CRYOSAT-2 IN-ORBIT Collision Avoidance manoeuvre Support Tools and Operation Evolutions

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ABSTRACT

The CryoSat-2 mission was launched from Baikonour Cosmodrome on the 8th April 2010 aboard a Dnepr launch vehicle (based on a modified SS18 Satan ICBM) into a near polar non-sun synchronous orbit at about 700 Km altitude. CryoSat-2 is an ESA Earth Explorer mission operated from ESOC/ESA in Darmstadt, with the prime objective to measure changes of sea-ice floating in the polar oceans as well as the evolution of land ice masses in Greenland and Antarctica. This paper describes how the MASTER statistical model of the space debris environment has been used for the ESA Earth Observation missions in order to define the thresholds for reaction to a collision risk. This paper also explains the collision avoidance process for CryoSat-2, starting from the reception of the warning message up to the optimisation of the avoidance manoeuvre strategy, which has evolved over the years and currently uses new tools and interfaces for risk assessment and fast manoeuvre scheduling.

1 INTRODUCTION

The aim of the CryoSat-2 mission is to precisely measure the variations in the thickness of floating sea ice and understand the evolution of the ice masses in Antarctic and Greenland regions. CryoSat-2 was injected into a high inclination (92^o), "semi-frozen" non-sun-synchronous orbit at an altitude of 717 Km. This orbit allows the CryoSat-2 mission to collect science data over much higher polar latitudes than other polar synchronous missions. Its primary payload is a SAR Interferometric Radar Altimeter, named SIRAL, that operates in three different measurement modes: Low Resolution Mode (LRM), Synthetic Aperture Radar (SAR) and SAR Interferometric (SARIn). The nominal 3.5 year mission were completed in November 2013, and now the mission has been extended until at least end 2019, thanks to the outstanding science results and platform performances.

The debris environment, in which the satellite orbits, requires constant monitoring. This is carried out by the ESA Space Debris Office (SDO), which provides support to the Flight Operations Segment (FOS) team. Since launch, more than hundred critical conjunction events have been assessed, from which only twelve required the execution of a collision avoidance manoeuvre (CAM), confirming the reliability and robustness of the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) statistical model [1] of the space debris environment, when used for a CryoSat-2 like satellite.

The experience gained in the last six years has evolved the initial collision avoidance manoeuvre strategy confirming that the probability risk for Collision Avoidance Manoeuvre (CAM) reaction of 10^{-4} is acceptable.

Lot of progress has been made in defining a common terminology including simplified space debris techniques and analytic tools to support operations. These new software tools were recently adopted by the CryoSat2-SDO team including an advanced graphical visualization of the conjunction and a new tool (CORAM) to support manoeuvre planning and delta-V estimation.

This paper addresses the evolution of Collision Avoidance Manoeuvre (CAM) approach and the latest tools used by the CryoSat-2 and SDO teams.

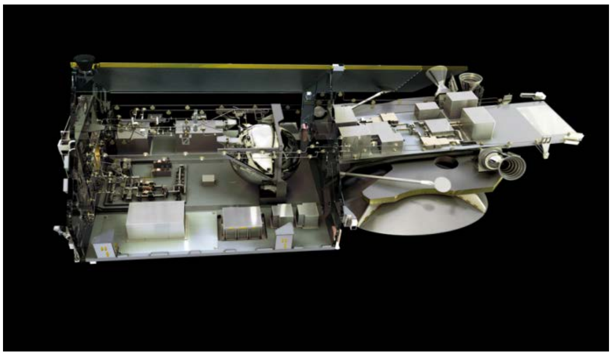

Figure 1. CryoSat-2 model

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Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

2 MISSION OVERVIEW

The design of CryoSat-2 has no deployable solar structures and is characterized by an extended nose ("Fig.1") supporting the radar altimeter antennas. All units are located in a box structure of about 4.6m x 2.3m x 2.2m and the two solar array panels are body mounted in a "roof" configuration. CryoSat-2 is a three axis stabilized spacecraft operating in four modes starting from Rate Damping (RDM) and Coarse Pointing Modes (CPM) up to Fine Pointing Mode (FPM) with YAW steering capability and Orbit Control Mode (OCM). The precise attitude is guaranteed by the AOCS sensors and actuators in use, STRs (3 units), FGM (3 magnetometers), CESS (6 heads), DORIS (1 antenna) and 2 actuators, MTQ (3 rods) and cold gas reaction control system (RCS) equipped with 10 redundant thrusters: 8nom.+8red. attitude THRs of 10mN and 2nom.+2red. orbit control THRs of 40mN. These units provide all functions needed for attitude and orbit determination and control in all mission phases from high rate damping to fine pointing.

