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## ESA's Cluster-II - End of Mission Operations

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### Abstract

This paper describes the challenges faced by the teams at ESOC to plan, prepare and execute the operations of re-entry into the Earth's atmosphere for the ESA Cluster-II satellite quartet. The challenges included finding of a manoeuvre solution that fulfilled the desired re-entry objectives, i.e. to avoid orbit circularisation and targeting a specific splash-down region away from populations and traffic, and avoid break-up and debris remaining in orbit, with limited fuel available. Maintaining the satellites operational through to the last orbit despite power degradation and communication limitations at low altitude and even handling of collision warnings. Keeping rigorous knowledge of the satellite's trajectory, resolving position uncertainties introduced by atmospheric drag to enable an airborne observation campaign to take place to observe in-situ the break-up.

**Keywords:** re-entry, disposal, no-debris, cluster, end-of-life, HEO, on-ground risk assessment

### Acronyms/Abbreviations

European Space Agency (ESA)  
European Space Operations Centre (ESOC)  
Flight Control Team (FCT)  
Flight Dynamics Team (FDyn)  
FM (Flight Model)  
Highly Eccentric Orbits (HEO)  
Mission Extension Operations review (MEOR)  
Space Debris Office (SDO)  
Science Program Committee (SPC)

## 1. Introduction

The Cluster-II mission satellite quartet was launched with two Soyuz rockets from Baikonur on 16 July and 9 August 2000 respectively [5]. Each of the four identical cylindrical shaped satellites (Cluster-1/Rumba, Cluster-2/Salsa, Cluster-3/Samba and Cluster-4/Tango), with 2.9 m diameter and 1.3 m height (shown in Fig. 1) weighted at launch 1200 kg, 650 of which were propellant (of which on average today remain only 10 kg.), and they are spin stabilized with spin rate of 14.0 rpm. The satellites were positioned in their final HEO Orbit using their own propulsion means. The purpose of the mission was to study in-situ the effects of Solar activity on the Earth's magnetosphere, in particular measuring fields and plasma properties with a suite of 11 scientific instruments on each satellite, flying in a formation (tetrahedron) to allow measurement of phenomena in 3D. It is one of ESA's missions that have generated the highest number of scientific publications.

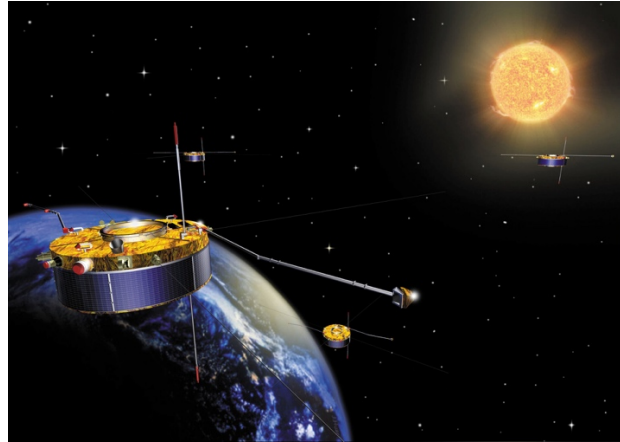


Fig. 1. Artist impression of the Cluster-II satellites

### 1.1 Successive Mission extensions

The satellites were designed for a nominal lifetime of 2 years, plus 3 years of an optional extension. At the time of launch there were no active guidelines for satellites disposals but given their HEO orbits were highly perturbed by Sun and Moon gravity; it was expected that the satellites would naturally re-enter the atmosphere around 2012-2013. No provisions were made at design time to handle this phase. The satellites were expected to be passivated after their useful lifetime and eventually fall uncontrolled and not observed.

Given the good operational status of the payload and platform, the mission was however extended repeatedly, eventually lasting a total of 24 years of continuous data acquisition. The initial re-entry epoch was postponed by actively manoeuvring the satellites, raising the orbit perigee sufficiently to avoid capture by the Earth's atmosphere. A further postponement of the re-entry was not possible due to fuel running low, which meant 3 out of 4 satellites would now nominally re-enter at the next cycle between 2024-26, and one (Cluster 1/Rumba) required a small manoeuvre (performed in 2015) to force the re-entry to take place at the same period (thus avoiding another cycle that would have resulted in a re-entry in 2038)[3][4].

