Orbit Aspects of End-Of-Life Disposal from Highly Eccentric Orbits

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Abstract: *End-of-Life disposal options are well established for missions in the Low Earth Orbit (LEO) and Geostationary Orbit (GEO) regions and consist, respectively, of near circular graveyard orbits or atmospheric decay. Science missions such as ESA's Integral and Cluster-II missions, however, sometimes operate on highly-eccentric Earth orbits (HEO) to achieve their mission goals, such as astronomical observations or measurements of the Earth's environment. The dominant perturbation forces on these orbits are typically caused by the gravity fields of Sun and Moon. This paper highlights ESA's investigations on orbit manoeuvres to change the long-term evolution and to finally influence the orbital lifetime, re-entry epoch, and re-entry location for the Cluster-II and Integral spacecraft. Manoeuvres, years before the end of the mission, to target a safe natural re-entry driven by third body perturbations several years after the end of mission, were analysed and implemented. The manoeuvre options considered are presented with a view to their cost in delta-v and therefore maximum post-manoeuvre operational lifetime and their effect on orbital lifetime and re-entry location.*

Keywords: *End-Of-Life Disposal, Highly Eccentric Orbits, Integral, Cluster-II*

1. Introduction

ESA's Cluster-II mission investigates the interaction between cosmic plasma and weak magnetic fields. Flying in a tetrahedral formation, four spacecraft collect the most detailed data yet on small-scale changes in near-Earth space and the physical processes between the charged particles of the solar wind and Earth's magnetosphere.

The task of Integral (**Inte**rnational **G**amma-**R**ay **A**strophysics **L**aboratory), is to gather some of the most energetic radiation that comes from space. The mission is dedicated to the fine spectroscopy and fine imaging of celestial gamma-ray sources with concurrent source monitoring in the X-ray and optical energy ranges. Integral is the most sensitive observatory in the hard X-ray to soft gamma-ray range ever launched.

International space debris mitigation standards request a permanent clearance of the Low Earth Orbit (LEO) and Geostationary Orbit (GEO) protected regions. Furthermore, the risk on-ground, following a potential atmospheric re-entry, shall be constrained by clear safety limits. Corresponding disposal options are well established for missions in GEO and LEO, and consist, respectively, of near circular graveyard orbits or atmospheric decay.

When the Integral and Cluster-II missions were designed these standards and corresponding ESA requirements were not yet established. Correspondingly, they are not enforced by current ESA rules for these two missions, however a best effort approach shall be taken. For Cluster-II the remaining delta-v constraints do not allow for a controlled de-orbit (i.e. direct re-entry boost). Instead, without dedicated disposal action, the combination of the perturbing accelerations will force the re-entry of all four spacecraft. The first re-entry will occur in 2024, followed by two re-entries in 2026 and the last one in 2038. Integral will not re-enter naturally within 200 years, however it will repeatedly drift into the LEO region and cross the GEO protected region. Similarly to Cluster-II, delta-v constraints do not permit a controlled re-entry.

Disposal options for HEO missions (with perigees in or close to the LEO region and eccentricities significantly above those of Geostationary Transfer Orbits, which have eccentricity ~0.73) are not well established and have been studied in recent years by ESA in more detail. This paper highlights ESA's investigations on orbit manoeuvres to change the long-term evolution and to finally influence the orbital lifetime, re-entry epoch, and re-entry location for the Cluster-II and Integral spacecraft. Manoeuvres, years before the end of the mission, to target a safe natural re-entry driven by third body perturbations several years after the end of mission, were analysed and implemented. The manoeuvre options considered are presented with a view to their cost in delta-v and therefore maximum post-manoeuvre operational lifetime and their effect on orbital lifetime and re-entry location.

2. Mission overview

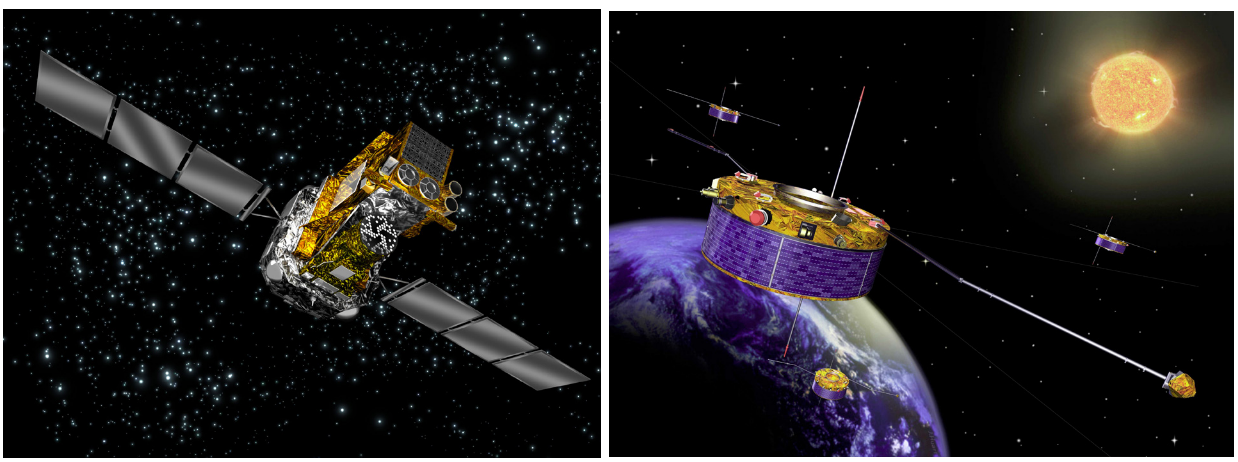


Figure 1. Artist's impression of Integral (left) and Cluster-II (right) [1]

2.1. Integral

Integral was launched on 17 October 2002 with a Russian PROTON launcher from Baikonur (Kazakhstan). Satellite control is performed from the mission operations centre located at ESOC. The nominal 2-year mission operations phase was completed on 1 January 2005 and several mission extensions have been granted since then. Integral operations are currently funded until 31 December 2016 and preliminary support for a further extension during 2017-2018 is given subject to review in late 2016.

Owing to background radiation effects in the high-energy detectors, scientific observations are always carried out while the satellite is well above the radiation belts. Therefore Integral follows a highly eccentric Earth orbit (HEO), where it spends most of the time above the belts. The orbital period is 3 days allowing regular ground station coverage pattern and advanced observation planning. The initial orbital parameters were a perigee height of 9000 km and an apogee height of 150000 km at an inclination of 56 deg.

2.2. Cluster

Cluster was expected to benefit from a 'free' launch on the first test flight of the newly developed Ariane-5 rocket. Unfortunately, the launcher's maiden flight on 4 June 1996 failed resulting in the loss of the payloads. When studies demonstrated that it would be possible to reuse some parts and to fly four spacecraft which were almost identical to those which were lost, the replacement mission was named Cluster-II and the four spacecraft were launched in pairs on two Soyuz/Fregat from Baikonur on 16 July and 9 August 2000. Satellite control is performed from the operations control centre located at ESOC.