The low thruster capability and their location, in the aft part of the spacecraft, means that, by design, CryoSat-2 is only able to perform in-plane (prograde and retrograde) manoeuvres. It is clear that an anti-flight direction (retrograde) orbit control manoeuvre can be executed only after a YAW turn of 180 degrees.

3 SPACE DEBRIS ENVIRONMENT AND STATISTICAL TOOL

The collision prediction service is provided for EO missions by the SDO team. According to the current space debris environment, and based on computations taking into account the orbit and spacecraft properties for CryoSat-2 made with the Assessment of Risk Event Statistic (ARES) tool which is part of the Debris Risk Assessment and Mitigation Analysis (DRAMA) [2] suite, the ACcepted Probability Level (ACPL) for LEO-EO missions (and in particular to Cryosat-2) has been defined to be 1:10000, and this value has been progressively confirmed by the experience. The selection of this value is based on a compromise between the risk reduction and the remaining risk, all with an acceptable manoeuvre rate. At an ACPL of 10^{-4} ("Fig.2") almost all risk is reduced (96%) and the expected number of manoeuvres per year is about 2.3.

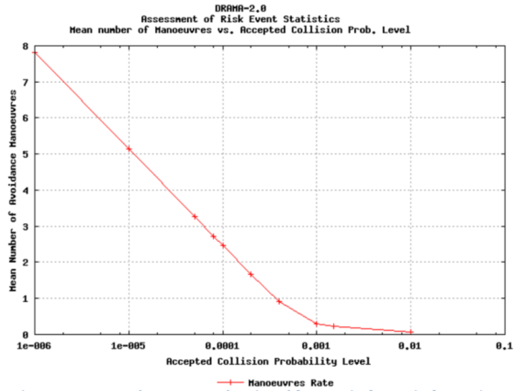

Figure 2. ACPL vs mean number of CAM

4 RECOMMENDED STANDARD

Lots of progress have been made in the last six years by the different space organizations and agencies in order to establish processes and standards in order to share data regarding close approaches between objects. This resulted in the creation of the Conjunction Data Message (CDM), which became a standard by the Consultative Committee for Space Data System (CCSDS), with the Blue book published in June 2013. It defines the format and content of data to be shared in case of conjunctions between objects (active satellites or debris (non-active satellites, rocket bodies and fragments thereof)) in space. Thanks to this standard, it is possible to use a common terminology and notation and to exchange data between different space debris analysis centres. At ESOC, several tools were developed supporting the operational aspect of the debris avoidance process.

The information from JSpOC (Joint Space Operations Center), currently the only organization providing CDMs to ESA, is used by SDO for risk computation and analysis. It consists of miss distance, relative position and velocity between the chaser and target the time of close approach (TCA), full 6x6 covariance as well as orbital state data for both chaser and target. In addition, orbit determination related data is provided, which allows the assessment of the quality of the data (position and covariance). With this data, the SDO computes the probability of collision for each of the events, which is then used to assess if an event can be considered as "high risk".

In turn this message is used by the missions to evaluate the risk of a specific conjunction event or multiple conjunctions and evaluate the options and plan the best corrective action / manoeuvre. The CDM terminology and corresponding data has been adopted and introduced in the current SDO-SCARF web based interface ("Fig.3"), which replaces the previous CRASS (collision risk assessment tool) system, which was less accurate because the data used was based on TLEs instead of the current CDMs which that use SP data.

The results of the CRASS tool were delivered by email to the mission control team, while with SCARF, the missions can directly access the processed data, and are only notified by the SDO in case of a high risk.

