AEOLUS Operations for Assisted Reentry

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***Abstract* – Aeolus, the European Space Agency (ESA) wind mission, was designed and built prior to the implementation of End-of-Life (EOL) deorbiting policies by ESA. In order to significantly reduce the global risk of casualty, the concept of an assisted reentry was introduced in 2022. It was iteratively refined by the operations team at the European Space Operations Centre (ESOC), aided by industry (Airbus), until its successful execution in July of 2023. The paper describes the design, execution, and outcome of the assisted reentry operations.**

I. INTRODUCTION

Aeolus, the ESA wind mission, was operated from the European Space Operations Centre for its entire operational phase E2. The Flight Dynamics (FD) team at ESOC was responsible for its orbit determination, manoeuvre optimization, command generation, and attitude monitoring. The spacecraft carried the Atmospheric LAser Doppler INstrument (ALADIN), the first Doppler wind lidar in space, allowing for the measurement of global atmospheric wind profiles. It followed a Sun-synchronous dusk-dawn reference orbit with a local time at ascending node of 18:00, a 7 day ground-track repeat cycle, and at an altitude of 320 km.

The spacecraft was designed and built prior to the implementation of EOL deorbiting requirements by ESA, and thus a controlled reentry was not initially envisaged. At the request of ESA, in 2022, Airbus presented the concept of an assisted reentry, a first of its kind. It consisted of the execution of multiple in-plane retrograde manoeuvres to lower the perigee height of the spacecraft down to 150 km, the limit of what the AOCS could tolerate, and a final retrograde manoeuvre, which would lower the perigee height to about 120 km. This would force the reentry to take place within approximately 2.5 revolutions after its execution. The Atlantic corridor was chosen as the region of reentry as it was determined to have the lowest global risk of casualty for the expected dispersion.

Over the course of 2022 and 2023, the Aeolus Reentry Working Group, comprised of mission management, industry, and operational teams, convened monthly. It gradually turned the concept into a full-fledged operational plan.

Routine orbit control manoeuvres were halted in June of 2023. The spacecraft was left in free drift, decreasing the altitude from the original altitude of 320 km down to 280 km. The deorbiting operations were successfully executed from the 24th to the 28th of July of 2023.

II. ROUTINE OPERATIONS

The Aeolus routine operations consisted of daily orbit determinations (GPS-based), generation of products and commands, as well as the planning and execution of weekly positive in-plane orbit control manoeuvres (OCMs), the latter of which ensured a maximum deviation of 25 km of the ground-track at the equator with respect to the reference trajectory.

Two OCMs were executed at fixed slots on Wednesdays and Fridays. Operations were highly automated (with a single manual check per OCM) to keep workload manageable. The Wednesday OCM was optimized on Monday for the screening for conjunction risks by the Space Debris Office (SDO) at ESOC, followed by its final implementation (with a readjusted size) on Tuesday. The Friday OCM was both screened and implemented on Thursday following a compressed schedule. Ground station passes were scheduled on Friday morning so that the manoeuvre (executed late on that day) could be uplinked only when given clearance from any collision risk. Each OCM was optimized to target a certain ground-track deviation by the time of the following OCM, as depicted in Fig. 1 (for a target of 10 km). Individual OCMs could be differently configured.

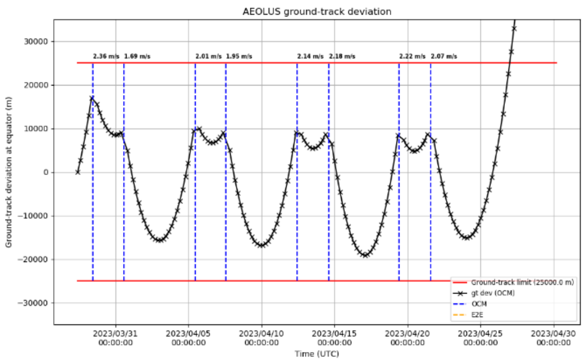

Fig. 1. *Typical ground-track deviation prediction.*

The scheduling of station passes was performed every week based on the predictions of the Monday orbit determination plus optimization, and it was valid from Monday to Sunday (inclusive) of the following week. Predictions needed to be accurate by up to 50s, as per mission requirement. For some missions operated at ESOC, it is possible to schedule the station passes by using a reference orbit, corrected for the current local time deviation of the mission. However, for Aeolus this was not possible due to its comparatively large deadband: ground-track deviations could rise to 25 km, or a deviation of 52s. Therefore, planning was based on prediction including future optimized OCMs, of which Fig. 1 is a typical example. FD actively monitored the time deviation and notified the station scheduling office in case it was excessive.