In order to have a clear naming convention, we will use spacecraft names as given in Table 1 and use the term “Cluster” for the overall mission (i.e. dropping the “II”), in particular Cluster-1 and Cluster-2 will refer to the specific spacecraft and not to the original or recovered overall mission.

Table 1. Naming conventions for the Cluster-II spacecraft

Name	Rumba	Salsa	Samba	Tango
Numbered Name	Cluster-1	Cluster-2	Cluster-3	Cluster-4
Flight Model	FM5	FM6	FM7	FM8
COSPAR ID	2000-045A	2000-041B	2000-041A	2000-045B
US catalog ID	26463	26411	26410	26464

As for Integral, the nominal mission operations phase lasted 2 years and several mission extensions have been granted since then. Cluster is currently funded until 31 December 2016 and preliminary support for a further extension during 2017-2018 is given subject to review in late 2016.

In order to explore the magnetosphere Cluster-II orbits on a highly eccentric orbit, initially near-polar with orbital period of 57 hours at a perigee height of 19000 km and apogee height of 119000 km. Throughout the mission several large orbit manoeuvres were performed changing the relative distances of the spacecraft along their orbits and therefore the size and orientation of the tetrahedron built by them. This allowed to investigate the variability of the magnetosphere on different size and timescales. The last large orbit control manoeuvres have been performed in 2009.

3. Analyses of disposal options

The topic of options for End-of-life approaches for Integral was first raised in the frame of the mission extension review in 2012. A quick analysis for Integral showed that

- No natural re-entry occurs within 200 years (see Figure 2), but occasional crossings of the LEO, and more often of the GEO, protected zones do happen (Figure 3).
- With the delta-v available in 2012 a direct re-entry manoeuvre was infeasible at that time (i.e. at the end of the by then approved mission lifetime) but marginally possible in 2020 and 2028 due to the then lower perigee requiring smaller delta-v. However this assumed that the same delta-v would be available at that time, which would certainly not be the case, if the SC would be operational at all at this time. However the idea of an earlier manoeuvre that may lead to a different long-term evolution of the perigee altitude and ultimately to re-entry was raised.
- A raise of the perigee in 2013 would not lead to a long-term clearance of the LEO region, i.e. the perigee height would drop again below 2000 km later on.

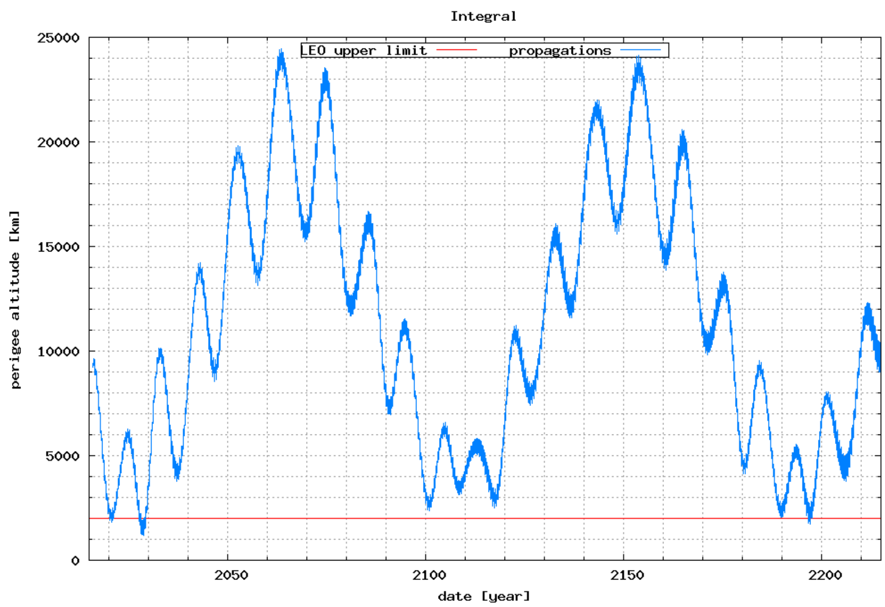


Figure 2. Evolution of perigee altitude for Integral without manoeuvre. For comparison the upper LEO limit of 2000 km is shown in red.

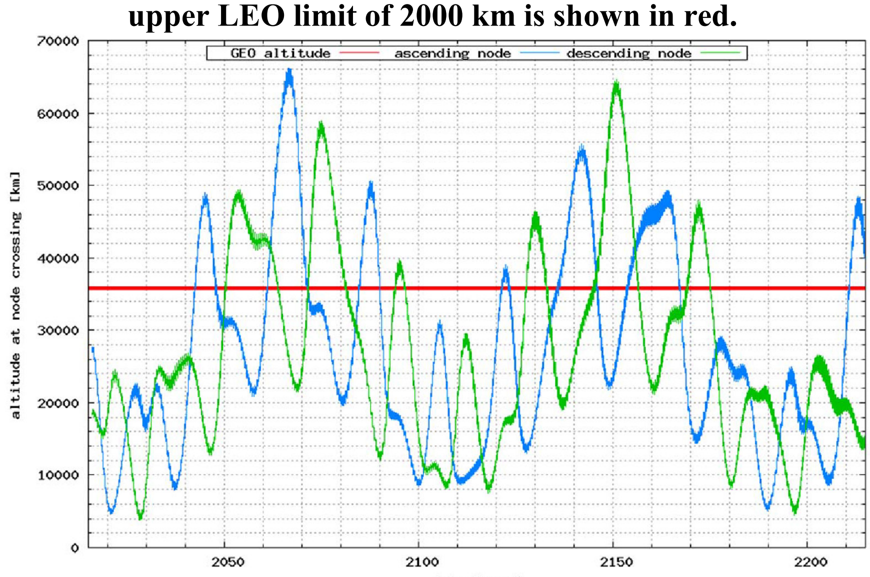


Figure 3. Altitude at node crossings for Integral without manoeuvre. For comparison the upper protected GEO altitude range shown in red.

For Cluster the investigations of re-entry trajectories have a longer history. In 2007

- the orbit of Cluster-2 (Salsa) was adjusted as part of the constellation change manoeuvers to avoid the otherwise expected re-entry in spring 2010, shifting the re-entry date to 2011, beyond the then foreseeable mission extension until end of 2010,
- the option to shorten the on-orbit lifetime of Cluster-1 from 2037 to 2025/6 was discussed and
- the option to perform manoeuvres of less than 15 m/s in 2010 to prevent re-entry in 2011 and instead start another period of increasing perigee altitudes was identified ([2]).

