OPERATIONAL COLLISION AVOIDANCE AT ESOC

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Abstract

The European Space Agency's (ESA) Space Debris Office provides a service to support operational collision avoidance activities. This support currently covers ESA's missions Cryosat-2, Aeolus, the constellation of Swarm-A/B/C, seven Sentinels, as well as missions of third party customers.

In this work, we describe the current collision avoidance process for ESA and third-party missions in LEO. We give an overview on conjunction event detection, collision risk assessment, orbit determination, orbit and covariance propagation, process control, and data handling. We pay special attention to the effect of warning thresholds on the risk reduction and manoeuvre rates, as they are established through risk mitigation and analysis tools, such as ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) software suite.

In order to handle the large number of Conjunction Data Messages and the associated risk analyses, a database-centric approach has been developed. All CDMs and risk analysis results are stored in a database. In this way, a temporary local "mini-catalogue" of objects close to our target spacecraft is obtained, which can be used e.g. for manoeuvre screening and avoidance manoeuvre planning.

The database is also used as the backbone for a web-based tool, which consists of the 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.

Finally, we provide statistics on the identified conjunction events, taking into account the known significant changes in the LEO orbital environment, and share ESA's experience along with recent examples.

GLOSSARY

ACPL	Accepted Collision Probability Level
ARES	Assessment of Risk Event Statistics
CAMOS	Collision Avoidance Manoeuvre Optimization Software
CDM	Conjunction Data Message
CORAM	Collision Risk Assessment and Avoidance Manoeuvre
CORCOS	Collision Risk COmputation Software
CRASS	Collision Risk ASsessment Software
CSM	Conjunction Summary Message
DISCOS	Database Information System Characterizing Objects in Space
DRAMA	Debris Risk Assessment and Mitigation Analysis
ECSS	European Cooperation for Space Standardization
EISCAT	European Incoherent Scatter Scientific Association
EO	Earth Observers
ESA	European Space Agency
ESOC	European Space Operations Centre
IADC	Inter-Agency Space Debris Coordination Committee
ISO	International Organization for Standardization
JSpOC	Joint Space Operations Center
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
MASTER	Meteoroid and Space Debris Terrestrial Environment reference
NASA	National Aeronautics and Space Administration
ODIN	Orbit Determination by Improved Normal Equations
ODR	Orbital Data Request
OEM	Orbit Ephemeris Message
OGS	Optical Ground Station
O/O	Owner and/or Operator

SCARF	Spacecraft Conjunction Assessment and Risk Frontend
SDO	Space Debris Office
SP	Special Perturbations
SSA	Space Situational Awareness
TCA	Time of Closest Approach
TIRA	Tracking and Imaging Radar
TLE	Two-line Elements
UN	United Nations
USSTRATCOM	US Strategic Command

1. INTRODUCTION

Today, the European Space Agency (ESA) operates several missions in the Low-Earth orbit (LEO) region, i.e. to altitudes of up to 2000 km. The highly inclined Sun-synchronous orbits offer a wide range of advantages especially for Earth observation. Concurrently, this regime is densely populated with space debris, posing a risk of collision to the operated satellites. ESA's Space Debris Office is addressing this particular threat by routinely performing conjunction analyses for active satellites in LEO.

1.1. ESA's Space Debris Office

The Space Debris Office (SDO) provides operational and contingency support to ESA and third-party missions, during the Launch and Early Operations Phase (LEOP) and routine operations, including collision avoidance and re-entry predictions and analyses. Different sensors (e.g. ESA's Optical Ground Station (OGS) telescope, Fraunhofer's Tracking and Imaging Radar (TIRA), the radar systems of the European Incoherent Scatter Scientific Association (EISCAT), Zimmerwald telescopes) can be utilised for the acquisition of measurements, which are then processed at the SDO to provide additional information in those mission phases.
The development and the maintenance of an infrastructure in support of ESA's commitment on space debris mitigation and risk reduction is another key task of the SDO, which is emphasized by the development and maintenance of several debris environment and risk analysis tools, The Meteoroid and Space Debris Terrestrial Environment reference model (MASTER) and the DRAMA tools suite are downloaded and applied in analyses by users worldwide[1], and the Database Information System Characterizing Objects in Space (DISCOS) database provides information on on-orbit objects[2].
The office is supporting the development of debris environment remediation technologies, like Active Debris Removal, especially in the context of ESA's Clean Space initiative. Further, based on the office's expertise in running operational services on Space Situational Awareness (SSA) data and space surveillance techniques, office members lead the Space Surveillance and Tracking Segment of ESA's SSA Programme.
By coordinating ESA's debris research through contributing to the European Cooperation for Space Standardization (ECSS), the International Organization for Standardization (ISO) and to United Nations (UN) mitigation efforts, and by having key members in the 13-nations Inter-Agency Space Debris Coordination Committee (IADC), the SDO is actively promoting ESA-internal views & public awareness on space debris issues.

1.2. Objectives

The goal of this paper is to provide an overview on the recent developments in ESA's collision avoidance service provided to ESA missions and third parties.
With an increasing number of supported missions and various recent changes in the way data on conjunction events is received from external sources, it was necessary to introduce several changes to the processes at SDO. This includes the continuous development of a web-based frontend allowing the different missions to access the processed information on any event related to that mission.
Apart from the operational procedures, this paper also discusses how the experience from collision avoidance operations are used to cross-validate space debris tools by the SDO: the most prominent example is the DRAMA/ARES (Assessment of Risk Event Statistics) tool, which gives mission designers the possibility to evaluate the mission needs for collision avoidance already at a very early project phase.
This paper thus reflects the most recent and on-going activities of the SDO in the context of a continuously evolving environment in the collision avoidance area.

1.3. Methodology and outline

In order to understand recent changes in the procedures, it is important to have a full picture of how the different processes evolved. Therefore, after a quick overview in Section 2.1, the historic evolution of the process at SDO will be described in Section 2.2, also introducing the user into the different types of data and formats involved in the process. Then, the current approach will be described in Section 2.3.
There has been always the need to define reaction thresholds, which trigger events in the collision avoidance process. The different methods to approach collision avoidance and the associated thresholds will be presented in Section 2.4.
The Sections 2.5 and 2.6 give an overview on how experiences from the operational collision avoidance have been used to validate the ARES tool.
The updated web-based frontend, which provides access to collision avoidance analysis to the supported missions, is presented in Section 2.7. Finally, some statistics and a few recent examples underline the methodology presented in Section 3.
An important aspect in the operational collision avoidance is to assess the efficiency of a method, by addressing questions like: how much risk is mitigated by collision avoidance manoeuvres? What is the number of false positives where a manoeuvre was performed but a collision would not have occurred without the manoeuvre? While it is difficult to validate the number of false positives, as this would imply an actual collision for a satellite that is cov-

[1] Accessible via https://sdup.esoc.esa.int

[2] Accessible via https://discosweb.esoc.esa.int

ered by a collision avoidance support, it is possible to assess the risk mitigation introduced by a collision avoidance process. This has been done in the past, e.g. via an analysis of Conjunction Summary Messages (CSM) and combining those data with the one obtained from dedicated tracking [2], and will thus not be part of this paper.

