Current Collision Avoidance service by ESA's Space Debris Office

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ABSTRACT

Since about 15 years, ESA's Space Debris Office provides a service to support operational collision avoidance activities. This support currently covers the ESA missions Cryosat-2, Sentinel-1A/B, Sentinel-2A/B, Sentinel-3A and the constellation of Swarm-A/B/C in low-Earth orbit and Cluster-II in highly eccentric orbit approaching the GEO region. The support process is open to all interested parties and today has been provided to third party customers for 6 years.

In this paper we are describing the current approach focusing on an outline of the used tools for conjunction event detection, collision risk assessment, orbit determination, and orbit and covariance propagation, process control and data handling.

Finally, we highlight our operational experience in providing statistics on the identified conjunction events, taking into account the known significant changes in the LEO orbital environment.

1 INTRODUCTION

In view of the severe fragmentation events during the last decade, such as the destruction of Fengyun-1C in 2007, the Iridium-33/Cosmos-2251 collision in 2009, and the Briz-M explosions of 2012, which resulted in a significant amount of additional objects to the debris population, the need to consider collision avoidance as part of routine operations is evident to all mission operators and should also be seen as a good practice in view of space debris mitigation.

Operational conjunction analyses and collision avoidance activities at ESA started for the ERS-2 and Envisat spacecraft and nowadays concentrate on ESA’s Earth Explorer missions and the Copernicus’ Sentinel spacecraft in LEO as well as on third party customers, which includes the five satellite constellation RapidEye, operated by Planet – see Figure 1 for the current missions in LEO under full support and Table 1 for a more complete list of missions covered in the past.

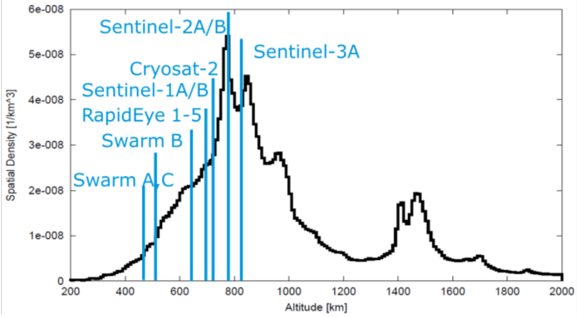

Figure 1. Missions in LEO currently covered by full collision avoidance support – operational altitudes and spatial density of objects > 10 cm (MASTER-2009)

1.1 Space Debris Office

ESA’s Space Debris Office is in charge of and coordinates all operational and R&D activities on space debris mitigation within ESA.

The activities include model developments, internal studies and operational services including collision avoidance and re-entry risk assessments, as well as technical support to debris-related safety analyses and for the development of standards.

To support these activities the Space Debris Office develops and maintains an infrastructure of debris environment and risk analysis tools, such as the Meteoroid and Space Debris Terrestrial Environment reference model (MASTER) and the DRAMA tools suite and the Database Information System Characterizing Objects in Space (DISCOS) database which provides information on on-orbit objects.

In addition the Space Debris Office provides support to the Space Surveillance and Tracking segment of ESA’s SSA Programme and to the coordination of ESA studies on space debris remediation concepts.

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Table 1. Missions covered by collision avoidance support during the last 15 years(MC indicates screening using mini-catalogue)

Satellite	Comment
ERS-2	Manoeuvre/TLE screening, CDM processing including de-orbiting phase in 2011
Envisat	Manoeuvre/TLE screening, CDM processing until failure in 2012
Cryosat-2	**Manoeuvre/MC screening, CDM processing since launch**
Swarm-A, B, C	**Manoeuvre/MC screening, CDM processing since launch**
Sentinel-1A/B, -2A/B, -3A	**Manoeuvre/MC screening, CDM processing since launch**
Proba 1, V	Only review of JSpOC alerts, automated CDM processing
Proba 2	**MC screening, CDM processing, support of thruster experiments**
RapidEye 1-5	**Manoeuvre/MC screening, CDM processing, since 2012**
Cluster-II 1-4	**Manoeuvre/TLE/MC 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 (LEOP)
Artemis	CSM/JSpOC alert received until operations handed over, now case-by-case support

1.2 Collision Avoidance at ESA

For many years close conjunctions were identified by ESA's internal screening of mission orbits versus the public catalogue provided by USSTRATCOM. In the aftermath of the Iridium-33/Cosmos-2251 collision event, USSTRATCOM has started to provide dedicated data messages based on high precision SP data. ESA's collision avoidance process has evolved significantly since then, exploiting all the features that these messages offer to provide an extended service to missions.

Today, conjunction data messages (CDMs) provided by the US 18th Space Control Squadron are retrieved and analysed in an automated way, returning the approach details and an estimate of the associated collision probability.

Conjunction events showing high risks are further assessed and mission-specific processes are in place for decision-taking and manoeuvre recommendation. We are able to propose optimised manoeuvres considering various constraints.

This operational process and the tools supporting it are described in more detail in sections 2 and 3 of this paper. Section 4 highlights our operational experience in providing statistics on the identified conjunction events, taking into account the known significant changes in the LEO orbital environment.

1.3 Risk Thresholds and Manoeuvre Criteria

Since key data are known only with limited precision it can't be known for sure whether a collision will occur or not: the trajectories of both objects around the time of closest approach have uncertainties due to their limited knowledge in the recent past (orbit determination uncertainty) as well as uncertainties in the propagation to the time of closest approach (model uncertainties, e.g. air drag, manoeuvre performance).