Such manoeuvres of about 13 m/s total delta-v were indeed executed successfully in mid-2010. This led to natural long-term evolutions of the perigee altitude implying re-entries in the years 2024 – 2026 for three of the SC and one in 2038 for the last one (Cluster-1, Rumba) – see Figure 4 for the status at the time of the mission extension review in 2012.

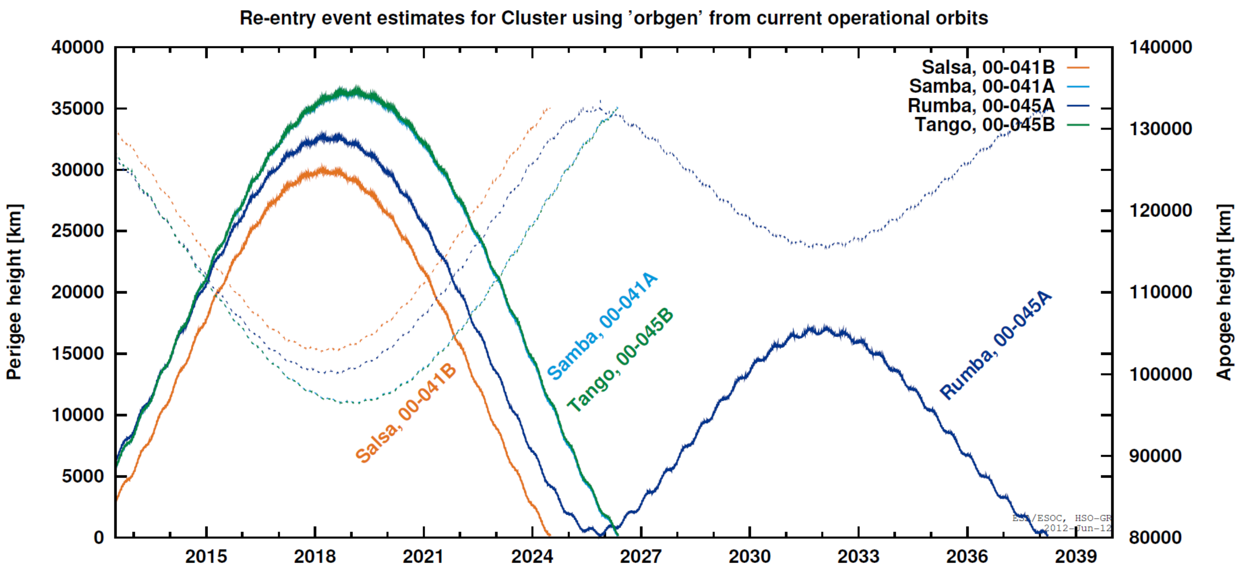


Figure 4: Evolution of perigee and apogee height for the 4 Cluster spacecraft without manoeuvre.

In the frame of the mission extensions granted in 2012, it was decided to study the orbital evolution and manoeuvre options in more detail and develop models to assess the on-ground casualty risk in case of re-entry.

These studies were performed in 2013 and 2014 and are detailed in the following subsections. For Integral they concluded in an approach of performing a sequence of large manoeuvres in January and February 2015 which changed the trajectory of Integral in a way that it will re-enter in 2029. For Cluster a strategy involving three manoeuvres of Cluster-1 (Rumba) in March 2015 was selected. This advanced its re-entry to 2025, leading to a lower on-ground risk due to the perigee being over the Southern instead of Northern latitudes.

3.1. The case of Integral

In 2012 three activities were initiated: Two studies investigating systematically various conceivable disposal scenarios and their optimisation, secondly, a numerical parametric study of manoeuvre options changing the eccentricity and thirdly a re-entry break-up model was developed to perform analyses of the break-up process and surviving fragments.

Global studies

The two studies on “End-Of-Life Disposal Concepts for Lagrange-Point and HEO Missions” treated both Integral as an example mission in more detail. They covered a wide range of disposal options, such as direct and delayed re-entry, Moon transfer, super-GEO, under-GEO, super-LEO graveyard and moon resonances which may be achieved via a variety of manoeuvre strategies. Furthermore, robustness of the strategies was studied. Contrary to the numerical analysis detailed above and below, which is parametric in nature, these studies followed an optimisation approach using semi-analytical propagation schemes allowing a wider range of manoeuvre options to be studied.

While one study, [3], showed all but the delayed re-entry and the super-LEO to be beyond the delta-v budget available, it assessed only limited manoeuvre strategies for those two scenarios. Therefore, they identified the rather costly options of adjusting the perigee altitude but missed the option of changing the apogee altitude (semi-major axis) via a manoeuvre at perigee. However in a follow-on study [4], a full optimisation in manoeuvre location, size and direction was performed. These latest results are then in line with the second study, [5], and both identify and explore the connection between the third-body perturbation and the location of the argument of perigee with respect to the Earth-Moon-Plane (see Figure 6).

While optimisation targets are not fully comparable among the studies, they do consistently show optimal manoeuvres lowering the eccentricity in the timeframe of 2013 to 2018, in-line with the parametric studies.

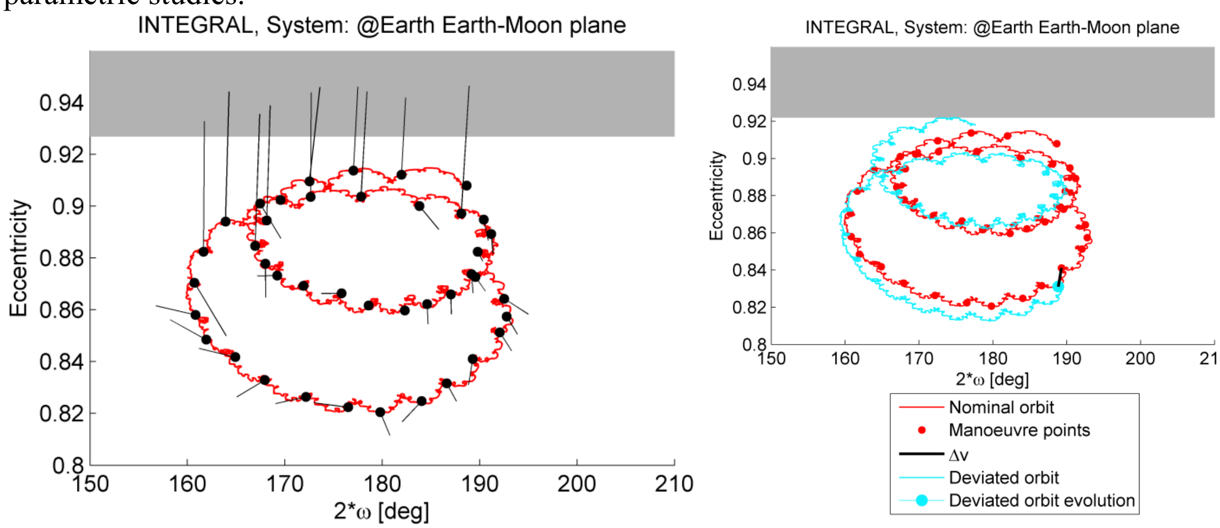


Figure 5. Integral disposal by 2029: Phase space evolution in the eccentricity-2ω phase space (Earth-Moon plane). The shaded area indicates eccentricities beyond the critical eccentricity for re-entry (at perigee altitude of 50 km). Left: between 2013/01/01 and 2028/08/07 (red line). The black line represents the re-entry manoeuvre for each time analysed in the study (black dots). Right: Nominal evolution (red) versus disposal trajectory (blue) for a disposal mano in 2014. Taken from [5].

