CRYOSAT COLLISION WARNING AND LOW THRUST AVOIDANCE MANOEUVRE STRATEGY

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ABSTRACT

As a consequence of the steady growth of space debris, the resulting collision risk between Earth orbiting objects has, in recent years, become a non-negligible factor for launch and on-orbit operations.
Most of the Earth orbiting satellite shall have propulsion and operation capabilities to perform collision avoidance manoeuvres and end-of-life de-orbiting.
The CryoSat satellite case is here presented.
CryoSat is the first of the ESA's Earth Explorer Opportunity Mission spacecraft.
The first step in avoiding a collision between two orbiting objects is the detection of potential collision events.
In the framework of the CryoSat mission Phase-A/B, one collision event has been predicted for the three and a half years of CryoSat nominal mission lifetime.
The optimum avoiding manoeuvre strategy with low thrust has been computed and here described. Given the low thrust available for the CryoSat mission, the avoidance manoeuvre has to be planned and started well in advance of the predicted impact date. An analysis of the required delta-v as a function of the collision manoeuvre starting point and the number of thrust arcs has been performed.

1. INTRODUCTION

Since the first satellite break up in 1961, more than 100 spacecraft have fragmented into orbit. More than 25,000 objects have been tracked, of which more than 8,000 are still orbiting the Earth. Most of these objects, which are not operational anymore, could present a serious hazard for operational satellites.

The space-faring nations are all aware of the hazard and detrimental impact of space debris on all areas of space flight and are fixing rules while designing a space mission.

The majority of future Earth orbiting space missions must have both propulsion and operation capabilities to perform collision avoidance manoeuvres and end-of life de-orbiting of the spacecraft [3.].

The first step in avoiding a collision between two orbiting objects is the detection of potential collision events.

Opportune avoidance criteria should be fixed.

In case of the CryoSat satellite, as first "Phase-A" [12.] approximation, data coming from the experience of the ESA's ERS-1 and ERS-2 satellites have been used to fix a collision reference ellipsoid as a threshold for quantifying conjunctions.
A collision reference ellipsoid with an extension of 1km × 2.5km × 1km (radial × along-track × out-of-plane) has been assumed for the CryoSat satellite.

During Phase B [13.] a deeper analysis has been performed while keeping the mentioned reference ellipsoid.

Starting from the TLE catalogue of space debris, different filtering techniques have been applied in order to remove the objects whose orbital parameters prevent them from posing a threat to the CryoSat satellite.

The collision probability has been calculated.

One collision event has been predicted and assumed for the three and a half years of CryoSat nominal mission lifetime.

This result comes also from considering that, apart from the assessment of the collision risk itself, operationally, in case of the ERS-1 and ERS-2 satellites, only 2 collision avoidance manoeuvres have been performed in 14 years of accumulated mission.

The assumed avoidance manoeuvre would be one height-adjust manoeuvre, and a delta-altitude of 1400 m has been assumed. The mentioned raising manoeuvre would require around 3.5 hours (2.2 orbits) to be performed, given the available thruster on board the satellite.

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The optimum avoiding manoeuvre strategy with low thrust has been computed and here described. Given the low thrust available for the CryoSat mission, the avoidance manoeuvre has to be planned and started opportunely in advance with respect to the predicted impact date.

2. CRYOSAT: MISSION OVERVIEW

CryoSat is the first selected Earth Explorer Opportunity Mission belonging to the ESA Earth Observation Envelope Program (EOEP).

The purpose of the CryoSat mission is to determine trends in the ice masses of the Earth and in particular to test the prediction of thinning Arctic sea ice due to global warming, which will change the climate of the Arctic and possibly other regions. Additionally, it will provide information about the contribution of the massive Antarctic and Greenland ice sheets to global sea level rise.

Such effects will be observed on a global scale by a high spatial resolution altimeter, the SIRAL.

CryoSat, whose main characteristics are listed in Table 1 and shown in Fig. 1, and whose launch date is tentatively planned for late 2003, will be flying on two different 92º-inclined Earth orbits, the Science Phase Orbit and the Validation Phase Orbit.

Nominal lifetime for the CryoSat satellite, whose main responsible is ASTRIUM GmbH, is 3.5 years.

CryoSat will board a small thrust-level Cold Gas Propulsion System (RCS), using 16 Attitude Control Thrusters (10mN) for force-free attitude control and 4 Orbit Control Thrusters (40mN) for orbit transfers, orbit maintenance and evasive manoeuvres.

