RE-ENTRY OBSERVATION SETUP AND INTERNATIONAL EXECUTION (ROSIE) MISSION

Jiří Šilha(1,3), Matej Zigo(1), Stefan Loehle(2), Clemens Mueller(2), Juraj Tóth(3), Tomáš Paulech(3), Fabian Zander(4), Byrenn Birch(4), Ranjith Ravichandran(4), Gerard Armstrong(4), Tobias Lips(5), Patrik Kärräng(5), Beatriz Jilete(6), Benjamin Bastida Virgili(6), Stijn Lemmens(6)

(1) Astros Solutions s.r.o., Nad Lúčkami 3141/35, 84 105, Bratislava, Slovakia, Email: jiri.silha@astros.eu
(2) High Enthalpy Flow Diagnostics Group, Institut fuer Raumfahrtsysteme, Universitaet Stuttgart, Pfaffenwaldring 29, 70569 Stuttgart, Germany
(3) Faculty of Mathematics, Physics, and Informatics, Comenius University Bratislava, Mlynska dolina, 842 48 Bratislava, Slovakia
(4) University of Southern Queensland, 487-535 West Street, Toowoomba Qld 4350, Australia
(5) HTG - Hyperschall Technologie Göttingen GmbH, Am Handweisergraben 13, 37120 Bovenden, Germany
(6) ESA/European Space Operations Centre, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany

A daylight airborne campaign has been conducted in September 2024 to observe the re-entry flight of the Cluster-II *Salsa* satellite, one of four satellites of the space weather *Cluster* mission. *Salsa*, with its highly eccentric orbit, was a suitable target for the observation, because a sufficiently precise prediction of the entry location was possible to allow for an airborne observation. Furthermore, the cluster satellite is a high-speed daylight entry and therefore only the second object of this kind observed after the WT1190F entry in 2015. This target selection also provides an opportunity for repeated experiments using the same targets focused on the other three Cluster satellites re-entering in 2025 and 2026. A team of nine researchers from four different institutions and three different countries deployed 26 scientific instruments on board, 10 instruments observed the entry successfully.

1 INTRODUCTION

The Re-entry Observation Setup and International Execution (ROSIE) project aims to implement industrial-level procedures and methodologies into airborne re-entry observation missions for the analysis of satellites' destructive re-entry. The objective is to perform observation campaigns using standard aircrafts equipped with scientific instruments in order to acquire invaluable data sets for further improvement and/or validation of destructive re-entry event modelling. Such data sets are unique and provide an unprecedented opportunity to improve the understanding of destructive re-entry, such as fragmentation cloud evolution, spectrographic backward mapping of the fragments' origin and ablation signatures of specific materials. All these questions are addressed within this project during different airborne missions using experimental data acquisition and data processing methods.

Airborne Observation is an already established and demonstrated technique, that yields unique data, which is in many cases not acquirable using ground infrastructure. Currently, re-entry events are primarily targeted to appear above the non-populated ocean sites. Due to this fact, the only option for an observation of such an event, is to setup a remote, usually airborne, observation campaign. The airborne campaign itself is a high-risk data acquisition technique, which requires sensitive planning and a-priori mission analysis. Due to these requirements, the best candidates for the mission targets are objects with well-known and stable trajectories. Any uncertainty in the location and time of the re-entry event significantly increases the risk of the airborne campaign and in many cases makes the campaign non-feasible.

2 CLUSTER MISSION

The Cluster mission consisted of four identical spacecraft (Fig. 1) with cylindrical shape, 1.3 m high and 2.9 m wide. The total dry mass per spacecraft was 550 kg and the launch mass was 1200 kg. The primary objective of the Cluster mission was to investigate small-scale plasma structures of the Sun in three dimensions across critical plasma regions, including the solar wind, bow shock, magnetopause, polar cusps, magnetotail, and auroral zones [1].

