

# A Satellite Retires – The ERS-2 Deorbiting In Summer 2011

Frank J. Diekmann<sup>1</sup>

Xavier Marc<sup>1</sup> and Alistair O’Connell<sup>1</sup>

<sup>1</sup>ESA/ESOC, D-64293 Darmstadt, Germany

Miguel Canela<sup>2</sup> and Jean-Baptiste Gratadour<sup>2</sup>

<sup>2</sup>ESA/ESTEC, 2201 AZ Noordwijk, The Netherlands

Wolfgang Lengert<sup>3</sup>

<sup>3</sup>ESA/ESRIN, 00044 Frascati, Italy

The ERS-2 deorbiting started on 6<sup>th</sup> July 2011 after 16 years of successful operations of this ESA Earth Observation satellite. Many orbit lowering maneuvers were necessary to reach the target altitude of 570 km. Apart from the late failure of a backup gyro, which had no impact on the overall activity, all subsystems onboard performed perfectly. Although not originally foreseen in the early mission days, the later decision to deorbit ERS-2 was mostly compliant with international guidelines and ESA requirements on space debris mitigation and ensured a re-entry of the satellite in less than 25 years. The ERS-2 deorbiting was the first such activity of an ESA polar orbiting satellite. It was started with an initial re-orbiting in Feb 2011 in order to achieve a 3-days repeat cycle for scientific reasons for a period of 3 months. This orbit change served as a dress rehearsal for the later orbit lowering maneuvers and platform operations. The deorbiting related operations were implemented at ESA’s Operations Centre ESOC in Darmstadt, Germany, in close collaboration with the Mission Management, the ESTEC based Post Launch Support Office and industrial support by ASTRIUM Toulouse. This included the definition of the overall operations concept, the maneuver strategy, on-board configuration trade-offs, contingency plans, new and modified procedures, extensive simulation and training sessions and an extended ground station network. This paper summarizes these activities together with the deorbiting background and objectives, timeline and results.

## I. Introduction

**A**FTER 16 years of successful service, ESA’s Remote Sensing Satellite ERS-2 had finally reached the end of its lifetime in summer 2011. On 5<sup>th</sup> September the ERS-2 Deorbiting Phase was successfully concluded. Together with its predecessor ERS-1 (1991-2000) this concluded a period of 20 years of continuous Earth observation measurements and paved the way for the development of many new Earth observation techniques. Examples are the SAR Interferometry influencing the development of many operational services and new applications of radar based observations, and the GOME instrument, the first high precision instrument for measuring stratospheric ozone concentrations<sup>1</sup>. The Mission Management and all science data archiving and processing was performed by the ESA centre ESRIN in Frascati, Italy. The Post Launch Support Office (PLSO) at ESTEC in The Netherlands provided technical support.

ERS-2 was launched from Kourou with the Ariane-4 flight V72 at 01:44 UTC on 21<sup>st</sup> April 1995 and placed into polar orbit at 780 km altitude. Telemetry was received at ESOC, the control center of the European Space Agency ESA, a few minutes later, confirming that ERS-2 was in good order. Routine operations started already 3 months after the LEOP phase. Redesign of the nominal operations phase became necessary after degradation or failure of 5 out of 6 gyros and the loss of both on-board data recorders in 2003.

Several reference orbits had been defined for ERS-2. All of these orbits were near-polar and near circular; sun-synchronous and with a repeating ground track. The periods over which the ground tracks were repeated were 35-days for one and 3 days for another (Table 1). During most of the mission, ERS-2 was maintained in the 35 days

orbit (orbital period of 100.6 min, 14.31 orbits/day). The orbit was reached on 28/04/1995 and was finally changed to achieve a three days repeat cycle on 21/02/2011.

**Table 1. ERS-2 Reference Orbits.**

	<b>35-day</b>	<b>3-days</b>
Mean Nodal Period	6035.9281 s	6027.907 s
Mean Semi-Major Axis	7159.49565 km	7153.135 km $\pm$ 64m
Mean Inclination	98.5429 deg	98.5227 deg $\pm$ $9 \cdot 10^{-3}$ deg
Mean Eccentricity	$1.165 \cdot 10^{-3}$	$1.165 \cdot 10^{-3} \pm 5 \cdot 10^{-5}$
Mean Argument of perigee	90.0 deg $\pm$ 3 deg	90.0 deg $\pm$ 3 deg
Mean Local Solar time at descending Node	10h30m	10h30m $\pm$ 1 min

ERS-1 and ERS-2 were several times flown in a Tandem configuration and in the period 2007-2010 three campaigns of Tandem observations were also performed with Envisat<sup>2</sup>.

The ERS-2 deorbiting after 16 years of operations and 84730 orbits was the first such activity of an ESA polar orbiting satellite. About 160 kg of fuel was still available at the end of the nominal lifetime to lower the orbit in a careful and controlled way. While this paper provides an overview of the deorbiting background and activities, platform related details can be found in Ref.3.