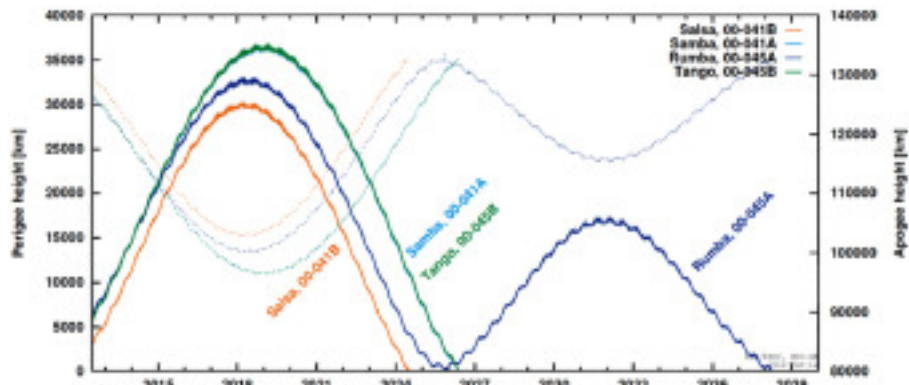


Fig. 2. Evolution of the perigee altitude of the 4 satellites without the Cluster 1 manoeuvre

### 1.2 The decision to perform a targeted re-entry

At the 2023 ESA's Science Program Committee (SPC) meeting, given the impending demise of the satellites, it was decided that the science mission should stop at the time when the first satellite re-enters, in September 2024. At the time, and as part of the Mission Extension Operations Review (MEOR) the Operations teams highlighted the need to manage the re-entry to avoid orbit circularisation during re-entry – which in such case could have happened anywhere in between approximately -50 and +50 degrees in latitude, including highly populated areas. The teams also highlighted the need to monitor the satellites to be able to determine their position accurately to support collision avoidance warning handling and to make sure the passivated batteries would not spontaneously recharge, due to the power cycling caused by eclipse seasons – an anomalous effect that was repeatedly observed in the past.

With the go ahead from the SPC, the teams started developing concrete plans to target the re-entry of the satellites, starting with the FM6 (also known as Cluster 2 or Salsa) which was forecasted to re-enter in September 2024. A targeted re-entry meant that the teams would choose the re-entry location, adjust the trajectory accordingly well in advance of the re-entry epoch, to bring the vehicle well below the Karman line in one single step. We do not refer to it as a controlled re-entry, because unlike other vehicles, like the Space Shuttle, there is no active control of the re-entry in the atmospheric phase. The satellite is expected to burn-up almost entirely upon re-entry.

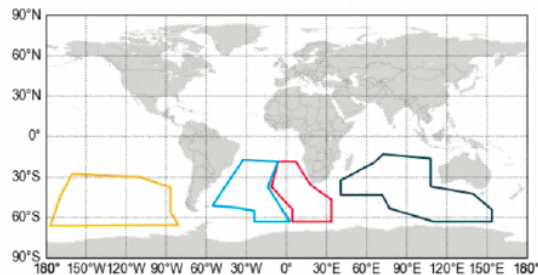


Fig. 3. Graphical representation of the preferred re-entry locations

## 2. Re-entry approach analysis [9]

### 2.1 ESA Re-Entry Approach for HEO

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 [10], 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 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 breakup 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.

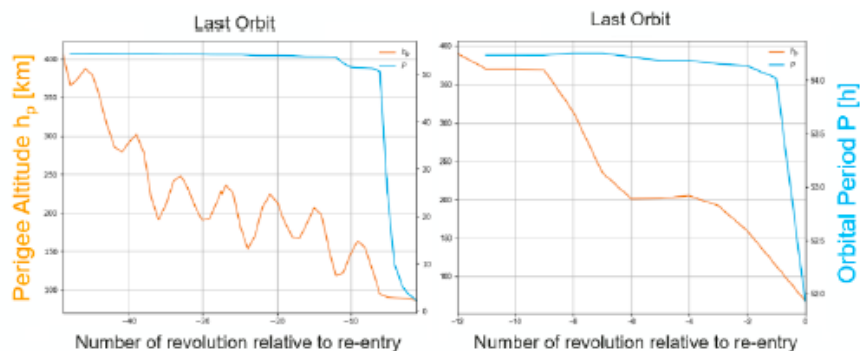


Fig. 4. Circularised re-entry profile (left) and steep re-entry profile (right).

### 2.2 Latitude and Longitude targeting

Once the re-entry strategy secured the latitude-band target with a steep re-entry over south hemisphere, it will then 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 [4],[11], 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 checked through the spacecraft lifetime and can be adjusted with (generally small) “trim” manoeuvre.

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. 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 results in diverting re-entry trajectory, in some cases leading to circularisation.

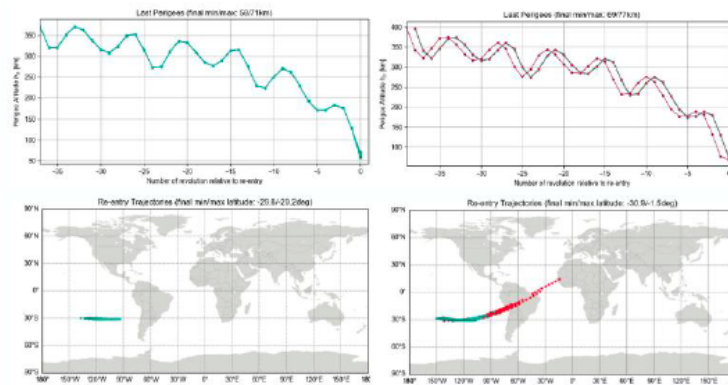


Fig. 5. Re-entry perturbed analysis: Stable re-entry trajectory (left) and unstable re-entry trajectory (right).