III. Assisted Reentry Plan

A. Conventions

The following conventions will be used:

- **Manoeuvre** is an in-plane retrograde manoeuvre, unless specified otherwise. Each manoeuvre implies the slew of the spacecraft from nominal attitude to retrograde attitude, by 180 degrees, and then back. See Fig. 2.
- **Perigee height** is defined to be the lowest geodetic height in a revolution, which does not happen at the actual perigee due to the presence of the equatorial bulge of Earth. Perigee height of a phase is the overall lowest height achieved during that phase.
- **Reentry longitude** is the longitude measured at the last ascending equatorial crossing of the planned reentry trajectory. It is potentially fictitious if the reentry occurs prior to that point.

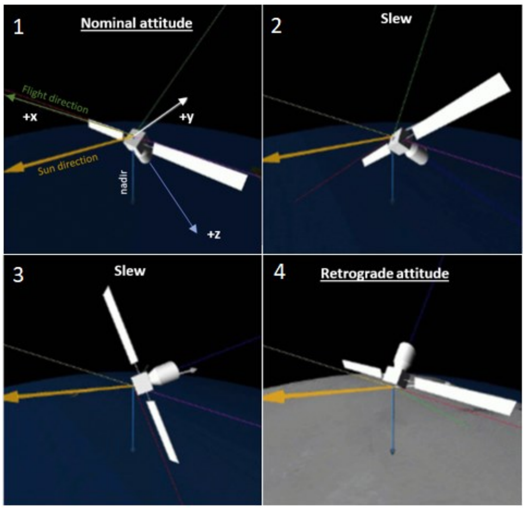

Fig. 2. *Slewing from nominal attitude to the retrograde attitude for manoeuvre execution (credit: ESA).*

The authors would strongly recommend any mission attempting any kind of deorbiting to clearly define the perigee height, as, in their experience, any lack of clarity in this definition had led to confusion.

B. Initial Concept

Aeolus was launched in 2018 with a nominal lifetime of 3.5 years. The usefulness of its scientific data for the improvement of weather models led to its successive extension, until the end of fuel of the mission. Fuel consumption is connected to the execution of OCMs, which are larger in case of stronger solar activity. In 2022 it was predicted that fuel would be exhausted by the very beginning of 2024 for the average solar activity predictions of the National Oceanic and Atmospheric Administration (NOAA).

After the end of its fuel budget, Aeolus would decay from its altitude of about 320 km until it would reenter the atmosphere uncontrollably, in a matter of weeks or few months. The spacecraft was not guaranteed to burn completely upon reentry, and thus debris could impact the surface of Earth. A controlled reentry targeting the South Pacific Oceanic Uninhabited Area was not possible with the available thrusting capabilities.

In 2022, at the behest of ESA, Airbus proposed the concept of an assisted reentry, with the aim of decreasing the global casualty risk below a probability threshold of 1/10000. The perigee height of the spacecraft would be lowered with retrograde burns down to 150 km, the limit altitude at which it was guaranteed that the spacecraft AOCS system would be able to control the attitude. A final burn would bring the perigee height down to about 120 km, forcing a reentry (80 km height) after 2.5 nominal revolutions. Fig. 3 shows a simplified depiction of the concept.

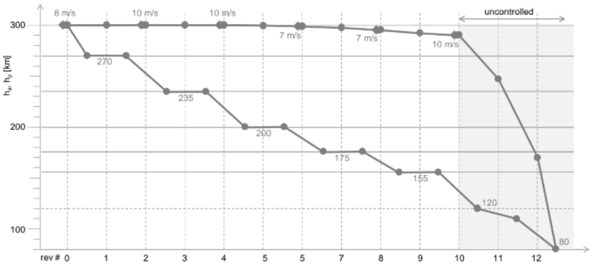

Fig. 3. *Perigee and apogee height and retrograde manoeuvres for initial draft of plan (credit: Airbus).*

The estimated standard deviation in reentry location was close to a quarter of an orbit. For that given dispersion, Airbus computed that a 20-degree band of reentry longitudes in the Atlantic Ocean, with ground-tracks bounded by the coasts of South America and Africa, was the region that best reduced the global casualty risk.

