A STATISTICAL LOOK ON ESA'S CONJUNCTION EVENT PREDICTIONS

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ABSTRACT

On a routine basis, ESA predicts close conjunctions for its own satellites and assesses the associated collision risk. This process is supported by acquiring external tracking data to improve the knowledge on orbit state and associated uncertainties of the secondary object, and by evaluating close approach notifications and conjunction summary messages received from the US Joint Space Operations Center (JSpOC). The process also includes screening of planned manoeuvres for close conjunctions. ESOC-operated missions in low Earth orbit and in highly-eccentric orbits are covered. Recently, the process has been extended to cover third party missions.

We describe the applied process and present the latest status, including a history of high-risk conjunction events and processed CSMs, and we revisit major recent software developments.

As this process has been in place for some years, we can use the archived results for a detailed assessment of the close conjunctions from an operator's perspective. We analyse the evolution of object classes and the accumulated risk from TLE-based information for secondary objects. The impact of the severe collision events in 2007 and 2009 is also part of this discussion.

1 INTRODUCTION

Spacecraft, in particular operated in the Low Earth Orbit (LEO) and Geostationary Orbit (GEO) regimes, face a risk due to collision with other space objects. Depending on the energy-to-mass ratio that characterises such a collision event, the effect might be either 'catastrophic', i.e. leading to the destruction of the objects, 'lethal', i.e. leading to the loss of main functionalities or the ability to meet the mission objectives, or even negligible. In any case, recent severe fragmentation events, such as the destruction of Fenyun-1C in 2007, the Iridium-33/Cosmos-2251 collision in 2009, and the Briz-M explosions of 2012 increased the space debris population and underline the need to consider collision avoidance as part of the routine operations. Active collision avoidance should also be seen as a good practice in view of space debris mitigation. ESA has an operational collision avoidance process in place that currently covers LEO missions and missions in eccentric orbits. The process can also be applied to third-party missions [1].

We start our discussion by (re)-introducing ESA's collision avoidance process in section 2. As this process has been in place for some years now, we are in a position to use the archived close approach predictions as well as other related analysis results for a detailed revisit of the process, taking an operator's perspective. We will focus on the data and results obtained since 2007 in section 3. We cover the breakdown of conjunction events by object classes, the accumulated collision risk, and the performed collision avoidance manoeuvres. We briefly address Conjunction Summary Messages (CSMs), and experiments to validate CSMs in section 4. In section 5 we finally use the new upcoming version of ESA's Debris Risk And Mitigation Analysis tool (DRAMA) [2] for a cross-check of the obtained estimates, i.e. we estimate the collision avoidance manoeuvre frequency for a selected example, and how this frequency evolved in recent years.

2 APPLIED PROCESS

In this section we describe ESA's collision avoidance process, based on detailed description in earlier work ([3], [4]).

Figure 1 introduces the main roles and functions of this two-step process. We note that two tools are central. ESA's CRASS (Collision Risk Assessment Software) is used to predict daily conjunction events and to assess the associated collision probability ([5],[6]). ODIN (Orbit Determination by Improved Normal Equations) is 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].

Figure 1 introduces the first step (orange): a daily, automated screening to identify close approaches between covered mission and a catalogue containing Two-Line Element (TLE) data obtained from USSTRATCOM; and the second step (green) that is applied in the case of high-risk conjunction events when the estimated collision probability exceeds a given threshold. In case of high-risk event tracking data might be acquired and processed by an operator in the loop leading to improved orbit and covariance information. ESA primarily uses the Tracking and Imaging Radar (TIRA) located near Wachtberg in Germany for its collision avoidance activities. TIRA is owned by the Fraunhofer research establishment. Such tracking activity has not been performed since 2011, except during the Envisat contingency in April and May 2012.

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For the covered missions precisely known orbits and covariance information are available from the flight dynamics teams. Object property information for all involved objects is obtained from ESA's DISCOS database [8]. As final step of the process CRASS distributes results via electronic mail to registered users in the flight control teams, flight dynamics, and mission management.