Parametric studies

After establishing an extrapolation of the available delta-v as a function of time, a first set of simulations was performed investigating the effect of a manoeuvre at apogee changing the perigee altitude (as a refinement of the quick checks of the direct re-entry option looked at earlier). Since counterintuitive effects were expected in the long-term evolution, manoeuvres both in- and against the flight direction were simulated thereby raising or lowering the post-manoeuvre perigee. A single large manoeuvre consuming all the available delta-v was simulated varying the time of the manoeuvre (and therefore the available delta-v taking into account the fuel consumed during nominal operations during the time until the manoeuvre). It turned out that only very early manoeuvers (during the first half of 2013) would lead to trajectories leading to re-entry (Figure 6 left).

Since third-body perturbations are the main driver of the orbit evolution of such HEO orbits and since more different orbital periods should lead to more different evolution of phase angles with the Moon, manoeuvres most efficient in changing the orbital period, i.e. at perigee, were also explored, and confirmed to lead to stronger differences in the eccentricity evolution (Figure 6 left). In particular, these manoeuvres implied a re-entry during the second dip in perigee altitude in the 2028/2029 timeframe for manoeuvers as late as 2018, as also shown later by the global studies ([4], [5]).

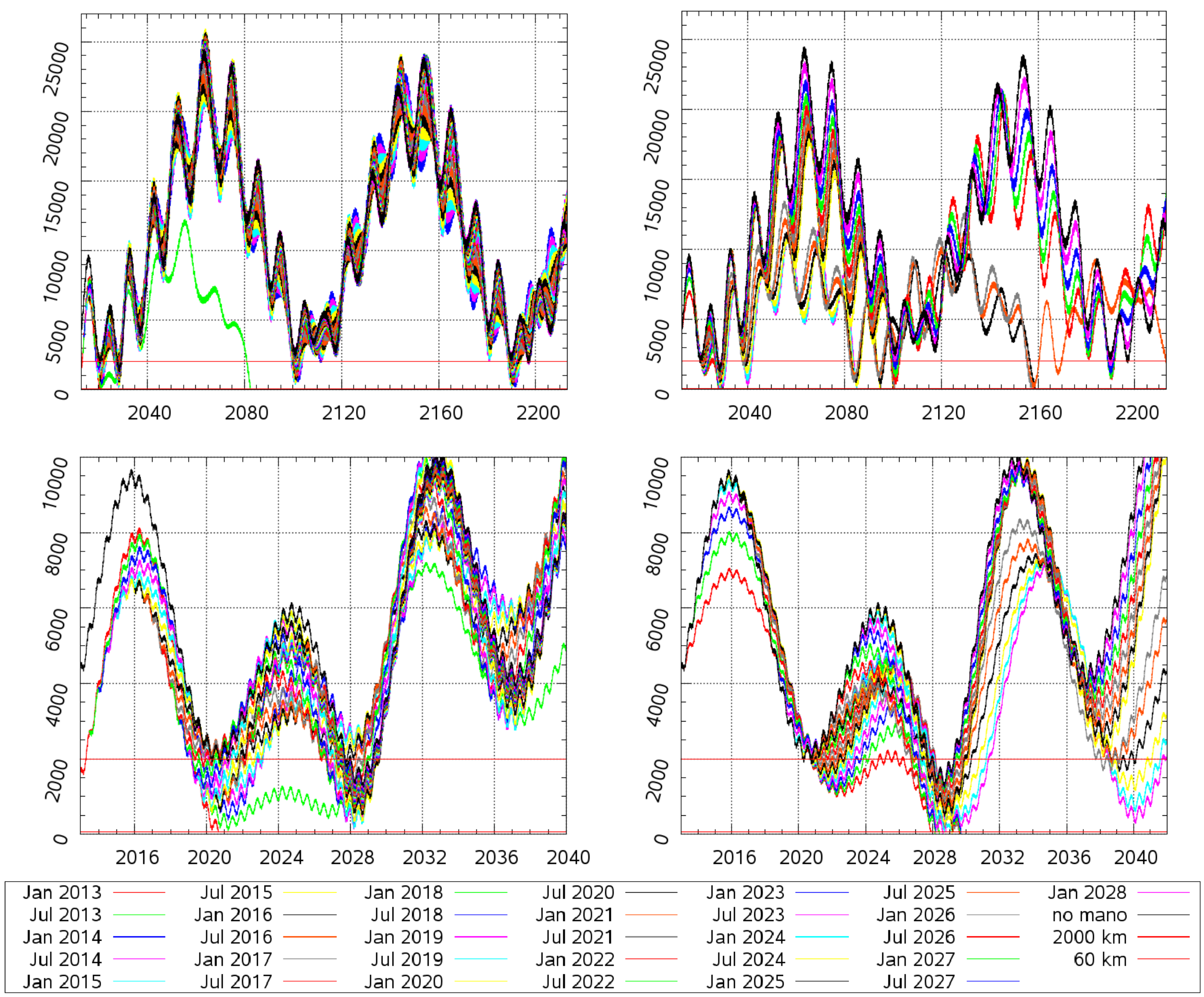
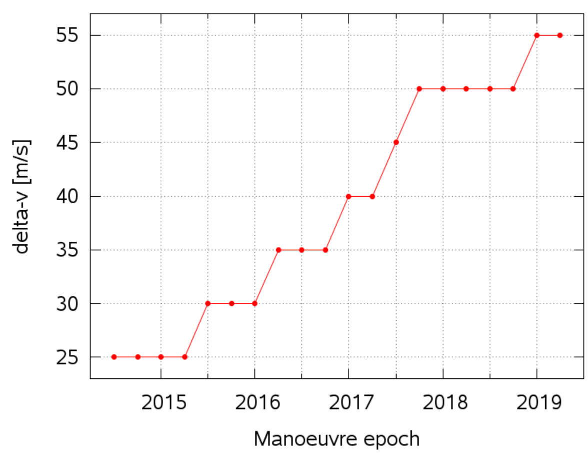


Figure 6. Perigee altitude evolution for manoeuvres at apogee (left) and perigee (right). Bottom row gives zoom of upper row figures.