C. Aeolus Reentry Working Group

The reentry plan needed to be finalized by June 2023 at the latest. The Aeolus Reentry Working Group (ARWG) was formed in 2022 and convened monthly until January of 2023. This group comprised:

- ESA mission management
- ESA operations (ESOC), in particular:
    - Flight Control Team (FCT)
    - Flight Dynamics
    - Ground Stations
    - Space Debris Office
- ESA project support (ESTEC)
- Industry (Airbus)

Each update of the plan could have consequences for multiple teams. The presence of all parties ensured that everybody was aware of any developments, and issues were brought up in a timely fashion, avoiding lengthy off-line exchanges. The group was perceived as extremely productive, and similar arrangements would be recommendable for future complex preparations.

D. Assisted Reentry Operational Plan

The reentry plan proposed by industry envisaged the execution of six manoeuvres ranging from 7 to 10 m/s. In routine operations no routine prograde in-plane manoeuvre had ever exceeded the magnitude of 3 m/s. The only attempted retrograde in-plane manoeuvre early in the mission had resulted in a spacecraft AOCS mode fall back. The spacecraft AOCS had neither been designed for nor tested at lower altitudes. The proposal needed to be translated into an operational plan.

The plan was split into the following phases (see Fig. 4):

- **Phase I:** execution of two retrograde manoeuvres (labelled 1.1 and 1.2) of 8-10 m/s to reduce perigee height from 320 to 250 km.
- **Waiting A:** a period of 3 to 5 days in natural decay at the limit altitude for the nominal AOCS attitude control using reaction wheels as main actuator. Assessment of the spacecraft performance.
- **Phase II:** execution of four identically sized manoeuvres 2.1-2.4 of 8-10 m/s, separated by two revolutions, lowering the perigee height down to 150 km. The Thruster Control Mode (TCM) is activated such that the attitude is controlled via thrusting until Phase III.
- **Waiting B:** 14 hours long. Orbit determination based on GPS mass memory dump and assessment of manoeuvre performance and attitude control behaviour for the prediction and reoptimization of the last manoeuvre.
- **Phase III:** execution of last manoeuvre of 6-10 m/s to bring the perigee height to 120 km, correcting also for any delta-v underperformance in the previous phase. Completion of spacecraft passivation.
- **Reentry:** reentry of spacecraft into the atmosphere after 2.5 revolutions, targeting a reentry at the ascending equator crossing over the Atlantic. No monitoring possible due to the deactivated transmitter and tumbling, handover to SDO and radar providers.

Aeolus followed a 7 day repeat orbit, thus it was possible to define a plan and execute it in any week at will. The timing of the manoeuvres, passes, etc. would apply to any selected week.

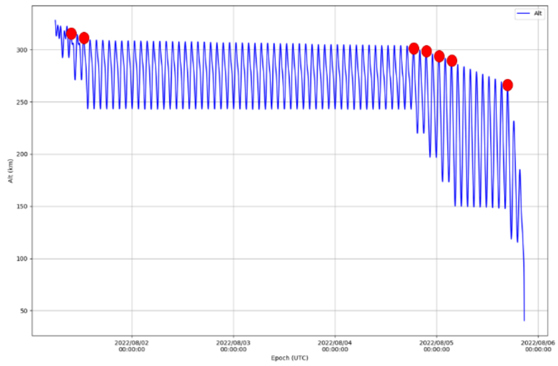

Fig. 4. *Height evolution of an early version of the plan.*

E. Reentry Dispersion

The manoeuvre optimization conducted by FD targeted a reentry at the ascending equator over the Atlantic, about 2.5 revolutions after the end of the last manoeuvre. Propagation after the last manoeuvre was performed with an increased drag coefficient representing a tumbling spacecraft, consistent with the ballistic coefficient used by industry. Each iteration of the plan was provided by FD to industry, which was responsible for modelling the tumbling spacecraft and the corresponding dispersion.

F. Fuel Budget

The allocated fuel budget for this activity totalled 57 kg:

- 37 kg for the nominal manoeuvres
- 5 kg for attitude control in TCM
- 5 kg static residuals (i.e. inaccessible fuel)
- 5 kg margin for 10% underperformance
- 4 kg fuel uncertainty on the remaining fuel
- 1 kg slews

G. Severe Contingencies and Cancellation

In case of failure or uncertain success of any of the steps above (eg. unreliable behaviour of the thrusters), it was agreed by all parties that the assisted reentry operations would be aborted, and the spacecraft would reenter the Earth uncontrolled. The casualty risk wouldn't be higher than the original baseline of uncontrolled reentry.