Notifications on close approaches are received from JSpOC since 2009, and with increased data content as Conjunction Summary Messages (CSMs) since July 2010. Today, CSMs provide full orbital state information and full 6x6 covariance matrices, which allows performing a collision risk assessment.

The detailed analysis from processing tracking data or CSMs 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 screened for the introduction of secondary, i.e. new, close conjunction events.

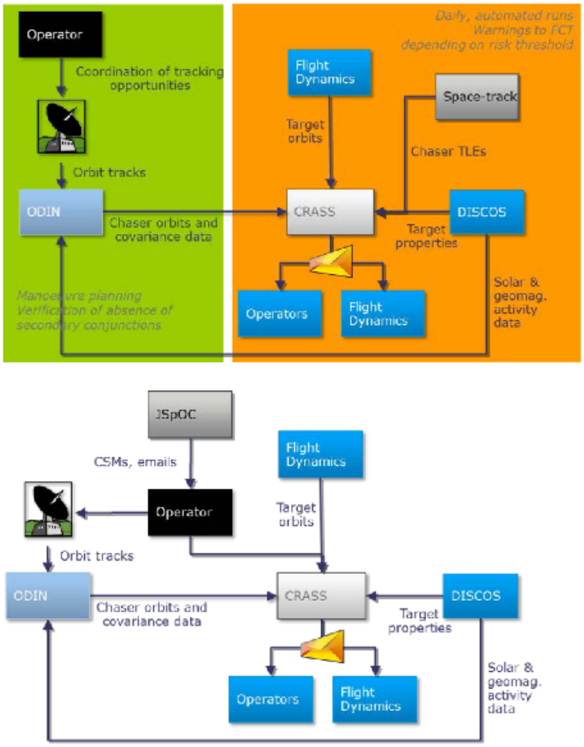

Figure 1. Outline of ESA's collision avoidance process (modified from [3]) as applied by ESA's Space Debris Office with indication of core tools and entities; original process based on TLE data (top), adapted process for available CSM data (bottom).

Two additional aspects of the applied collision avoidance process should be mentioned here, too:

First, TLEs come without associated uncertainty information. Several approaches have been discussed already on how sufficient estimates for this essential information for risk assessments can be obtained. Here, we only want to refer to the approach implemented in CRASS [9], and to a more recent revisit by [10].

Second, it is clear that the reaction threshold for classifying a close approach as high-risk event and for performing collision avoidance manoeuvres is crucial. Ref. [1] presented an analysis using ESA's DRAMA software on the annual collision probability as function of the quality of the orbital information of the secondary (chasing) objects. For TLE-based information the ignored risk due to the uncertainties of the orbital information in LEO typically is equal to the avoided risk, i.e. only half of the collision probability can be covered by the process. It was also shown for a representative case that reducing the uncertainties by one order of magnitude (as it is the assumed case for CSMs compared with TLEs) the largest part (~90%) of the collision probability can be avoided, i.e. collision avoidance manoeuvres can also be reduced by roughly one order of magnitude.

A quick history of the identified high-risk conjunction events and the received and processed CSMs is outlined in Figure 2. It should be noted that the chart addresses all covered missions, which is a varying number. Support for Cryosat-2 was added after its launch in June 2010. ERS-2 operations ended on 15 September 2011 after a stepwise lowering of the operational orbit to a final ~570 km near-circular orbit during Summer 2011. Envisat lowered its operational altitude by 17 km in October 2010, and finally CRASS support for Envisat was terminated on July 1, 2012, following the end of operations declared on June 29, 2012, (the end of the Envisat mission was declared on May 9, 2012). The statistic shows that ERS-2 and Envisat with their large cross-section and the operational orbit at around 780 km altitude were the main contributors to the total of issued CRASS warnings, and also performed the majority of collision avoidance manoeuvres in the covered time frame (9 for ERS-2, 10 for Envisat, out of a total of 22). Figure 2 shows that the termination of the support for the ERS-2 and Envisat missions led to a drop of the number of received and issued warnings, as well as to a lower number of conducted collision avoidance manoeuvres (two collision avoidance manoeuvres in 2012 compared to the five collision avoidance manoeuvres in 2011 and nine in 2010).