Following this, a few options which don't use the total delta-v available were explored: Moon resonances and partial or split manoeuvres. In the case of Moon resonances the delta-v was selected to achieve a post-manoeuvre orbit whose orbital period was in resonance with the Moon's orbital period – the reachable resonances ranged from ratios of 12:1 to 7:1 (the delta-v necessary, and therefore the possible post-manoeuvre operational period, changes with time since the efficiency in terms of changing the semi-major axis varies due to the varying eccentricity). While some enlarged variability as a function of the manoeuvre date was observed on the very long term (after 100 years) for the higher orbits no significant advantage was observed. However no systematic targeting of the perigee orientation with respect to the Moon was attempted.

Partial manoeuvres, i.e. manoeuvers not exhausting the full available delta-v, were simulated at the beginning of 2015, i.e. after the end of the then-approved operational mission lifetime, and repeated for 2017 (envisaged further mission extension). Results showed that manoeuvres larger than 25 m/s in 2015 would lead to re-entry at the 2028/9 occasion while allowing up to 8 more years of nominal operations (in terms of fuel consumption), in 2017 35 m/s would be needed allowing up to 4 more years of operations. Down to 15 m/s re-entry would be achieved around the 2100 minimum, while smaller delta-vs would not lead to re-entry. It was also investigated whether any of those trajectories would leave enough delta-v for a direct re-entry at the 2020 minimum, which turned out to not be the case.

All the non-re-entering trajectories were inspected for their LEO clearance. Such options were indeed identified, however also tended to be delta-v costly, violate the GEO protected region and may suffer from chaotic long-term behaviour.



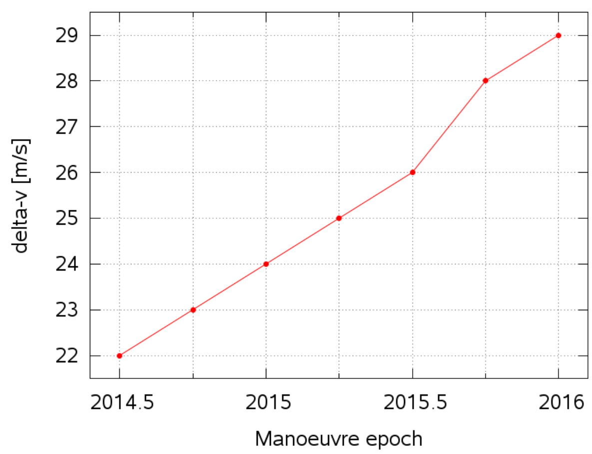


Figure 7. Minimum delta-v (quarterly screening) needed for re-entry as a function of manoeuver date. Left: 5 m/s granularity. Right: 1 m/s granularity for early dates

Of the re-entry options, those performing an early manoeuvre would therefore not only be cheapest in terms of delta-v and as a consequence also offer the longest overall potential mission duration, but also have the advantage of a definitive risk mitigation even in case of a later malfunction which otherwise could prevent a successful disposal manoeuvre. Hence, it was decided to further investigate the re-entry option via a more complete 2-parametric screening of manoeuvre date and size, while keeping the manoeuvre at perigee (see Figure 7). Topics explored were: robustness/sensitivity against the main uncertainties, i.e. manoeuvre size and epoch, effect of orbit control, solar radiation pressure and air drag during the final phase. Robustness was sought in the very basic issue of ensuring re-entry but also on the pattern of the final orbits.

Last orbits and breakup

For the eccentric orbit of Integral (and also Cluster) the perigee altitude of the last orbits is driven by lunisolar perturbations and may reach several 10s of km difference from one orbit to the next. In case the pattern is steep enough, Integral will enter the deeper layers of the atmosphere without first circularising its orbit, as is usually the case for the more typical uncontrolled re-entries from circular orbits. Since then the breakup occurs near the location of the perigee, this would allow to predict (and potentially control) the latitude band of the break-up process and therefore limit the distribution of fragments on ground in terms of latitude. Even more, if the orbital period can be controlled precisely at end of life and is not perturbed by air drag until the very last revolution, one may even predict and control the time of the re-entry and therefore the sub-satellite longitude of the final perigee and therefore the longitude range of the fragments reaching ground.

While not the focus of this paper, also the breakup study performed in parallel (for more details see [6]) gave relevant input to the desired pattern of the last perigee altitudes: While for perigee altitudes of around 70 km the number, mass and casualty area of surviving fragments have a minimum, a lower perigee limits the spread of fragments along the ground track. In case of a perigee at sparsely populated latitudes in the South, such as for Integral, the risk on ground therefore profits in general from even lower perigee altitudes since they tend to limit the most Northern latitudes reached by fragments.

Figure 9 shows some example scenarios for the decrease pattern of the last perigee altitudes (taken from Cluster, similar scenarios occur in the Integral case). Top left shows a steep pattern with the difference between the last perigees being more than 50 km bridging the altitude range where fragments can reach Northern latitudes or escape – such a scenario would be desirable from an on-ground risk point of view. The top right shows a rather shallow pattern, with the last perigees at a plateau with less than 30 km decrease per orbit and not "crossing" the altitude of 60 to 90 km where breakup occurs rather slow and may involve fragments reaching rather Northern latitudes. However, more critical are situations of a (near-)circularisation, if near a critical altitude, such as in the bottom figure, the orbital period is strongly affected by a first "near re-entry". This may lead to a stabilisation of the perigee altitude since lunisolar perturbations get weak once the semi-major axis is reduced significantly. It has, however, to be noted that any particular scenario like this is to be considered as an unreliable prediction as long as no proper break-up model is used but a standard numerical propagator – as such, it just indicates a situation which should be avoided in order to limit the on-ground risk.

The numerical study established a lower limit on the delta-v needed as a function of manoeuvre date, e.g. of 24 m/s at the beginning of 2015, confirming increased fuel cost in case of later manoeuvre dates. It also showed that the final pattern significantly depends on the manoeuvre date – even when shifting by a single orbital revolution. This clearly indicated that a targeting of the pattern would realistically not be possible, taking a realistic scenario involving a split into several manoeuvres and other operational constraints into account. On the contrary, the pattern is not that sensitive to an error in the manoeuvre size, i.e. a difference in the order of some 10s of cm/s hardly changed the pattern, but may change the absolute altitudes of the last perigees and therefore the re-entry process. Therefore, a simple final depletion burn is not suitable to target the final decay pattern and even less the longitude, it opens however the option for a fine-tuning manoeuvre at end of operations. Similarly, assuming some spread in solar radiation pressure and air density, the pattern is well preserved and orbital periods tend to be similar, however the actual altitudes might be different at the very last orbit(s). This indicates that pattern targeting should be feasible, while altitude targeting might be at the rim of feasibility and has still to be studied in detail. However, a favourable scenario with a steep decrease pattern should be the least susceptible to such differences. Targeting the longitude, even roughly, however seems to be infeasible.