Therefore, key ingredients to any collision avoidance strategy are criteria on when to execute an avoidance manoeuvre. Prime criterion is the collision risk since it encodes the key data of the close approach event (nominal separations, approach direction and trajectory uncertainties), but of course operational constraints also have to be taken into account, mainly the time needed to prepare and execute a potential avoidance manoeuvre driving the time a decision has to be taken on the avoidance manoeuvre parameters and whether to execute it or not (often this final go/nogo manoeuvre decision can be taken later).

The question remains what a good reaction threshold actually is. In order to analyse this, it is convenient to use ESA's ARES [1],[2] tool (within the DRAMA tool suite). It allows the estimation of overall collision risk as well as the annual frequency of close approaches with risks above levels selected by the user as a function of spacecraft size as well as the quality (SP- or TLE-based or user defined) and age (time to event) of the secondary (catalogue) orbit information. It is thus possible to trade-off ignored risk vs. avoided risk via selecting the risk threshold at the cost of a number of manoeuvres obtained as frequency of events having higher risk than the selected threshold.

Using this approach it turned out that for the missions in LEO a risk threshold of 10^{-4} one day to the event leads to a risk reduction of around 90%, i.e. an accepted or ignored risk which is an order of magnitude smaller than the " natural" risk, i.e. compared to not implementing a collision avoidance strategy. This can be achieved at the expense of 1 to 3 manoeuvres per year. It is noted that for these analyses and the corresponding operational implementation the geometry of the operational spacecraft has to be treated the same way to obtain the expected risk reduction. In ESA it is common practise to treat the spacecraft as an encompassing sphere centred at the actual spacecraft's centre of mass – in case smaller spheres are used (e.g. resulting in a frontal area closer to an actual average of the spacecraft area) smaller risk thresholds are needed to achieve the same fractional risk reduction, however typically at the expense of the same manoeuvre rate.

2 CURRENT OPERATIONAL COLLISION AVOIDANCE PROCESS AND TOOLS

In this section we describe ESA's current collision avoidance process and underlying tools – the evolution of the process is covered more extensively by earlier work (e.g. [3]).

Today, the collision avoidance process is based on operational orbit and manoeuvre information for the ESA and third party spacecraft (targets) and conjunction data messages (CDMs) provided by the US 18th Space Control Squadron resp. Joint Space Operations Center (JSpOC). The CDMs cover details on conjunctions between objects contained in the US catalogue (chasers) and the target trajectories, in particular time of closest approach (TCA), separations, state vectors and covariances at TCA as well as auxiliary information on the orbit determination quality. Due to a data sharing agreement between the US Strategic Command (USSTRATCOM) and ESA, signed on October 30th, 2014, the SDO has access to CDMs covering larger volumes around the target trajectories and longer lead times.

In view of the large number of CDMs and the associated risk analyses, a database-centric approach has been developed: All CDMs and risk analysis results are stored in a database. The database is also used as the backbone for a web-based tool, which consists of a visualisation component and a collaboration tool that facilitates the status monitoring and task allocation within the support team as well as the communication with the control team. The visualisation component further supports the information sharing by displaying target and chaser motion over time along with the involved uncertainties. 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 for third party missions not operated from ESOC.

The processing chain is summarised in Figure 2 and discussed in the following.

CDMs are downloaded automatically and the associated risks computed using the CORAM software and object geometry taken from DISCOS. The resulting data set is stored in the central database.

Propagating the chaser state vectors contained in the CDMs with DISCOS information on the physical object properties a temporary local "mini-catalogue" of objects close to our target spacecraft is obtained. The generation of this mini-catalogue is triggered automatically after every CDM retrieval.

It is used for computing risks based on the operational target trajectories which is automatically triggered by the availability either of the updated mini-catalogue (due to new CDMs) and whenever new ephemeris becomes available from the flight dynamics team, be it due to updated orbit determination or due to incorporation of planned manoeuvres. Also the resulting data sets on the close events obtained via this processing chain are stored in the central database.

This in particular allows screening of manoeuvre trajectories for close approaches without an extra screening request to JSpOC as long as manoeuvres are small enough such that the difference to the no-manoeuvre trajectory is smaller than the screening volume (JSpOC is kept informed of manoeuvres in any case though).

This part of the processing chain is fully automated (grey shaded area in Figure 2), but the analyst can also manually trigger extra analyses, e.g. running (avoidance) manoeuvre ephemeris against the mini-catalogue and inserting the resulting data sets into the database.

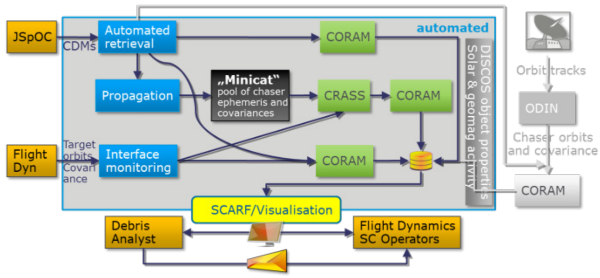

Figure 2. Extended operational collision avoidance process at ESA/ESOC with CDMs – current status

As mentioned above conjunction events showing high risks are further assessed and mission-specific processes are in place for decision-taking and manoeuvre recommendation. This is supported by a manoeuvre optimisation component of the CORAM software which also runs as part of the automatic sequence for conjunctions showing high risk in a default configuration suitable for typical manoeuvre scenarios, but can be configured and run by the analyst according to specific needs. For details see section 2.2.

In parallel to and in support of these processes, ESA maintains the capability to acquire external tracking data and to improve the knowledge on the orbit and on the associated uncertainty covariance of the chaser object using the ODIN (Orbit Determination by Improved Normal Equations) software.