## II. ERS-2 Deorbiting Objectives

Since its launch in 1995, the ERS-2 mission had been extended several times. A last extension for a period of 3 years until mid 2011 was approved by the ESA member states in 2007 and was finally confirmed to be the last extension in 2010. Although no plans for a deorbiting existed during the developing phase in the eighties and since at the end of its operational lifetime more than half of the original fuel of 314 kg still remained onboard, it was decided to lower the orbit as far as possible. Initial studies for deorbiting were already performed in 2003, but then put back on hold until 2009, when first preparations for a mission termination started. This decision allowed meeting the following objectives:

- 1) Comply to space debris mitigation inter-agency agreement
- 2) Minimize the satellite re-entry time to less than 25 years
- 3) Free the orbit region between 700 km and 900 km
- 4) Deactivate the satellite once in graveyard orbit

Although not originally foreseen in the early mission days, the later decision to deorbit ERS-2 was nevertheless compliant with international guidelines<sup>4</sup> and the more technically oriented guidelines of the "European Code of Conduct", which was also signed by ESA in 2006. In order to tailor the Code of Conduct to the needs of ESA projects, ESA developed their own requirements on space debris mitigation<sup>5</sup>, which came into force in April 2008 and referred to all future projects only. With the remaining fuel left onboard a re-entry of the satellite should be ensured in less than 25 years. This appeared particularly relevant for ERS-2, since the density of space debris objects in the orbit region between 700km and 900 km had significantly increased in the previous years.

The "Requirements on Space Debris Mitigation for ESA Projects" also states that the passivation of a space system shall be completed within two months after the end of the operational phase, where passivation is defined as "*the elimination of all stored energy on board of a space system*". This activity was considered the final phase of the ERS-2 deorbiting and includes depletion of the remaining fuel, disconnecting battery charge and disconnecting all transmitters before terminating the mission.

## III. Boundary Conditions And Constraints

An optimal deorbiting strategy was the subject of many discussions and then a careful preparation by an experienced team of ESA engineers supported by specialists from Astrium in Toulouse (France). This was especially important in view of several critical constraints to be taken into account for the ERS-2 end-of-life operations.

### A. Circular Versus Elliptic Orbit

Already during initial internal discussions on a deorbiting strategy in 2003 it was decided to choose a circular deposit orbit for ERS-2 instead of an elliptic one as for SPOT-2 deorbiting<sup>6</sup>. One reason was the fact that for a given perigee altitude, circular orbits result in lower lifetimes as demonstrated by ERS-2 simulations at ESOC. There was

also plenty of fuel available to reach the target orbit altitude. The main reason for keeping the orbit eccentricity low was however the fact the ERS-2 attitude control strongly depended on the performance of the Digital Earth Sensor (DES), which could hardly identify the Earth's boundaries at altitudes below ca. 500 km. A circular disposal orbit was found to accommodate best the DES visibility constraints while providing an acceptable time until re-entry.

## **B. Spacecraft**

The most stringent constraints for deorbiting were dictated by the satellite itself. They are explained in more detail in Ref.3. Among the most important ones are:

### 1) Onboard Fuel

At the end of the routine operations phase an amount of 160 kg (out of 314 kg available onboard at launch) was still available for deorbiting operations. This was an estimate based on a "pulse counting" method for the onboard thrusters used for orbit maintenance with an uncertainty of ca. +/- 10%. The amount of hydrazine available closer to depletion was also estimated with the PVT Method ( $PV=nRT$  law for an assumed perfect gas<sup>6</sup>). Maneuvers had to be scheduled and adjusted such as to exhaust this fuel, reaching the desired deposit orbit and reach fuel depletion in visibility of one of available ground stations.

### 2) Gyros

The attitude control was severely affected by the limited availability of the gyros onboard<sup>3,7</sup>. Three of the original 6 gyros already failed after an increase in noise between 1997 and 2000 and two further showed a degraded performance. For routine operations a number of new AOC modes were developed<sup>7</sup>, of which the "gyroless piloting" was used since 2001. By the time of de-orbiting in 2011, only Gyros 3, 4 and 6 remained functional. The large in-plane maneuvers necessary for the deorbiting were only possible using 3-gyro piloting, mono-gyro (with Gyro6) and "extended" mono-gyro piloting (with Gyro4). Only Gyro4 presented nominal performances, whereas Gyro3 appeared particularly noisy. 3-gyro piloting was excluded because it did not allow sufficient redundancy in case of gyro failure. The use of Gyro4 for piloting was not validated for altitudes below 700 km. Mono-gyro piloting relying only on Gyro6 offered better performances and allowed longer burns. Eventually, it was decided to define two distinctive phases for the descend operations. In the first phase, the burns would be designed to accommodate the constraints of both mono-gyro modes. During this phase, maneuvers would normally be performed with Gyro6; however in case of anomaly with this gyro it would be possible at any time, to continue the execution of the maneuvers plan using Gyro4. This phase would end before the altitude had been lowered below 700km. In a second phase, longer burns would be performed with Gyro6 only.