### 2.3 Break-up analysis and 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 back into low 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 both the ESA-SCARAB and ESA-DRAMA tools. The SCARAB Cluster-II model was employed in an extensive parametric analysis to investigate the conditions under which the spacecraft could generate escaping fragments [12].

The results of this study are displayed in Figure 6, where the types of generated fragments (on-ground or escaping) are mapped across a grid of perigee altitudes and semimajor axes. 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. As a further precaution, an additional check is conducted at the end of the re-entry strategy definition using the DRAMA model. This additional validation is specifically designed to confirm the absence of escaping fragments under the proposed re-entry strategy.

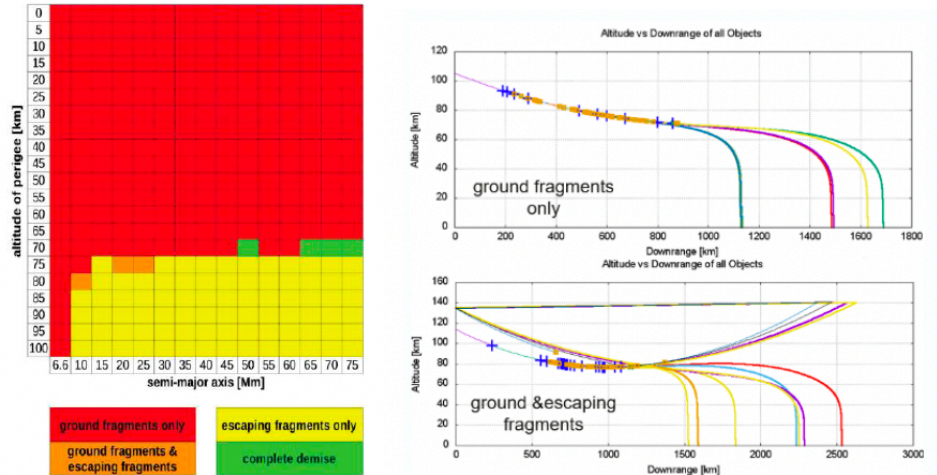


Fig. 6. (left) SCARAB Parametric break-up analysis on the first perigee pass within the atmosphere; (right) DRAMA analysis results, showing ground fragments only (top) and ground & escaping fragments (bottom).

### 3. Manoeuvre implementation [9]

#### 3.1 Choosing the manoeuvre location and direction

The re-entry profile of Cluster-2/FM6 as per August 2023, before the disposal manoeuvre, showed circularisation, as visible in Figure 4. To address this concern, a coordinated analysis between SDO and the Cluster-II mission was initiated to investigate suitable re-entry strategies.

In the case of Cluster-2/FM6, 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 was conducted. The recursive application of the selection procedure for latitude and longitude targeting, summarised before, lead to a final selection of three possible candidates 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. 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.

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 which also ruled this option out. With Options 1 and 2 ruled out, the Option 3 was selected as re-entry strategy for Cluster-2/FM6, as it met all the requirements to ensure a safe and reliable re-entry.

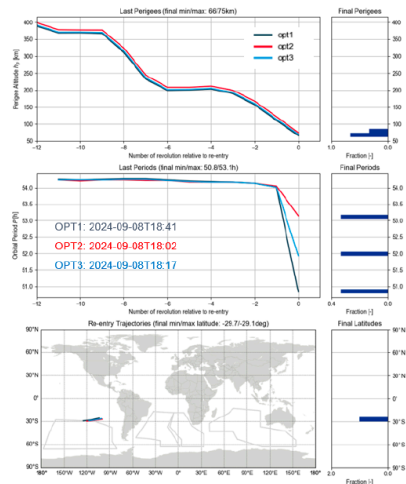


Fig. 7. Three possible disposal strategy for Cluster-2/FM6. The re-entry epochs are in UTC.

### 3.2 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, the first close to perigee and the second near apogee. The first adjusted the orbital period and targeted the re-entry longitude, the second mainly modified the perigee height evolution and achieved a steep re-entry profile. This was followed by two axial trim manoeuvres on 24/25 January 2024, at similar locations, to perform small corrections after the precise evaluation of the main manoeuvres' performances. The successful implementation of this series of manoeuvres led to the correction of the circularization for Cluster-II, as shown below on the left.