2.1 Database

As seen above the current approach is database-centric, individual CDMs and risk analysis results are stored in the database after processing. The data stored are essentially the CDM data augmented by the risk figures. This is not only the case for the JSpOC CDMs but also the results of mini-catalogue processing, i.e. in this case the results are also fed into the database using the same representation, with the only difference being the originator. The CDMs in the database are always grouped according to the conjunction event, which is defined by the target, chaser and their time of closest approach (TCA). An unique event ID is created when a close approach notification is received for the first time and subsequent messages are linked to that event by the ID.

This central database facilitates SDO internal process monitoring and task coordination but also streamlining interfaces to mission control teams and therefore contributes to the overall reduction of process risk. In particular the following tools and processes build upon the database:

- An automated warning system, which alarms the on-call analyst via a text message sent to the on-call phone.
- A web-based graphical user interface – the Spacecraft Conjunction Assessment and Risk Frontend (SCARF) – which gives the analyst but also the flight control teams access to the analysis results. This is covered in more detail in section 3.1.

2.2 Algorithms

Currently, the core software to process incoming CDMs and to obtain risk estimates is called CORAM (Collision Risk Assessment and Avoidance Manoeuvre) [4]. For a given pair of target and chaser (either from CDM or mini-catalogue and operator ephemeris or a mix of CDM for chaser and ephemeris for target), close conjunctions are analysed by CORAM. It offers two tools based on a common software core: CORCOS (COllision Risk COmputation Software) is dedicated to the computation of collision risk between two objects and CAMOS (Collision Avoidance Manoeuvre Optimization Software) which is devoted to the evaluation of different mitigation strategies through the optimization of avoidance manoeuvre parameters.

CORCOS provides a collection of algorithms for the evaluation of the collision risk, such as

- Alfriend-Akella [5], a well-known method to compute collision risk that performs the two-dimensional integration of the hard body projection in the encounter plane.

- Patera's method [6], performing the contour integration of the projection.

- Covariance scaling [7], evaluating the probability via a process in which the covariance is scaled for each of the two objects in a given interval.

- Maximum probability according to Klinkrad's algorithm scaling the covariance [8]

- Maximum probability assuming spherical scaled covariance [9]

- Patera's slicing method [10] for low-velocity encounters

- Non-spherical object shapes via projection of the Minkowski sum to the B-plane and z-buffering [7][11]

- Monte Carlo simulation analysis [7].

In the automatic processing chain after every reception of CDMs CORCOS runs evaluating the CDM directly via an Alfriend-Akella and Klinkrad algorithm, followed by insertion into the database. In a second run the same algorithms are evaluated on a mixed input, i.e. using chaser information from the CDMs and operator ephemeris for the target, again results are stored in the database. In case the automatic run was triggered not by CDM reception but by new operator ephemeris this is the first processing step.

Next, the operational ephemeris is screened against the mini-catalogue for conjunctions using the "traditional" CRASS (Collision Risk ASsessment Software, originally developed and used to screen operational ephemeris against the TLE catalog) which identifies conjunctions, for which no CDM may be present in the database (e.g. due to size of the JSpOC screening volume combined with the difference between JSpC and operational target ephemeris). In case new conjunctions are found they are processed with CORCOS using the same two algorithms and the mini-catalogue and operational ephemeris for chaser and target as input.

In manual analyses for high risk events covariance scaling is frequently used, whereas the other algorithms are currently rarely used in an operational context – in particular low-velocity encounters necessitating Patera's or Monte Carlo algorithms are extremely rare.

CAMOS supports the planning of avoidance manoeuvres. It allows optimising various objective functions such as minimising risk or delta-v, or maximising (total or radial) separation varying size, direction and epoch of manoeuvres. Constraints (bounds, fixed, free) can be introduced on the manoeuvre parameters, the separations at TCA, and the probability of collision [7].

CAMOS can be run in parametric and evaluation mode. In parametric mode, CAMOS can assess one or several strategy analyses, which means a one- or two-dimensional parametric execution of a manoeuvre optimisation problem. This mode allows the user to evaluate, e.g., the effect of the manoeuvre execution time on the collision risk, with optimised manoeuvre direction for each selected value of the manoeuvre execution time in the grid. In evaluation mode the optimisation runs just one case within one strategy. This mode can produce optional information on the evolution in time of certain trajectory functions, like longitude, latitude, eclipse, or location over the South Atlantic region.

3 ANALYST FRONTENDS

In this chapter we present the frontends which are at the disposal of the analyst and which facilitate the process monitoring and control as well as communication with mission operations teams.

3.1 Spacecraft Conjunction Assessment and Risk Frontend (SCARF)

SCARF (Spacecraft Conjunction Assessment and Risk Frontend) is a web-based visualisation and collaboration tool which has been created with the main intention of being able to obtain a situation picture for any conjunction event in a concise and easy-to-use format in very short time. This also facilitates the status monitoring and task allocation within the support team and the communication with the mission control teams. In addition, task automation was also one of the main goals, for example to generate email notifications to the mission control teams from pre-defined templates including the event information.

Some of the key features of SCARF are:

- Accesses database of CDM processing results
- Fully web-based.
- Graphical presentation of CDMs.
- Graphical trending analysis.
- Risk Highlighting.
- CDM Filtering/Sorting.
- Assigning and recording of event escalation steps.
- Condensed views for analysts.
- Email generation from templates.
- Report generation from templates.
- Direct link to 3D interactive approach geometry visualization.

SCARF was developed by CGI (Consultant to Government and Industry) and will be further expanded in the future.

Information is presented in several views. Besides the main dashboard, event and analyst view, which are presented in more detail below, there are views for documentation, user settings and overall tool administration.

SDO analysts have access to all views, whereas mission control teams have access (but can't trigger any action) to the dashboard and event view (and their user settings).