H. Thruster Control Mode

The attitude control by thruster actuation was necessary under an altitude of 250 km. It was activated in Phase II and lasted until the execution of the Phase III manoeuvre. During this time it would rapidly deplete fuel (up to 1-2 kg per revolution for the most pessimistic estimate) and would have a delta-v effect in positive in-plane direction. It needed to be accurately assessed for optimizing the last manoeuvre. As a result, on one hand the Waiting B phase had to be as short as possible to avoid fuel depletion, and on the other hand long enough to perform orbit determinations, assess the behaviour of TCM, and optimize the last manoeuvre accordingly.

In face of the uncertain magnitude of the thrusting, and to avoid premature depletion of fuel in face of excessive thrusting, the FCT and industry analysed and prepared commands for the Equilibrium Attitude (EA), which consists of a pitch bias, severely reducing torque by taking advantage of the geometry of the spacecraft (see Fig. 5). During the preparation and simulation campaign, three configurations were tested, and the highest pitch bias of the three, 29 deg, was selected. It was to be commanded in Waiting A if it were observed that the thrustless attitude control could not cope with the torques. The EA proved to be necessary for the success of the reentry operations.

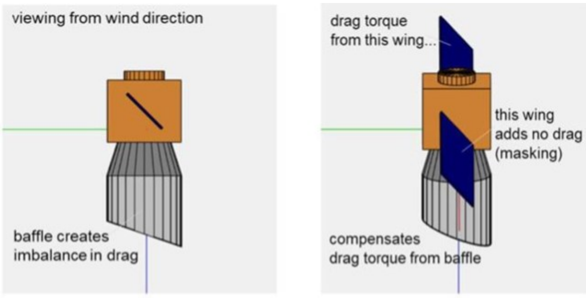

Fig. 5. *Nominal vs Equilibrium Attitude (credit: Airbus)*

I. Decay+ Updated Plan

Given the high interest for the scientific data produced by Aeolus, and with no existing alternative providing a comparable service, an effort was made to extend operations for as long as possible in the routine phase. The concept of decay+, proposed by mission management, comprised of a free drift from 320 to 280 km of height before initiating the reentry operations, yielded savings of about 6 kg in fuel budget in Phase I.

The size of the final manoeuvre was decreased to absorb potential underperformance of Phase II manoeuvres. This was achieved by shifting their argument of latitude, and the perigee location accordingly. This modification turned out to be fundamental for the success of the reentry. Finally, the distancing between manoeuvres 2.2 and 2.3 was increased to 3 revolutions to better fit the station visibility pattern.

The adjusted plan was the following:

- **Phase 0 (new):** decay to 280 km.
- **Phase I:** one manoeuvre of 8-10 m/s.
- **Waiting A:** 3-5 days.
- **Phase II:** four manoeuvres of 9 m/s, TCM.
- **Waiting B:** 15 hours. Perform orbit determination and command final manoeuvre.
- **Phase III:** manoeuvre of 6 m/s.
- **Reentry:** spacecraft reenters.

Introducing Phase 0, however, created some complexities. Its duration depended on rate of decay or the solar activity, ranging from one to two months. The final reentry schedule could not be fixed more than two weeks in advance. The declaration of final reentry date was synchronised with the station planning schedule; each Monday (product generation for scheduling) FD analysed the expected decay and whether Phase I should be triggered in the next planning week, with the 280 km perigee height crossing. If not, no reentry was declared and passes were scheduled for a free decay, and if yes, then the definitive plan was distributed, and station passes were scheduled.

Station scheduling was less precise due to the lack of OCMs in routines. Theoretically, the timing error in free drift could increase quadratically with time. The margins for pass booking were increased to 300s for X-band antenna providers, while for S-band provisions were made to reschedule as frequently as necessary.

IV. Flight Dynamics

A. *Orbit Determination*

Antennas supporting the reentry were Kiruna-1 and Kiruna-2 from ESA, and Troll-3, Troll-9, Svalbard-3, Svalbard-64, and Inuvik from KSAT. X-band dumps were possible only for Svalbard and Troll antennas.

Orbit determination for the reentry was primarily based on GPS data, the same as in routine operations. Real-time GPS data and ranging data, covering the duration of the pass, were retrieved from the S-band passes. Mass memory dumps of GPS data, containing the entirety of the available GPS data in the past, and the measurements of the attitude thrusting were retrieved during the X-band passes. By design, it was not possible to download recorded Housekeeping Telemetry (HKTM), hence the full GPS data, using S-band over the acquisition stations. This limitation resulted in engaging X-band acquisition throughout the entire reentry campaign and required full validation of the station X-band antenna also for low orbit altitude passes (e.g. 150-250km). GPS data was invalid during manoeuvre execution due to the orientation of the GPS antenna in the retrograde manoeuvre attitude.