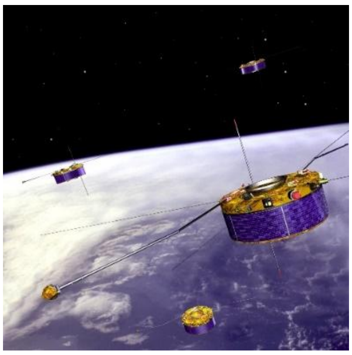

Figure 1. Author's depiction of four Cluster satellites. Photo credit: ESA

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 primary target missions of ESA for the next few years concerning the investigation of re-entries are Cluster I/II/III/IV (see Tab. 1 for naming convention) leading eventually to the DRACO (Destructive Re-entry Assessment Container Object) mission where a satellite aiming for destructive entry is launched by purpose [Jilete]. Thanks to the highly elliptical orbits and the geometry of the four Cluster satellites, the location and time of their re-entry can be estimated far ahead with acceptable accuracy [2]. The DRACO mission is developed to investigate demise effects, perform in-situ measurements and the re-entry event trajectory will be controlled and known [3]. These events provide a unique opportunity to perform a remote observation campaign.

Name	Rumba	Salsa	Samba	Tango
Numbered name	Cluster-I	Cluster-II	Cluster-III	Cluster-IV
Flight model	FM5	FM6	FM7	FM8
COSPAR	2000-045A	2000-041B	2000-041A	2000-045B
US cat. ID	26463	26411	26410	26464
Predicted re-entry	Oct 2025	Sep 8 2024	2026	2026

Table 1. Cluster satellites notation. The Re-entry time predictions are taken from ESA's re-entry prediction service.

3 AIRBORNE CAMPAIGN OBJECTIVES

The mission objectives have been developed based on the spacecraft's design, the re-entry trajectory, and the possible observation geometries. A trade-off analysis was conducted to determine the most appropriate instrument configurations. The following research questions were addressed for the *Salsa* re-entry event:

1. **Main Break-up:** to better than 5s (in GPS time)

2. **Fragmentation sequence, trajectories:** to better than 5s, 1km

3. **Fragment identification:** distinguish fragment’s spectra from the observed data

The main concept involved defining roles for each participant during the campaign and establishing procedures for an efficient and meaningful mission. For the Salsa mission, we defined major roles for the airborne campaign. First, the **Mission lead**, the entity responsible for the mission planning and technical tasks for the configuration of the aircraft. The Mission lead is also the responsible for the mission risk identification. For the Salsa mission, this role was in responsibility of University of Southern Queensland (UniSQ). The second role is the **Science lead**, who is responsible for accurately understanding the customer’s data requests and science questions to be addressed by the mission. Based on this understanding, the Science lead identifies the most suitable instrument suite and selects flight participants and experts accordingly. Mission and Science Lead work closely together for a successful mission. This role was assigned to the High Enthalpy Flow Diagnostics Group (HEFDiG). The third role is the **Mission participant**, who is responsible for providing its suggested scientific instruments together with a team for their operation. The Mission participants can be anyone who can provide relevant data using their own instruments, corresponding to the requirements of the customer and selected by the Science lead. Each Mission participant is responsible for its own data processing. One of the Mission participants on the *Salsa* mission was the Comenius University Bratislava (UNIBA). The **Campaign coordinator** is responsible for the overall campaign administration, mission team communication and management, overall risk identification, mitigation, and management, as well as communication with the customer. This was the responsibility of Astros Solutions s.r.o. (Astros).

4 MISSION PLANNING

The primary planning challenges for the Salsa mission arose from the remote location of the re-entry event and the limited time available for mission preparation. Furthermore, *Salsa* is a satellite in a highly eccentric orbit, entering the atmosphere at a shallow angle and speeds exceeding 10 km/s. As a result, the re-entry is a comparably short event. Predictions showed at maximum an observation time of around 70 seconds.

Five separate windows for the use as observation stations are necessary, to achieve the required redundancy between instruments and sufficient tracking cameras for the object identification during re-entry. Each station requires 1-2 operators. As a result, the aircraft must accommodate around 10 passengers while also providing enough space for instruments close to the windows, cable management for power, workstations, and time synchronization across stations. Not the least, the aircraft’s range capabilities must be sufficient for the long distances in the Southern Pacific Ocean.