3.1.1 Dashboard View

The most relevant information for each mission is presented in the dashboard, as shown in Figure 3: It allows for a quick look on several key parameters for the event assessment. The highest probability, smallest miss distance and smallest radial miss distance are shown in the first line, which are extracted from the CDMs received for that mission. In addition, there are several "top 10" lists for these criteria on the right, showing the most critical events and highlighting those, that are associated with a collision probability higher than 10^{-5} and are thus potential candidates for a later escalation. An event is considered as escalated as soon as the mission control teams have been informed, which, for most missions, happens if a threshold of 10^{-4} is exceeded 3 days before the event. Those events are also shown in the top right corner coloured in red.

Some supporting charts are also shown in the dashboard: the evolution of maximum collision probability, the cumulative risk, the number of events (total and above the risk threshold), as well as scatter plots showing collision probability and miss distance of upcoming events over time.

3.1.2 Event View

More detailed event-specific information is provided in the event view. It can be reached via clicking events from the dashboard view or by entering a valid event ID. The view also allows the SDO analyst triggering emails via templates, inserting comments and even requesting screening for the ESA missions based on available ephemerides. The latter can then be directly forwarded to JSpOC for a dedicated ephemeris screening. In Figure 4 a numerical listing of the detailed conjunction data is shown for an exemplary event.

All event actions are logged and presented to the analyst, including CDM insertions, owner/status changes (for example after an event escalation), email notifications and comments.

Individual CDMs can be selected in the event view and their content is displayed in an easy-to-read format. The timeline is fully automated and is updated as soon as there are changes in the database to the displayed event.

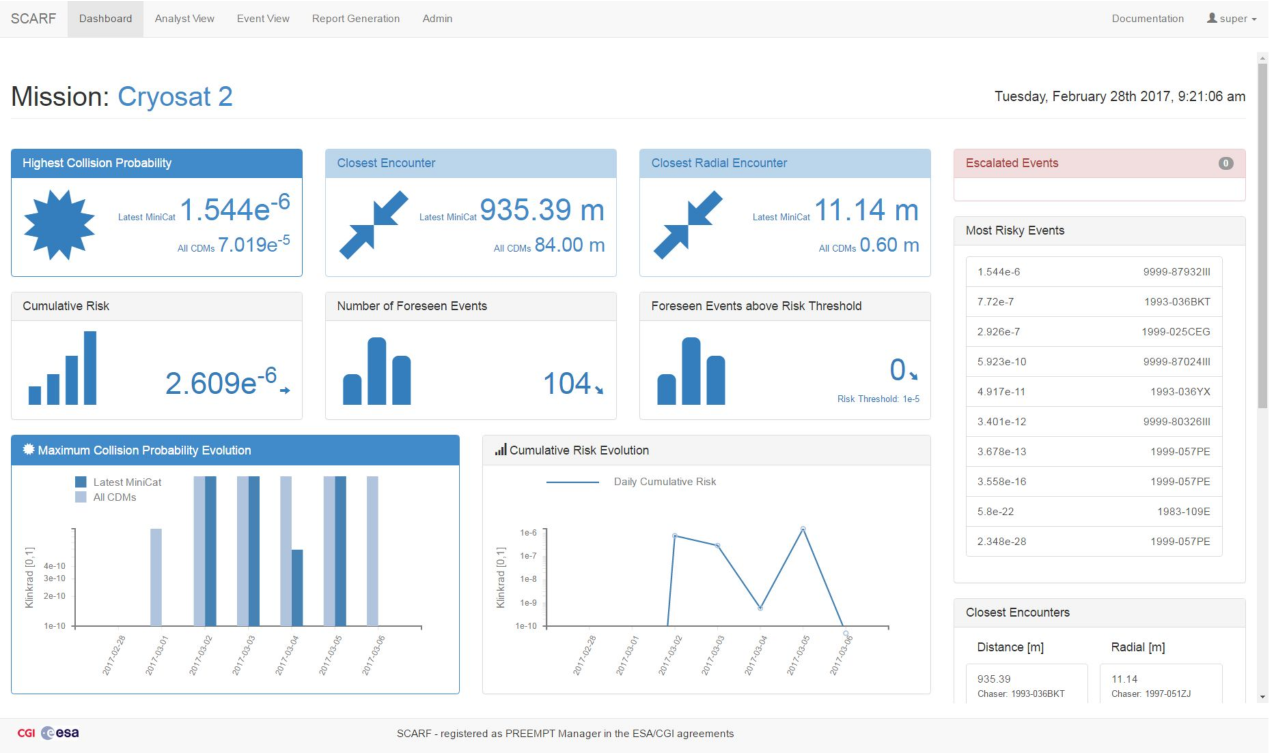

Figure 3. Screenshot showing the dashboard of the SDO's collision avoidance management tool SCARF.