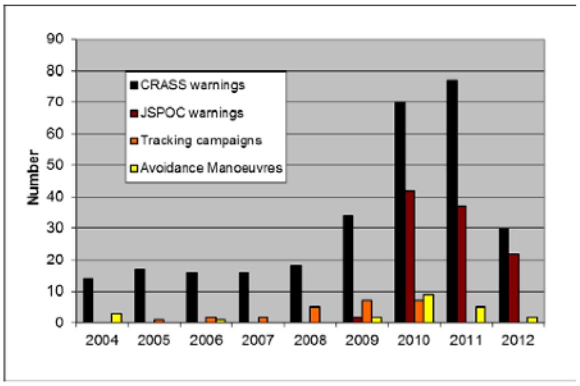

Figure 2. Collision avoidance statistics as of end of 2012 covering Envisat, ERS-2, and Cryosat-2 activities: received CRASS warnings, close approach warnings received from JSpOC, performed tracking campaigns, and performed collision avoidance manoeuvres (incl. 1 rescheduled routine manoeuvre in 2011 and incl. 1 for METOP-B that was performed during the LEOP under ESA responsibility in 2012)

Despite of these changes, Figure 2 still indicates the major changes to the LEO regime after the destruction of FengYun 1C on January 11, 2007, and the collision between Iridium 33 and Cosmos 2251 on February 10, 2009. Note that currently, while the process in LEO only covers Cryosat-2, the relative number of JSpOC close approach warnings are now received more frequently than CRASS warnings are issued. This might reflect the less dense environment at the altitude of Cryosat-2, where a lower number of small fragments can be expected, which in turn lowers the number of TLE-based warnings.

CRASS is also used to cover the four Cluster satellites orbiting in highly-eccentric orbits with conjunction event predictions and risk assessments, and, also covers the XMM satellite while drifting through the GEO region.

The ESA process and the related tools are regularly maintained. The most recent changes cover the introduction of a web-based monitoring tool (PAMI) that allows to quickly and comprehensively assess the status of the different CRASS runs via internet, to identify problems and to exchange messages within the collision avoidance team. This has proven to be of great help, in particular during week-ends when the engineers in-charge are only working on-site in case of high-risk events. We have also modified CRASS to process CSM data in the form of XML data structures.

Currently, new software is being developed under industry contract covering improved collision risk estimation and collision avoidance manoeuvre optimisation [12]. The risk algorithms cover, for a given pair of chaser and target, low velocity encounters not assuming linear motion and complex body shapes. Both, theoretical as well as Monte Carlo methods are implemented. The manoeuvre optimisation aims at either minimising the risk for a given manoeuvre delta-v or at minimising the delta-v for reaching a given acceptable collision risk taking into account typical operational constraints on the manoeuvre. It is foreseen to integrate the software into the processing chain either by automatically post-processing the conjunctions identified by CRASS or by directly plugging some of the risk algorithms into the CRASS software.

In addition, ODIN has been adapted to provide callable interfaces and to be ready for integration in scripted processes. Filters and conversion tools for different tracking sensors were added and verified.

3 RESULTS OBTAINED IN THE COLLISION AVOIDANCE PROCESS

In this section we will assess in detail the recorded close conjunctions. We take an operator's perspective, addressing constraints to the applied processes and gained experiences.

We stress that the direct output from the CRASS tool does <u>not</u> factor in any applied collision avoidance measure.

