of manoeuvres. Various constraints on the manoeuvre plan (bounds, fixed, free) are possible.

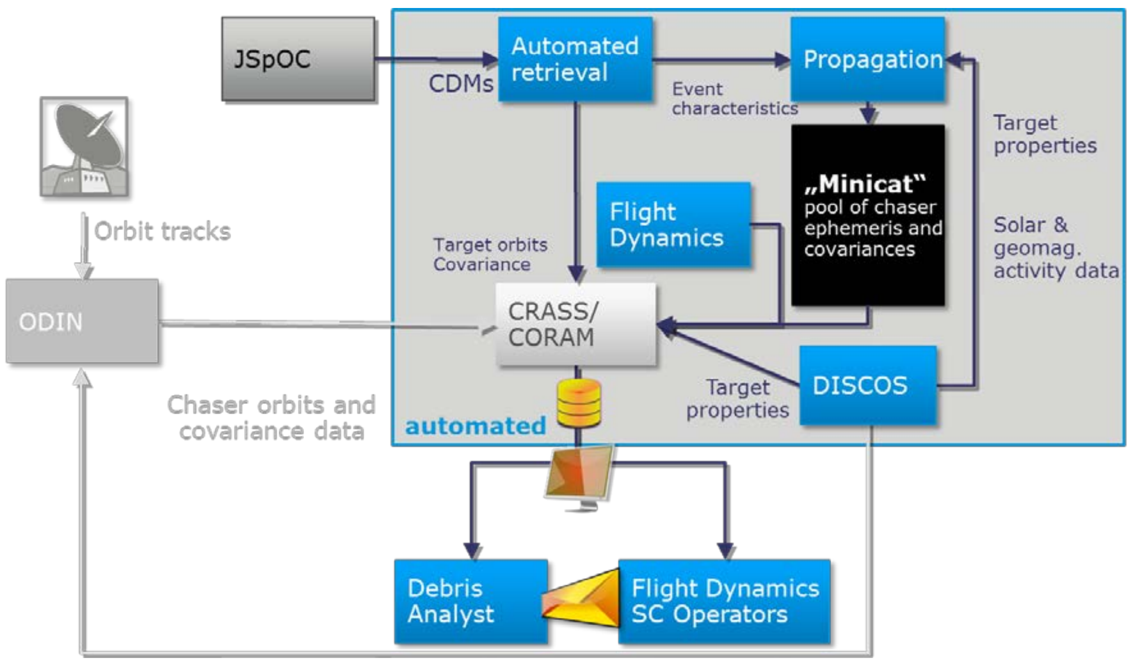

Figure 2. Flowchart of collision avoidance process at ESA/ESOC with CDMs [1]

A major step in the process evolution has been the introduction of a temporary, local, so-called mini-catalogue of objects. That "Minicat" is generated by propagating CDM-derived orbit information and covariance data using object properties from the ESA DISCOS [6]. The "Minicat" enables for timely manoeuvre screening and optimisation based on previously received catalogue data. For small manoeuvres and quick analyses it is no longer required to wait for a feedback on an updated situation picture from the JSpOC. The risk analysis can be performed whenever a new ephemeris becomes available.

It has been achieved that the MiniCat is also updated automatically whenever new operational orbit information or manoeuvre plans for the covered missions are made available from the flight dynamics systems. As a result, and under unique event IDs, external CDM-based risk analysis and internal manoeuvre-screening risk analysis are both automatically stored in the database. All stored data are grouped according to the conjunction event (defined by the target, chaser and their time of closest approach (TCA)). and can be retrieved accordingly, e.g. through a front-end [8].

If an identified close approach exceeds the acceptable collision risk, a recommendation on the need to execute a collision avoidance manoeuvre is discussed with the flight control team and the flight dynamics, and finally given by the Space Debris Office to the mission management. This recommendation is supported by multi-dimensional evaluations by CAMOS. The assessment finally includes in the recommendation the size and direction of the avoidance manoeuvres. Of course and as a common practice the proposed manoeuvre trajectory is re-screened for the introduction of secondary, i.e. new, close conjunction events.

2.2.2 Overarching process control

The increasing number of missions, the need for screening planned orbital control manoeuvres for close approaches, and the need to provide support 24/7 made it necessary to implement a process control and tasks allocation system. A simple but robust, and fully sufficient solution to reflect planned operations has been found with the Redmine tool, usually used for tracing software development activities. Figure 3 gives a screenshot of a possible situation indicating planned parallel manoeuvres for different missions. Each of the Redmine events (or tickets) has a status (planned, preparing, manoeuvring, post-manoeuvre screening, closed) and an assignee to ensure that all events are processed in due time and the related communication to the flight control teams can be traced by other team members.