3.2. The case of Cluster

Contrary to Integral it has always been clear that the Cluster spacecraft would finally re-enter and studies therefore focussed initially on the on-ground risk of the naturally occurring re-entries. Even before the results of the breakup study, performed in parallel ([6] and extended in [7]), were available, it was obvious that advancing the re-entry of Cluster-1 (Rumba) from 2038 to the mid-2020s would be beneficial to lower the on-ground risk since then the perigee would be located over Southern instead of Northern latitudes. Since shortening the on-orbit time by more than a decade also reduces the risk of an on-orbit collision or break-up, it was decided to investigate manoeuvres to achieve earlier re-entry.
Three manoeuvre strategies were investigated via a parametric study of the manoeuvre size and year: Perigee lowering, apogee raise and inclination lowering. Leaving aside operational considerations all three turned out to lead to re-entry once a delta-v of 9 m/s was applied. More detailed results are shown in Figure 8, indicating that inclination lowering might be more efficient and the cost of the other strategies would rise the later the manoeuvre was performed.

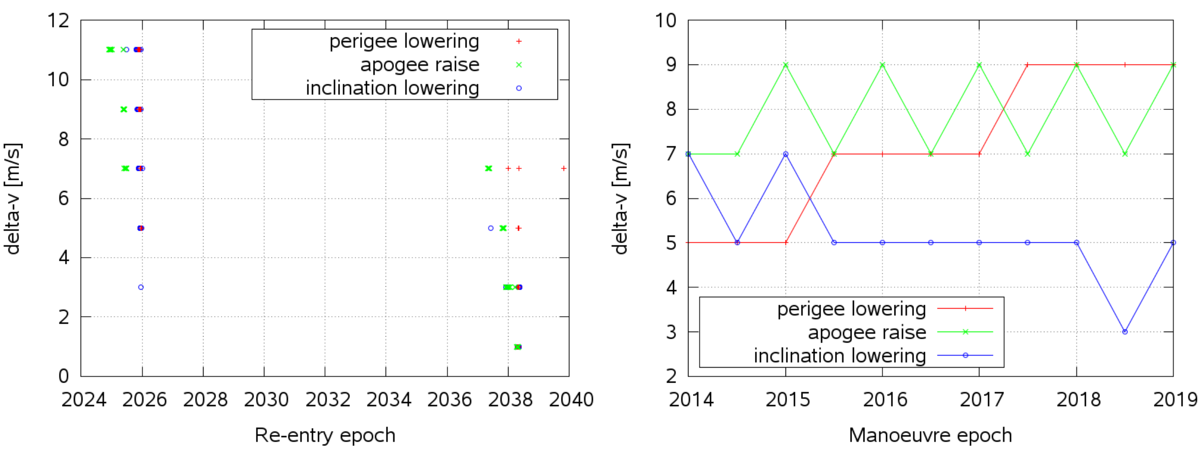


Figure 8. Results of parametric manoeuver study.
Left: relation between re-entry epoch and delta-v size.
Right: minimum delta-v needed for re-entry in mid-2020s as a function of manoeuvre date.

As for Integral the question arose whether the final re-entry location is predictable. Also for Cluster the pattern of the perigee altitude is driven by lunisolar perturbations and if the decrease is steep enough there is no circularisation due to air drag. The latter may lead to a re-entry and break-up over densely populated areas thus likely violating the accepted level of on-ground risk as the break-up study has shown. If circularisation can be avoided, the latitude can be predicted and is located favourably South for all 4 spacecraft assuming an advance of the Cluster-1 (Rumba) re-entry to the mid-2020s.

Orbit changes during normal operations outrange natural perturbations and can lead to changing perigee altitude patterns short before re-entry. Comparisons of the patterns, obtained by starting propagations from the operational orbit in different years, indicated that the pattern i.e. the decrease rate, doesn't change much, however the absolute altitude might be slightly shifted, which may trigger or avoid circularisation, in particular in case of a rather slow perigee decrease rate. As of mid-2014 (see Figure 9)

- Cluster-2 shows a very steep perigee decrease rate, which seems to be robust against perturbations due to orbit control.
- Cluster-3 shows a more shallow perigee decrease rate, which in this case turned out to be very favourable in terms of demise, since no fragments reached ground. However the scenario of complete demise is very instable and very dependent on the actual decrease pattern.
- Cluster-4 showed a strong circularisation since a the first perigee crossing significantly shortens the orbital period, rendering the third-body perturbations rather ineffective during the following orbits.