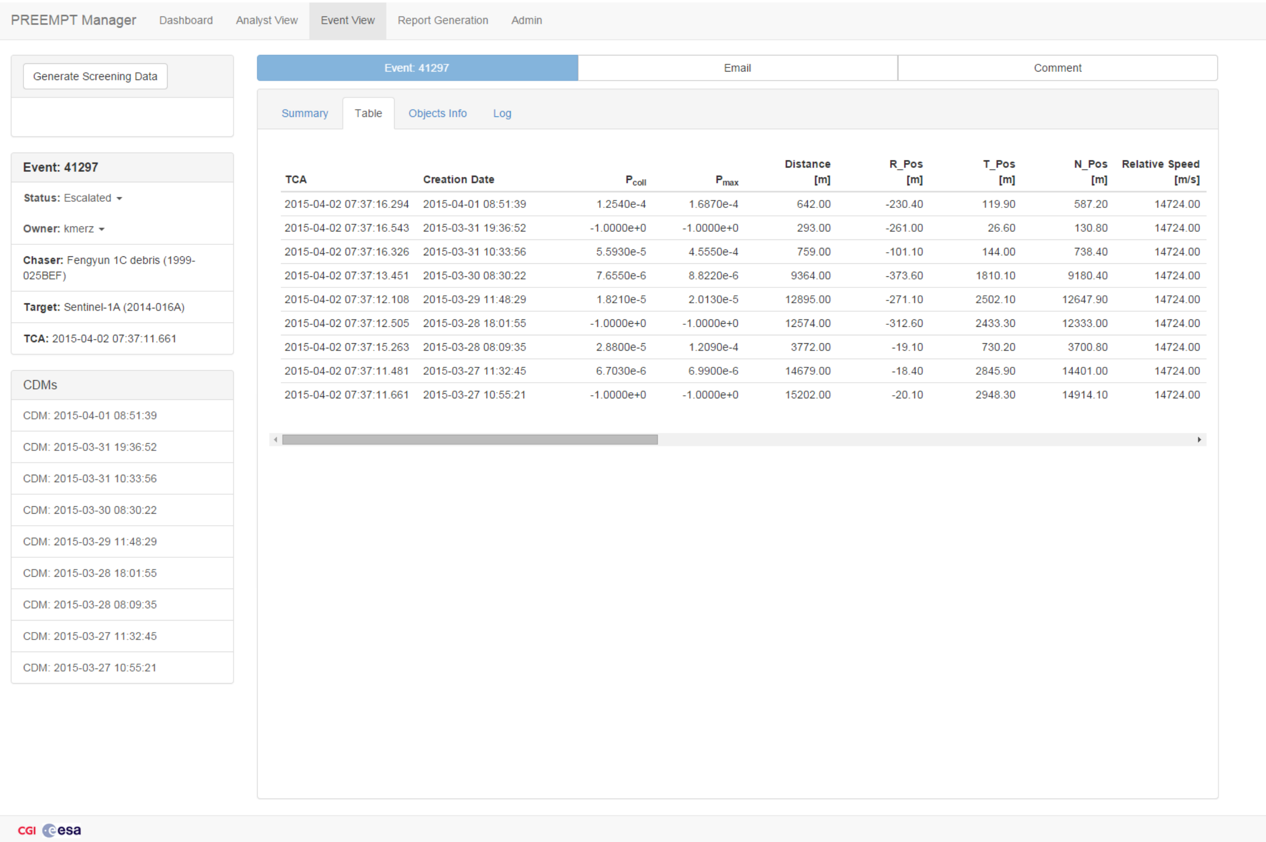

Figure 4. Screenshot showing the event view of the SDO's collision avoidance management tool SCARF.

3.1.3 Analyst View

The analyst view provides a presentation of CDM information, where information belonging to one CDM is presented in on line of data on the screen. The type of data to be shown is defined by the user's settings.

The CDMs whose data are shown are selected via dedicated user-configurable filters for the event ID, the target, the chaser, the TCA, a certain time span, the owner, the assignee, the collision risk, the total miss distance (also for the individual components), the position and velocity uncertainties, the originator, the approach azimuth/elevation, etc.

It is possible to easily sort the data by any column and optionally group CDMs by event ID.

3.1.4 Future Developments

Further developments are planned for the future, among them

- A reporting facility, providing statistics on high risk events during a configurable timeframe.
- A multi-mission dashboard view, providing high-level information for a set of spacecraft.
- Enhanced data provision, such as plots with CAMOS results.
- Expanded options to trigger activities from SCARF, such as configuring and launching CORAM runs.

3.2 Visualization

Another frontend serves the 3D dynamic visualization of close approaches, as shown in Figure 5: The analyst is able to see the target and chaser trajectories with the Earth in the background. Covariance ellipsoids and CDM data are shown. An interactive control of camera position, view angle, time and zoom provides a lot of flexibility for the visualization of conjunction details and object positions (boxes) at the time of closest approach. The visualisation is dynamic, i.e. target and chaser together with their covariance ellipsoids are moving along their trajectory with time, where time can either run smoothly or is controlled by the user.

The visualisation frontend is reachable from SCARF via the event view.

3.3 Manoeuvre Process Monitoring and Control

The need for screening planned orbital control manoeuvres for close approaches and the increasing number of missions require a systematic 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 [12], more commonly used for tracing software development activities.

Each manoeuvre is treated as a Redmine event (or ticket) and 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.

As views list, calendar and Gantt Views are used for which events can be filtered by status. Figure 6 gives a screenshot of a possible situation indicating planned parallel manoeuvres for different missions.