CryoSat	
Mission	3.5 years
Launch	Late 2003
Orbit	Non Sun-Synchronous
Altitude	~ 720 km
Inclination	92º
Mass	~ 730 Kg
Repeat cycle	1year, 30days, 2days
Payload	SIRAL altimeter DORIS receiver Laser reflector

Table 1. CryoSat characteristics

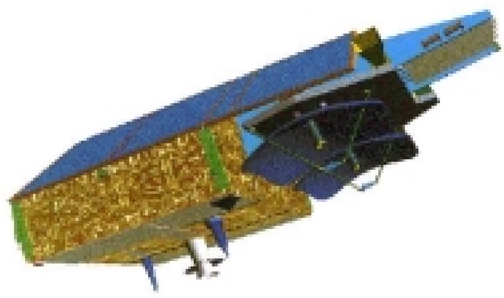

Fig. 1. The CryoSat satellite

3. AVOIDANCE CRITERIA

The decision to perform or not an avoidance manoeuvre between an operational satellite and a tracked object (either a different operational satellite or a space debris) depends on several factors such as the minimum allowed fly-by distance, the fly-by geometry and the associated collision probability, together with position uncertainties, at conjunction epoch, of the bodies involved into the analysis. Additionally, the effect of the evasive manoeuvre on mission operation and payload performance should not be neglected.

In the case of the CryoSat satellite the assumed avoidance criteria mirror those used for the ERS-1 and ERS-2 satellites.

A CryoSat satellite collision manoeuvre would be performed in case the assessed collision risk based on the best available orbit information is larger than 1/10,000 or if the distance of the closest approach is consistently smaller than 300m (considering uncertainties of chasers, targets and propagation models).

4. COLLISION RISK

As a first approximation, and in order to establish an eventual collision avoidance strategy for the CryoSat satellite, investigations have been conducted taking as reference what previously performed and accepted for the ERS-1 and ERS-2 satellites, whose orbits are very similar to the CryoSat's one.

For both ERS satellites, ESOC has performed conjunction event predictions and collision risk assessment, based on the USSPACECOM catalogue [1.], [2.].

The referenced data refer to a time frame that goes from December 4th 1995 and February 17th 1997 (14 months).

A collision reference ellipsoid with an extension of 10km × 25km × 10km in radial, along-track and out-of-plane directions has been used as threshold for qualifying conjunctions.

A total of 4596 conjunctions met such a reference collision ellipsoid.

Table 2 shows the conjunction events of the ERS-1 and ERS-2 satellites with members of the USSPACECOM catalogue population as function of the fly-by distance expressed in functions of the reference ellipsoid (10km × 25km × 10km).

Fraction of reference ellipsoid	1/1	1/2	1/10	<1/25
Total conjunction (ERS-1 +ERS 2)	4596	1167	44	6

Table 2. Conjunction events of ERS-1 and ERS-2 with USSPACECOM catalogue population

A collision reference ellipsoid of 1km × 2.5km × 1km (radial × along-track × out-of-plane) has been assumed for the CryoSat satellite, which is 1/10 of the original ERS threshold volume.
As from Table 2, 44 passes are predicted within 1/10 of the original reference ellipsoid (see Table 2) in the ERS scenario for a 14-month time period.

It has to be taken into account that the prediction of conjunction events does not necessarily reflect the risk of collision occurrence, being the total collision risk for a single conjunction event is a function of the relative approach velocity, the collision cross-section A_{col}, the debris's probability density and the time.

Assuming a collision cross-section A_{col} of $3m^2$, the annual risk of collision resulted to be 1:60, or one collision every 60 years. Applying this result to the CryoSat case, it translates into about 0.06 collisions in the 3.5-year CryoSat lifetime.

Based on the presented considerations, as first approximation it was assumed that one collision risk manoeuvre was supposed for the 3.5 years nominal lifetime of CryoSat.

This assumption as been also supported from considering that, in case of the ERS 1 and 2 satellites, only 2 collision avoidance manoeuvres have been performed in 14 years of accumulated mission.

5. FILTERS

In the framework of the CryoSat Phase-B contract a deeper analysis has been performed in order to confirm the assumed single collision evasive manoeuvre along the 3.5 years of CryoSat mission lifetime.

To maintain consistency with what previously assumed and reported, the comparison with the ERS-1 and ERS-2 satellites has been kept.

The complete set of TLE (Two Line Elements) has been assumed while propagating them together with ERS-1, ERS-2 and CryoSat data for a period of two weeks.