During Phase II it was necessary to monitor the manoeuvre performance, the thruster activity for attitude control, and the Time Offset Values (TOV) at the stations. New station predictions were provided within this phase as necessary to ease signal acquisition. The first X-band dump of the Waiting B phase was necessary to perform a final orbit determination, determining:

- Manoeuvre 2.1-2.4 performance
- Magnitude of thrusting for attitude control
- CD coefficient at 150 km

FD concluded that the parameters above could only be solidly determined using the X-band dumps containing full GPS and attitude thrusting information. Real-time GPS data and radiometric data alone could be used for monitoring, but not for manoeuvre optimization.

The station visibility pattern was forced by the location of the reentry on the Atlantic and by the limit in duration of Waiting B. The pattern is depicted in Fig. 6.

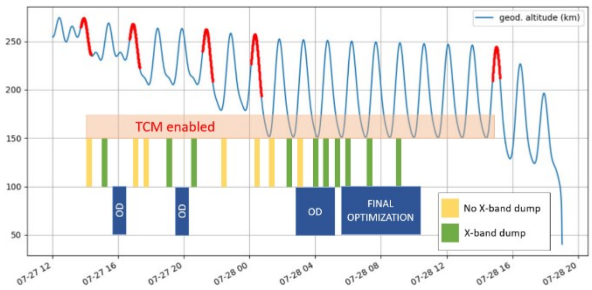

Fig.6. *Station visibility pattern from Phase II onwards. X-band passes are necessary for prediction updates (note the gap around manoeuvres 2.3 and 2.4).*

B. *Attitude Control Thrusting in TCM*

Attitude control thrusting was intermittent. However, on average, it was expected to counteract the air drag force and was expected to be proportional to it. For predictions, it was possible to model the thrusting as a factor to be applied on the air drag force; industry indicated that the thrusting could yield a 70% reduction in air drag (drag coefficient of 0.6 vs 2.0). The modelling is depicted in Fig. 7, where it is compared against the manoeuvre execution times.

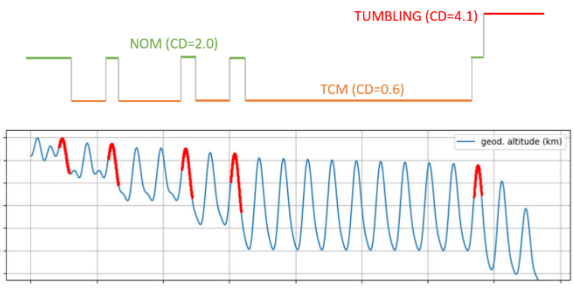

Fig. 7. *Modelling of CD during final phases.*

TCM had only been activated as part of manoeuvre execution. Its behaviour had to be gauged by FD with the final OD, using the telemetry of X-band data dumps, containing accurate information about the timing and size of the thrusting. The strategy was to import this information from telemetry into the orbit system, to update the equivalent drag factor, and to consider the updated factor when optimizing the last manoeuvre.

C. *Optimization*

The reentry optimizations were performed using the python libraries of the novel GODOT software developed at ESOC for analysis and operations.

The reentry was divided into linked simple sub-trajectories, each one of them a propagation or a single-parameter optimization. The end state of each sub-trajectory was the starting state of the following one. Each sub-trajectory could specify a different dynamic model, important for modelling attitude control thrusting. It was split up as follows:

- **Phase 0:** propagate integer number of days until finding first 280 km perigee height crossing to initiate manoeuvring.
- **Phase I:** optimize a manoeuvre at slot starting at 13:00 UTC to achieve 250 km perigee height during Waiting A.
- **Phase II:** optimize four manoeuvres of identical size to achieve 150 km perigee height during Waiting B.
- **Phase III:** optimize manoeuvre to reenter at ascending equator crossing 2.5 revs. after.

The regular optimization had input parameters that could be configured, such as manoeuvre slot times, argument of latitude of the manoeuvres, target altitudes, duration of the waiting A phase, and expected factor of drag force for attitude thrusting. From Phase I onwards, it was possible to run an optimization in less than a minute. The python setup was easily modifiable to include or modify sub-trajectories, and enable or disable the optimization for any of them.