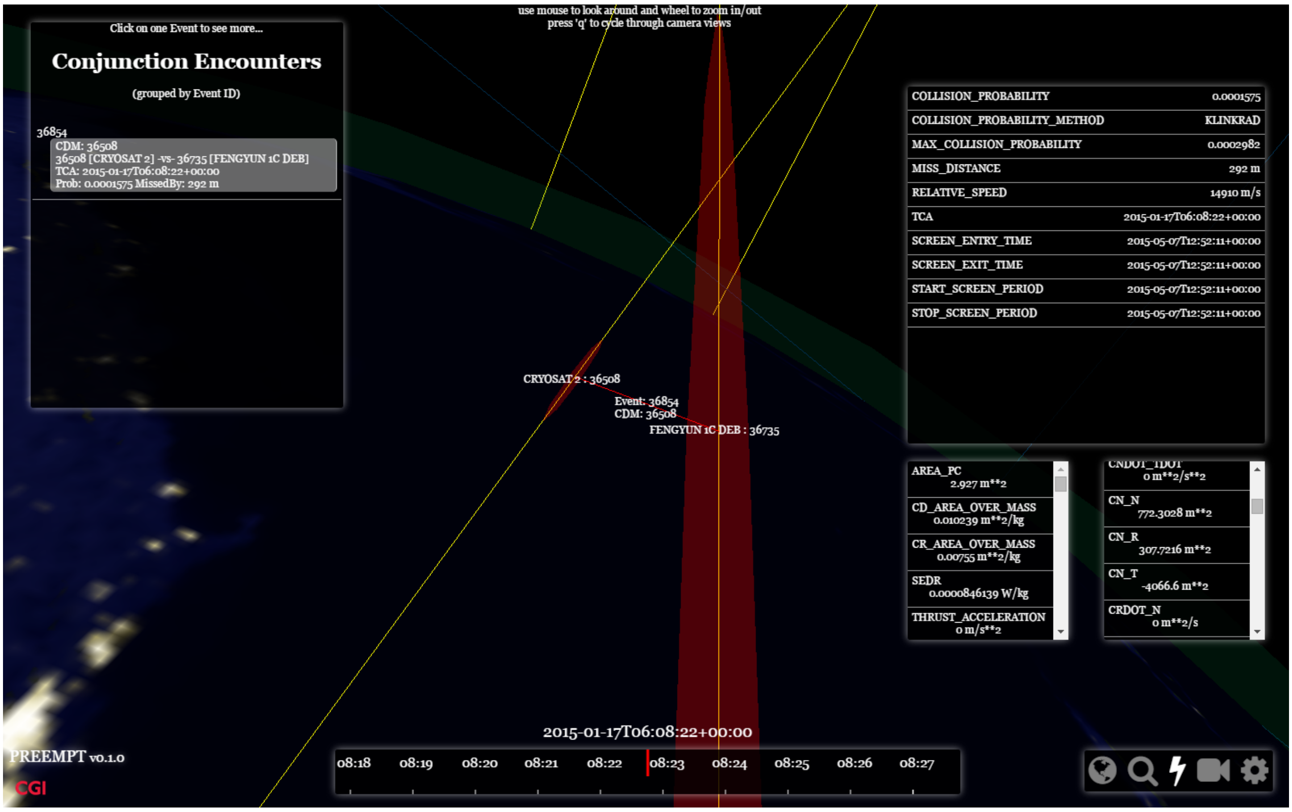

Figure 5. Conjunction visualization with details and object positions and covariance ellipsoids (here 3 sigma) shown for a Cryosat-2 encounter with a Fengyun-1C debris object.

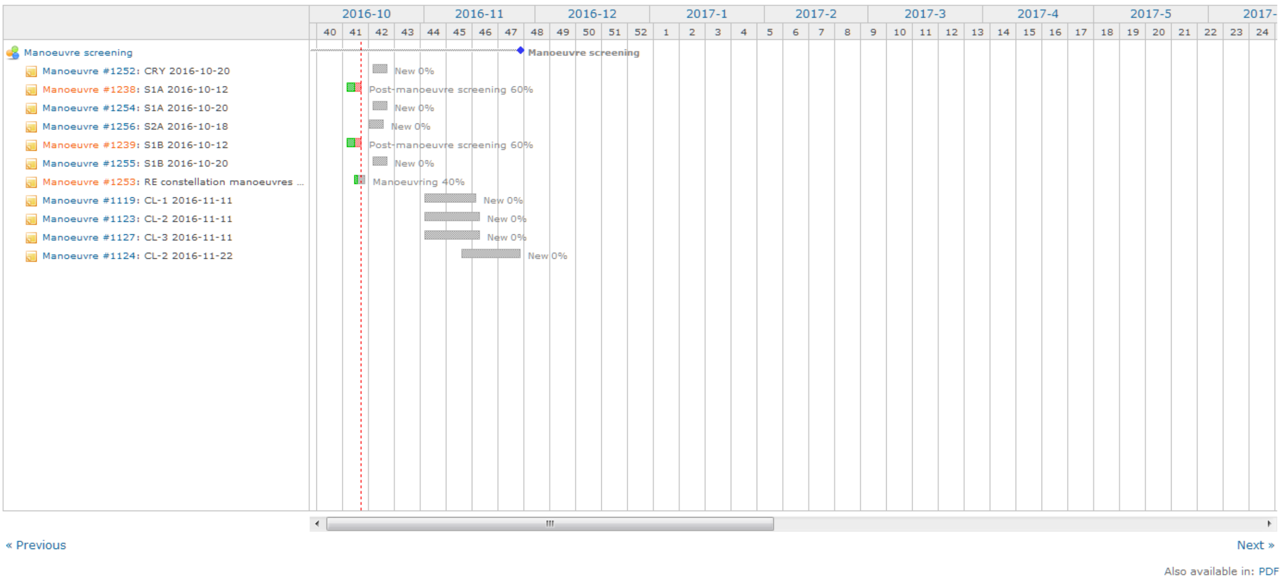

Figure 6. Process control and assignment of tasks in Redmine.

4 CONJUNCTION EVENT STATISTICS

In this section we will provide some statistics on the identified conjunction events for the time period between 2004 and 2016, highlighting the recent changes since the introduction of the CDM.

4.1 Overall statistics

In Figure 7, the number of CRASS/mini-catalogue warnings-based warnings, received JSpOC warnings (close approach notifications), tracking campaigns and avoidance manoeuvres is shown for the time period between 2004 and 2016.