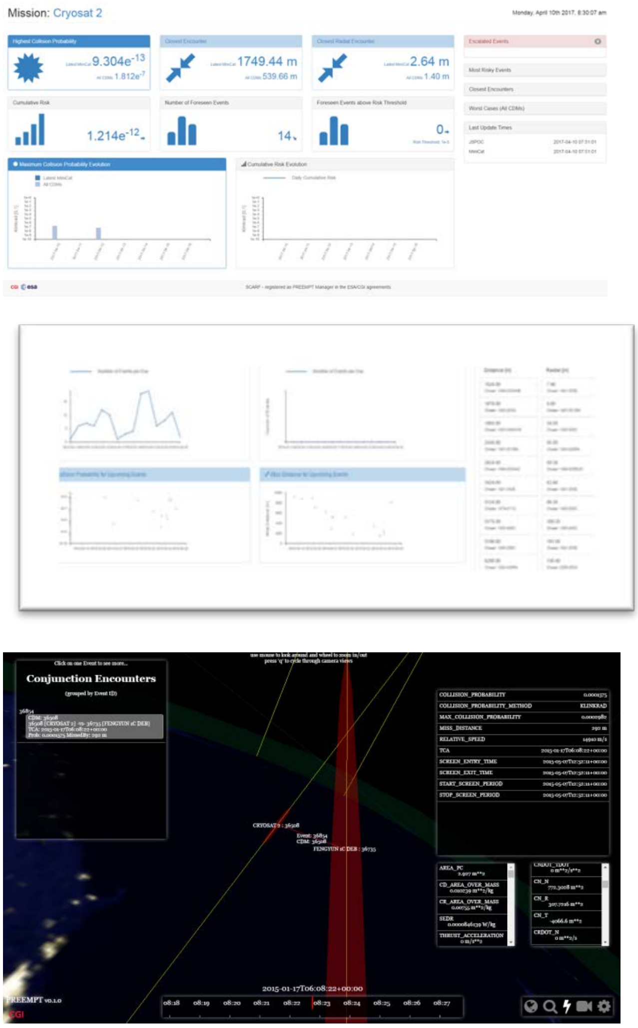

Figure 3.SCARF web interface

Some of the key features of SCARF are the access to the DB of CDM processing results, graphical presentation of the CDM, CDM trend analysis, CDM filtering, access to the escalated events, direct link to the 3D visualization of the geometry approach and others. The dashboard view offers a quick look of the highest probability, smallest miss distance, smallest radial miss distance and the most critical events including the escalated ones.

5 ESA-SDO COLLISION WARNING PROCESS

The consolidated sequence of events and activities to be performed when a CDM is received (including the ones flagged as High Risk) is outlined in the figure below ("Fig.4"):

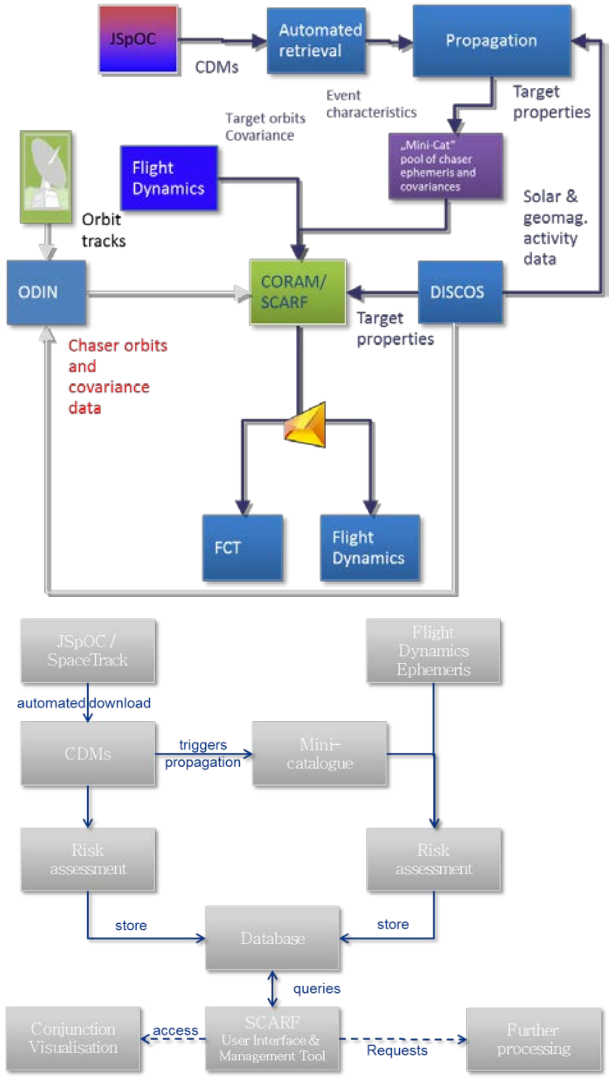

Figure 4. SDO Collision warning process

Acronyms:

ODIN: orbit determination with improved normal equations. Used to improve orbits of objects involved in the high risk conjunction events by using external tracking data acquired by radar.

DISCOS: database and information system characterising Objects in space

DRAMA: debris risk assessment and mitigation analysis

ARES: assessment of risk event statistic. It is part of DRAMA tool

ESA's MASTER: meteoroid and space debris terrestrial environment reference. The model describes statistically the natural and the man-made particle environment of the Earth down to 1 micrometre.

CORCOS: risk assessment toll. It is used to compute the collision probability of an encountered event with high accuracy.

CAMOS: tool used for manoeuvre parameter

CORAM: collision risk assessment and avoidance manoeuvre strategies

JSpOC provides Conjunction Data Messages (CDMs) to the SDO for the support of the ESOC operated missions 3 times per day and cover a time span of 7 days. The CDMs provide full orbital state information and up to 6x6 covariance matrices of both chaser (Debris) and target (CryoSat-2), from which is it possible to compute the collision risks.

Once a CDM is received and the initial collision risk based on the CDM information has been computed, it is also screened against the operational orbit provided by the Flight Dynamics team. The outcome of this second screening (called MiniCat because a small catalogue is created based on all the chasers provided in the CDMs from JSpOC) might be slight different from the initial CDM provided by JSpOC, as the orbit accuracy and propagation for the target object might be a bit different, and also planned manoeuvres could be included in the operational orbit.

Both outcomes from the JSpOC and the MiniCat CDM processing are available and distributed through the SCARF web interface, guaranteeing up-to-date and high accuracy information system to the missions. If a chaser object is predicted to exceed the accepted risk threshold ($P_{coll}>10^{-4}$), a warning email is distributed and the "Escalated Events" in the dashboard web page is populated.

6 COLLISION AVOIDANCE PROCEDURE

Once an event has been escalated, the risk assessment process starts by taking into account all information available, from probability to geometry of conjunction, making sure that all data is reliable and error free (which means assessing the orbit determination parameters). At this stage, the most relevant information for the mission is the probability of collision ("Fig.5"). Based on it, and only if it exceeds the defined threshold, all parties are informed and the manoeuvre planning discussion is initiated.

The planning of a collision avoidance manoeuvre requires the coordination between all FOS teams: Flight Dynamics, Flight Control Team and Space Debris Office, and optimally should start at least 12 to 24 hours before the conjunction event. Since currently CDMs are being received 3 times per day, and the screening volumes for which the CDMs are provided to ESA are relatively large, it is very unusual to have an event appearing with a shorter announcement time. This was not the situation in the past, when the volume for the high risk notifications from JSpOC was much smaller than the current one.

Even if an event can initially be of high risk, in the course of the days other CDM messages may be received which can confirm or not the risk. In the case that a collision avoidance manoeuvre is considered necessary, SDO performs an internal screening with the MiniCat (as well as providing the orbit with the manoeuvre to JSpOC for screening) to check whether the planned manoeuvre clears the identified risk and does not introduce new ones of similar or higher risk, with other objects, based on the most recent orbit information and the newest CDMs available. In such a case the SDO will inform the FCT and FD and the collision avoidance manoeuvre (CAM) will need to be recalculated. On the contrary if the screening of the CAM manoeuvre does not introduce other risks, the manoeuvre planned will be scheduled for official execution pending the approval of the SOM and the Mission Manager. Considering that a High Risk warning could be issued over a weekend or during public holidays, a number of people are required to be on-call (not less than 2-FCT, 1 or 2 – FD, 1 SDO and Mission Manager), and are ready to support the risk assessment and manoeuvre preparation at any time.