A breakdown of the secondary objects involved in close approaches identified by CRASS TLE-based analyses per object class, as well as the accumulated risk, can be evaluated from the recorded results. For our analysis we assume objects entering a screening volume of an ellipsoid with the dimensions 10 km x 25 km x 10 km in radial, along-track and out-of-plane direction since 2008. As an example we give in Figure 3 the results for Envisat. The cataloguing process of the FengYun 1C fragments apparently had already identified most of the fragments by 2008, as FengYun 1C fragments significantly contribute to the total number of close conjunction events at a stable level. Fragments of Iridium 33 or Cosmos 2251 contribute since early 2009. Today fragments of Iridium 33, Cosmos 2251 and FengYun 1C together contribute to roughly two thirds of all of our close conjunction events.

The increasing share over time reflects the gradual addition of such newly-generated fragments to the catalogue. This in turn reflects a major problem of any collision avoidance process. For some months after a fragmentation event the process is essentially insensitive to a significant part of the newly created but not yet correlated catalogue objects. The JSpOC provides screening results for such objects already if they are present in their "analyst catalogue", even if not correlated with a specific launch event, as "known objects".

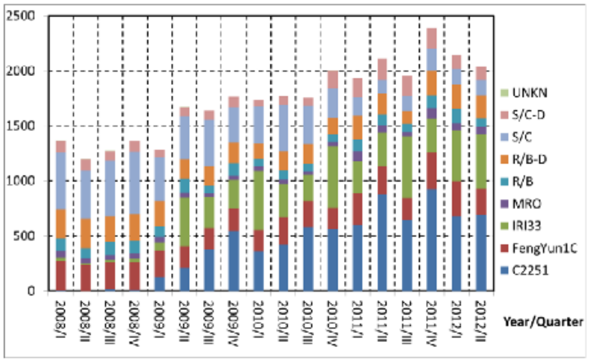

Figure 3. Classes of secondary objects that entered into a screening ellipsoid of 10 km x 25 km x 10 km in radial, along-track, and out-of-plane direction around Envisat (C2251 and IRI33 – fragments of the collision between Cosmos 2251 and Iridium 33, FengYun 1C – fragments of the Chinese FengYun 1C spacecraft, MRO – mission-related objects, R/B – rocket bodies, R/B-D – debris from rocket bodies, S/C – spacecraft (active or inactive), S/C-D – debris from spacecraft, UNKN- unknown class).

This analysis of the increasing contribution of fragments in the close conjunctions is also supported by Figure 4, where we give the ratio between "background" chaser classes and chasers from the severe collision events related to FengYun 1C and Iridium33/Cosmos-2251 (only selected if the event exceeds a collision risk of 10^{-6}), accumulated for all covered missions. A remarkable feature in Figure 3 is a repetitive relative increase of close conjunctions with Iridium 33 fragments. This is due to a slower relative drift of the orbital planes between those fragments, compared to the other two fragment clouds. As a result the orbital plane of a sun-synchronous satellite, such as ERS-2 or Envisat, becomes coplanar to the narrow band of nodes of Iridium 33 fragment orbits every 8-9 months. The highest number of Iridium-33 close conjunctions has been experienced in March and at the end of November 2010, and during August 2011.

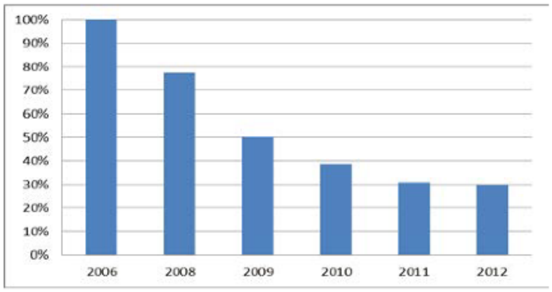

Figure 4. Ratio between "background" chaser classes and chasers from the severe collision events related to FengYun 1C and Iridium33/Cosmos-2251 (selected if exceeding a collision risk of 10^{-6}), accumulated for all covered missions.