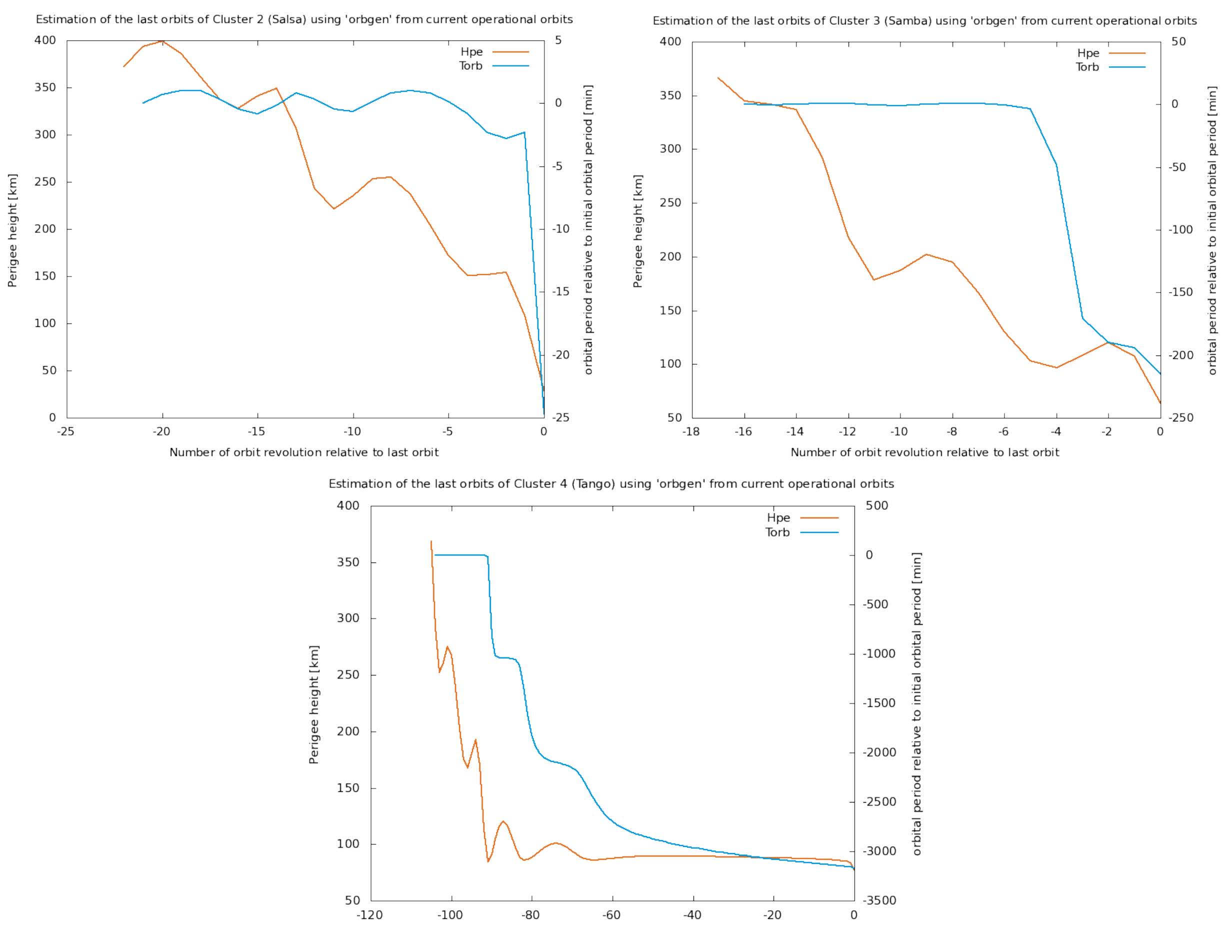


Figure 9. Perigee altitude [km] and absolute change in orbit revolution time [minutes] for the last perigee passages till re-entry for Cluster-2 (top left), Cluster-3 (top right), Cluster-4 (bottom) based on an operational orbit of epoch 2014

Therefore, for Cluster-2 the operational orbit should be monitored to check whether any (small) disposal correction maneouvre is required to guarantee re-entry without prior circularisation (i.e. make sure the current re-entry scenario persists). For Cluster-3 and -4 the scenario should be made more predictable by performing a small manoeuvre at end of life that triggers a perigee decrease pattern at re-entry that is similar to that of Cluster-2. For Cluster-1 this topic will also be addressed. Initial studies on this topic have been started.
As for Integral sensitivity analysis in the solar radiation pressure and air drag indicate that longitude targeting will most likely not be possible.

4. The manoeuvres

By mid-2014 a strategy for both Integral and Cluster-1 (Rumba) involving a manoeuvre during the first quarter of 2015 leading to re-entry in 2029 for Integral and 2025 for Cluster-1 was baselined. Operational constraints and post-manoeuvre target orbits were refined leading to a final operational strategy which was finally approved and implemented. Core considerations related to orbit aspects and the actual manoeuvres are given in the following.

4.1. The case of Integral

The driver for selecting January and February 2015 was twofold: On the one hand, the numerical study showed that the cost in terms of delta-v was increasing the later the manoeuvre was performed, therefore limiting the post-manoeuvre and overall operational lifetime. On the other hand, the manoeuvres had to take place outside eclipse seasons, including potential backup manoeuvres in case of failures of a nominal manoeuvre. This led to the beginning of 2015 as the first opportunity.

Major drivers for the actual manoeuvre size and implementation were the ground station coverage during the manoeuvre (sequence), attitude constraints, failure recovery scenarios and the post-manoeuvre ground station coverage pattern and mission planning requirements. In order to limit changes to the ground segment, options with a repeating ground track were studied and finally a target orbit with 3 revolutions in 8 days selected, even though this was not fuel-optimal in the sense that a smaller delta-v would have also lead to re-entry in 2029.

The manoeuvre itself was split into three major burns plus a touch-up for final fine-tuning. Ground station coverage during manoeuvres was a strong requirement, however nominally there is not enough coverage near perigee provided by the Kourou ground station. Therefore, the first manoeuvre was performed off-perigee having the main effect to adjust the orbit such that subsequently every 4th perigee had coverage from the Perth ground station allowing to execute the large following manoeuvre operations under station coverage, allowing in particular efficient manoeuvres centred at perigee. To achieve this the intermediate orbits were selected to also have a repeat pattern, having also the effect that manoeuver operations could be resumed after a given number of days/revolutions in case of a failure of one of the manoeuvres.

The manoeuvres were executed successfully as planned. Key characteristics are given in Table 2. Details of the constraints and options studied for the actual manoeuvre sequence are reported in [8].

Table 2. Integral disposal manoeuvre details

	Disposal Manoeuvre #	1	2	3	4
Execution	Revolution #	1495-1496	1499-1500	1503-1504	1506-1507
	Date (dd/mm/yyyy)	12/01/2015	24/01/2015	04/02/2015	12/02/2015
	Start time(Z)	23:51:01	16:17:01	15:15:55	15:02:07
	End time(Z)	00:07:42	16:48:10	15:31:39	15:03:22
	Duration - actual (hh:mm:ss)	00:16:41	00:31:09	00:15:44	00:01:15
	Expected nom. duration	00:15:21	00:28:32	00:14:09	00:01:20
	Expected max. duration	00:19:18	00:35:07	00:17:52	00:02:50
	Attitude off-set (deg. in-plane)	0	18	15	8
	Total thruster force - mean (N)	34.092	31.032	30.309	30.094
Performance	Delta-V - planned (m/s)	8.393	14.913	6.896	0.146
	Delta-V - estimated (m/s)	7.733	14.964	6.817	0.158
	Deviation (m/s)	+0.660	-0.051	+0.079	-0.012
	Propellant use - predicted (kg)	13.156	23.117	10.628	0.225
	Propellant use - measured (kg)	13.005	23.700	10.892	0.273
	Deviation (kg)	+0.151	-0.583	-0.264	-0.048
Orbit	Apogee - post-DV (km)	150824	143877	140883	140679
	Perigee - post-DV (km)	8720	8760	8665	8801
	Eccentricity - post-burn	0.824815	0.817916	0.814409	0.813169
	Semi-major axis - post-DV (km)	86139	82645	81155	81098
	Period - post-DV (hrs)	69:52:12	65:41:29	63:53:40	63:49:25
	Inclination - post-DV (deg)	54.466	54.380	54.225	54.195

A post-manoeuvre assessment was performed based on a long-term planning orbit taking into account the planned orbit control strategy which maintains a repeat pattern of 3 orbits in 8 days and the longitude at every third perigee in the band of 105 deg +/- 5 deg.

In the nominal scenario, this orbit was propagated further showing re-entry on the 27th of February 2029. A robustness analysis has also been performed varying initial epoch, applying a delta-v in the range of ±10 cm/s near perigee and varying the solar radiation pressure coefficient. This aimed at analysing robustness against potential variations in the orbit control and the effect of uncertainties in the perturbation modelling. In total 290 Monte Carlo propagations were performed, all of them leading to re-entry close to the nominal time.