The simplest way to predict a collision event occurrence is to step along the trajectory of the target satellite and the catalogued objects, computing for each time-step their distance and detect the trespassing of the fixed security threshold. Due to the high number of orbiting objects this method tends to impose a high computational load.

In order to avoid unnecessary computational burden, four filters are used to eliminate those objects whose characteristic make impossible for them to really collide with the target satellites.

A first sieve rejects all the obsolete object states. Of the remaining filters, two are purely geometrical and one uses the known properties of the orbital motion of the analysed objects.

The objects resulting from such sorting are the ones effectively propagated with high accuracy in order to come out with the collision risk probability.

The applied filters, which have been basically designed as defined in [1.], [2.], [6.], have been defined as follows:

- ***The Epoch Filter.*** This filter removes from the TLE data sets the objects that have an epoch outdated w.r.t. the simulation starting epoch. This is performed in order to discard unreliable data sets. The TLE will not be reliable if not updated for a certain time. This time will depend on the data accuracy, the evolution of the error and the time span in which the collision is assessed.

- ***The Perigee-Apogee Filter.*** This filter removes those objects that have an altitude interval that does not intersect the target satellite altitude belt, which is, obviously, identified by taking into account the orbit perigee and apogee. Those objects whose altitude belt does not intersect the target satellite orbit altitude range will not be able to collide with it.

- ***The Radial Filter.*** This filter eliminates those objects that, at the intersection line between the target and chaser orbit planes, have a position separation different from the radius of the target orbit along the same line.

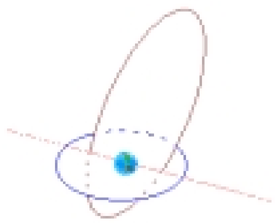

Fig. 2. Radial filter

- ***The Time Filter.*** This filter eliminates those objects that cross the planes intersection line at a very different epoch with respect to the main object.

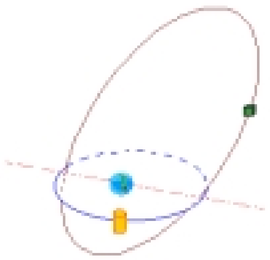

Fig. 3. Time filter

The simulation, performed during a two weeks time (starting date 07/17/98, 03:05:16,64) along the ERS-1 and ERS-2 orbits and the CryoSat orbit (starting date 08/17/00, 00:00:00), showed that from the initial 8000 (8119 for ERSs, 8373 for CryoSat) USSPACECOM catalogued objects it is possible to lower to 3, 7 and 11, respectively, the number of objects that will require an accurate propagation. More in details, about the 13,5% of the initial TLE sets were rejected due to the epoch sieve (TLE older than 15 days), the 60% did not pass the perigee-apogee filter, the 26% and the 0.5% were rejected due to the radial and the time filter respectively.

The obtained results are depicted Fig. 4, which reports the number of TLE sets after the successive application of each of the mentioned filters.

The orbit states of those objects that were not rejected by the selected four filters, and those of the target satellite must be propagated after applying a transformation from the original TLE format.

To obtain the osculating orbital elements of the revealed target objects it is necessary to add the periodic effects of the perturbation exactly in the same way they were removed.

The SGP4 model has been used for this work.

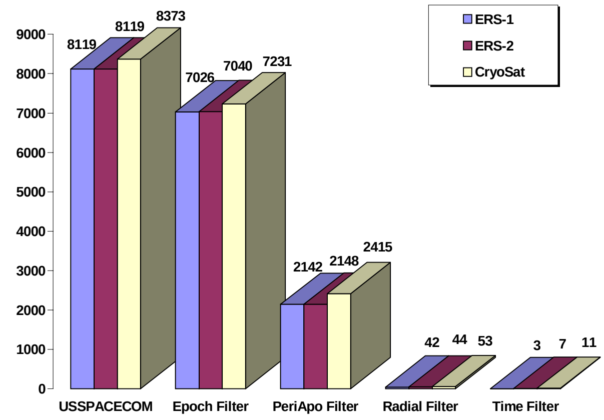

Fig. 4. ERS-1, ERS-2 and CryoSat "filtered" data

The CryoSat collision risk probability has been calculated being in the order of o[10^{-7}], well below the value fixed as avoidance criteria.

Once again, and keeping in mind the operational results of the ERS-1 and ERS-2 missions, the consistency of performing a unique evasive manoeuvre during the CryoSat 3.5 years of mission lifetime has been confirmed.