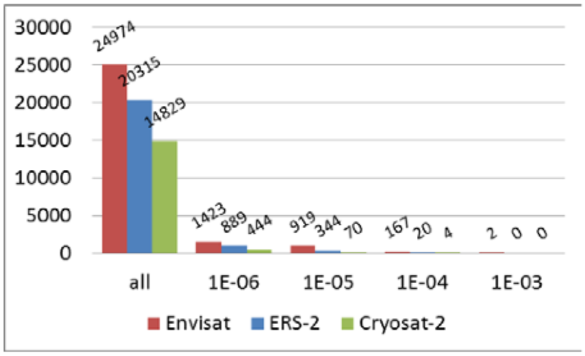

Figure 5. Count of archived close approaches identified by CRASS where the (last) assessed collision risk exceeds a certain level (10^{-6} - 10^{-3}) for all events for three covered missions.

The recorded CRASS results based on TLE data also allow studying the accumulated risk (total, per selected cut-off threshold, and for both per object class). Note that we consider the maximum reached risk per event during the entire forecast time span of 7 days. We select the risk thresholds 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6} as well as consider all objects entering the screening ellipsoid irrespective of the estimated collision risk. The selected analysis time frame for the selected subset from the CRASS archives is as follows:

- Envisat: (as of) 2008/07/01 to 2012/06/30
- ERS-2: (as of) 2008/07/01 to 2011/09/05
- Cryosat-2: (as of) 2010/07/01 to 2013/03/31

Figure 5 gives the total count of these identified close approaches. It should be noted that only events where the last assessed collision risk exceeded a certain level are considered. It becomes clear that for the vast majority of events (up to about 95%) the estimated collision risk does not exceed 10^{-6}. The accumulated collision risk of these many low-risk events nevertheless becomes significant (see section 5).

In a next step of our analysis we may look at the accumulated collision risk during the entire considered timeframe. In Figure 6 we present the accumulated maximum risk figures per individual event and 7 day forecast time frame. A further more detailed look allows Figure 7, as we detail for a selected mission the accumulated risk per month and per individual risk cut-off.

Figure 7 nicely confirms previously discussed observations – a significant part of the total collision risk is contained in the comparably rare high-risk (risk>10^{-4}) conjunction events, and another significant part is accumulated by the large number of low risk events showing distinct variations due to the coplanarity of the spacecraft' orbit with fragment clouds.

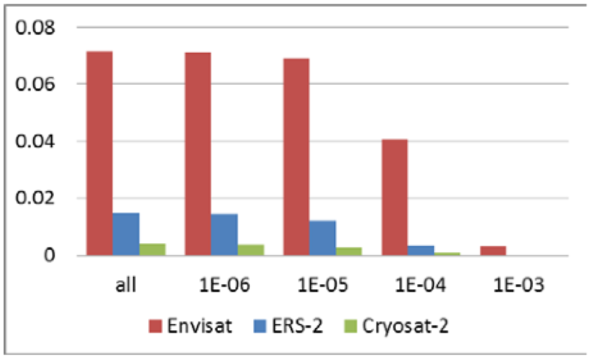

Figure 6. Accumulated maximum risk per 7 day forecast window for events identified by CRASS where either the (last) assessed collision risk exceeded a certain level ($10^{-6}..10^{-3}$) for all events.

4 CONJUNCTION SUMMARY MESSAGES

CSMs are provided to ESA by JSpOC for all close conjunction events within 72 hours of which (in LEO) the total miss distance is below 1 km and the miss distance in radial direction is below 200 m. As for many reported collision avoidance processes, ESA considers CSMs as one of the most valuable inputs. ESA received a close approach warning from JSpOC for one of the three missions discussed here every 10 days on average.

The described ESA process considers the acquisition of tracking data and therefore allows to verify the information contained in the CSMs through comparing the determined and propagated orbits. First experiences and verification results with CSMs were reported quickly after the first reception in [11], and also in [3].