D. Ground Station Validation and Preparation

Manoeuvre failure could impair signal acquisition by the stations. Multiple acquisition tests, prepared by FD and carried out by the Operations Manager (OM), were performed with each antenna of the station network. These tests were conducted with the actual spacecraft, for which FD prepared station predictions simulating manoeuvre underperformance or failure, and the station attempting to acquire the signal under those conditions.

For each test the OM specified the desired TOV (the delay of the spacecraft). KSAT stations were able to apply TOVs to the antenna track. The residual pointing error (whatever cannot be corrected by applying TOV) would also be specified for some tests. The Kiruna station "parked" the antenna at the expected location at the horizon until acquisition of signal, which is equivalent of passively applying a range of TOVs.

Dozens of tests were successfully concluded prior to reentry. Additionally, two Ground Station Operational Validation (GSOV) tests tracking Aeolus were performed successfully. The GSOV is an end-to-end test with participation of FD, the OM, and the LEOP network, in which the antennas acquire the signal of a real spacecraft and measure TOVs, while FD performs orbit determinations and computes TOVs to be applied for upcoming passes. The test concludes successfully with the distribution by FD of new orbit predictions.

E. Radar Support

SDO activated support with several entities (e.g IADC, EU-SST, USSPACECOM) which are usually involved in reentries of any kind. SDO and FD established non-operational interfaces to support tracking by the TIRA research radar from Fraunhofer FHR, and the radars from the LeoLabs company. The primary goal was to gather data on the reentry trajectory of the tumbling spacecraft, for which two TIRA passes were expected.

V. REENTRY OPERATIONS

A. Phase 0

The last routine OCM was executed on the 16th of June, 2023, thus marking the beginning of Phase 0. During this phase, pass scheduling deviations did not exceed 280s, and no X-band passes needed to be rescheduled.

Every Monday a decision was made on starting the reentry in the following week, depending on whether the 280 km perigee height crossing in that period was reached. On the 26th of June, 3rd of July, and 10th of July, no reentry had been declared. On the 17th of July, multiple scenarios were prepared with the optimization software, with combinations of starting date (24th – 27th of June) and Waiting A durations (3 to 5 days). Reentry was expected to take place over the East Atlantic. The final ground-track of each one of those plans is presented in Fig. 8.

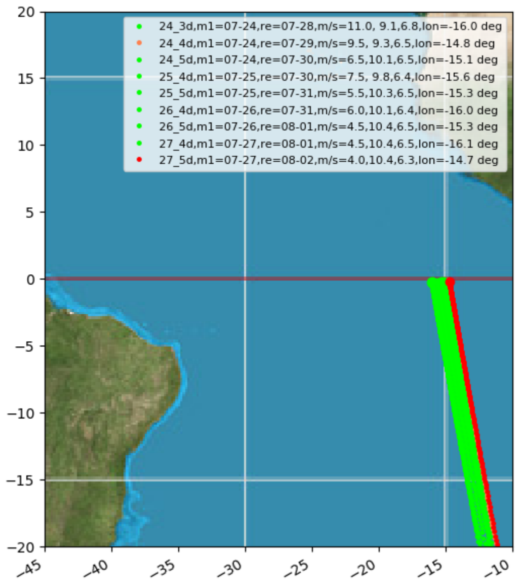

Fig.8. *Ground-track for each alternative. Reentries to the East of -15.0 deg longitude were undesirable.*

The alternatives were presented to the operations teams and management. Reentries too close to the Western coast of Africa were discarded due to higher casualty risk. Organisational and operational criteria were considered as well. The plan that was selected was one with Phase I starting on the 24th of July (Monday), Waiting A phase of 3 days, and reentry on the 28th of

July (Friday). This plan fit a working week, and the TIRA radar was available for that period. Fig. 9 depicts the altitude profile of this plan.

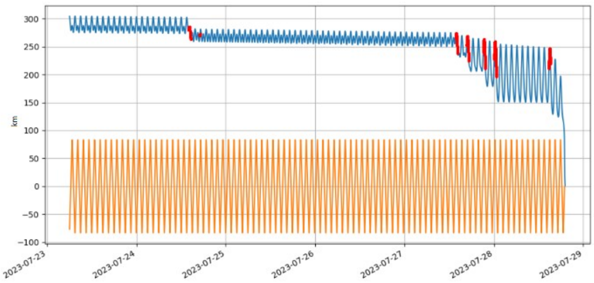

Fig.9. *Altitude profile of operational reentry plan.*

The manoeuvre of Phase I would have been of 11 m/s, suffering from inefficiency owed to its long duration. It was decided that it would instead be split into two manoeuvres: 1.1 (long) and 1.2 (short). By the 23rd of July, Phase I manoeuvres of 9.0 m/s and 0.8 m/s were commanded. Planned manoeuvres sizes were of 4 x 9.4 m/s for Phase II, and 6.6 m/s for Phase III. The nominal longitude of reentry was -16.3 deg.