2. COLLISION AVOIDANCE PROCESS AT ESA

In this section we describe ESA's collision avoidance process, based on detailed descriptions in earlier work [1,2]. Still, ESA and European national space agencies depend on surveillance data from non-European (mainly US sources) for several applications in the operations of their space infrastructure, including launch and early operations, mission support, collision warning, re-entry prediction and assessment, and overall space traffic awareness. While that data is central for collision avoidance, it is also of paramount importance for studies on space debris mitigation effectiveness.

2.1. Collision avoidance overview

In view of recent severe fragmentation events, 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 space debris population, the need to consider collision avoidance as part of the routine operations is evident to all mission operators and should also be seen as a good practice in view of space debris mitigation.
The operational collision avoidance activities at ESA started in 2006 and concentrate on ESA's/Copernicus Earth observers (EO) in the LEO as well as on third party customers, with past and current missions shown with their operational altitudes in Figure 1. Third party support includes the five-satellite constellation RapidEye, operated by BlackBridge.
The overall underlying concept is to detect conjunction event, which today is based on CDMs received from the Joint Space Operations Center (JSpOC), and to subsequently perform a collision risk assessment, which can include an additional orbit determination based on external data and subsequent orbit and covariance propagation. Table 1 gives the currently covered missions and the provided services.

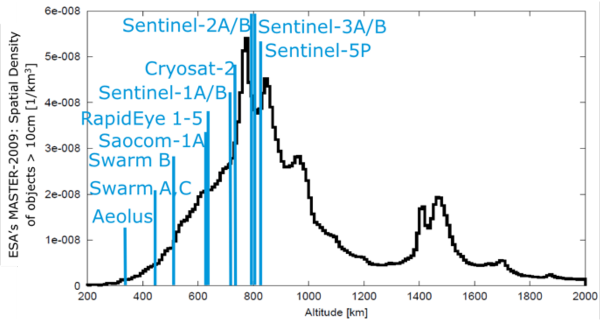

Figure 1. Operational altitudes for covered missions, and the spatial density of objects (MASTER-2009, >10cm).

Table 1: Supported ESA and third-party missions and services provided, February 2019.

Satellite	Comment
ERS-2	Manoeuvre/TLE screening, CDM processing, fully operational from 2006 ended after de-orbiting phase in 2011
Envisat	Manoeuvre/TLE screening, CDM processing, fully operational from 2006 ended after satellite failure in 2012
Cryosat-2	Manoeuvre/MiniCat screening, CDM processing, since launch in 2010
Swarm-A, B, C	Manoeuvre/MiniCat screening, CDM processing, since launch in 2013
Sentinel-1A, B	Manoeuvre/MiniCat screening, CDM processing, since launch in 2014, 2016
Proba 1/V	Only review of JSpOC alerts
Proba 2	Manoeuvre/MiniCat screening, CDM processing
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 (e.g. during LEOPs)
Artemis	CSM/JSpOC alert received until operations handed over, Now case-by-case support
Sentinel-2A, B	Manoeuvre/MiniCat screening, CDM processing, since launch in 2015, 2017
Sentinel-3A, B	Manoeuvre/MiniCat screening, CDM processing, since launch in 2016, 2018
Sentinel-5P	Manoeuvre/MiniCat screening, CDM processing, since launch in 2017
Aeolus	Manoeuvre/MiniCat screening, CDM processing, since launch in 2018
SAOCOM-1A	Manoeuvre/MiniCat screening, CDM processing, since launch in 2018

2.2. Evolution of the ESA operational collision avoidance process

When the operational collision avoidance started in 2006, there were basically two key processes involved. Figure 2 introduces the main roles and functions of this two-step process. The first was ESA's CRASS (Collision Risk ASsessment Software), which used to predict daily conjunc-

tion events and assessed the associated collision probability based on Two-Line Elements (TLEs) [6,10]. ODIN (Orbit Determination by Improved Normal Equations) was used to improve orbits of objects involved in high-risk conjunction events through processing of external tracking data, acquired by radar or optical means [7].
The first step in the process is shown on an orange background: a daily, automated screening was performed to identify close approaches between the covered missions and a catalogue containing TLEs obtained from USSTRATCOM. In absence of covariance information for TLEs empirically found look-up-tables with realistic values for TLE uncertainties were used [4,5]. The second step (green) was applied in the case of high-risk conjunction events, when the estimated collision probability exceeded a given threshold. In case of a high-risk event, tracking data could be acquired and processed by an operator in the loop, which led to improved orbit and covariance information. ESA has primarily been using TIRA, which is located near Wachtberg in Germany for its collision avoidance activities. TIRA is owned by the Fraunhofer research establishment. As CDMs increased the knowledge of the orbits and provide covariance information, the extra effort became unnecessary, and such tracking activity has not been performed since 2011, except for the Envisat contingency. For the covered missions, precisely known orbits and estimated covariance information are available from the flight dynamics teams. Object property information for all objects is obtained from ESA's DISCOS database [3]. As the final step of the process, the tool CRASS distributed the results via email to registered users in the flight control teams, flight dynamics, and mission management.
Notifications on close approaches have been received from JSpOC since 2009, and with increased data content as CSMs since July 2010. Today, CDMs provide full orbital state information and up to 6x6 covariance matrices, which allow for a more realistic assessment of the collision risk compared to TLEs, which come without any uncertainty figures.
To consider the new data coming from CSMs/CDMs, the original process had to be adapted and resulted in what today is referred to as an *intermediate* status, shown in Figure 3.

