Bringing Salsa Home: Cluster-II-2 Re-entry Strategy

S. Sanvido(1), M. Losacco(1), S. Lemmens(2), B. Bastida Virgili (2), B. Jilete(3), P. Meyers (4), S. Hawkins(2), F. Letizia(2), J. Siminski (2), C. P. Escoubet (2), B. Sousa(2), D. Sieg (2), L. Guerra(5), B. Abascal Palacios (6)

, (1) IMS Space Consultancy, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany, Email:{Silvia.Sanvido, Matteo.Losacco}@ext.esa.int
(2) European Space Agency, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany, Email:{Stijn.Lemmens, Benjamin.Bastida.Virgili, Saskia.Hawkins, Francesca.Letizia, Jan.Siminski, Philippe.Escoubet, Bruno.Sousa, Detlef.Sieg}@esa.int
(3) Gmv Gmbh, Email: Beatriz.Jilete@ext.esa.int,
(4) Luxembourg National Trainee at ESA Space Debris Office, Robert-Bosch-Straße 5, Darmstadt, 64293, Germany, Email: Philippe.Meyers@ext.esa.int,
(5) Cs Group – Germany, A 13, ecos office center, Berliner Allee 65, 64295 Darmstadt, Email: Luca.Guerra@ext.esa.int,
(6)LSE Space Gmbh, Robert-Bosch-Straße 16A, 64293 Darmstadt, Email: Beatriz.Abascal@ext.esa.int

ABSTRACT

On September 8, 2024, after two decades of groundbreaking research into the Earth's magnetosphere, ESA's Cluster-II-2 satellite (also known as Salsa) re-entered the Earth's atmosphere. Launched in 2000, Salsa was the first of the four satellites in the Cluster-II constellation to complete its mission and return home. In the years leading up to its re-entry, ESA-SDO worked closely with the Cluster-II mission in order to design and implement a safe re-entry strategy, regularly monitoring the satellite's trajectory and providing risk mitigation recommendations. This included assessing the on-ground risk to the region of the Earth affected by the re-entry and ensuring that any surviving fragments would fall in a remote area of the ocean, away from populated regions. The re-entry of Cluster-II-2 was also the focus of a dedicated on-ground- and air-based re-entry campaign, resulting in the first-ever observation of a satellite re-entering from a hypervelocity trajectory.

1 INTRODUCTION

ESA's Space Debris Office (SDO) provides guidance and recommendations for the re-entry strategies and on-ground risks assessment at the end of a satellite's life [1][2]. This support extends to both internal ESA missions and external partners, and covers a range of mission scenarios, including low Earth orbit (LEO) and highly elliptical orbit (HEO). While the re-entry from the former are known to be difficult to predict due to uncertainties in the spacecraft-atmosphere interaction, the orbit evolution of objects in HEO is driven by the more predictable third-body perturbation, opening the possibility to design a re-entry strategy months or even years in advance with respect to the expected re-entry epoch [3]. Under favourable conditions, a strategy for an HEO re-entry can tailor the longitude/latitude of the re-entry location to within a few degrees of uncertainty, minimizing the risk for on-ground population. The recent re-entry of the ESA- Cluster -II-2 satellite represents a successful operational implementation of such a strategy.

Looking ahead to the re-entry of the remaining three satellites in the Cluster -II constellation, expected by 2026, this paper aims to present the re-entry strategy implemented for the successful return of Salsa, discuss the challenges and build on the lessons learned.

The paper is organized as follows: paragraph 2 introduces the Cluster -II mission, while paragraph 3 gives an overview of the ESA-SDO approach to the design of the re-entry strategy for HEO missions. The following paragraph 4 discusses the application of such a procedure to the Cluster -II-2 re-entry, following a chronological order for the events leading up to the re-entry. Finally, the last section is devoted to conclusions and lessons learned for the upcoming re-entry of the next Cluster-II satellite, Rumba.

2 CLUSTER-II MISSION

The Cluster II mission, as its name suggests, is a small constellation of four satellites launched in 2000 to fly on HEOs and study the physical connection between the Sun and the Earth. Each of the four identical cylindrical satellites (Cluster-1/Rumba, Cluster-2/Salsa, Cluster-3/Samba, and Cluster-4/Tango), shown in Figure 1, weighs 1200 kg, 650 kg of which is propellant, and is spin-stabilized with a spin rate between 14.0 and 15.0 rpm. Its main body, with a diameter of 2.9 m and a height of 1.3 m, contains 11 instruments for the study of charged particles and the magnetic field, making it possible to model the magnetosphere of our planet. The osculating orbital parameters of the two missions, as of August 2023, are reported in Table 1. a, e, i , Ω, ω indicate respectively the semimajor axis, the eccentricity, the inclination, the longitude of the ascending node and the argument of perigee.

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

The first re-entry for the Cluster-II mission (Cluster-II-2/Salsa) happened on the 8 September 2024 over the Pacific Ocean. The second expected re-entry, Cluster-II-1/Rumba, was supposed to naturally occurs in 2038, but a disposal manoeuvre was performed beginning of 2015 to anticipate its re-entry in October 2025 [14]. The last two satellites, Cluster-II-3/Samba and Cluster-II-4/Tango are expected to re-enter in 2026.

Table 1- Osculating orbital parameter for the Cluster-II constellation, as per August 2023.

Spacecraft	A [km]	e	i [deg]	Ω [deg]	ω [deg]	Re-entering epoch
Cluster 2 – 1 /Rumba (2000–045A)	72,768	0.78	145.0	2.2	216.7	8 Sept 2024
Cluster 2 – 2/Salsa (2000–041B)	72,763	0.83	142.0	2.6	216.3	Expected Oct 2025
Cluster 2 – 3/Samba (2000–041A)	72,779	0.66	136.8	352.8	206.7	Expected 2026
Cluster 2 – 4/Tango (2000–045B)	72,780	0.66	136.7	352.8	206.7	Expected 2026

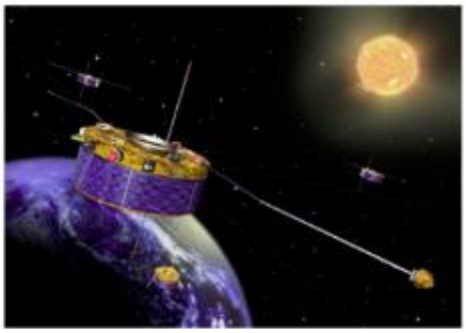

Figure 1. Artistic representation of the Cluster II satellites (Credit: ESA).