2.2.3 Standardisation and interoperability aspects

By coordinating ESA's debris research and contribution to ECSS/ISO and UN standards and having key members in the 13-nations Inter-Agency Space Debris Coordination Committee (IADC), the Space Debris Office is very active also in defining and standardising space debris mitigation approaches, and is actively promoting the awareness on space debris issues. The office is also providing staff support to lead the Space Surveillance and Tracking Segment of ESA's SSA Programme. This all makes it possible to contribute with actual operational experience to designing and developing space surveillance assets, to establish the required efficient interfaces and to reflect the interoperability aspects of collision avoidance tools, techniques and processes.

Today, international guidelines for collision avoidance exist only implicitly in the UN Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space with guideline 3: *Limit the probability of accidental collision in orbit*, in the IADC Space Debris Mitigation Guidelines (IADC-02-01, Rev. 1, 01/09/2007) addressing the *Prevention of On-Orbit Collisions* in section 5.4, and are currently discussed also for the review of ISO 24113 "Space systems -- Space debris mitigation requirements".

An important and crucial milestone has been achieved with the introduction of the CDM format by the Consultative Committee for Space Data Systems (CCSDS) as a blue book (recommended standard) in 2013 (CCSDS 508.0-B-1). This format allows data providers, operators and developers of processing and visualisation components to interoperate very efficiently.

2.2.4 Mission-specific aspects

Mission-specific needs to collision avoidance are common. These needs might be, e.g., due to platform-related limitations (such as thruster firing limits in size, impulse, and directions), operational constraints in the ground segment, or the achievable accuracy of the orbit determination. In order to reflect these needs, further assessment and dedicated, mission-specific processes have to be in place for decision-taking and manoeuvre recommendation (for example, see an analysis for the Cryosat-2 mission, also covered by the ESOC collision avoidance service by [8]). Obviously, tools and techniques must be also capable in meeting these needs.

Figure 3. Process control and assignment of tasks in Redmine.

3. FRONT-END DEVELOPMENTS

With the upgrade of the collision avoidance tools and process at ESOC emerging user needs could be addressed, too. These needs reflect the more and more continuous flow of arriving relevant information, the potential distribution of teams needing consistent, traceable, concise, and easily accessible information, a demand for better visualization to support decisions, and also the support of distributing analysis work within a larger and growing team of specialists. A web-based solution optimally meets these needs to obtain a situation picture in very short time. A web-based solution is also a clear benefit if third party missions not operated from ESOC are supported. The move to a central backbone database allowed the development of such a web-based tool with all needed functionalities.

The SCARF (Spacecraft Conjunction Assessment and Risk Frontend) tool that became operational mid 2014 [9] provides as key features a visualization of the CDM processing over time, trending analysis of fly-by distances and risk evolution, the possibility to flag events to make them visible to specified user groups, to assign events for action, and to record all state transitions during this escalation process, various filtering and sorting options, and, finally, an email notification capability that supports analysts in providing information from templates including the condensed event information.

For each mission the most relevant information is presented by SCARF in the dashboard - for a quick look on the most relevant key parameters. A dedicated analyst view gives access to all CDMs according to highly flexible filtering criteria line by line to allow efficient browsing. The highest number of details can be accessed through the event viewer that gives all available information for a certain event, the event timeline, and gives access to send out emails and orbit files.

The capability to create emails with a consistent and repeating content has been found to be very interesting for operators in order to reflect the email notification in operational procedures. SCARF also is capable to link to an interactive approach 3D geometry visualization tool that again is fully web-based.

4. CONCLUSION

We introduced the collision avoidance process at ESOC covering ESA and third party missions. The ESA tools developed and maintained by ESA's Space Debris Office at ESOC supporting the collision avoidance process can be grouped by mission phases. The tool for the mission design phase DRAMA/ARES allows estimating the manoeuvre frequency and related fuel budgets as function of the acceptable risk level and, vice versa, supporting the selection of risk thresholds. DRAMA uses ESA's MASTER model and is able to support different scenarios for available chaser information. Tools for the operational phase are grouped around a central database containing all received and analysed CDMs, and include CRASS/CORAM for risk estimation and manoeuvre optimisation, DISCOS for physical characteristics and owner/operator data on objects, a local MiniCat generated from propagated CDMs, and a customised Redmine for tracing the processing of orbit maintenance manoeuvre events for collision avoidance. The web-based SCARF has been introduced as an efficient, multi-purpose solution for analysts and mission control teams to manage conjunction events, ensure efficient and consistent information distribution, and provides a 3D visualisation option.

Collision avoidance is and will be subject to frequent upgrades to reflect the availability of new data sources, evolving processing techniques, and new collaboration scenarios. Interoperability of tools and approaches is hence important and can be facilitated through standardising formats, and through making available dedicated tools with documented algorithms that meet international and national space debris mitigation regulations.

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