We verified CSMs against conjunction event analysis based on TIRA orbits and operational orbits for several occasions. These analysis were supported by colleagues from the Air Force. Here we present the results for the assessment of the close conjunction between Envisat and a Cosmos-3M upper stage on Sep 11, 2010. The estimated collision probability was 1/9259. The approach geometry was oblique with an approach azimuth of 35 deg. Other considered examples were the close conjunctions between ERS-2 and Scout X-4 operational debris on Jul 24, 2010, and between Cryosat-2 and Kitsat-3 on Oct 8, 2010.

Table 1 gives the results for both, TLE and CSM data compared to the operational orbit of ESA. The obtained RMS from 4 acquired TIRA tracks using our orbit determination software is better than 10 m in range and 10 mdeg in azimuth and elevation. The results show a very good agreement between the JSpOC and TIRA-based predictions, not deviating by more than 10m in radial direction, while there is a significant disagreement to the TLE-based prediction.

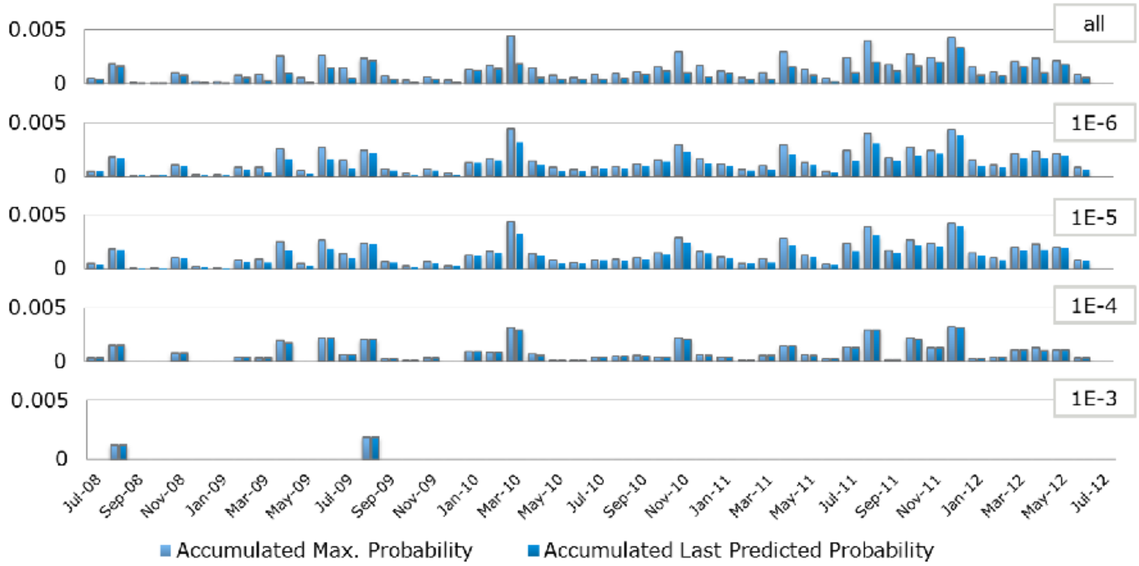

Figure 7. Evolution of the accumulated collision risk for Envisat per month (either for the maximum risk of event per 7 day forecast window, or for the last risk of forecast per event), where either the (last) assessed collision risk exceeded a certain level ($10^{-6}..10^{-3}$) or for all events.

Table 1. Assessment of the Envisat vs. Cosmos-3M upper stage close conjunction on Sep 11, 2010.

	Operational orbit vs. TLE	**Operational orbit vs. orbit from TIRA observations**	**SP data (CSM) for both objects**
Epoch of closest approach	**08:26:12.84**	**08:26:12.68**	**08:26:12.676**
Radial Miss (m)	**46**	**524**	**514**
Along -Track Miss (m)	**-109**	**333**	**366**
Cross-Track Miss (m)	**-153**	**472**	**516**

5 CROSS-CHECK WITH DRAMA

ESA's DRAMA software is designed to estimate the annual collision risk and the collision avoidance manoeuvre rate for typical uncertainties associated with a TLE catalogue or CSM data for a selected satellite and using ESA's MASTER model. Therefore, it is very interesting to compare the actually performed manoeuvres to these estimates. The relevant DRAMA module ARES (Assessment of Risk Event Statistics) is currently subject to an upgrade with more details provided by [2]. A preliminary test version of ARES was used for that study.