3 ESA RE-ENTRY APPROACH FOR HEO

HEOs are characterized by a perigee in or close to the LEO regions and apogee altitude above 40,002 km [21], which guarantees the satellite position outside of the Earth's radiation belt for most of the orbital period and therefore represent favourable orbits for scientific missions. Over the years, more than 30 missions have been operating in this type of orbits (e.g. Chandra, MMS, THEMIS among the US missions; ISO, XMM, Cluster, Integral and Proba3 are the ESA ones), and future missions in these orbits are planned such as the ESA Plasma Observatory [18] and SMILE. Some of these missions are expected to cross LEO and GEO Protected Regions, and, for this reason, disposal actions are required to limit such interference [2]. Even if third-body perturbation re-entries allow a more precise estimation of the re-entry epoch with respect of re-entries driven by atmospheric perturbations, the design of disposal strategy for HEOs still needs complex and largely ad-hoc procedures. Several recent studies [3-6] aimed to define an efficient disposal strategy for scientific missions on these orbits, suggesting innovative analytical models or specific metric shift [7]. ESA's approach to designing a disposal strategy for HEOs, which is consistent with most of these studies, is briefly discussed in this section. A more detailed discussion of this approach can be found in [15].

Figure 2 shows the preferential re-entry areas which are targeted by the ESA re-entry procedure for HEO.

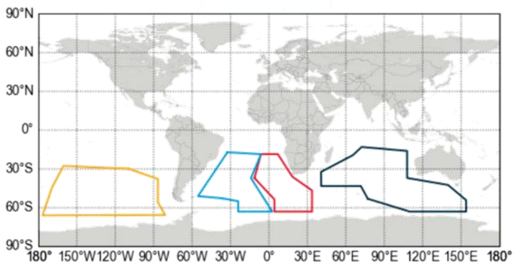

Figure 2. Graphical representation of the preferred re-entry locations.

3.1 Latitude band targeting

HEOs missions re-entry are driven by third-body perturbation, as superposition of the short-term (half of the orbital period of the third body) and long-term contributions of the Moon's and Sun's gravity fields [9], which act on the satellite's orbit creating a strong oscillatory variation of the eccentricity value, leading to an oscillation of the perigee altitude while the semimajor axis remains almost constant. Once that the satellite reaches very low altitude (at the vicinity of the Karman line), the combined effect of the perturbations may lead to two opposite scenarios. If long- periodic and high order effects interact compensating each other, the perigee altitude will decrease slowly leading to the orbit circularisation. As the name suggests, the circularisation will lead to a drag-driven re-entry for which the atmospheric uncertainty will prevent the prediction of the re-entry epoch and re-entry location until the very end of the spacecraft lifetime. On the contrary, in case these effects superimposed, a fast decrease will occur, even of several 10s km between two consequent perigee passes, leading to a steep re-entry with higher velocity and steep path angle. In the latter case, the atmospheric break-up of the satellites occurs near the location of the perigee, a favourable condition that can be exploited to potentially control the latitude band of the break-up process and of the impact area for possible surviving fragments. Therefore, HEOs re-entry strategies are designed selecting a steep re-entry profile to ensure the atmospheric break-up within a limited latitude band around the final perigee pass. Figure 3 shows the differences between a circularised re-entry profile, recognisable by the typical final plateau in the perigee altitude evolution, and a steep and desired re-entry profile.

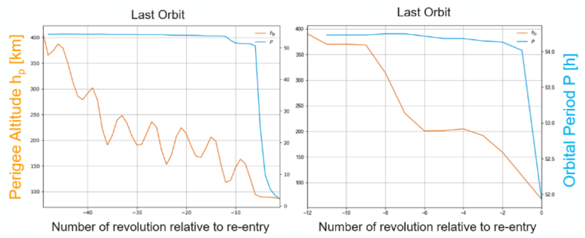

Figure 3. Circularised re-entry profile (left) and steep re-entry profile (right).

3.2 Longitude-band targeting

Once the re-entry strategy secured the latitude-band target with a steep re-entry over south hemisphere, the re-entry strategy will focus on tailoring the re-entry longitude-band. To be successfully implemented, this step requires a high accuracy on the orbital period, whereas manoeuvres are executed weeks or months before the re-entry epoch, with significant time in between for uncertainty to accumulate. As discussed in [11 , 12], solar radiation pressure and atmospheric drag have no significant influence on the decay behaviour, but they do affect the final longitudes. These perturbations contribute to the issue of assessing which is the predictability of the trajectory evolution. To address this, a robust approach should be devised and routinely repeated to ensure that the assessment works with the best available orbital knowledge. In practice, this is done analysing the sensitivity (longitude-shift) of the re-entry arc with respect to the parameters related to these perturbances, such as solar pressure area and drag coefficient. This longitude-shift is generally regularly check through the spacecraft lifetime and can be adjusted with (generally small "*trim*") manoeuvre. As an example, Figure 4 shows analysis of the longitudinal shift of the re-entry arc for the ESA-INTEGRAL mission between Nov 2021 to Oct 2022, for two different cross-sectional areas: 24m (average random tumbling area), 31 m (maximum area).