The selected aircraft model for the Salsa mission was a FALCON900 (Fig. 3), a business jet that offers up to 16 seats and a maximum flight range of 7,400 km. It has 12 separate side windows, six of which can be used for station setup to support operation at each station.

Figure 3. Falcon 900 business jet VH-CAD, owned by FalconAir LTD, parked in the hangar for the

instruments' installation and mounting.

The observation was planned to aim at detecting the fragmentation of a Cluster satellite in plain daylight conditions (~11:00 local). Detection of the fragmentation means the timely correct detection of break-up events, so that the sequence of fragments appearing can be determined and provided to the modelers. The focus was put on the main break-up which was predicted to occur at ~70km altitude (see science objective). The next main goal was to identify the fragments. Therefore, a suite of spectral filtered imaging cameras was deployed.

In total six observation stations were defined and deployed onboard the aircraft operated by three different entities – UniSQ (3 stations), HEFDiG (1 station) and UNIBA (2 stations). The floor plan for the Salsa mission is depicted in Fig. 2 [4].

Figure 4. Floor plan for the Salsa mission [4].

The final configuration of the instrumentation inside the jet can be seen in Fig. 5. All mission preparation was realized in Sydney, Australia with good ground support for last-minute adaptations and solving hardware problems.

Figure 5. Final Setup onboard the aircraft. Left - View from the cockpit; Right - View towards the cockpit.

During the SALSA mission planning phase, Hypersonic Technology Goettingen GmbH (HTG) was responsible for modelling and predicting the nominal re-entry trajectory. This data served as input for defining a precise mission flight path. Because of the *Salsa* manoeuvre performed in early 2024, the predicted location of the re-entry event was South and/or West of Easter Island. Fig. 6 shows the transfer flight path from Sydney to the mission and back. Fuel and pilot's rest restrictions required to stop in Auckland, NZ, and Tahiti, French Polynesia, on the way to Easter Island. On the way back stops were made on Cook Island and again Auckland, NZ before completing the mission in Sydney.

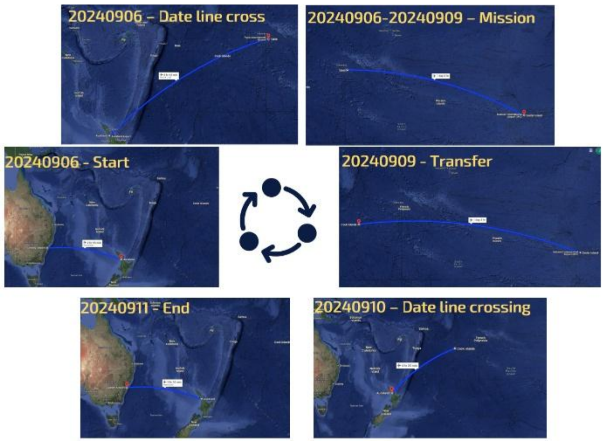

Figure 6. Depiction of all the transfers that mission participants needed to perform for the Salsa mission.

5 MISSION EXECUTION

The departure from Easter Island to the location of the predicted *Salsa* re-entry was on 8th of September 2024 at 10:00 am local time. The image of the aircraft along with the mission participants before the departure can be seen in Fig. 7. A ground station was deployed on Easter Island, too. This station was run by UNIBA.

Figure 7. Falcon 900 and all the mission participants departing from Hanga Roa airport to the Salsa re-entry on 8th of September 2024. From left to right: Ranjith Ravichandran (UniSQ), Gerard Armstrong (UniSQ), Byrenn Birch (UniSQ), Fabian Zander (UniSQ), Clemens Mueller (HEFDiG), Stijn Lemmens (ESA), Stefan Loehle (HEFDiG), Jiří Šilha (Astros), Juraj Tóth (UNIBA).