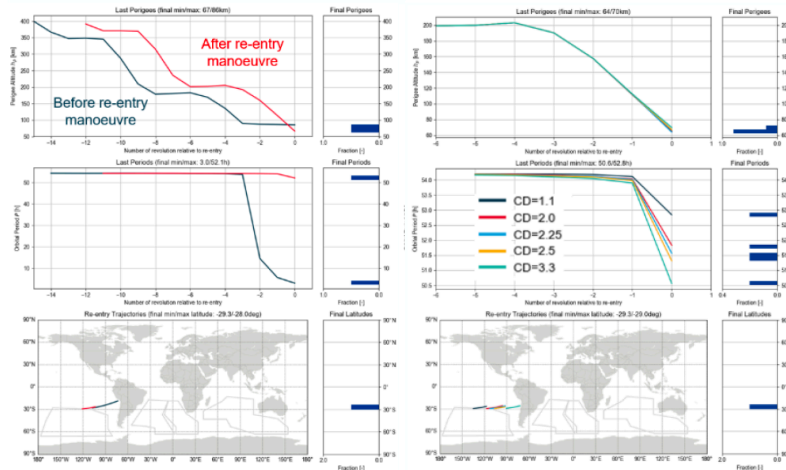


Fig. 8. (left) disposal manoeuvre effect (right) re-entry profile for the range of CD [1.1, 3.3], based on Orbit Determination from the 25th August 2024.

### 3.3 Determination of the actual re-entry location and epoch

As Salsa lowered its perigee altitude below approximately 400 km, the differences between modelled and actual drag perturbation began to show, and the Flight Dynamics team started the drag coefficient (CD) calibration to estimate an evidence-based CD value for each perigee passage. 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  $\pm 50\%$  uncertainty to the drag coefficient. As a result, the regular re-entry forecast for the last weeks of Cluster-2/FM6 was performed for the CD values between 1.1 and 3.3 to cover all possible scenarios in terms of re-entry epoch and re-entry location (see Fig. 8-right). 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.

## 4. LEO crossing phase

### 4.1 Further cell degradation due to Van Allen Belt crossing

Cluster-II Solar array panels extra degradation has been identified when the SC orbit started crossing the Inner Earth radiation Belts (Van Allen belts). The first time this irregular extra degradation was identified during the period 2010-2014 when the SC perigee altitude was as low as 250 km (Cluster-2/FM6)[7]. After 2014 the perigee altitude was raised again together with some other orbit corrections and degradation stabilised to values of around 0.5 W loss per year. From 2023 Cluster-2/FM6 spacecraft perigee altitude decreased again in preparation to re-entry in 2024. Consequently, the spacecraft started crossing Van Allen belts again once per orbit (54h) and the same Solar array degradation as in 2010-2014 period was identified with an average Power loss of 0.2 W per orbit. As expected, the same degradation was identified in Cluster-1/FM5 from 2024 when spacecraft started crossing the radiation belts.

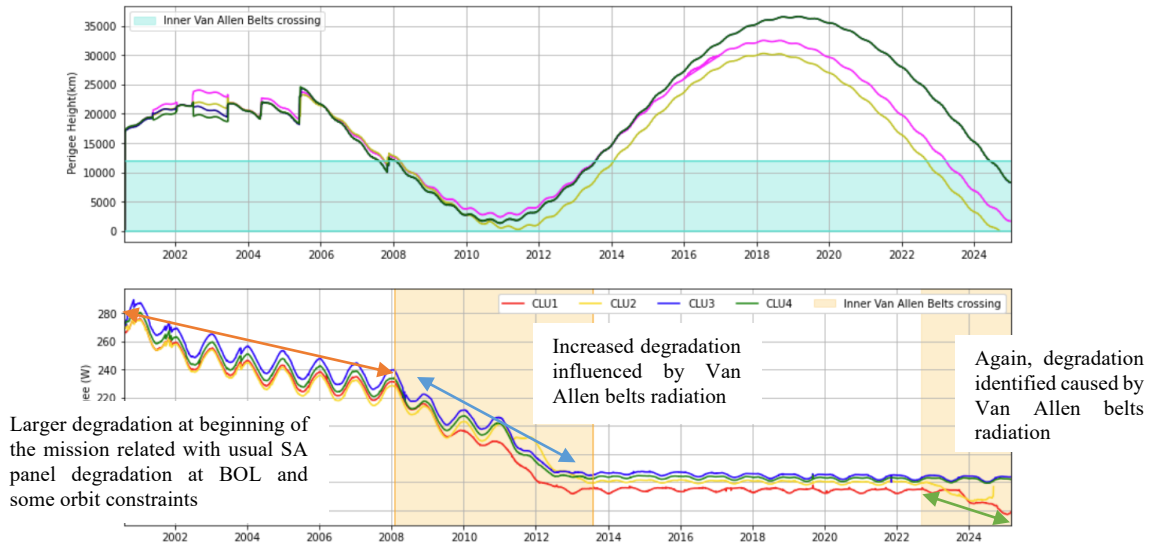


Fig. 9. Evolution of SC perigee altitude and Solar array power degradation

The inner radiation belts are considered from 12000 km altitude to 600 km altitude. The main driver for the extra degradation proved to be protons [8] with higher density inside the proton belt around 2000 km.