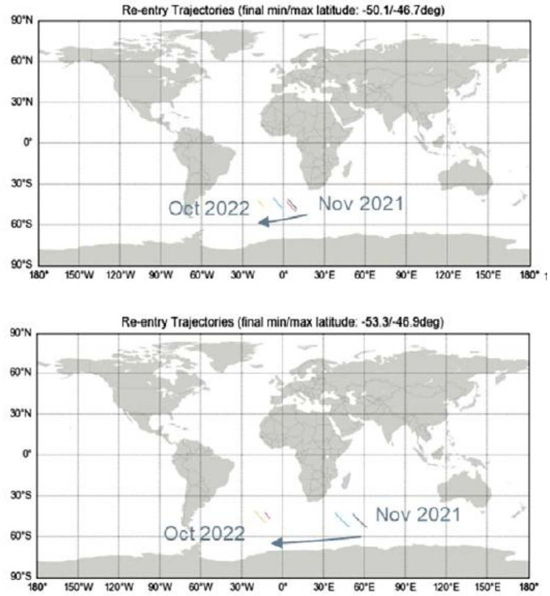

Figure 4. Resulting re-entry locations for Integral considering different initial propagation epochs from the nominal mission plan for two different cross-sectional area values: (top) 24 m, (bottom) 31 m 2.

3.3 Robustness check

Once a baseline manoeuvre strategy is defined in terms of latitude and longitude bands, a further assessment of its robustness is performed by perturbing the solution by applying stochastic accelerations. In the first place this is done to consider the typical levels of uncertainty associated with the orbit determination process. These uncertainties are driven by the limitations in accuracy of using a 3 degree of freedom (3DoF) propagation model for timescales of years, even if orbital dynamics are well-known. To assess this level of uncertainty, the actual orbital evolution as recorded by means of a space surveillance system can be compared with the predicted evolution. In addition, specific failure models that can result in spurious delta-v (e.g. battery failure, propellant leakage) can also be included in the assessment. Two examples of such analysis are shown in Figure 5 where 100 perturbed trajectories are defined starting from the baseline orbital evolution of one of the Cluster-II satellites. For the re-entry strategy on the left, all the generated trajectories result in a final arc over the Pacific Ocean, without displaying circularisation and confirming the robustness of the disposal manoeuvre against uncertainties. On the contrary, the re-entry strategy on the right result in diverting re-entry trajectory, in some cases leading to circularisation.

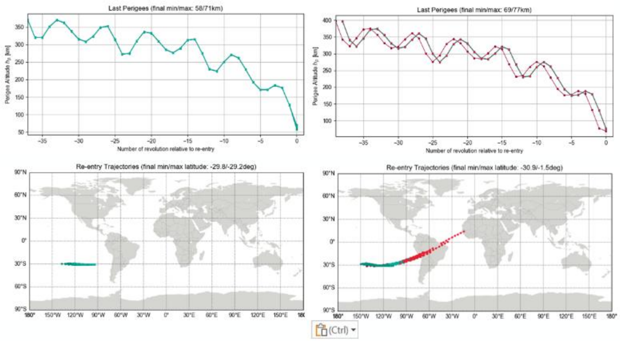

Figure 5. Re-entry perturbed analysis: Stable re-entry trajectory (left) and unstable re-entry trajectory (right).

3.4 Avoid escaping fragments

Re-entry from HEOs is known to potentially generate escaping fragments if the final perigee altitude at atmospheric capture is too high. These escaping fragments pose significant risks as they can detach from the main body and escape into deep space on near-circular orbits. This creates a hazard for operational satellites and a potential on-ground risk when they eventually re-enter the atmosphere in an uncontrolled manner.

To mitigate this risk, the final step of the re-entry strategy design involves a detailed analysis using a 6-degree-of-freedom (6DoF) simulation. For the specific case of the Cluster-II mission, analyses were conducted using both the ESA-SCARAB and ESA-DRAMA tools. The SCARAB Cluster-II model, shown in Figure 6, was employed in an extensive parametric analysis to investigate the conditions under which the spacecraft could generate escaping fragments [13].

The results of this study are displayed in Figure 7, where the types of generated fragments (on-ground or escaping) are mapped across a grid of perigee altitudes and semimajor axes. The fragmentation matrix produced with the SCARAB software indicates full demise when the orbit remains within the altitude of maximum heating. Regarding the possibility of complete demise, given the uncertainties in fragmentation modelling and atmospheric composition, only direct observation of the event can confirm whether these numerical predictions are accurate or achievable in practice. From the results presented, it is concluded that it is necessary to target a final perigee altitude below 75 km to avoid the generation of escaping fragments.

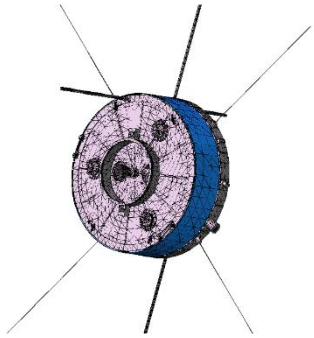

Figure 6. SCARAB model of CLUSTER-II.

As a further precaution beyond the classification obtained from the SCARAB analysis, an additional check is conducted at the end of the re-entry strategy definition using the DRAMA model (illustrated in Figure 8). This additional validation is specifically designed to confirm the absence of escaping fragments under the proposed re-entry strategy. An example of the results from this verification is shown in Figure 9.

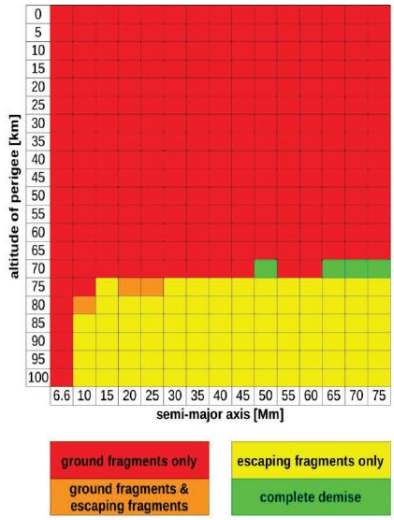

Figure 7. Parametric break-up analysis on the first perigee pass within the atmosphere for Cluster-II [13].

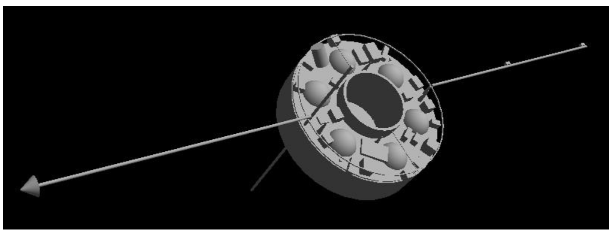

Figure 8. DRAMA model of Cluster-II.