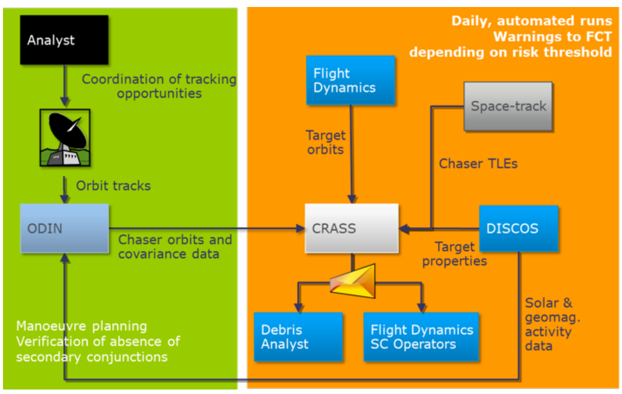

Figure 2. Original process (pre-CSM/CDM) featuring the both key tools ODIN and CRASS.

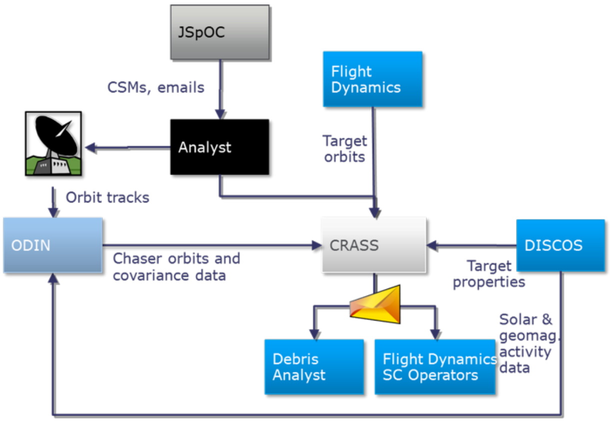

Figure 3. Extended operational collision avoidance process at ESA/ESOC with CSMs (intermediate status).

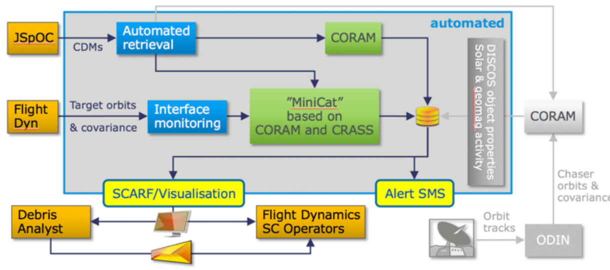

Figure 4. Extended operational collision avoidance process at ESA/ESOC with CDMs – current status with central database

The detailed analysis of a close approach situation leads to a recommendation from the Space Debris Office given to the mission management whether or not to perform collision avoidance manoeuvres, and, if required, on the size and direction of the avoidance manoeuvres. Any proposed manoeuvre trajectory is re-screened for the introduction of secondary, i.e. new, close conjunction events.

2.3. Current approach

A data sharing agreement between US Strategic Command (USSTRATCOM) and ESA was signed on October 30th, 2014. This agreement provides ESA with higher quality and more timely information in exchange for information on planned orbit manoeuvres. Before 2010, the data exchange was limited to the provision of low accuracy Two-line Elements (TLE) data, which come without information on accuracy. The estimated TLE accuracy is several 100 m up to several km (1-sigma). After 2010 and until the agreement in 2014, ESA received better data for conjunction events (CSMs/CDMs), which come with accuracy information (typically, a few tens of metres), but only allowed for a limited screening volume of 3 days before the event and within, 200 m radial, 1 km in total. Full 6x6 covariance matrices are received since 2016.
With the CDMs and the data sharing in place, it was required to adapt the process as shown in Figure 3 and add more automation, as the number of incoming CDMs increased significantly, including the combined processing using owners and/or operators (O/O) information on the

protected asset (target) and JSpOC's CDM information on the object of concern (chaser). Today's process is outlined in Figure 4.

The new approach is database-centred, with individual CDMs and risk analysis results always being stored into the database after the processing.

Another major change was the introduction of a temporary local "mini-catalogue" of objects close to our target spacecraft. This MiniCat is generated from propagating CDM states with DISCOS information on the physical object properties. The MiniCat is being used e.g. for manoeuvre screening and to update the risk analysis immediately whenever a new ephemeris becomes available. Furthermore, the mini-catalogue is also being triggered to run automatically, for example when new operational orbit information is available or if manoeuvre options should be screened. In that 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). A unique event ID is being created when a close approach notification is received for the first time and subsequent messages are linked to that event by the ID.

These updates, implemented into the process, facilitated the development of the conjunction management tool SCARF (Spacecraft Conjunction Assessment and Risk Frontend) and the provision of a streamlined interface to mission control teams. An overview on this tool is given in Section 2.7.

Currently, also the core algorithm to process incoming CDMs and to obtain risk estimates, CRASS, is being complemented by another tool called CORAM (Collision Risk Assessment and Avoidance Manoeuvre) [10]. For a given pair of target and chaser (either from CDM or mini-catalogue and operator ephemeris), close conjunctions are analysed by CORAM. It offers two tools based on a common software core: CORCOS (COllision Risk COmputation Software) is devoted 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 optimisation of avoidance manoeuvre parameters.

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

- Alfriend-Akella [8], 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 [14] performing the contour integration of the projection.
- Covariance scaling [11], where the covariance is scaled for both objects in a given interval and for every scale factor, the probability is evaluated.
- Maximum probability according to Klinkrad's algorithm scaling the covariance [13]
- Maximum probability assuming spherical scaled covariance [9]
- Patera's slicing method [15] for low-velocity encounters
- Non-spherical object shapes via projection of the Minkowski sum to the B-plane and z-buffering [11]
- Monte-Carlo

After every reception of CDMs, a CORCOS process computes the probability for the JSpOC provided CDM and the mini-catalogue is updated. A CRASS run based on the mini-catalogue and the operator ephemeris is run when either the mini-catalogue or the operator ephemeris have been updated. A CORCOS run follows the CRASS run and generates a CDM that is inserted in the database.

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

CAMOS can be run in parametric and evaluation mode. In parametric mode, CAMOS can assess one or several strategy analyses, where a strategy analysis is 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 vs. time of certain trajectory functions, like longitude, latitude, eclipse or location over the South Atlantic region.

An overview summarizing the evolution of the key tools involved in the operational collision avoidance process at ESA's SDO is shown in Table 2.

Table 2: Evolution of the collision avoidance process at ESA's SDO showing the main tools and data formats involved.