#### 4.2 Earth Albedo effect and perigee power drop

As in any solar cell, Cluster spacecraft's Solar array efficiency is influenced by temperature. It was identified that the Solar array panels were overheating during each perigee crossing creating a loss of efficiency that in turn generated the so-called Perigee Power drop. The lower the perigee altitude, the greater the solar panels temperature and consequently bigger loss of efficiency. And the source of this temperature increase is proved to be Earth Infrared radiation and Albedo effect. The temperature increase is influenced by other factors on top of Earth-SC distance (perigee altitude), see Solar array temperature model in Equation 1 [7]. This explains the seasonal effect on Perigee power drop causing incremented albedo effect during the winter months due to greater Earth surface illuminated by the Sun that is reflected as radiation to the SC.

$$\begin{array}{c}
 \text{IR+albedo radiation from day side} \quad \text{IR radiation from night side} \\
 \left( c \cdot \frac{A_{day}}{A_{Earth}} + d \cdot \left( 1 - \frac{A_{day}}{A_{Earth}} \right) \right) \\
 \underbrace{\hspace{10em}} \\
 SAT = a + \underbrace{\frac{b}{DSS^2}}_{\text{Sun-Spacecraft thermal coupling}} + \underbrace{\frac{\hspace{10em}}{R_p^2 \cdot DES^2}}_{\text{(Sun-Earth)-Spacecraft thermal coupling}}
 \end{array}$$

Eq1. Model for Solar array temperature (DSS: Sun-Spacecraft distance. DES: Earth-Spacecraft distance)

As example during last months of Cluster-2/FM6 when the spacecraft altitude was at its lowest, Solar array power available in perigee was reduced by more than a half the recorded value in apogee.

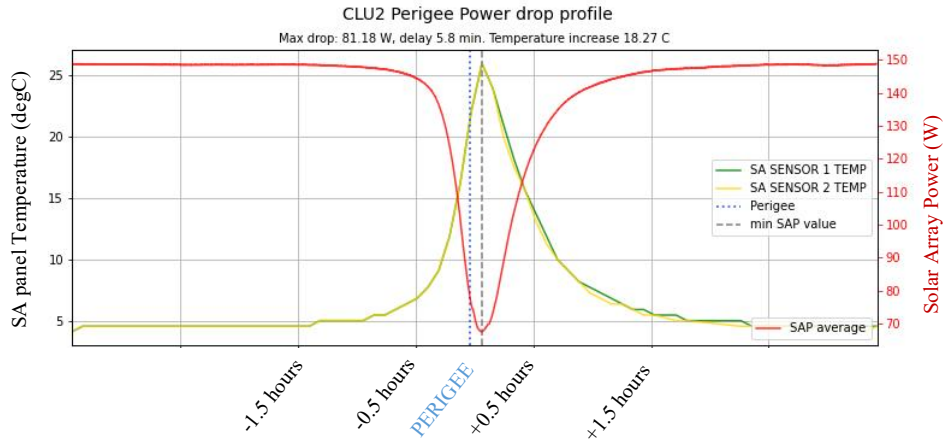


Fig. 10. Perigee power drop vs Solar array temperature increase

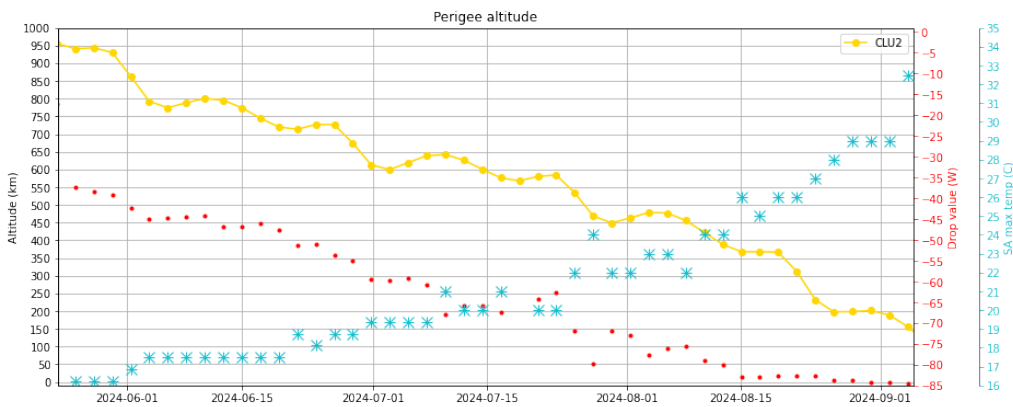


Fig. 11. Perigee power drop vs Solar array temperature increase over the last 3 months

Although this power drop does not produce a permanent degradation in Solar array, the loss of power could reach values as high as to affect spacecraft routine operations.