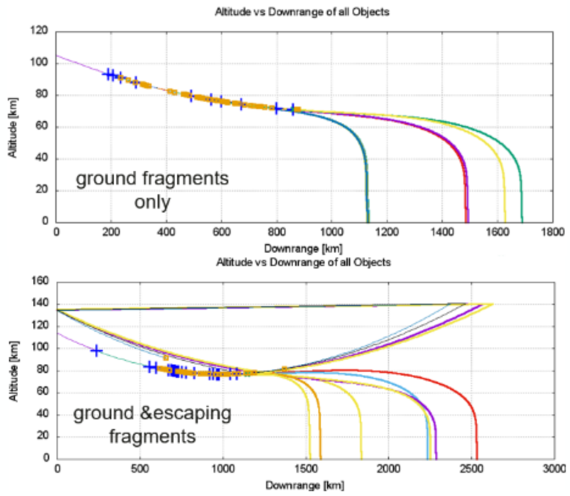

Figure 9. DRAMA analysis results for Cluster-II, showing ground fragments only (top) and ground&escaping fragments (bottom).

4 CLUSTER-II-2 RE-ENTRY STRATEGY

This section contains the chronological summary of the re-entry strategy for Cluster-II-2, from the first strategy investigation up to the atmospheric re-entry.

4.1 Disposal manoeuvre investigation

The re-entry profile of Cluster-II-2 as per August 2023, before the disposal manoeuvre, showed circularisation, as visible in Figure 10. To address this concern, a coordinated analysis between SDO and the Cluster-II mission was initiate to investigate suitable re-entry strategy.

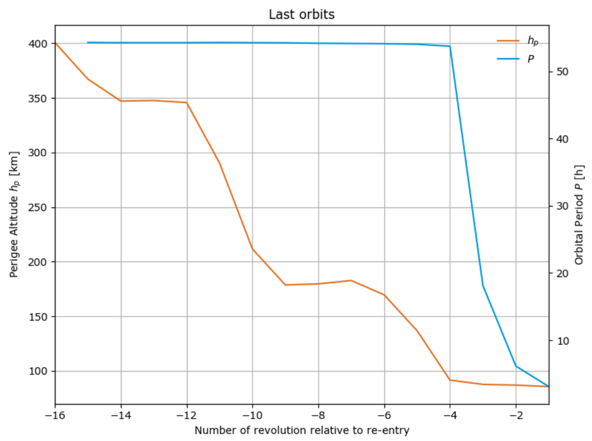

Figure 10. Cluster-II-2 (circularised) Re-entry profile as per August 2023, before the disposal manoeuvre.

As discussed previously, the identification of a successful re-entry strategy for HEO requires several steps and it is in general a long procedure. In the case of Cluster-II-2, the analysis of a possible re-entry strategy started already in 2021, when the available propellant for a disposal manoeuvre was decided and an investigation of all possible disposal strategies compatible with this decision were investigated. The recursive application of the selection procedure for latitude and longitude targeting, summarised in paragraph 3, lead to a final selection of three possible candidate in mid-2023.

The three final options were quite similar in terms of re-entry conditions, effectively correcting the circularization of the re-entry profile and successfully targeting a re-entry latitude/longitude band over the Pacific Ocean. Figure 1 illustrates the re-entry profiles and locations of these three options, including the estimated re-entry epochs, all occurring during daytime. The figure clearly highlights the impact of drag perturbation on the last perigee pass before the final atmospheric capture, resulting in a difference of more than one hour in the orbital period between the solutions and leading to a corresponding longitudinal shift in the re-entry location.

However, despite the favourable steep re-entry profiles and similar conditions, the assessment of robustness and the potential generation of escaping fragments revealed fundamental differences for the three options.

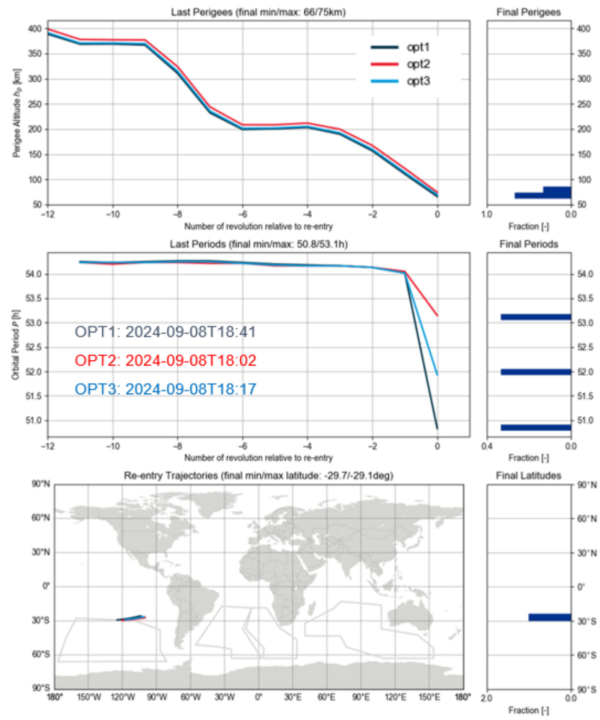

Figure 11. Three possible disposal strategy for Cluster-II-2. The re-entry epochs are in UTC.

In fact, the perturbed analysis results for Option 1 indicated a 1% probability of impact on land, leading to its exclusion from the pool of viable solutions. On the other hand, the DRAMA results for Option 2 showed the generation of escaping fragments. This outcome aligns with the assessment discussed in Section 3.3, as the final perigee altitude at atmospheric capture for Option 2 was 74.7 km, very close to the 75 km threshold and higher than the final perigee altitudes of Option 1 and Option 3, which were 66 km and 70 km, respectively.

With Options 1 and 2 ruled out, the Option-3 was selected as re-entry strategy for Cluster-II-2, as it met all the requirements to ensure a safe and reliable re-entry.