Figure 8 gives, as an example, the DRAMA/ARES estimates for ERS-2 for the years 2009 to 2011, reflecting the changes to the space debris environment as modelled in MASTER. The estimates show that on average 1 manoeuvre per year can be expected for a CSM-like catalogue accuracy and an accepted collision probability of 10^{-4}. The estimated frequency grows over time, which corresponds to a growth in the number of space debris objects.

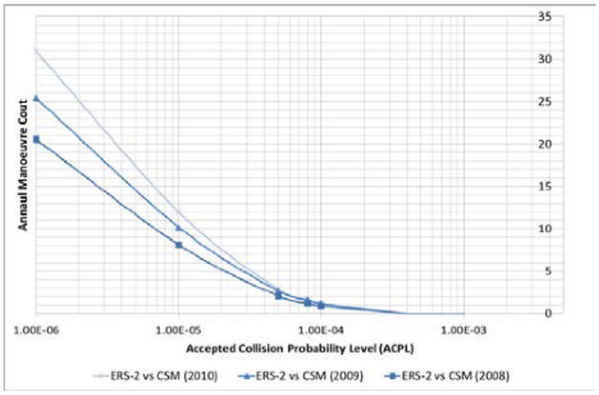

Figure 8. Annual count of collision avoidance manoeuvres for ERS-2 as function of the accepted collision probability level, assuming a CSM-like accuracy for the conjunction partners and a population based on MASTER for the situation in 2008, 2009, and 2010.

In fact, ERS-2 did not perform collision avoidance manoeuvres in 2008 and 2009, 4 (!) manoeuvres in 2010, and 1 in 2011. 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.

6 CONCLUSIONS

ESA missions are covered by a routine service operated since 2004 that identifies close conjunction events and assesses the related collision probabilities based on operational ephemerides and TLE data. The process foresees dedicated tracking campaigns to improve orbits and covariance information of secondary objects involved in identified high-risk events, and is able to process external information, such as CSMs.

Severe fragmentation events in LEO significantly increased the frequency of close conjunctions since 2007 and 2009. These generated fragments of FengYun 1C, Cosmos-2251 and Iridium-33 were involved in two thirds of all close conjunction events of Envisat and ERS-2. Statistical analysis of the archived results for Envisat, ERS-2, and Cryosat-2 show that for the vast majority of events (up to about 95%) the estimated collision risk does not exceed 10^{-6}. The accumulated collision risk of these many low-risk events becomes significant nevertheless, and shows showing distinct variations due to the coplanarity of the spacecraft' orbit with fragment clouds. Another significant part of the total collision risk is set by the rare high-risk (risk>10^{-4}) conjunction events.

Tools, processes and applied decision criteria for collision avoidance manoeuvres criteria need to be reviewed and maintained regularly, e.g. to react to the availability of better external data. In this respect we present a verification of the high quality of the received JSpOC CSMs that was possible though comparing the estimates to results from dedicated tracking campaigns in 2010.

Further support to process definition and maintenance is possible through ESA's DRAMA software. The DRAMA module ARES covers aspects of the mission planning. Reviewing the performed collision avoidance manoeuvres and archived conjunction event predictions allow verifying estimates from such modelling tools. DRAMA is under upgrade now and we used a preview version to compare the conducted collision avoidance activities to the tool's estimates, which showed a good agreement. Finally we note that collision avoidance is widely accepted as a part of routine operations of spacecraft today. Unfortunately, this became a necessity partly due to the severe changes to the environment near 800 km altitude. ESA's Space Debris Office provides tools, such as DRAMA, that allow to take into account collision avoidance already in the mission design phase. For the operational phase of missions, the Space Debris Office at ESA/ESOC has a complete operational collision avoidance process available that has demonstrated capabilities to support ESA and third party missions.

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