Year	CRASS (TLE)	CRASS and tracking with	CRASS/ CSM, CDM	CRASS/ OEM	MINI-CAT	Visualization	CORAM (Manoeuvre Optimisation)
2004	X						
2005	X						
2006	X	X					
2007	X	X					
2008	X	X					
2009	X	X					
2010	X	X	X				
2011		X	X				
2012			X				

2013			X	X			
2014			X	X	X		
Since 2015			X	X	X	X	X

2.4. Warning thresholds

From an operational point of view, it is important to define reaction thresholds. An overview

Table 3 of the different screening methods used by the SDO is given in Table 3. The table gives for each method the threshold to trigger events, which can be a meeting with the mission team, additional tracking or a manoeuvre; it shows how the manoeuvre screening works for each method: in former times, the screening was based on TLE information only, while nowadays, orbit files containing manoeuvres are sent to JSpOC for the screening against the SP catalogue. As soon as a manoeuvre is considered, the target or goal to achieve for a foreseen manoeuvre (also shown in the table) can be defined on a probability threshold which means that the post-manoeuvre event assessment has to result in a collision probability below that threshold. In former times, when the screening was TLE-based, no manoeuvre target was used. Finally, Table 3 also gives the time period each method was used in the SDO.
The current method is referred to as *CSM/CDM full volume with varying threshold*, where the collision risk threshold for a given event, triggering a meeting with the flight dynamics and mission operations teams, is mission specific. In the meeting manoeuvre options are discussed, which might result in additional MiniCat runs for the proposed target orbits. A manoeuvre will be triggered if the risk remains above the mission specific decision threshold up to the latest time a go/no-go decision is possible.
In order to derive this threshold, ESA's ARES tool (part of the DRAMA tool suite) is used. It allows estimating the annual collision probability as a function of the quality of the orbital information of the secondary (chasing) objects (TLE- or CSM-based) and trading off ignored risk vs. avoided risk.

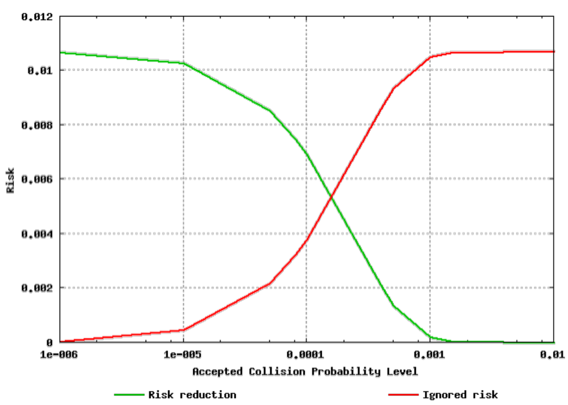

Figure 5: Risk reduction and ignored risk as a function of the accepted collision probability for TLE-based chaser uncertainties. The example is for ESA's Envisat satellite.

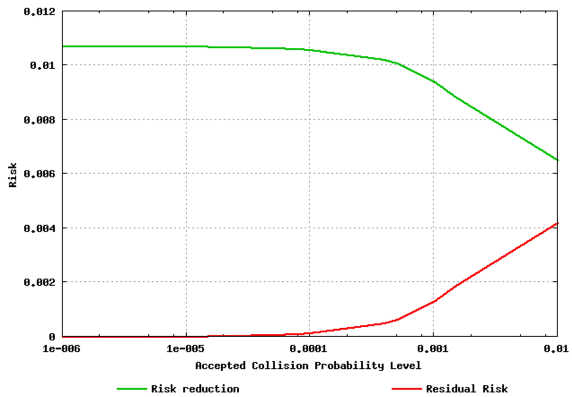

Figure 6: Risk reduction and ignored risk as a function of the accepted collision probability for CSM/CDM-based chaser uncertainties. The example is for ESA's Envisat satellite.

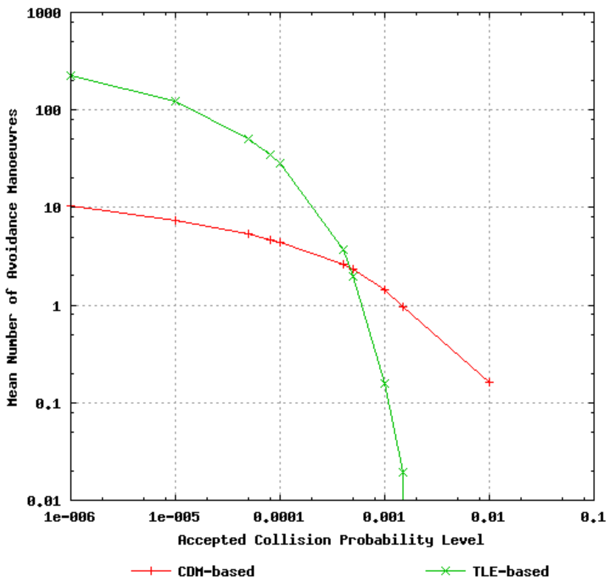

Figure 7: ARES analysis of the mean number of avoidance manoeuvres as a function of the accepted collision probability level (ACPL) for CDM- and TLE-based operational collision avoidance. Example satellite: Envisat.

As an example, in Figure 5 and Figure 6, the risk reduction and the accepted (i.e. ignored in the collision avoidance actions) risk is shown as a function of the accepted collision probability level. Note how the risk figures decrease for high-quality uncertainty information for the chasers, which is the case for the CSM/CDM-based approach in Figure 6. Besides the risk estimate, ARES is also assessing the expected manoeuvre frequency for the selected reaction threshold and orbit uncertainties. As Figure 7 shows, about one order of magnitude improvements can be achieved for the CSM-based approach as compared to the TLE-based one.

2.5. Debris risk assessment in early mission design

With operational collision avoidance being a key component for a successful LEO mission, one requires a careful planning of the resources at a very early stage in the mission planning. For this purpose, the tool ARES (Assessment of Risk Event Statistics) within the DRAMA software suite has been developed.
DRAMA is the recommended ESA tool to be used in early design phases of a project to assess debris-related aspects, like collision avoidance statistics, impact and damage assessment, disposal orbit design and re-entry analysis. The space debris population, which is the essential input for most analyses, is provided through ESA's reference model MASTER.
ARES as part of DRAMA and relying on MASTER flux results, allows mission planners to estimate the expected number of annual collision avoidance manoeuvres based on a risk threshold the mission is going to accept. This ultimately results in the additional required amount of fuel mass for the manoeuvres. An example is shown in Figure 7 for the Envisat mission, highlighting not only the relationship between the accepted collision probability level (ACPL) as a manoeuvre reaction threshold and the annually expected number of avoidance manoeuvres, but also the influence of the uncertainties associated with the chaser orbits. With the advent of CDMs (based on a numerical Special Perturbations, or SP theory), the uncertainties are significantly reduced and thus lead to a lower number of required manoeuvres. For example, an ACPL of 10^{-4} would result in 28 manoeuvres per year for a TLE-based approach, while only 4 manoeuvres are required using CDMs.