4.2 Disposal Manoeuvre execution

The final refinement of the Option-3, accounting for the specific Cluster-II mission constrains, resulted in a multi-burn strategy. The disposal strategy included the execution of two main axial manoeuvres on 15/16 January 2024, close to apogee, to modify the perigee height evolution and achieve a steep re-entry profile. This was followed by two smaller axial trim manoeuvres on 24/25 January 2024, close to perigee, to adjust the orbital period and target the re-entry longitude. The successful implementation of this series of manoeuvres led to the correction of the circularization for Cluster-II, as shown in Figure 12.

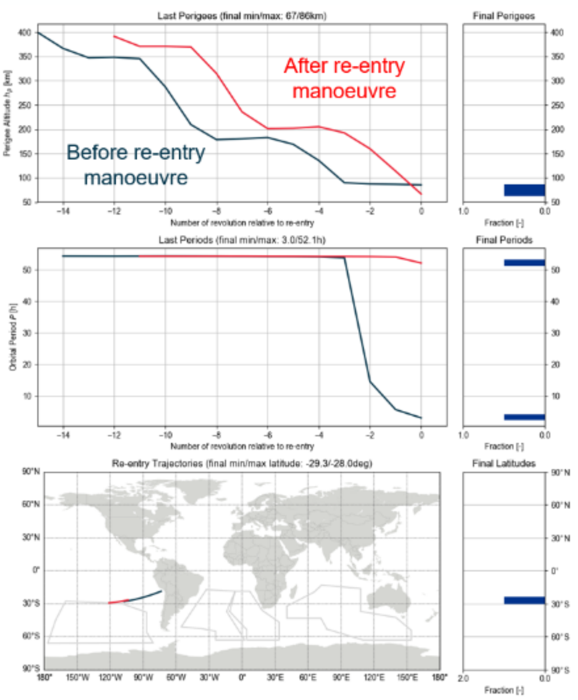

Figure 12. Cluster-II-2 Disposal manoeuvre effect.

Following its execution in early February 2024, the trajectory of Cluster-II-2 was analysed to assess the effect of the re-entry manoeuvre with respect to the planned strategy. Figure 13, Figure 14 and Figure 15 show the positive results of this analysis, confirming that the spacecraft was expected to re-enter over the Pacific Ocean without circularization or impact on land, and without generating escaping fragments.

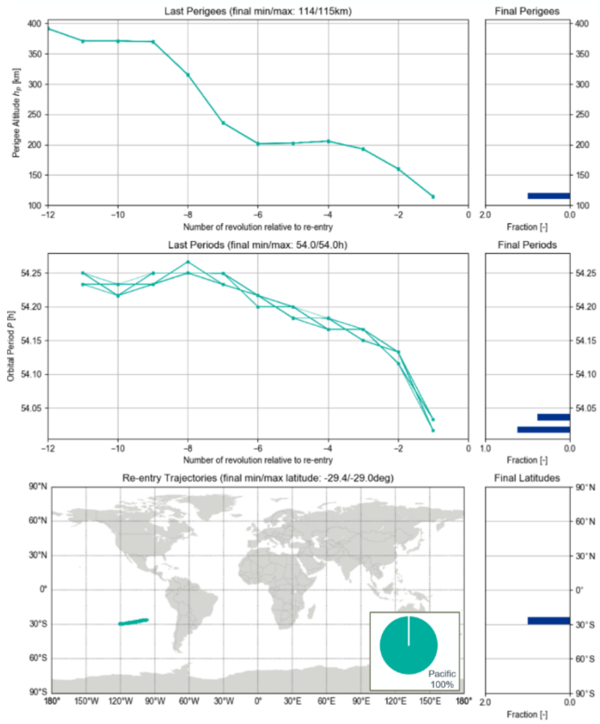

Figure 13. Perturbed analysis results for the disposal manoeuvre of Cluster-II-2. The re-entry trajectory is stable against perturbances.

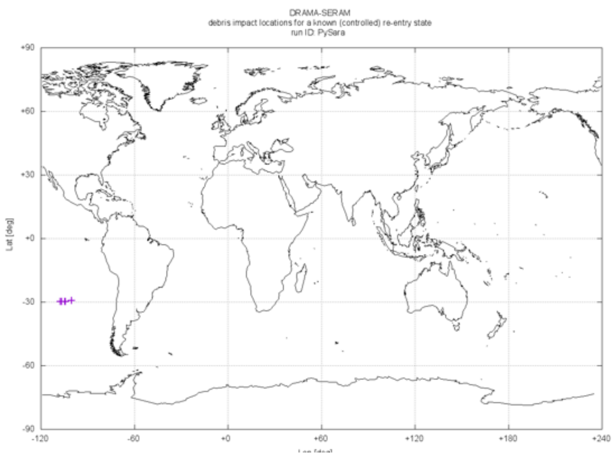

Figure 14. DRAMA analysis results for the disposal manoeuvre of Cluster-II-2, showing no impact on land or the surviving fragments (marked as '+' in the picture).

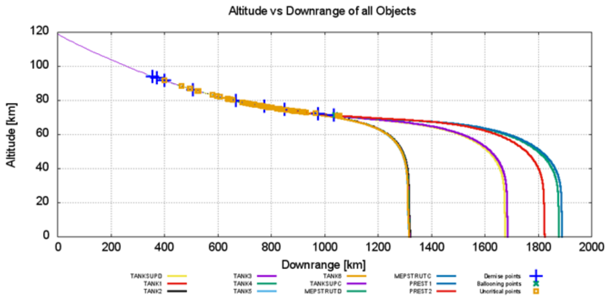

Figure 15. DRAMA results for the disposal manoeuvre of Cluster-II-2, excluding the generation of escaping fragments.