The figure gives an impression on the significant changes the LEO region experienced, with the two fragmentation events involving Fengyun-1C in 2007 and Cosmos-2251/Iridium-33 in 2009, respectively. The all-time high comes with some delay, as also some delay was experienced in the availability of orbit information of the associated fragments. In combination with the large cross-section of Envisat, in particular, this lead to 9 manoeuvres in 2010.

The termination of the ERS-2 mission in 2011 and of the Envisat mission in 2012 lead to a drop of the number of received and issued warnings, as well as of conducted collision avoidance manoeuvres. Reflecting the less dense environment at the altitude of Cryosat-2 and SWARM. Recently launched missions, again, use more congested LEO altitudes (Sentinel-1,-2 and -3) Sentinel-2A). Accordingly, an increase can be seen.

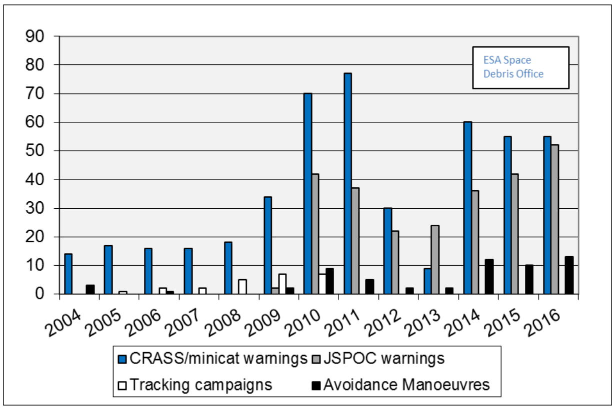

Figure 7. Collision avoidance statistics from ESA's SDO (end 2016).

Figure 8 shows the history of CDMs retrieved from JSpOC and inserted in the database. It reflects the evolution of the JSpOC screening volumes and the increasing number of missions supported. Most prominent feature is the steep increase in the first quarter of 2016 mainly due to the increase in the CDM delivery frequency from daily to 3 times per day but also the addition of a new spacecraft. The decrease at the end of 2014 is mainly due to a reduction of the screening volume. Overall these CDMs belong to more than 100000 conjunctions.

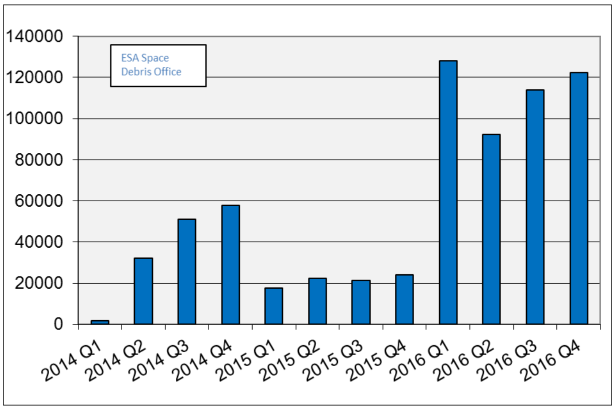

Figure 8. Quarterly count of CDMs received from JSpOC and inserted into the database.

The collected CDMs also allow for a statistics of the covariances, see e.g. [13]. It is planned to upgrade ARES with such results.

4.2 Conjunction characteristics

Figure 9 shows the share of identified chaser objects in close-approach events (TLE-based) for different classes over the years. It gives an impression on the significant changes the LEO region experienced, with the two fragmentation events involving Fengyun-1C in 2007 and Cosmos-2251/Iridium-33 in 2009, respectively.

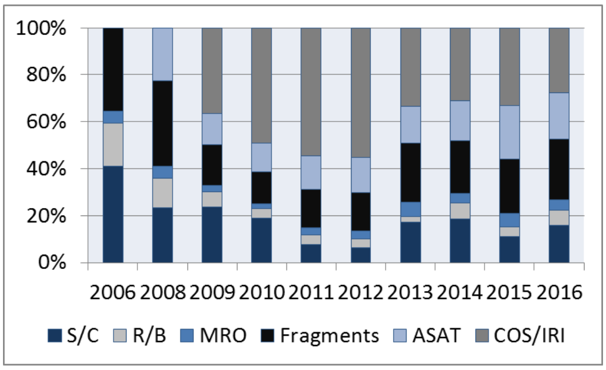

Figure 9. Classes of close approach objects sampling of the LEO environment – O/O vs. TLE orbits for all ESA missions.

Close approach distances for the year 2016 are shown in Figure 10 for 8 spacecraft monitored by ESA in 2016 (two of them launched in 2016). Spacecraft in higher altitude show higher numbers as expected.

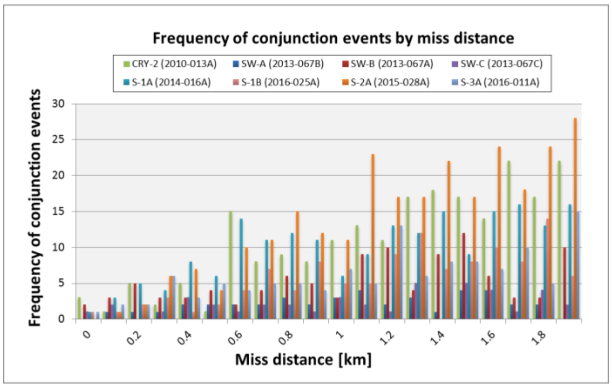

Figure 10. Frequency of conjunction events for Sentinel-1AB, -2A and -3A,Cryosat-2 and SWARM-A, -B and -C in 2016, grouped by miss distance (Sentinel-1B and -3A coverage starts June 2016), based on TLE screening

4.3 Timeliness of high risk warnings

When providing the collision avoidance service to ESA and third party missions, a key parameter is related to the close approach event alert times, which have a significant influence on the reaction time, manoeuvre planning and execution, on-call schemes, etc. Figure 11 displays the share of CDMs as a function of the time between the first notification received from JSpOC for an event and the TCA of that event.