The planned re-entry location was roughly 2000 km West of Easter Island. This location was predicted by HTG's re-entry simulations using SCARAB (SpaceCraft Atmospheric Re-entry and Aerothermal Break-up) [5] using the latest trajectory provided by the ESA Flight Control Team, Flight Dynamics Team and Space Debris Office [6]. The flight plan was then organized by UniSQ and HEFDiG accordingly the day before the mission. It took two hours to reach the destination. It took two hours to reach the destination. The aircraft was positioned for viewing the event out the starboard side. Additionally, the aircraft performed a bank manoeuvre during the predicted re-entry to maximise the potential viewing time, which was calculated to start at 18:46 UTC. All the instruments were recording during the planned event.

From the total of 26 scientific instruments on board, 10 captured the event. As an example, Fig. 8 shows an image of the camera that was equipped with a bandpass filter to isolate Potassium (K) emissions captured by Station no. 6. In Fig. 8, the Moon and clouds are seen above the horizon, too. This camera captured *Salsa* for 15 seconds.

The collected data from all the instruments is now being analysed. The analysis is then used to support HTG's reconstruction of the events, i.e. the re-entry flight.

Figure 8. Salsa captured by UNIBA instrument DMK camera situated at Station No. 6. Object appears as a point like source in the lower left corner. The camera is seeing Potassium (K) only.

6 CONCLUSIONS

The ROSIE mission to observe the demise of the satellite *Salsa* is considered successful. The collected scientific data are now being processed to be compared to the simulation to better understand the re-entry events and the high-fidelity models such as SCARAB. A compilation of lessons learned for future missions has been collected and documented.

Currently, a follow-up mission for observing another object is being prepared within the ROSIE project. The possible targets for the follow-up campaign will be one of the remaining Cluster satellites Cluster I, III or IV. The selection is currently ongoing by analysing the potential benefit from a scientific perspective.

The experience and procedures collected from ROSIE shall be used for the airborne campaign to be conducted for the DRACO mission which is designed to monitor in detail the physics of the demise process.

7 ACKNOWLEDGEMENT

This work has been supported by ESA under Contract No. 4000145029/24/D/MRP - Setup, Run, And Collaborate in International Remote Re-Entry Observation Campaigns.

The ROSIE-Salsa observation mission is a joint effort, with academic partners from University of Stuttgart (HEFDiG), Comenius University in Bratislava (UNIBA), the University of Southern Queensland (UniSQ) and industrial partners from Hypersonic Technology Göttingen (HTG) and Astros Solutions in close cooperation with the European Space Agency - ESA.

8 REFERENCES

1. Escoubet, C., Fehringer, M., and Goldstein, M. (2001): The Cluster mission. Annales Geophysicae. 19. 1197-1200. 10.5194/angeo-19-1197-2001.

2. Lemmens, S., Merz, K., and Funke, Q. (2017): Planned yet uncontrolled re-entries of the Cluster-II spacecraft, Proceedings of 7th European Conference on Space Debris.

3. Jilete, B., Lemmens, S., Van Den Eynde, J. et al., (2025): DRACO scientific return concept: determining the truth of satellite demise, Proceedings of 9th European Conference on Space Debris.

4. Loehle, S.; Zander, F.; Kaerraeng, P.; Lips, T.; Armstrong, G.; Birch, B. et al. (2025): Design and Execution of the Airborne Re-entry Observation Campaign of the Cluster-II Salsa Re-entry. under review. In: CEAS Space J.

5. Kanzler, R., Lips, T., Fritsche, B., Breslau, A., Kärräng, P., Spel, M., Pagan, A., Herdrich, G., Lemmens, S. (2021): SCARAB4 – Extension of the High-Fidelity Re-Entry Break-Up Simulation Software based on new Measurement Types, Proceedings of 8th European Conference on Space Debris.

6. Sanvido, S., Losacco, M., Stijn, L. et al. (2025): Bringing SALSA Home: CLUSTER-II-2 Re-entry Strategy, Proceedings of 9th European Conference on Space Debris.