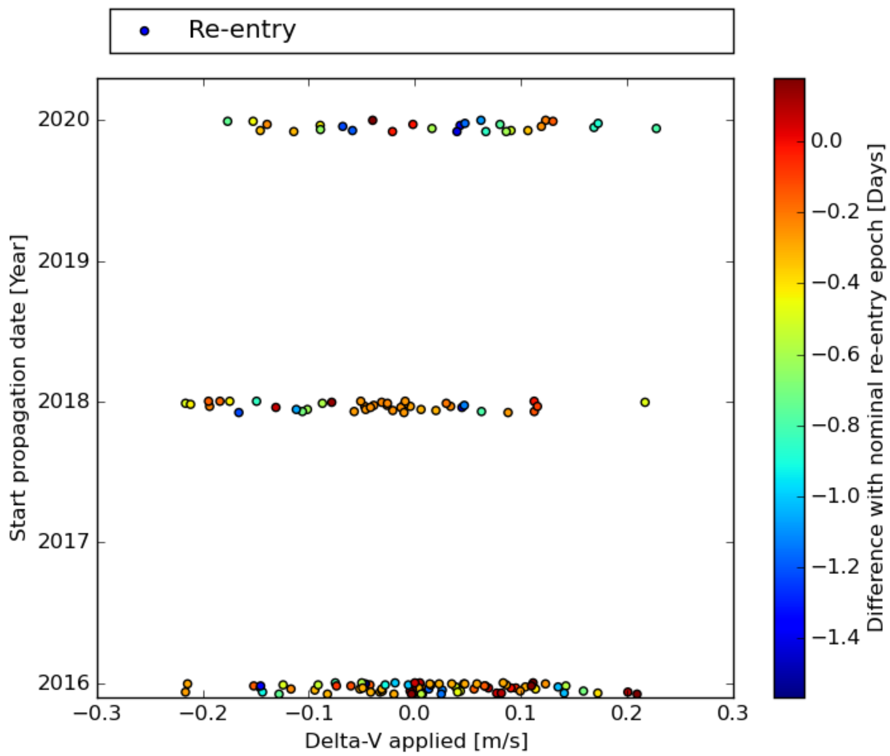


Figure 10. Re-entry time (as difference w.r.t. nominal time) as function of start epoch and delta-v

4.2. The case of Cluster

As shown above three basic options to change the orbit of Cluster-1(Rumba) in order to advance the re-entry to the mid-2020s were identified: Apogee raising, perigee lowering and inclination reduction. As major driver the constellation of all four should still fulfil the nominal mission, requiring that the orbital period of the four spacecraft had to remain the same. So either all four SC would have to manoeuvre or the Cluster-1 manoeuvres had to be neutral to the semi major axis, i.e. an inclination lowering strategy or a balanced combination of perigee lowering and apogee strategies increasing eccentricity only would have to be followed (plus potential touch-up/fine-tuning). Since the inclination had to be changed by only 0.15 deg, which induces only a minor difference to the relative configuration of the satellites, and this is also less costly than the pair of eccentricity change manoeuvres, this was selected as baseline strategy. For manoeuvres during later years the required inclination change gets larger, therefore it was decided to perform the manoeuvres as early as possible.

Being a rapidly spinning satellite, the cost to slew to an optimal firing attitude for a re-entry manoeuvre was higher than the fuel penalty when performing the manoeuvres with the current attitude. Therefore possible delta-v directions were constrained to a certain cone for the radial thrusters and the spin axis direction for the axial thrusters. Optimisation showed that it is most efficient to perform a manoeuvre to reduce the inclination with a radial thruster pair (inclination is reduced by 0.146 deg with a manoeuvre at true anomaly 196 deg). As a side effect the semi-major axis is reduced by 152 km. To keep the period and phasing relative to the other satellites it was necessary to compensate this effect with a pair of manoeuvres each raising the semi-major

axis by about 75 km. These manoeuvres were placed about 5.5 orbits before and after the inclination change manoeuvre to allow orbit determinations in between.
These two manoeuvres could have been performed using either axial or radial thrusters at very similar fuel cost, however with different side effects on the eccentricity and inclination. The option using axial thrusters implied a larger increase in eccentricity and since this is also advantageous for advancing the re-entry (as the two options of apogee raising or perigee lowering have shown) this approach was selected.

As a further constraint, the large 2nd manoeuvre had to be performed during ground station visibility to monitor the solar aspect angle evolution, which was near the safe operating limit. As a pulsed manoeuvre with a radial thruster pair can lead to residual torques which change the attitude, there was a chance that the manoeuvre would have to be aborted. In the end, all manoeuvres were executed successfully, with details as given in Table 3.

Table 3. Cluster-1 (Rumba) disposal manoeuvre details

	Manoeuvre 1	Manoeuvre 2	Manoeuvre 3
Date	09/03/2015	17/03/2015	25/03/2015
Delta-v [m/s] command generator	0.717	5.603	0.7333
Delta-v [m/s] calibrated	0.724 (+1 %)	5.694 (+1.6%)	0.740 (+1%)
Time start	09:19:21	14:07:30	05:12:22
Time end	09:20:12	14:25:02	05:13:13
Location in orbit (true anomaly)	37 deg	196 deg	32 deg
Fuel spent (remaining)	0.057 kg	0.466 kg	0.058 kg (5.442 kg)
Oxidant spent (remaining)	0.086 kg	0.705 kg	0.087 kg (12.412 kg)
Semi major axis change*	+78 km	-151 km	+82 km
Eccentricity change	+0.0004	+0.00253	+0.0004
Inclination change	-0.004 deg	-0.146 deg	-0.004 deg
* Note: The accumulated change is 78 -151+82= +9 km as the disposal manoeuvre sequence was combined with the start of a small relative drift between Cluster-1 and Cluster-4 to achieve the next planned formation for the tail crossing in Autumn 2015.			

Post-manoeuvre assessments show that re-entry will occur at the beginning of November 2025 assuming natural perturbations only with an uncertainty of about a day or less due to solar radiation pressure and air drag. As indicated above, the real date will of course depend on the actual manoeuvers during the remaining operational lifetime and the potential manoeuvre at end-of-life.

5. Conclusions

It has been shown that achieving re-entry from Highly Eccentric Orbits (HEOs) is feasible by a modest manoeuvre and exploiting lunisolar perturbations to increase eccentricity over years after the manoeuvre. This approach is far less delta-v costly than a direct eccentricity change leading to a perigee low enough for immediate re-entry and has been successfully implemented for ESA's Integral and Cluster missions.

Furthermore, it is possible to achieve a re-entry directly from the eccentric orbit, without prior circularisation. Such an eccentric re-entry has the huge advantage that the re-entry latitude can be predicted years in advance. It opens also the opportunity to limit the distribution in latitude of fragments reaching ground during the re-entry and therefore to stay below the on-ground casualty expectation threshold.

Meeting current space debris mitigation guidelines is another achievement for both highly successful ESA missions that were designed long before these standards and corresponding ESA requirements were established.

6. References

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