Furthermore, an assessment of the temperature profile and altitude for the last two perigee passes was conducted (pass -1 being the perigee pass before atmospheric capture and pass 0 being the perigee pass at atmospheric capture) to assess the likelihood that the spacecraft's instruments would survive the final orbit, ensuring telemetry data until the re-entry epoch. The temperature values, visible in Figure 16, were estimated to be high enough that the impact on system functionality was required to be evaluated. Specifically, the loss of orbit determination capability could critically affect the accuracy of the re-entry prediction in the last day before re-entry. The possibility of this scenario prompted the coordination of a supportive on-ground sensor network to observe Salsa's re-entry. This was crucial to ensure that, even in the event of telemetry failure, re-entry conditions could be predicted based on these sensor data. This was particularly relevant considering that Salsa's re-entry was the target of an airborne observation campaign. A detailed discussion of how these optical observations were integrated in the re-entry prediction pipeline of Cluster-II-2 is presented in [19].

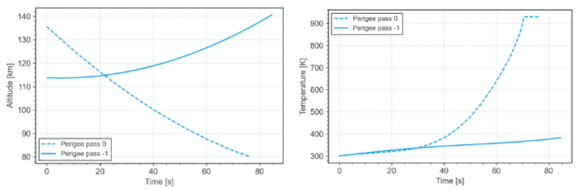

Figure 16. DRAMA results: altitude (left) and temperature (right) profiles for the Cluster-II-2 re-entry during perigee pass -1 (solid line) and perigee pass 0 at atmospheric capture (dashed line).

4.3 The IADC re-entry campaign and the regular weekly monitoring.

Cluster-II-2 was selected as the target for the second IADC (Inter-Agency Space Debris Coordination Committee) re-entry campaign of 2024, which was officially opened five months before the re-entry date, on May 5, 2024, much earlier than usual due to the peculiarity of its eccentric orbits. At the same time, as part of the robustness assessment of the re-entry location as commented in paragraph 3.3., ESA-SDO started to regularly predict the re-entry conditions on a weekly basis. These predictions, which were shared with the IADC campaign, were performed using a fully numerical propagator (OrbGen) based on the Cluster-II orbit determination provided by the flight dynamic team.

As Salsa lowered its perigee altitude below approximatively 400 hundred km, the effect of the drag perturbation began to show, and the Cluster-II mission flight dynamics team started the drag coefficient (CD) calibration to estimate an evidence-based value for this coefficient. During the last weeks of Salsa, this calibration phase indicated a possible over-estimation of the drag coefficient, nominally set at 2.2. This information, combined with the fact that re-entry prediction tools are generally validated using circular re-entry data and may lack accuracy for hypersonic re-entry as in the case of HEO, led to the decision to apply a ± 50% uncertainty to the drag coefficient. This cautious choice was additionally supported by the data collected during the GOCE re-entry mission[16][17]. As a result, the regular re-entry forecast for the last weeks of Cluster-II-2 was performed for the CD values between 1.1 and 3.3 in order to cover all possible scenarios in terms of re-entry epoch and re-entry location. An example of this analysis is shown in Figure 17.

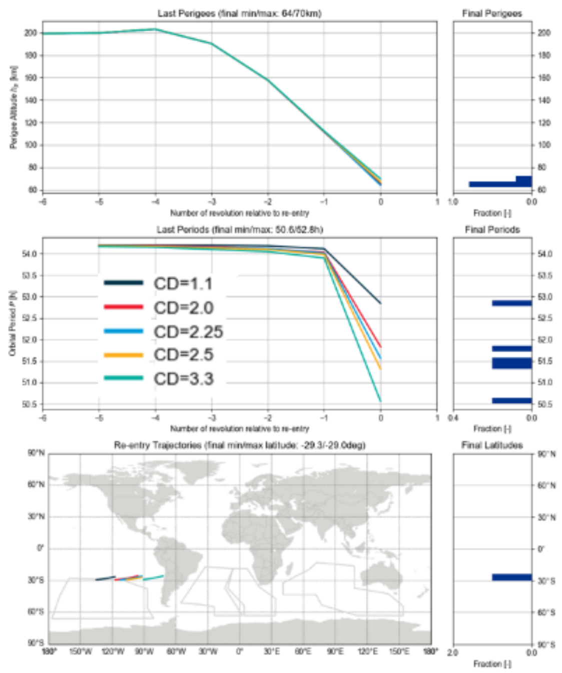

Figure 17. Cluster-II-2 Re-entry profile for the range of CD [1.1, 3.3], based on Orbit Determination from the 25th August 2024.

4.4 East-shift correction: one last manoeuvre.

As the date of re-entry approached, the weekly review of the re-entry corridor consistently showed an increasing shift of the re-entry arc toward East. In order to maximize the possibility of the airborne re-entry campaign, expected to take off from Easter Island, it was decided to perform a final touch manoeuvre on 22 August 2024, to correct this trend and re-align with the post-disposal re-entry condition. Figure 18 shows the effect of this last manoeuvre on the re-entry of Cluster-II-2. The figure shows the location of the re-entry arc with respect to the nearest lands. The solid-line circles around the islands represent the limit of the territorial water (12 nautical miles), while the dashed circles represent the limits of the Economic Exclusive Zones (200 nautical miles).

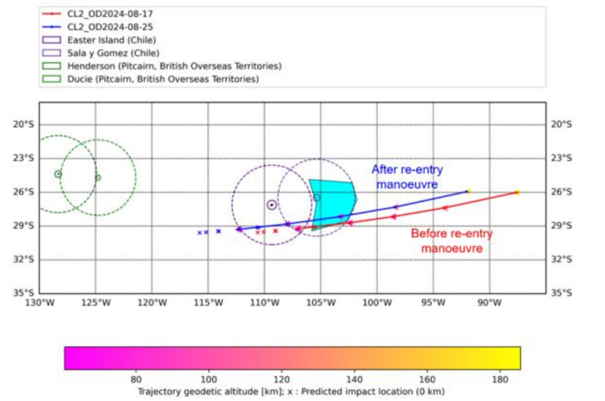

Figure 18. Effect of the last manoeuvre of Cluster-II-2, executed to correct the shift toward East and improve the possibility of success for the airborne campaign.