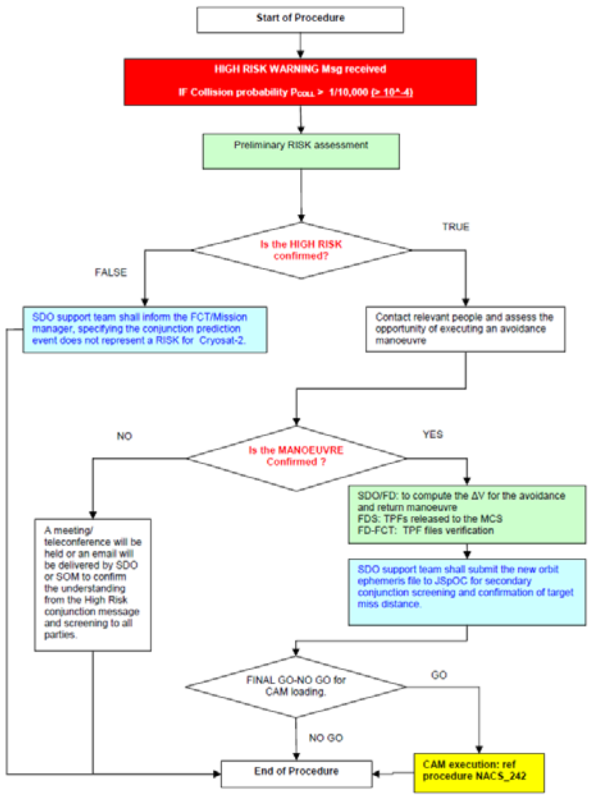

Figure 5. FCT procedure flowchart

If the probability of collision is larger than 10^{-4}, it is likely that a manoeuvre is necessary. However, in that case the direction of the approach is also considered. Depending on the type of approach, a slight change on

the orbit of the chaser (thanks to a new orbit determination) may significantly reduce the risk.
Furthermore, the solar and geomagnetic activity affect the propagation of both target and chaser orbits, which results in an unpredictable environmental variable that increase the complexity of the risk assessment.

In case of a high risk event, the SDO clarifies if the Chaser is an active and controllable satellite (and if it is the case, coordinates with the operator of the chaser satellite), and also analyses if the risk is increased by a multiple conjunction (cloud of debris) or not. The latter event might result in a very complex situation in terms of manoeuvre planning, since any small orbit correction could potentially increase the risk of a conjunction with a different object.

Another parameter to take into consideration is the covariance. If the covariance 1-sigma in radial direction is very large (~ 100 m or more), it might indicate the tracking update rate is poor. This can also be observed in the orbit determination parameters provided in the CDM. In such a case, the SDO may recommend to wait for updates of the chaser orbit as the information available is not considered reliable.

Last but not least the FCT shall consider if there is enough margin between the close conjunction event and the timing for the FD/FCT team to generate, verify and uplink the command sequence required for the CAM and eventually distribute to the SDO the new orbit prediction (including the CAM) for a second screening. These operations require not less than 6 to 10 hours.

In any case the final decision whether to manoeuvre shall be taken by the SOM and Mission Management, supported by all information provided by the different teams.

As part of the detailed assessment of the manoeuvre characteristics a new tool has been recently introduced in the CAM process. This tool is named CORAM (collision risk assessment and avoidance manoeuvre strategies) and is in use by the SDO team for probability (CORCOS) and manoeuvre parameter computation (CAMOS). It uses the CDMs information for the chaser and the operational orbit for the target (CryoSat-2) as input for calculation of the probability of collision and manoeuvre parameters. Opposed to the old criteria for a CAM sizing, which was based on the radial separation and on the covariance sigma in the radial direction, the new tool allows to select a manoeuvre size based on the reduction of the collision probability. This new tool requires as input a predefined and agreed value for the escape probability (10^{-6}), which is the maximum probability of collision that should be computed at the time of the close approach if the CAM is executed. As before, the manoeuvre direction (prograde or retrograde), is selected according to the relative radial position between target and chaser, in order to avoid crossing the zero in radial direction. The value of 10^{-6} for the escape probability has been selected considering the usual values for the background risk that is accepted (as extracted from the ARES tool).