The release of a new version of DRAMA and MASTER is planned for May 2019.

2.6. Cross-validation of ARES via manoeuvre rates

The actual manoeuvre rates can be used to validate the corresponding ARES predictions. As an example, the annual manoeuvre rates for CSM, as estimated by ARES, are shown in Figure 8. For an ACPL of 10^{-4} about 1 annual manoeuvre can be expected. In fact, ERS-2 did not perform collision avoidance manoeuvres in 2008 and 2009, while a total of 4 (!) manoeuvres in 2010, and 1 in 2011, have been performed. Considering that the 2010 record number of collision avoidance manoeuvres was mainly due to passing twice through fragment clouds from the Iridium 33/Cosmos-2251 collision, these numbers agree very well with the DRAMA/ARES estimates.

Table 3: Screening methods and associated warning thresholds

Method (data screened)	Threshold to trigger…	Threshold to trigger manoeuvre	Manoeuvre screening	Manoeuvre target	Period of use
TLE screening	Meeting: $P_c > 10^{-4}$ $D < 300$m	$P_c > 1\times10^{-3}$ to 5×10^{-3} $D < 300$m	TLE screening	None	2003-2011
TLE screening + Tracking	Tracking: $P_c > 10^{-4}$ $D < 300$m	Distance based (no manoeuvre for low risks)	Screen against precise chaser orbit only	None	2006-2011
JSpOC alerts	Meeting: After alert was received	$D_{radial} < 3\sigma_{chaser}+3\sigma_{target}$+cross-section radii	Request to JSpOC for a new alert message	$D_{radial} > 3\sigma_{chaser}+3\sigma_{target}$+cross-section radii	2010
CSM/CDM	Meeting: $P_c > 10^{-4}$	$P_c > 10^{-4}$	Request to JSpOC	($P_c < 10^{-6}$)	2010-2013
CSM/CDM full volume	Meeting: $P_c > 10^{-4}$	$P_c > 10^{-4}$	MiniCat and JSpOC	($P_c < 10^{-6}$)	2013-2016
CSM/CDM full volume with varying threshold	Meeting: Mission-specific P_c threshold	Mission-specific P_c threshold	MiniCat and JSpOC	Mission-specific P_c threshold	Since 2016

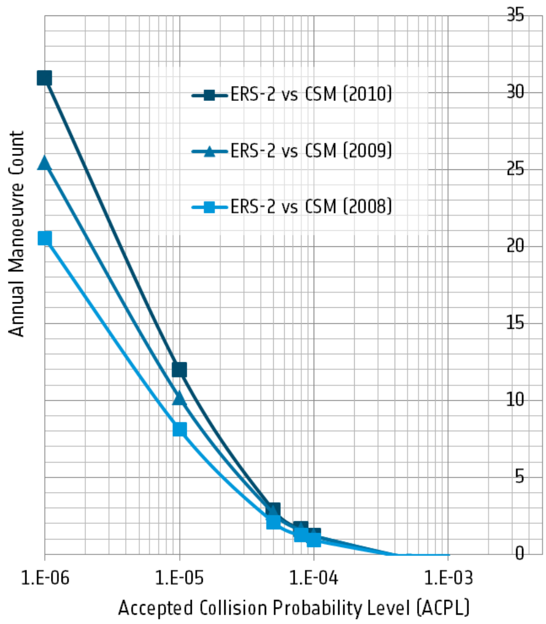

Figure 8. Assessment of the annual collision risk and manoeuvre rates for ERS-2 by ESA's ARES tool.

2.7. Collision avoidance management tool

With the new database-centred approach outlined in Section 2.3, the basis for a web-based visualisation and collaboration tool called SCARF (Spacecraft Conjunction Assessment and Risk Frontend) 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. Besides that, 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:

- 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.
- 3D interactive approach geometry visualisation

SCARF has originally been developed by CGI [16] and is successfully used by the SDO and mission control teams. Maintenance and further development have been taken over by the SDO. Future releases will address features like improved summary displays for analysts or triggering further analysis from SCARF, e.g. configuring, launching and post-processing CORAM runs.

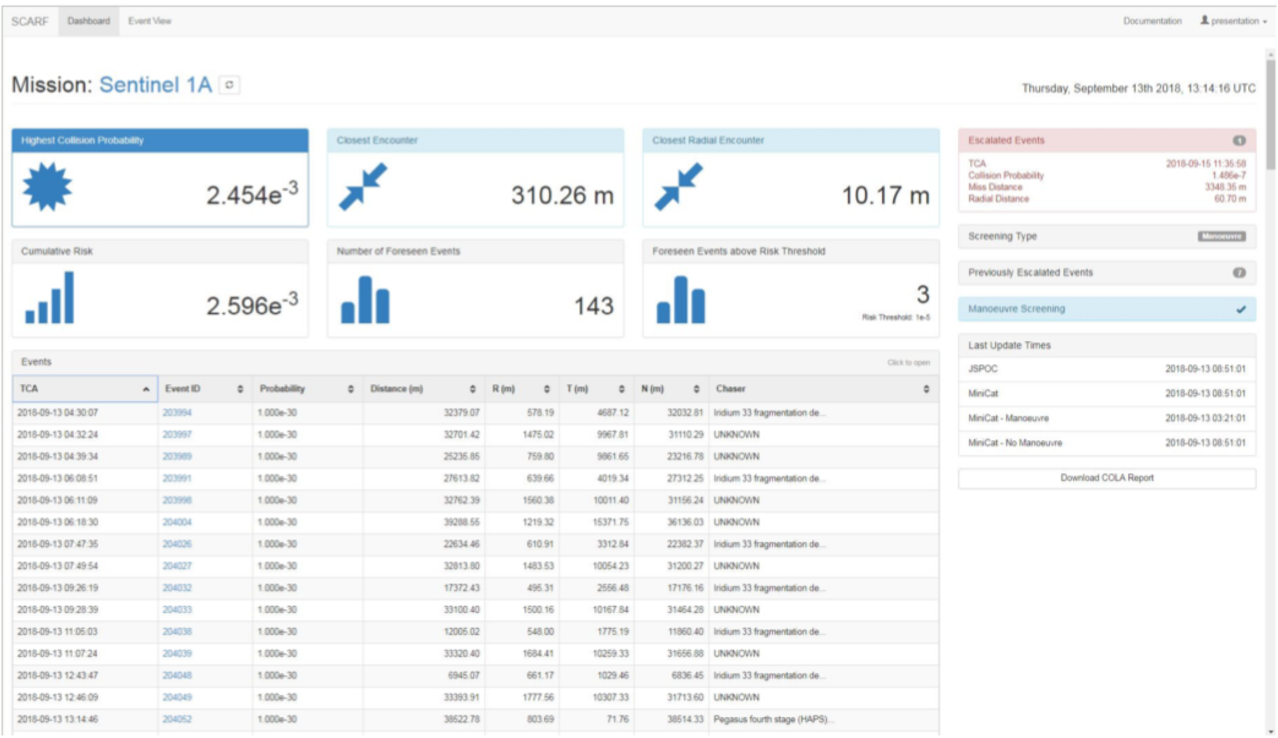

Figure 9: Screenshot showing the dashboard of the SDO's collision avoidance management tool SCARF. An exemplary event for Sentinel-1A is depicted.