Cluster's 28V main bus was designed to be regulated by the means of an External and an Internal Power Dumper (EPD and IPD) dissipating surplus energy at begin of life. After the 2024 short eclipse season, the combined effect of cell degradation and perigee power drop required the progressive switch-off of payloads and subsystems around perigee to keep Cluster-2/FM6 power-positive and avoid a main bus undervoltage:

- 03/06/2024: Heater H off around perigee
- 05/06/2024: ADCE off around perigee
- 14/07/2024: SSR off
- 18/07/2024: Cluster-2/FM6 end of science, all payloads off

In this configuration, the spacecraft survived at a 0W power margin without suffering from a main bus undervoltage until its final perigee before re-entry.

#### 4.3 Communication restriction at low altitude

The International Telecommunication Union (ITU) has established limits on Power Flux Density (PFD) received on ground in Article 21 of its Radio Regulations, specifically -154 dBW/m<sup>2</sup> in any 4 kHz at 5 degrees elevation and -144 dBW/m<sup>2</sup> in any 4 kHz above 25 degrees elevation in S-Band. Depending on the altitude, power mode, telemetry bit rate, and modulation, the Cluster spacecraft may violate ITU's PFD limits. When the Cluster constellation first started reaching perigee altitude values when regulations could be violated in the late 2009, actions were taken to ensure compliance with ITU regulations. Since then, Flight Dynamics (FDyn) generated event files indicating the times when the spacecraft crosses the 6000 km altitude (threshold for regulation violation at low bit rate) and 3000 km (threshold for high bit rate) respectively during descent and ascent. In an attempt for automation, FCT implemented

rules in mission planning system to create time-tagged commands for switching off the transmitter around perigee considering those altitude markers.

Throughout the entire period of several months preceding the re-entry of Cluster-2/FM6, where the satellite has been again below those altitude thresholds, transmitter has been systematically switched off at those markers to avoid the violations, which also contributed to shedding power that we were missing due to Earth Albedo (as explained in previous sections of this paper) – but adding a restriction to the possibility of taking contacts around those periods. Similar actions were taken in Cluster-1/FM5 when spacecraft perigee reached values of 6000 km altitude in 2024.

After consultation with ESA's Frequency Management Office, the transmitter was kept on during the final descent of Cluster-2/FM6 on 8<sup>th</sup> September 2024, while PFD exceedances were limited by selection of a high telemetry bitrate. This allowed for a final Kourou pass from 17:24 to 18:38, just minutes before spacecraft re-entry.

#### *4. Cluster-2/FM6 – MethaneSat Collision avoidance warning on 10-07-2024*

On the 10-07-2024 the ESOC Space Debris Office issued a warning to the Flight Control Team that identified a close approach for Salsa (Cluster-2/FM6) at 2024-07-18 21:31:27, with a collision probability of  $5.7 \times 10^{-8}$ , and initial miss distance of 50854m and a radial miss distance of -1416.1m. The chaser object was MethaneSat (2024-043D) with a Box + 2 Panel shape, and a mass of 362 kg. MethaneSat is an American-New Zealand space mission launched in 2024 aboard SpaceX's Transporter 10 rideshare mission. It is an Earth observation satellite that monitors and studies global methane emissions to combat climate change. The conjunction had been monitored already for 5 days, and the general trend was that the probability was increasing as the covariance was reducing. Hence the collision avoidance procedure was triggered.

A meeting was held on the same day, involving the Space Debris Office (SDO), the Flight Control Team (FCT) and the Flight Dynamics Team (FDyn), and given the present probability value was above the corresponding threshold it was decided to proceed with the implementation of a collision avoidance manoeuvre (CAM). The FCT booked additional tracking passes to improve orbit knowledge of Cluster 2/FM6. SDO proceeded to devise strategies to increase the separation between the satellites, and based on that FDyn would perform trajectory optimisation. FCT was also preparing to switch off the payload in anticipation of the manoeuvre execution, which had to be executed latest one perigee before the encounter, therefore on the 16-07-2024. As the power situation was also marginal during perigee crossings, and to avoid the risk that the satellite would suffer an undervoltage prior to manoeuvre execution, it was additionally decided to shed further power, by switching off the mass memory and therefore stop recording of further science data.