It turns out that for most of the events, the notifications are received several days in advance, as the extended screening volumes for most mission provide a screening for seven days into the future. For about 1% of the conjunctions the first CDM is received within half a day to the event and for another approx. 3% within half and 1.5 days of the TCA. As the planning, implementation and execution of collision avoidance manoeuvres takes several hours, such events prompt for a fast reaction. However, Figure 11 does only show the shares for the total number of events, without further discriminating whether or not the individual events are above a decision threshold.

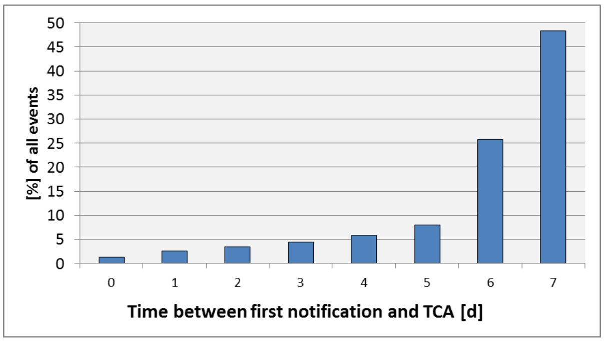

Figure 11. Share of events versus the time between first notification (first CDM received for an event) and the TCA.

Figure 12 shows the classification of the conjunctions according to the highest collision risk observed throughout all CDMs received for an event. As expected, the number of events above the typical decision threshold of 10^{-4} is very low. The maximum in the total share of the events is for the category in the 10^{-7} regime, the latter being sensitive to the defined screening volumes. For the majority of events (88%) the maximum estimated risk never exceeds 10^{-10}.

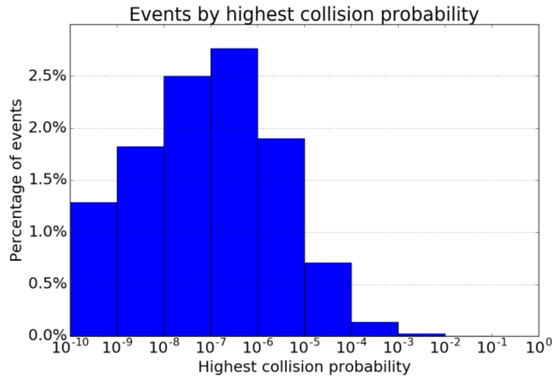

Figure 12. Frequency of events for different risk levels (logarithmic) based on CDMs. Only the highest of the estimated collision risk is considered.

Concerning alert times Figure 13 gives the time to TCA when a risk reached for the first time a level of 10^{-4} showing that approx. 8% of all events ever reaching this level reached it only during the last day to the event and another 7% reached it during the day before. Although this represents statistics based on small numbers one would potentially miss a relevant number of conjunctions if this was the actual trigger for any avoidance manoeuvre preparation. A closer inspection shows that most of those events show risk levels above $5 \cdot 10^{-5}$ earlier. All but exotic cases reach at least $1 \cdot 10^{-5}$ earlier, which is the typical threshold, at which the SDO analyst starts investigating the event with deeper scrutiny. It can therefore be concluded that the internal monitoring threshold of $1 \cdot 10^{-5}$ is appropriate to catch all relevant events.

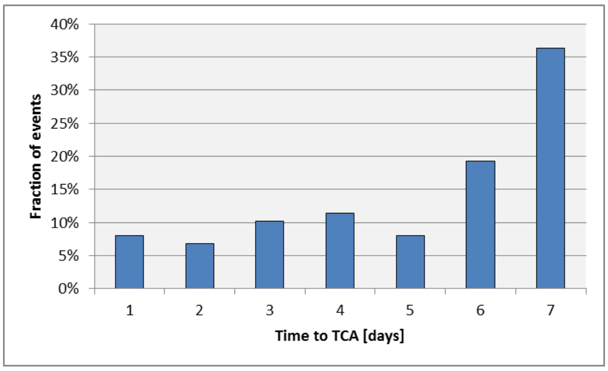

Figure 13. Share of events reaching 10^{-4} versus the time between first reaching 10^{-4} and the TCA.

5 SUMMARY AND CONCLUSIONS

ESA's Space Debris Office provides a service to support operational collision avoidance activities since about 15 years, i.e. dating back to before the severe fragmentation events of the last decade which made the need to consider collision avoidance as part of routine operations evident to all mission operators.

In this paper we described the current approach and operational tool-chain which evolved significantly throughout the last 15 years and has seen several upgrades to meet today's needs.

Today, the collision avoidance process is based on CDMs retrieved from JSpOC and operational orbit and manoeuvre information for the target spacecraft, which are processed automatically and results stored in central database.

SDO analysts and mission control teams access the screening results via a web-based frontend SCARF which allows the analysis and the management of conjunction events and links to a 3D visualization. Future upgrades of the frontend are foreseen, such as triggering further analyses directly via the web interface, providing more capabilities to share further data such as plots, a multi-mission dashboard view and reporting capabilities.

Statistics of the history of conjunction risk analysis have been presented, highlighting the significant changes in the LEO orbital environment during the last 15 years but also the change in data sources (TLEs vs CDMs) and missions flown and covered by the collision avoidance support.

However, the statistics are not only of interest to highlight the evolution of the past, but the acquired data set also allows tuning the operational procedures and schedules by investigating timeliness and frequency of high risk warnings.

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