6. CRYOSAT AVOIDANCE MANOEUVRES

In the framework of CryoSat Phase-A/B study it has been stated that only one collision risk manoeuvre should be assumed for the CryoSat satellite during its 3.5 years lifetime.

A 1.4 km height-adjust manoeuvre has been assumed.

Such assumption was supported from the following considerations:

- A Delta-V worst case needed to be calculated.
- Expected short collision notification time.
- Even if the Delta-V, and as a consequence the propellant budget, represented a mission critical requirement, the required Delta-V was expected to be very low.

The supposed raising manoeuvre would require around 3.5 hours (2.2 orbits) to be performed, given the available 40mN thrusters carried on board the satellite. Both the cases of the ideal Hohmann transfer and the continuous manoeuvre with available thrusters have been analysed. The resulting Delta-V (**1.480 m/s**) are identical (Table 3).

The evolution of orbital elements and thrust during the raising manoeuvre are shown in Fig. 5 and Fig. 6 respectively.

The starting time has been set in the middle of the stay in SPO, on 16th April 2005.

For completeness, a manoeuvre to lower CryoSat to its nominal orbit has been also calculated.

Table 4 shows the parameters used for the low-thrust simulations, and provides an estimate on fuel consumption, based on a tentative specific impulse value for the cold-gas thruster.

		One Manoeuvre		**Mission Total**
Strategy	**Leg**	**Δ a** $_{\text{mean}}$	**ΔV**	**ΔV**
		[m]	**[m/s]**	**[m/s]**
Hohmann Transfer	Raising	1400	0.740	1.480
	Lowering	1400	0.740	
Continuous Manoeuvre	Raising	1400	0.740	1.480
	Lowering	1400	0.740	

Table 3. Comparison between delta-V in case of Hohmann transfer and continuous manoeuvre

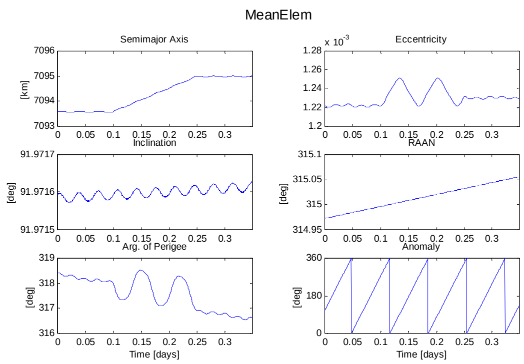

Fig. 5. Mean Elements of CryoSat during the Collision Avoidance Raising manoeuvre (test case date: 16/04/2005, J2 perturbations only).

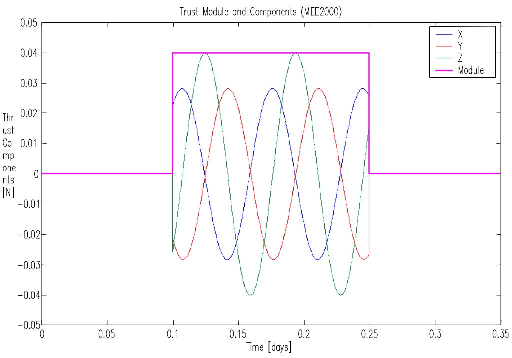

Fig. 6. Thrust Module and Components (MEE 2000) during the Collision Avoidance Raising manoeuvre from SPO to the Parking Orbit (test case date: 16/04/2005, J2 perturbations only).

	Raising	**Lowering**
Initial Mass [Kg]	700.000	699.121
Final Mass [Kg]	699.121	698.242
Burned Fuel [Kg]	0.879	0.879
Specific Impulse [s]	60	60
Durat. of Thrust Arc [s]	12950	12950
Equivalent Delta-V [m/s]	0.740	0.740

Table 4. Simulation parameters for the collision avoidance manoeuvre.

7. Manoeuvre Optimisation

The assumed altitude-raising manoeuvre has been optimised.

The OPXRQP optimisation algorithm has been used.

This algorithm implements a non-linear quadratic programming and was developed in the early eighties by the Numerical Optimisation Centre (England).

A new problem is derived from the physical one by means of scaling transformations

$$x_i = \varepsilon_{xi}\xi_i, \quad i = 1,\ldots,n \qquad (1)$$

$$F(\vec{x}) = \varepsilon_f\, f(\vec{\xi}) \qquad (2)$$

$$G_i(\vec{x}) = \varepsilon_{Gi}\gamma_i(\vec{\xi}), \quad i = 1,\ldots,m \qquad (3)$$

where $\vec{x}$ is the new vector of optimisation parameters, of dimension n; F the new cost function, and $\vec{G}$ the new vector of constraints, being m_e the first components equality constraints, and the remaining being the inequality ones.