4.5 Last week of Salsa

In the last week of its life, Salsa made three final orbits, decreasing its perigee altitude until the final capture on September 8, 2024. Table 2 shows the estimated epochs, geodetic perigee altitudes and orbital periods for the last three perigee passes, as obtained by propagating the orbit determination provided on August 31, 2024 by the Flight Dynamic team of the Cluster-II mission. As it can be seen, the uncertainty on the drag effect, considered here as a range of values for the CD, is predominant for pass -1, as the perigee altitude drops below 120 km, inducing a spread of more than 2 h on the orbital period of the following pass 0, and consequent uncertainty on the length of the re-entry arc. This maximum re-entry area, taking into account the two extremes of the CD range [1.1-3.3], is visible in Figure 19, and has been used for the issuance of the NOTAM and NAVAERA messages used to inform local aircraft and maritime authorities of the risk of potential re-entry in the area. Because of this uncertainty, the need to acquire good quality data after perigee -1 was of primary interest in order to make an accurate prediction of the final re-entry time and location, and great hope was placed in the fact that the Salsa platform would survive this low-altitude interface with the Earth's atmosphere and continue to provide extremely valuable telemetry data. What actually happened as Salsa approached perigee -1 was closer to the scenario described in the discussion of the temperature profile analyses of the possible disposal options, which raised the possibility of overheating. Specifically, as Salsa approached perigee -1, the solar array panels reached very high temperatures due to the albedo and the Earth's infrared radiation (due to the proximity to the Earth), and began to significantly decrease their efficiency. This eventually resulted in the SC not having enough power to sustain normal operation, causing an undervoltage situation that eventually triggered the S/C Survival Mode.

Table 2. Epoch, Geodetic perigee altitude and orbital period at the last three perigee passes of Cluster-II-2 for the range of CD [1.1., 3.3], based on propagation from the orbit determination provided on the 31st August 2024.

Pass	*Cd*	*epoch [UTC]*	*$H_{PERIGEE}$ [km]*	*Orbital period [h]*
-2	1.1	2024-09-04T08:19	157.5	54.15
	2.25	2024-09-04T08:18	157.6	54.13
	3.3	2024-09-04T08:17	157.6	54.11
-1	1.1	2024-09-06T14:25	111.6	54.09
	2.25	2024-09-06T14:20	111.9	54.03
	3.3	2024-09-06T14:15	112.0	53.95
0	1.1	2024-09-08T19:15	61.0	52.83
	2.25	2024-09-08T17:51	66.7	51.51
	3.3	2024-09-08T16:41	60.5	50.43

Fortunately, shortly after the perigee pass, the Cluster II mission team was able to recover Salsa from this survival mode and continue to support the re-entry prediction with extremely useful telemetry and radiometric data. ESA Flight dynamics team were able to provide a final orbit determination for Salsa until the evening before re-entry. After perigee pass -1, the uncertainty in the drag coefficient was irrelevant due to the fact that the S/C atmosphere interaction during capture is very short due to the steep re-entry conditions, meaning that the last re-entry prediction available for Salsa, shown in Figure 20, was accurate enough to narrow the research area for the airborne campaign. Based on this input, the aircraft, equipped with multiple instruments and lenses distributed over six window stations, reached the expected re-entry location at the estimated re-entry time. Despite the daylight conditions, Salsa's re-entry was successfully observed by several sensors. Figure 21 shows the Salsa S/C re-entering the atmosphere from one of the aircraft window stations. A more detailed discussion of the design and implementation of the Cluster-II-2 airborne campaign can be found in [20].

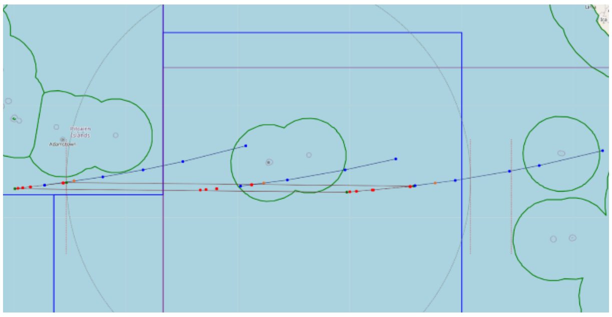

Figure 19. Re-entry arc for CD 1.1 (West), 2.25 (centre) and 3.3 (East) from propagations based on the orbit determination provided on the 31st August 2024.

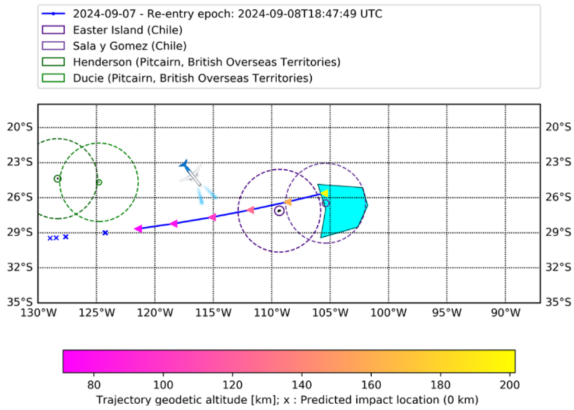

Figure 20. Last Salsa re-entry prediction based on the orbit determination provided on the evening of the 7th September 2024

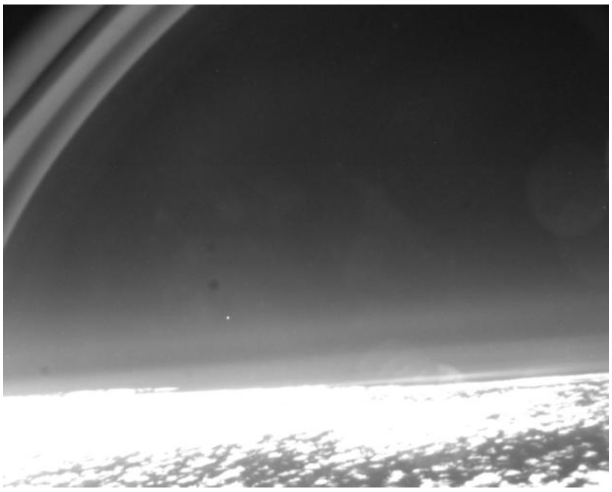

Figure 21. Salsa re-enters Earth's atmosphere and is captured as a small, bright dot. Credit: ESA/ROSIE/University of Southern Queensland. Acknowledgement: Image taken by Ranjith Ravichandran and Gerard Armstrong.