2.7.1. Dashboard view

The most relevant information is presented in the dashboard for each mission, as shown in Figure 9: 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, the cumulative collision risk, the number of foreseen events, the number of events above a threshold of 10^{-5}, and a sortable list of all future events with key parameters is shown. Escalated events are shown prominently in the top right corner coloured in red, to ensure fast access. An event is considered as escalated as soon as the mission control teams have been informed, which, for the most missions, happens as soon as the mission threshold on the collision risk is exceeded.
If different screening types are available, i.e. several manoeuvre options, a selection of the screening type limits the displayed event data to the respective screening type (manoeuvre option).
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.

2.7.2. Event view

After having obtained an overview for a given mission, more detailed information is provided in the event view, which also allows triggering emails via templates, inserting comments and even to request screening data for the ESA missions based on available ephemerides. The latter can then be directly forwarded to JSpOC for a dedicated ephemeris screening. In Figure 10, the timeline in the event view 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.

2.7.3. Analyst view

The analyst view provides a presentation of CDM information as one-liners, where CDMs are selected via dedicated filters for the event, the target, the chaser, the TCA, a certain time span, the owner, the assignee, the collision risk, the 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.

2.7.4. Visualization

Another key feature of the new collision avoidance management tool is the 3D dynamic visualization of close approaches, as shown in Figure 11: The analyst is able to see the target and chaser trajectories with the Earth in the background. Covariance ellipsoids and CDM data are shown as well. 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.

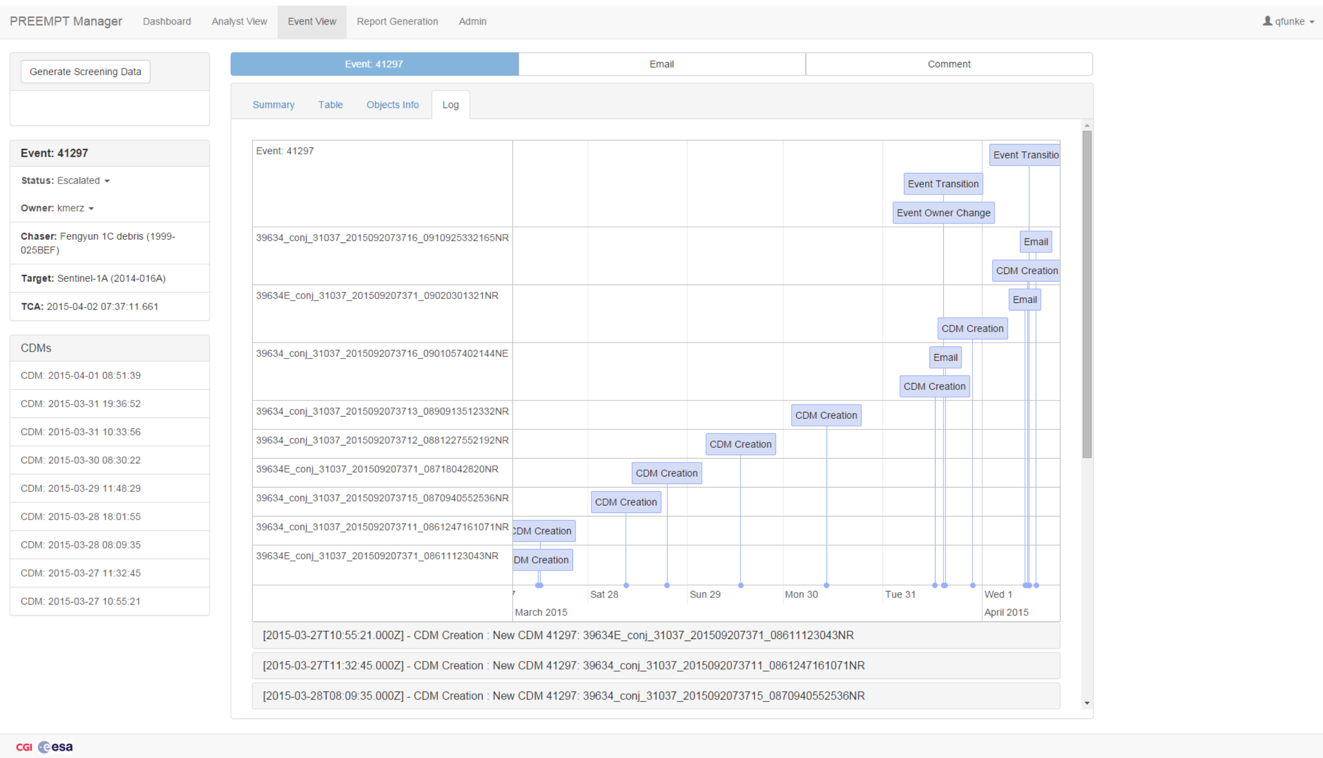

Figure 10: Event view in SCARF showing the log, which gives a timeline of all actions associated with a single event, e.g. CDM creation, email notifications, or event escalation.