The problem to be solved consists in the minimisation of the cost function:

$$F(\vec{x})$$

subject to the following constraints:

$$\begin{aligned} &G_i(\vec{x}) = 0, \quad \mathrm{i} = 1,\ldots,m_e \\ &G_i(\vec{x}) > 0, \quad \mathrm{i} = m_e + 1,\ldots,m \end{aligned} \qquad (4)$$

An augmented cost function P is defined which takes into consideration the set of active constraints by means of the penalty parameter *r:*

$$P(\vec{x},r) = F(\vec{x}) + \frac{1}{r}\vec{G}(\vec{x})^T\vec{G}(\vec{x}) \qquad (5)$$

The minima of the augmented cost function tend towards a minimum of the original function in the feasible region of $\vec{x}$ as the penalty parameter **r** approaches zero.

In case of the CryoSat satellite the propellant mass, and as consequence the Delta-V, has been optimised.

The propellant mass therefore represents the cost function $F(\vec{x})$.

The fixed constraints, G(X), are set on the final position (semi-major axis and eccentricity).

The optimised parameters are the true anomaly, i.e. the initial point along the orbit where the evasive manoeuvre will start to be performed, and the length of the thrust arc.

Fig. 7 shows the trend of the required Delta-V as function of the True Anomaly at manoeuvre start.

As from Fig. 7, the Delta-V varies depending on the position of the manoeuvre starting point.

In case of CryoSat such effect, being quite small due to the very small eccentricity of both initial and target orbits, does not really resulted a critical point.

A minimum Delta-V of about 0.740 m/s has been found. The optimum duration of the thrust arc resulted to be in the order of ~13,000 seconds.

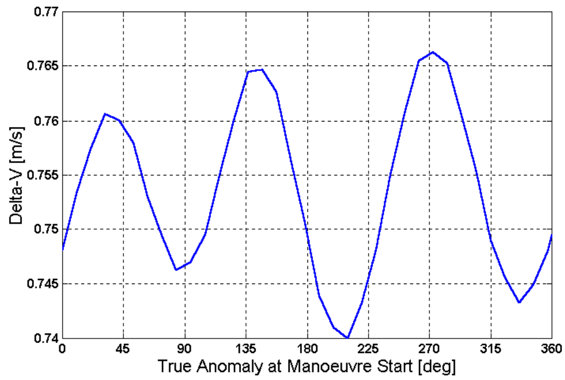

Fig. 7. Delta-V as function of the True Anomaly at the manoeuvre starting point

A different analysis has been performed in order to investigate the effect on the required optimum Total Delta-V in case of more than one manoeuvre.

Fig. 8 shows as the number of performed manoeuvres does influence the total Delta-V.

As from given trend, for an increasing number of manoeuvres the required optimum Delta-V decrease. Once again, in case of CryoSat, such a decrease resulted to be very small.

- ❑ Optimisation of the starting point of the manoeuvre (in case only one manoeuvre is envisioned) results in a maximum Delta-V reduction of 0.026 m/s (3.5%)
- ❑ Optimisation of the number of manoeuvres (between 1 and 4) results in a further maximum Delta-V reduction of 0.014 m/s (2.0%)

The complete optimisation of the manoeuvre would therefore allow to reduce the required Delta-V from a worst case scenario of 0.766 m/s to 0.726 m/s, with a 5.5% saving in propellant.

Fig. 8. Delta-V as function of the number of performed thrust arcs (or manoeuvres)

8. CONCLUSIONS

In the last years a clear trend towards a Space Debris policy mitigation has been shown by every space-faring nation.

Avoidance manoeuvres and end-of-life de-orbiting capabilities are becoming standard requirements in space mission definition and design.

An approach to the problem of avoiding a collision between two orbiting objects has been presented and applied to a future Earth Observation satellite.

The proposed approach goes from the determination of the collision risk through the optimisation of a manoeuvring strategy, while supported by opportunely fixed avoidance criteria.

Depending on the particular mission, an opportune collision avoidance strategy should be tailored, trading off on the mission requirements.

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This paper and the underlying work was performed in the frame of the ESA study on the CryoSat mission Phase-A/B. Figures and information have been provided with permission of ASTRIUM GmbH and ESA.

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