As the probability kept increasing towards  $10^{-7}$ , the go ahead was given on the 12-07-2024 for command generation and a go/no-go for uplink meeting scheduled for the 15-07-2024. During the days in between the probability oscillated above and below the threshold. But at the time of the meeting, considering the latest tracking data, the probability was below the threshold and therefore the Operations Manager took the decision not to upload the manoeuvre. As part of this event, it was considered that the thresholds were currently set too low and therefore adjusted by one order of magnitude higher for future conjunctions.

The event highlighted how the critical power situation was affecting the capability to ensure the safe performance of such ad-hoc manoeuvres.

## **5. Operations in the last orbits of Salsa**

### *5.1 Re-entry adjustment manoeuvre*

On the 16-08-2024 the SDO issued a request for a re-entry touch-up manoeuvre. Despite the uncertainties we had on the drag to be experienced in the one before last perigee (at a low altitude of 110km), it was still considered that the nominal prediction was meeting the objectives of the disposal campaign: impacting in a region with negligible casualty risk. However, over time we had seen that the baseline prediction shifted Eastwards by roughly 15 degrees since the manoeuvre was implemented in January. The assumption was that this shift was due to a poor representation of the actual atmospheric density on the low perigee passes, as there is no validation data between 350 and 70km and the impact of geomagnetic storms in poorly modelled in general (and the Sun activity was increasing).

Shifting further to the East reduced the likelihood of flying the planned airborne re-entry observation campaign as it would be beyond the plane's maximum range. If the chance of missing it, because the extremity of the re-entry area was too far East, was above 20%, we would need to call it off. Given that we were in Solar storm conditions a few days before, the next solar rotation of that region would roughly coincide with the re-entry, therefore SDO team consider the benefit of a less than 10 cm/s manoeuvre at apogee to raise the perigee slightly to compensate the incurred Eastward drift since January. For operational reason this would need to be implemented on the 20<sup>th</sup> or latest 23<sup>rd</sup> August.

After fast iterations among all the teams it was decided to implement a 5 cm/s manoeuvre for the apogee pass of the 22-08-2024 to correct the drift. This would lead to an increment of the SMA of about 1,5 km. After the FDyn optimization process that considers the satellites attitude constraints we ended up with an 8,6 cm/s manoeuvre. The manoeuvre commands were generated on the 19-08-2024, they were subsequently screened for risk of collision by SDO who gave the final GO for uplink. Uplink took place nominally on the 21-08-2024 from the Yatharagga ground station and execution took place nominally at 2024-08-22 22:17:00 UTC. The event showed the teams were still able to react fast, work collaboratively and implement and execute a manoeuvre in a very short time.

### *5.2 Tracking needs to resolve drag uncertainty*

From the 20-08-2024 the colleagues at SDO started issuing a regular bulletin informing the latest estimation for the re-entry epoch. The initial reported epoch was 2024/09/08 17:51:07 UTC +/- 1.55h. As we approached the actual time, we could see that the evolution of the uncertainty was moving rather slowly. By the 04-09-2024 the prediction was 2024/09/08 17:51:24 UTC +/- 1.4h. This was because the major source of the uncertainty was the passage at the one but last perigee, where the satellite would already be at an altitude of 110 km. This order of magnitude in the error, all but made impossible the flying of the plane for the monitoring of the re-entry, as it could imply a displacement of the re-entry point of a few hundred kms.

This meant that it was vital to perform tracking during the very last orbit, to correct the uncertainty and pass the exact re-entry location to the team in Easter Island before the plane took off for the mission. A total of 6 (almost) consecutive contacts were booked around the last perigee – with an interruption of one hour over perigee where no visibilities were available. The stations of Yatharagga, Weilheim, Villafranca-1, and Kourou were used with overlaps to ensure backup opportunities to track.

### *5.3 Safe Mode entry and recovery on the one but last perigee*

The satellite was fully nominal at the end of the Villafranca visibility that preceded the perigee crossing. But one hour later no signal was detected during the subsequent contact with Yatharagga. The team immediately initiated the no-TM procedure to restore communication with the satellite. Upon commanding a switch-on of the transmitter in the blind communication was restored and it was possible to verify that the satellite had entered safe mode, following a triggering of the main bus undervoltage monitoring.

After so many previous perigee passages with negative power available and the bus kept up by the capacitors, finally on the last perigee, the bus could hold it no longer and the spacecraft entered safe mode. This was a direct result of the intense heat experienced when crossing through the upper atmosphere at just 110km altitude. The team worked diligently to recover the satellite to normal mode and ensure acquisition of further vital tracking data to resolve the re-entry location uncertainty.

The last bulletin from SDO reported that re-entry epoch at 2024/09/08 18:47:36 UTC +/- 4s, which shifted the original prediction by almost one hour to the West. This meant that the East shift that had been predicted some weeks before had not taken place as feared.