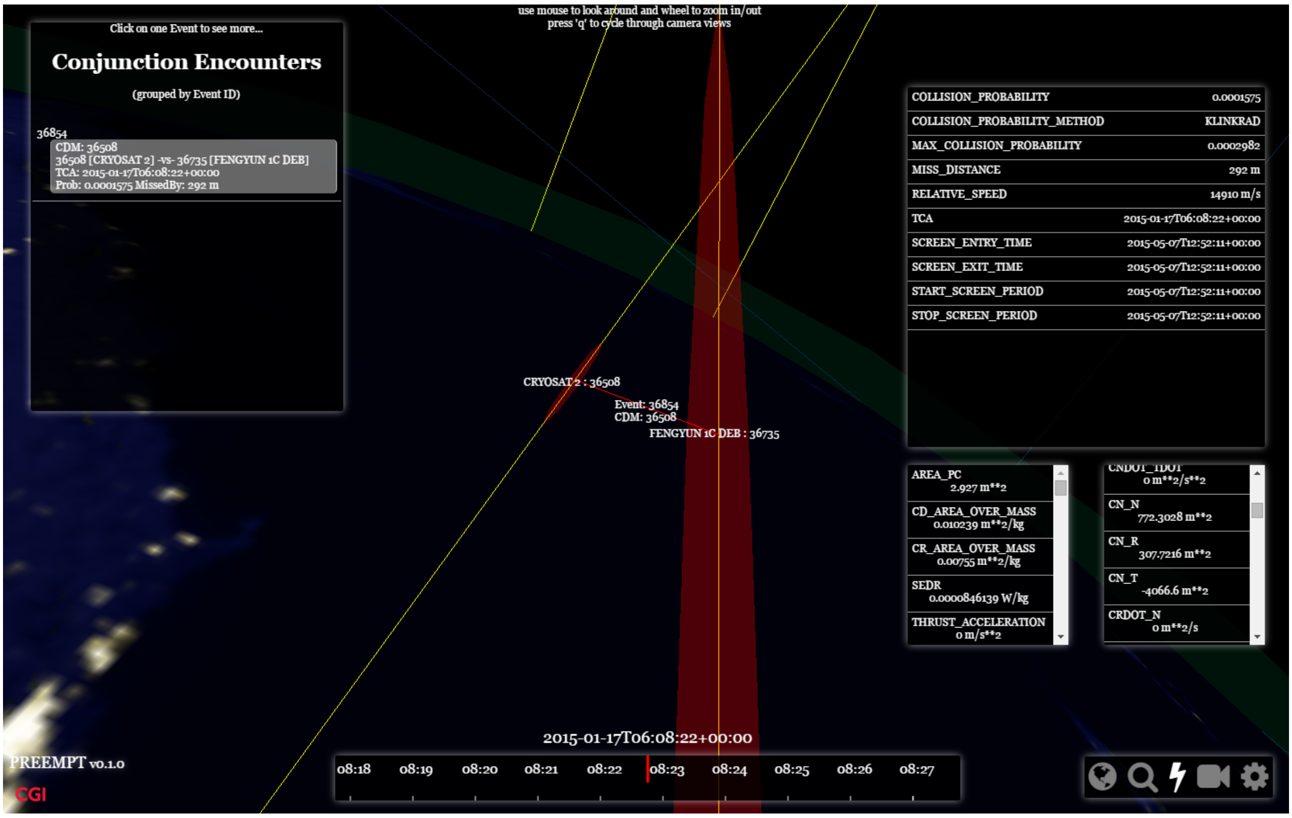

Figure 11: Conjunction visualization with details and object positions and covariance ellipsoids (here 3 sigma) shown for a Cryosat-2 encounter with a Fengyun-1C debris object.

3. STATISTICS AND RECENT EXAMPLES

In this section we will provide some statistics on the identified conjunction events for the time period between 2015 and 2018 (including). Figure 12 shows the chaser object share of received CDMs from 2015 to 2018. It can be seen that the Fengyun-1C and Cosmos-2251/Iridium-33 fragmentation events result in a significant number of close approach events, but their share is slowly replaced by other fragmentation event objects and such of unknown source. In

Figure 13 the number of TLE-based CRASS warnings, replaced by MiniCat in 2014, and received JSpOC warnings, tracking campaigns and avoidance manoeuvres is shown for the time period between 2004 and 2018. Note how the need for additional tracking campaigns went down after the introduction of the accurate CSM and CDM notifications provided by JSpOC in 2014. At the same time, the number of collision avoidance manoeuvres increased, which is due to the higher number of missions supported by the SDO and the growing number of debris objects in the used orbit regions. The reduction of JSpOC warnings in 2017 is due to the introduction of collision risk as additional criterion. In 2018, many new missions led to an increase of all numbers.

When providing the collision avoidance service to ESA and third party missions, a key parameter is the close approach event alert times, which have a significant influence on the reaction time, manoeuvre planning and execution, on-call schemes, etc. Figure 14 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.

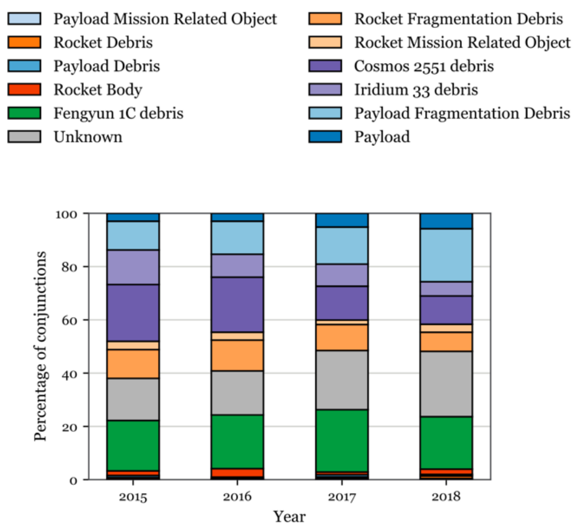

Figure 12. Classes of objects having close approaches with ESA missions. Based on CDMs as per screening volume.

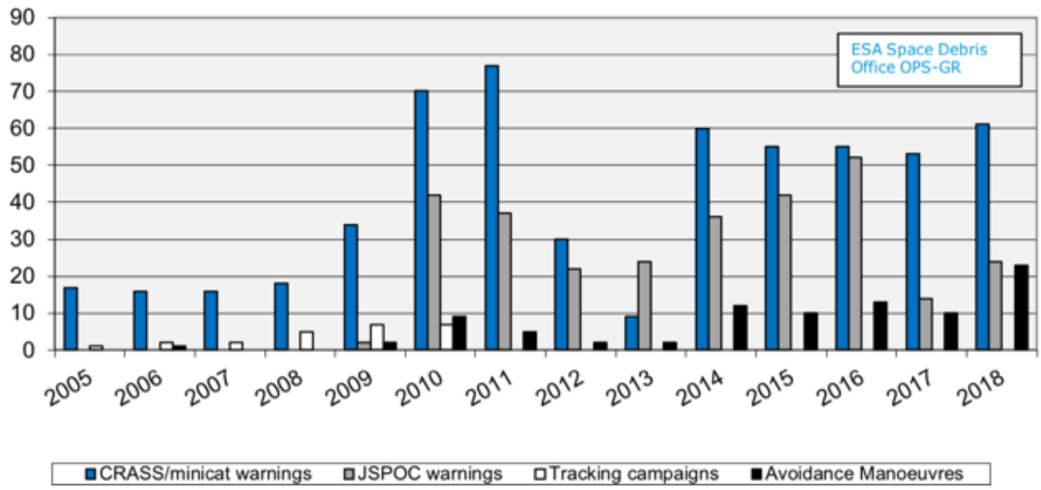

Figure 13. Collision avoidance statistics from ESA's SDO (end 2018).