B. Phase I

Manoeuvres 1.1 and 1.2 took place at about 14:00 and 17:00 UTC, during which times the operational teams were on console. The performance of the manoeuvres was monitored with each station pass, and orbit determinations were performed with the available GPS data. Manoeuvre 1.1 executed nominally (0.3% underperformance), but after it ended, the GPS unit was reconfigured to the back-up unit. After manoeuvre 1.2, the GPS backup unit also lost tracking of the satellites and was, for a long time, not able to provide a valid solution. Thanks to the passivation strategy applied by the FCT, the unit did not reconfigure a second time, which would have led to a Safe Mode. The GPS unit found a solution after more than 90 minutes. Using ranging data, it was established that manoeuvre 1.2 had executed nominally. With the recovered GPS data, manoeuvre 1.2 could then be assessed (4.1% underperformance) and new products and orbit predictions were distributed by 21:30 UTC.

C. Waiting A

After the analysis of the situation and in preparation for phase II, industry recommended a change in the settings for the GPS. In particular, the thresholds of what is considered a valid solution and how many GPS spacecraft need to be included in the solution were relaxed as the unusual size of the manoeuvres exceeded the configured tolerance of the GPS units. The aim was to prevent similar problems of prolonged duration of no valid solution after long duration manoeuvres and, although it was recognised that divergences between propagated S/C state and GPS measurements at reacquisition would increase, it was considered by all parties a good solution. This was then implemented during the Waiting A phase, after tests were conducted by industry in their simulator.

Manoeuvre 1.1, the large one of the two, had performed nominally, and no update of the calibration factor was necessary. The Phase II and Phase III manoeuvres were respectively adjusted to 9.4 m/s and 6.8 m/s.

D. Phase II

From this point on the operational teams were on shifts 24/7 until the conclusion of operations. The Phase II manoeuvres took place at 14:00, 17:00, and 21:30 UTC on the 27th, and 00:30 UTC on the 28th. TCM was left enabled after manoeuvre 2.1.

The orbit determination with the mass memory GPS data of the SG-64 pass at 15:20 UTC indicated nominal execution of manoeuvre 2.1, confirmed by low TOVs. Station predictions updates were thus not necessary.

During the return slew of manoeuvre 2.2, there was an AOCS-related FDIR that was triggered by a series of maximum length pulses on an active thruster. As a result, the Reaction Control System (RCS), holding both thruster branches of the AOCS, reconfigured to the redundant branch. Since the anomaly was still present this latter branch continued with excessive thrusting beyond the FDIR limit, ultimately switching the complete RCS off, leaving the spacecraft with no attitude control at all. This double failure would have led to an entry into Safe Mode but this was prevented thanks to the applied passivation strategy. During this anomaly another GPS reconfiguration took place. On the first visibility after the manoeuvre, the situation was very different from what was expected (disabled thrusting and an attitude depointing of more than 100 degrees). At this point it was not clear whether the reentry could continue. Quick reaction from industry and the FCT allowed for identification and rapid resolution of the causes. The RCS functionality was quickly restored, the attitude was regained, and the reentry could thus resume. A key cause for the issues was the combination of the relaxation of GPS thresholds that had been put in place after Phase I, and an erroneously propagated Position, Velocity, and Time (PVT) state during the slew back from 2.2 which resulted in a fast diverging orbit state as calculated by the GPS and used in the AOCS.

The orbit determination using the mass memory GPS data from the Troll pass at 19:10 UTC showed that manoeuvres 2.1 and 2.2 had executed nominally. Station predictions were then distributed at 21:00 UTC. Attitude control thrusting seemed to be excessive, but there had been other anomalies and so the data was not conclusive.

No data was available between manoeuvres 2.3 and 2.4 due to failures in acquisition by the Inuvik station at 22:40 and 00:10 UTC. Contact was reestablished with the Inuvik pass at 01:40 UTC. A mass memory dump was performed at the Troll pass of 02:25 UTC.