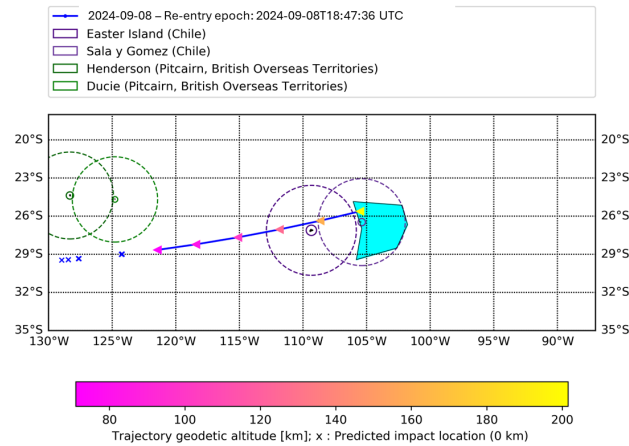


Fig. 12. Final prediction of re-entry epoch and location

#### 5.4 The re-entry of Cluster2/FM6

With the satellite fully recovered the FCT continued to track it. A contact was taken from Villafranca2 on the 07-09-2024 at the last apogee from 15:50 to 17:30 UTC. The corresponding orbit determination was still fed to the observation team in Easter Island.

On the 08-09-2024 we started tracking again the approach towards re-entry. 3 stations were used in succession with overlaps to ensure continuity. First Yatharagga in Australia, followed by Maspalomas in the Canary Islands and Kourou observed the satellite until it left the South American continent at an altitude below 500 km at around 18:35. During this contact the team sent the last commands to the spacecraft, with all team members having a chance to issue a farewell command (ping). A live event took place at ESOC with talks about the mission and many special guests coming to bid goodbye to a mission that had produced incredible science for a quarter of a century and been the backbone of Solar physics, Plasma Physics and Space Weather for the global scientific community. We could observe the contact being lost to the spacecraft at it went beyond the horizon. And we turned our attention to getting a message from the aircraft that was already airborne and in position to observe the re-entry.

#### 5.5 The airborne re-entry observation campaign

To observe the re-entry and understand the break-up and demise processes an airborne campaign (ROSIE) was planned and executed as a joint effort of academic partners from University of Stuttgart (IRS/HEFDiG), Faculty of Mathematics, Physics and Informatics, Comenius University (CUB), University of Southern Queensland (UniSQ) and industrial partners from Hypersonic Technology Göttingen (HTG) and Astros Solutions, in close cooperation with European Space Agency. A private jet was chartered out of Australia, and started the observation mission out of Easter Island, with 16 instruments on-board, mounted on the windows. Despite the re-entry taking place during daytime, which makes it extremely hard for the instruments to observe the re-entry, several of the instruments were able to record important data. The results of this campaign will be published separately.



Fig. 13. Photos from the airborne observation campaign (credits ESA/Astro-Solutions/ROSIE)

## 6. Outlook and re-entry of the remaining satellites

In the meantime, the same approach has been applied to all remaining Cluster-II satellites. As of the time of writing this paper, they are all properly targeted for a steep re-entry in the same region of the Pacific at the following dates:

- Cluster 1: 2025-10-22
- Cluster 3: 2026-08-31
- Cluster 4: 2026-09-01

The science mission has been terminated as of 30<sup>th</sup> September 2024, and the satellites are regularly monitored (typically contacts are once a week) to maintain good knowledge of their orbit. Cluster-1/FM5 is going through an almost 6-months long eclipse season, which makes it particularly difficult to track, since it requires activating the satellite completely in between eclipses (the batteries are all failed and no longer in use) [13]. Its Solar Arrays are even more degraded than those on FM6, and we may have to extend the switch off/on eclipse cycle further to ensure survivability around perigee crossings too all the way to October 2025 until its re-entry. The Flight Control Team is strongly reduced, with all engineers now assigned to other projects and supporting Cluster only in part-time. The Spacecraft Controller team that used to cover exclusively 24hr real time operations for Cluster are no longer available and have been integrated in the team that supports the other 6 interplanetary missions operated by ESA and give only partial support. Cluster-1/FM5 will also spend a lot more time in LEO than FM6, which means the likelihood of collision warnings is higher for this satellite. All and all, there remains challenging times ahead until all satellites are demised.

## 7. Conclusions

This paper has explained the process of accurately targeting the Cluster constellation satellites for a clean re-entry, to avoid debris being left in space, by carefully managing the demise process, including active monitoring of the satellites (in particular the critical power situation), touch-up manoeuvring and handling collision avoidance.

It highlights the efforts and commitment of ESA to the Zero Debris Charter with an example of a mission, that was not obliged to follow guidelines that came into force after it was already flying but nevertheless has found a way to apply them to the best of its capabilities.

Actively managed re-entries from HEO are not very common and Cluster mission will remain as one of its pioneers.

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