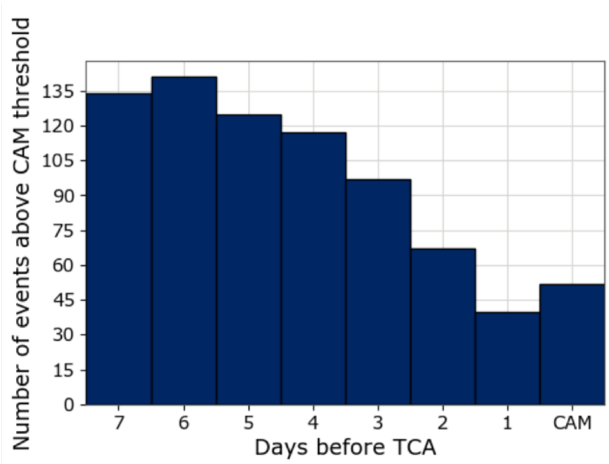

Figure 14. Share of events since 2015 versus the time between first rise above the risk threshold and the TCA. The number of performed CAMs are shown as well.

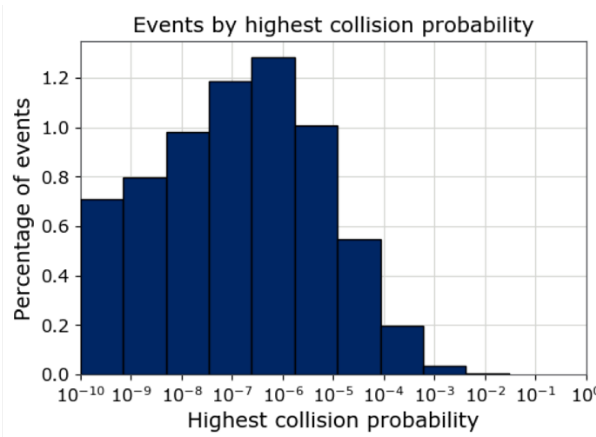

Figure 15. Frequency of events for different risk levels (logarithmic) based on CDMs. Only the maximum of the estimated collision risk was considered. Plot is for all CDMs received since 2015.

For most of the events, the notifications are received several days in advance, as the extended screening volumes for most missions provide a screening for seven days into the future. For a low number of events (about 10%) the first notification is received three days or earlier, which includes missions with a basic screening volume of three days. Only about 2% of the events are identified within last 24 hours to the TCA. As the planning, implementation and execution of collision avoidance manoeuvres takes several hours, such events prompt for a fast reaction. However, Figure 14 does only show the number of events above the reaction threshold, but not when the first notification was received.

Figure 15 shows the frequency of events being above different levels of the collision risk. As expected, the number of events above the most common reaction 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 (86.5%) the maximum estimated risk never exceeds 10^{-10}.

3.1. Sentinel-1A close approach example

The mission Sentinel-1A, which is the first satellite in the Copernicus Programme, was launched on April 3, 2014. Shortly after the launch, while Sentinel-1A was still in the LEOP, a close fly-by with the inactive NASA (National Aeronautics and Space Administration) astronomy satellite ACRIMSAT was detected for April 5. It was based on the first available orbit determination, Sentinel-1A even had no assigned international designator ID, yet. Even the thrusters were not checked out yet for any potential collision avoidance manoeuvre.

Thanks to an excellent collaboration with NASA and JSpOC, and a joint effort with the flight dynamics and flight control teams, the event confirmation, manoeuvre planning and screening were completed within just 20 hours by the LEOP team.

3.2. Envisat close approach example

On January 21, 2010, ESA's Envisat had a close approach event with a 3.8 ton CZ-2C second stage (2009-061A). Based on TLE analysis, a safe fly-by of about 1.39 km miss distance was predicted. A subsequent TIRA tracking resulted in an extremely close fly-by of only 64 m miss distance with an assessed collision probability of only 1 in 77. It was decided to perform two manoeuvres, with velocity changes of -/+4 cm/s in along-track direction: this resulted in a 100 m radial miss distance at TCA and the subsequent restoring of the ground track.

4. CONCLUSION

Collision avoidance is a reality in mission operations today, with flight control teams trying, as far as possible, to combine orbit maintenance and collision avoidance manoeuvres.

For more than one decade, ESA's SDO has a well-established collision avoidance process, including an excellent collaboration with USSTRATCOM/JSpOC, supporting several ESA and third-party missions. The operational tool-chain evolved significantly and has seen several upgrades to meet today's needs.

The automation of most of the CDM-related processing was required due to the large number of messages received. The current approach is centred around a database containing both CDMs received from JSpOC and those which are created internally from ephemeris screening. A new tool, CORAM, has been developed, augmenting the possibilities of the workhorse CRASS by introducing extended risk assessment functionality as well as a collision avoidance manoeuvre planning and optimization method.

With the introduction of SCARF, an easy-to-use web-based interface for the analyst and the mission control teams has been created. It allows for the analysis and the management of conjunction events and a 3D visualization. Future upgrades are foreseen, such as triggering further analysis directly via the web interface.

The operational procedures evolved to enable higher risk reductions via new data sources and risk thresholds after the move to CDMs as the baseline. The mini-catalogue in combination with the central database guarantees flexibility and is a prerequisite for (limited) manoeuvre screening with short turn-around times. While the need for dedicated tracking in support of operational collision avoidance has decreased significantly since the advent of CDMs, the SDO still maintains the capability to acquire dedicated tracking from TIRA.

The upgraded ARES tool in the DRAMA software suite is ready to support mission design and incorporates catalogue uncertainties based on CDMs.

There are several other open topics that will be addressed in the next evolutions of the SDO tools:

- An advanced trend analysis, which would allow to "predict" if the risk evolution of individual events would be positive – with the feasibility still to be proven. One possible approach would be to use the covariance matrix to predict a possible range of updates and associated risks.
- A systematic approach to deal with multiple (one or half an orbit repetitive) conjunctions of the same object pairing.
- A more detailed analysis of latency times between CDM reception and actual reaction time, which allows to assess whether the currently applied 24/7 on-call scheme can be relaxed or not.
- A discussion to achieve a cross-agency/industry consensus on how to set collision avoidance manoeuvre thresholds.

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