5 CONCLUSIONS

This paper discusses the pioneering design of a re-entry strategy for the Cluster-II-2 (Salsa) spacecraft, which safely re-entered the Earth's atmosphere on September 8, 2024, targeting a delimited area of the Pacific Ocean, up to the accuracy required to coordinate an airborne re-entry campaign.

This successful application of such a complex disposal strategy has provided several lessons learned, helping to understand the effects of drag perturbations on the final orbits for HEO and to assess the effectiveness of available re-entry prediction models, currently validated for circular re-entries, in predicting a hypersonic re-entry.

In addition, the data acquired during the successful observation of the Salsa re-entry, which is still being processed at the time of writing, is expected to provide extremely valuable scientific insights to improve our understanding and modelling of hypervelocity re-entry, thereby reducing the risk associated with future re-entries of this type.

Finally, the Cluster-II-2 re-entry set a remarkable precedent for the feasibility of implementing safe and robust re-entry strategies for HEOs, paving the way for future implementation in view of the upcoming re-entry of the Cluster-II-1 (Rumba) satellite, expected in October 2025, and the increasing interest in space missions for this type of orbits.

6 AKNOWLEDGMENTS

The authors acknowledge the contribution of the ESA Cluster-II mission team and their outstanding support throughout the re-entry strategy design and observing campaign.

7 REFERENCES

1. IADC, (2023). IADC Report on the Status of the Space Debris Environment, online at https://www.iadc-home.org/documents_public
2. ESA (2023). ESA Space Debris Mitigation Compliance Verification Guidelines, ESSB-HB-U-002.
3. Colombo C., Alessi E. M., Landgraf M. (2013). End-of life disposal of spacecraft in Highly Elliptical Orbits by means of luni-solar perturbations and Moon resonances. Proceeding of the 6th European Conference on Space Debris, ESA/ESOC, Darmstadt, Germany, 22-25 April 2013.
4. Colombo, C., Letizia, F., Alessi, E.M & Landgraf, M. (2014). End-of-life earth re-entry

for highly elliptical orbits: the Integral mission. Conference Paper in Advances in the Astronautical Sciences.
5. Armellin, R., San-Juan, J. F., Lara, M., (2015). Endof- Life Disposal of High Elliptical Orbit Missions: the case of INTEGRAL. Adv. Space Res., 56(3), 479–493.
6. Scala, F., Colombo C., Gkolias, I. (2018). Design of disposal orbits for high altitude spacecraft with a semi-analytical model. 18th Australian Aerospace Congress.
7. Lemmens, S., et al. (2017). Spacecraft Break-up Models for the Atmospheric Re-entry from Highly Eccentric and Interplanetary Trajectories. Proceedings of the Joint Conference: 31st ISTS, 26th ISSFD & 8th NSAT.
8. Lemmens, S., et al. (2016), From End-of-Life to Impact on Ground: an Overview of ESA's Tools and Techniques To Predicted Re-entries From the Operational Orbit Down to the Earth's Surface. Proceedings of the 6th ICATT Conference.
9. Eliasberg, P. E. (1965), Introduction to the Theory of Flight of Artificial Earth Satellites, Moscow, Nauka, p.149.
10. Funke, Q., Merz, K., Lemmens, S., Kanzler, R., Lips, T., Sieg, D., Ziegler, G. Letor, R., Sousa, B., Salt, D., Southworth, R., Volpp H.-J., (2015). End-Of-Life Disposal From Highly Eccentric Orbits. Proceedings of the 66th International Astronautical Congress.
11. Merz, K., Lemmens, S., Funke, Q., Frey, S. (2016), Optimization of End-Of-Life Disposal Maneuvers for Highly Eccentric Orbits, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, AIAA SPACE Forum, (AIAA 2016-5513).
12. Merz, K., Krag, H., Lemmens, S., Funke, Q., Böttger,S., Sieg, D., Ziegler, G., Vasconcelos, A., Sousa, B., Volpp, H.-J., Southworth, R. (2015), Orbit Aspects of End-Of-Life Disposal from Highly Eccentric Orbits, Proceedings of the 25th International Symposium on Space Flight Dynamics, München, Germany.
13. Kanzler, R., (2014), Detailed Cluster-II and INTEGRAL Reentry Break-up Analysis, Summary report, ESA Contract No. 4000109608/13/D/SR. Technical report, HTG GmbH, Katlenburg-Lindau, Germany, 2014.
14. Lemmens, S., et al. (2016). Planned yet uncontrolled re-entries of the Cluster-II spacecraft. Proceedings of the 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office Ed. T. Flohrer & F. Schmitz.
15. Letizia, F., Sanvido, S., Lemmens, S., Merz, K. ,Southworth, R., Sousa, B., (2023) ESA's current approaches to end-of-life strategies for HEO missions, Journal of Space Safety Engineering 10 (2023) 407–413.
16. J. Geul, E. Mooij, and R. Noomen, (2017), GOCE Statistical Re-Entry Predictions ,Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017.
17. B. Bastida Virgili, T. Flohrer, S. Lemmens, et al (2014). GOCE Re-entry Campaign. Proceedings of the fifth international GOCE user workshop, ESA Publications Division, European Space Agency, Noordwijk, The Netherlands.
18. Marcucci, M. F., et al. (2023), Plasma Observatory ESA M7 candidate mission: unveiling plasma energization and energy transport through multiscale observations, proceeding at the 25th EGU General Assembly, held 23-28 April, 2023 in Vienna, Austria and Online. Online at https://egu23.eu/
19. Losacco, M., et al. (2025), Predicting Cluster-II-FM6 re-entry with passive optical observations, proceeding at the 9th European Space Debris Conference, Bonn (Germany), 1-4 April 2025.
20. Šilha, J, et al., Re-entry Observation Setup and International Execution (ROSIE) mission, proceeding at the 9th European Space Debris Conference, Bonn (Germany), 1-4 April 2025.
21. ESA (2024), ESA's annual environment report, GEN-DB-LOG-00288-OPS-SD. Available online at https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2024.