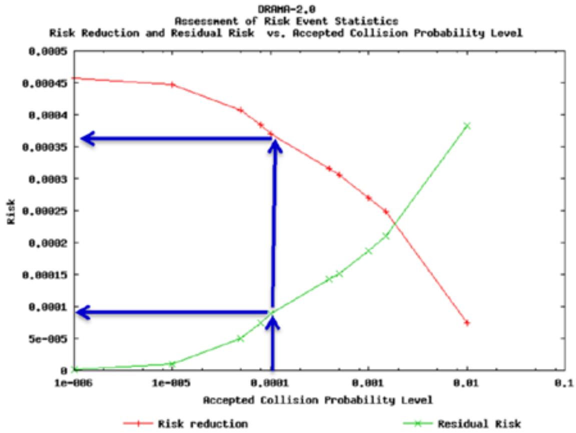

Figure 6. Risk evolution vs ACPL

In other words the residual risk for an ACPL of 10^{-4} is almost of 10^{-4} ("Fig.6"). Therefore if for anything above 10^{-4} with the escape probability set to 10^{-4}, we would double the residual risk (background residual risk is always present and equal to 10^{-4}). On the contrary for a target manoeuvre probability of 10^{-5} the residual risk is increasing by 10%, while for 10^{-6} the residual risk is only increased by 1% which is considered noise.

The CORAM tool is therefore used on CryoSat-2 for Delta-V estimation for the avoidance manoeuvre (debris avoidance). Usually, a return manoeuvre is performed to reacquire the CryoSat-2 ground-track dead-band and reference orbit, but the size of this manoeuvre may be optimized in order to initiate a new control cycle.
The output of the tool, used for the decision of the CAM delta-V, is summarized by two plots ("Fig.7"):
Plot1. Collision Risk vs DV and
Plot2. Radial Separation vs DV.

The entry point of the first plot is the ESCAPE PROBABILITY = 10^{-6} from which the DV is derived for both up (prograde) / down (retrograde) manoeuvres. Obviously, the CAM direction needs to be agreed before starting the manoeuvre sizing process based on the relative position of the Chaser and Target.

Finally, according to the estimated DV, the radial separation between Chaser and Target can be assessed. It is as well clear that in case of large covariance it may be required to perform a very large manoeuvre to be able to reduce the risk below the agreed escape probability. In case of multiple conjunction events, this method/tool is not completely applicable as it only optimises the manoeuvre size for a given event. In such a case, multiple iterations may be required in order to make sure that all the risky events are consistently handled and that no risk remains after the execution of the CAM.

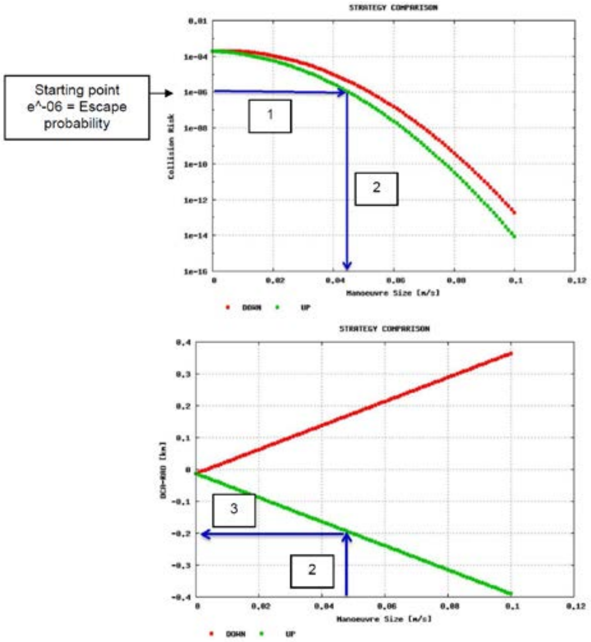

Figure 7. Delta-V manoeuvre estimation using the CORAM tool

Once the decision on the delta-V size and direction has been taken, the following information shall be provided to the FCT by FD once the manoeuvre planning has been completed: DVs (as decided based on the CORAM tool), THR On-Time(secs), TPFs (manoeuvre sequences), PSOs and fuel consumption.