E. *Waiting B*

The orbit determination based on the full GPS data (see Fig. 10), plus the thrusting data from telemetry, confirmed that the attitude thrusting was compensating 230% instead of 70% of the air drag, three times as much. Posterior analysis from industry proposed plume impingement as a possible cause, causing additional torque in the unfavourable direction. The spacecraft was effectively raising in altitude, and it was also expending 1.5 kg of fuel per revolution. Manoeuvres 2.3 and 2.4 underperformed by 5%, and this figure was used to update the calibration factor for Phase III.

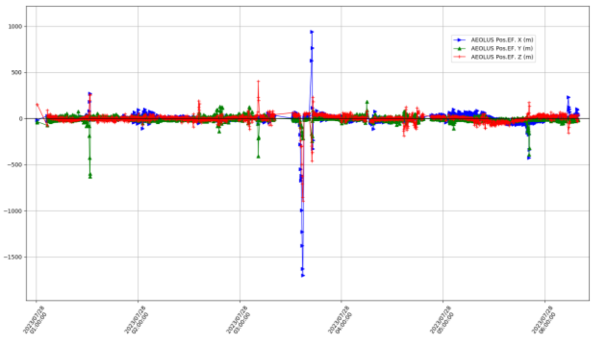

Fig.10. *GPS residuals of final orbit determination. The fit was good; residuals were in general under 100 m.*

With the current consumption estimates, fuel would be depleted before reaching Phase III. To avoid this and to proceed with the planned reentry, the Equilibrium Attitude was activated at 04:44 UTC, with the pitch being set to -28.8 deg. Although this considerably reduced the usage of fuel, the optimized final manoeuvre had, at this stage, become unfeasibly large, and so it was split into two. The spacecraft would be left in retrograde attitude between these two manoeuvres, a configuration for which the thrusting behaviour was completely unknown. The final delta-v would be varied depending on assumptions of thrusting level. The python setup had to be heavily modified to model this new scenario. Additionally, the reentry dispersion for this novel scenario had not been previously analysed.

In nominal conditions, the deadline for finalising the manoeuvre optimization and products was 10:30 UTC, and the final commands had to be prepared by 12:45 UTC. However, since the extra manoeuvre had to be executed one revolution prior to the final one, the deadlines had to be advanced by 90 minutes.

Commands were prepared for the two manoeuvres: 2.8 m/s followed by 7.8 m/s. However, the equilibrium attitude had, rather expectedly, increased the wetted area by 50%, and by 09:00 UTC it was estimated to bring the thrusting down to 86% of the air drag force. It became possible to execute a single manoeuvre of 12.3 m/s, and to revert to the nominal operational plan. The command stack was uplinked by the FCT in the pass at 12:02 UTC.

FD monitored the trajectory of the spacecraft for the remainder of Waiting B, confirming the estimate of the attitude thrusting effect with orbit determinations.

F. *Phase III and Reentry*

The manoeuvre started at 14:34 UTC and lasted for one hour. It was performed partially under Svalbard-64 visibility. Tank pressures were higher than predicted.

FD provided predictions to TIRA via SDO, and a pass was acquired at 16:20 UTC, at the nominal time. After conclusion of operations, orbit determinations using ranging data from that radar (kindly provided by SDO) suggested that the manoeuvre had not underperformed.

The satellite reentered at 18:46 UTC on the 28th July 2023 over Antarctica, close to entering the Atlantic Ocean on the predicted corridor, one quarter of revolution or less than one standard deviation before the nominal reentry point. The reentry was confirmed by USSPACECOM in close contact with SDO. The reentry was thus declared a success.

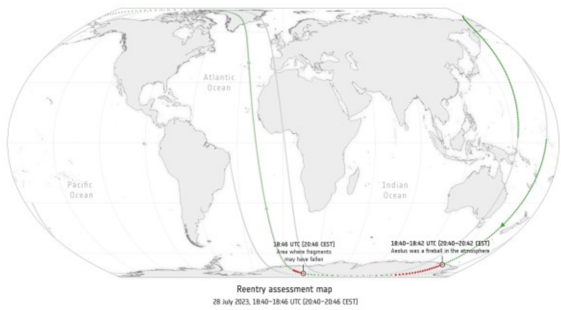

Fig.11. *Potential reentry location (credit: ESA)*

VI. Conclusions

The assisted reentry of Aeolus has successfully demonstrated a novel concept for the safe deorbiting of spacecraft. It was the result of extensive preparation and incredible teamwork. Communication, trust, leadership, creativity, management, technical excellence, ingenuity, and respect were crucial to guide the satellite back home.

VII. Acknowledgements

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