7 EFFECT OF FREQUENT CAMs ON SCIENCE DATA AND MISSION BUDGET

The collision avoidance manoeuvre (CAM) might have a non-negligible impact in the fuel budget and mission lifetime of a mission. In addition, whenever CryoSat-2 performs an orbit correction, the science data has to be halted during the time when YAW steering is disabled (and then SIRAL is in standby mode). For planned orbit maintenance manoeuvres, this can be foreseen in advance, but for CAM it is more unexpected. This time window might be different for a prograde and a retrograde manoeuvre:

- Science unavailability period for single prograde manoeuvre: about 1 and ½ orbit (~ 2.5 hours)
- Science unavailability period for retrograde manoeuvre and single prograde manoeuvre scenario: about 3-5 orbits (~ 5-8 hours). For a combined retrograde and prograde manoeuvre the outage may be longer in order to characterise the first manoeuvre so that the second manoeuvre restarts the orbit control cycle.

8 CRYOSAT-2 IN ORBIT EXPERIENCE

Over the past 7 years, the CryoSat-2 mission has experienced 112 High risk warning events, from which only 12 of them resulted in a CAM ("Fig.8"). The first CS2 alert from JSpOC (Cosmos 2251 debris with a radial miss distance of 71m) was received only 19 days after launch. The first CAM for Cryosat-2 was executed in September 2010, less than 6 month after launch. The most active year in term of collision risk was in 2014, when 4 CAM had to be executed, while in 2011 none of the 13 warning messages resulted in a CAM. In 2014. the Fengyun-1C, Cosmos-2251 and Iridium-33 debris were recurring in the warning messages. Indeed, these two major fragmentation events have significantly increased the amount of debris in the 700 to 800km altitude region and clearly affect the environment where Cryosat-2 is flying:

- Anti-satellite test which resulted on the fragmentation of Fengyun 1C, in January 11th 2007, with more than 3000 new debris larger than 10 cm catalogued.
- Iridium 33/Cosmos 2251 collision on February 10th 2009 at ~790km, first collision between two intact satellites, which created over 2200 catalogued debris fragments (>10cm)

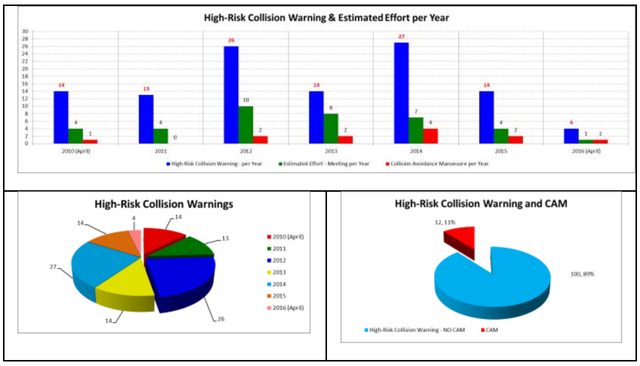

Figure 8. CryoSat-2 Statistics

9 CONCLUSION

Despite the large number of orbit analysis and conjunction assessments performed by the SDO in the last seven years only few critical events resulted in an avoidance manoeuvre confirming the validity of the space debris environment model MASTER at the CryoSat-2 altitude when an ACPL of 10^{-4} is selected. During this time, the operational methods and strategies to plan and execute the avoidance manoeuvre have evolved, as the providers of close approach data increased the quality and quantity of the data that is used to assess the risk of a close approach and made the previous process obsolete.

In addition, the ESA SDO adapted to the changes by improving the means of communication with the FCT, with the inclusion of new software adopted by the CryoSat-2 SDO team for a graphical visualization of the conjunction and the SCARF web interface. In addition, the CORAM tool was developed to support the manoeuvre planning and delta-V estimation, therefore making the CAM process much more efficient and facilitating the decision process and the response on whether to manoeuvre or not.

The inclusion of these new tools resulted in the need for the CryoSat-2 team to undergo additional training in the use of the tools and processes in order to understand how to use the new data and to be able to compute and analyse the risk and define the manoeuvre profile and size.

As a consequence the FCT procedure for CAM has been modified and simplified, making the overall process more robust and more efficient in terms of time and effort for the CryoSat-2 team.

10 References

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