### 3) Digital Earth Sensor

The dependency of ERS-2 piloting on the DES did not only affect the minimum altitude to be reachable, but also constraint its use by blinding by the Sun or Moon. Maneuvers therefore had to be scheduled close to the equator (prevented Sun blinding since these only occur at certain periods of the year around the eclipse exit/entry). To avoid also unwanted DES scans of the Moon, maneuver sequences had to be phased outside Moon blinding periods.

### 4) Real Time Telemetry

As both on-board tape recorders had failed before, real time telemetry could only be acquired above S-Band ground stations. A very limited set of on-board recorded telemetry data could then be transmitted as well. Consequently it was necessary to plan all maneuver burns in the visibility of a ground station in order to identify and react to anomalies during these critical operations.

## **C. Maneuver Sizing**

The in-plane maneuvers necessary to lower the orbit had to be limited to 300s in Phase 1 and up to 480s in Phase 2. This corresponded to a maximum  $\Delta v$  of -2m/s. It ensured in addition that in all cases spacecraft acquisition by the ground station network was possible. Long duration in-plane maneuvers could have resulted in large differences between the actual orbit and the orbit predictions used at the ground station. For these deviations, the nominal performance variability was considered together with the consequences of abnormal burn performances or an interruption of the burn before completion. It must also be noted that deviation in the orbital period would have resulted in a deviation in the spacecraft position that would have increased over time. This in return would have invalidated all orbit and maneuver predictions of the Flight Dynamics team.

## IV. The Dress Rehearsal - A First Orbit Change in February 2011

Since its launch, ERS-2 had been operated in a 35-days repeat cycle, following the same ground track that Envisat had before its own orbit change<sup>8</sup> on 20<sup>th</sup> Oct 2010. Following the Envisat orbit lowering, ERS-2 synergy could no longer be exploited. Using the last months of ERS-2 mission lifetime, a new and more attractive ERS-2 mission phase was started in March 2011 that repeated the ERS-1 “Ice Phases” of 1992 and 1994 in a 3-days repeat cycle. This short mission phase until July 2011 focused mainly on the polar areas (high northern and southern latitudes), even though data was also collected over other areas, in particular AMI Scatterometer data over the rain forest. Some of the most striking results of this period are images that revealed rapidly changing glacial features in Greenland like the Kangerdlugssuaq glacier and its advancing ice stream. Due to its new 3-days repeat cycle ERS-2 could also repeatedly cover the area north of Sendai in Japan, which was struck by the massive earthquake on 11<sup>th</sup> March 2011 and collect innovative radar information for interferometry applications of mainly the aftershocks.

To achieve this new repeat cycle, the satellite semi-major axis was initially lowered by ca. 6.25 km by consuming 5.3kg of fuel in a series of 11 (up to -1.2 m/s  $\Delta v$ ) in-plane thrusts. With this orbit change the de-orbiting scenario already started. Maintaining the same ground track as ERS-1 about 17 years ago only required an additional 2 kg of fuel in the following months. These maneuvers also included the last inclination correction for ERS-2, thus ensuring a correct control of local time of ascending node crossing for the rest of payload mission and the subsequent deorbiting phase.

This initial orbit change served at ESOC as a dress rehearsal for the actual deorbiting activities later that year. The same procedures were used as well as the same onboard elements. The piloting software, gyros, and thrusters were tested and experience was gained on how the spacecraft and the full system should react during the final deorbiting. These maneuvers contributed directly to the planned deorbit through the semi major axis reduction and the thrusters to be actively used for the deorbiting were accurately calibrated during the transition to the new 3-day repeat cycle. The maneuver period started on the 22<sup>nd</sup> Feb and ended after about 2 weeks.

## V. Preparing For A New Type Of Maneuver

During the 16 years of ERS-2 routine operations, the Flight Control Team members had changed several times. A young and motivated group controlling the mission since a few years was eventually confronted with performing the deorbiting operations. Already existing documentation was reviewed first and early concepts adjusted to the latest ground and space segment constraints. Existing flight control and contingency procedures were updated and about 30 new deorbiting procedures developed and tested.

Nominal operations expected for de-orbiting as well as all critical mission phases were exercised at least ones in an extensive Simulation Campaign. Main objectives of this campaign was to demonstrate the ability to observe, analyze and define a plan for recovery from injected anomalies during the simulation and also to demonstrate the ability to deal with failures not covered by pre-prepared contingency procedures. A thus motivated, proficient and well-trained small team of engineers supported the entire deorbiting period of two months in two daily shifts successfully until final spacecraft switch-off.

In addition, at the end of the mission there were still a few staff members from the early mission days in the supporting teams (e.g. FDS, Astrium, PLSO), whose knowledge, experience and memory reached back to the ERS-1 development days. This proved to be extremely beneficial in some areas, such as the analysis of on-board subsystem behavior or the adaptation of the FDS software system and clearly emphasized the importance and benefits of long-term operational continuity.

The concept and the strategy of the ERS-2 deorbiting were extensively discussed in many technical meetings and steering groups starting about nine months before. The final strategy – in particular the use of gyros and thrust durations – was eventually agreed at ESA level during an ERS-2 Deorbiting Strategy Review Board Meeting. After a final Operations Readiness Review at ESOC on 9<sup>th</sup> June 2011 the preparation activities and all remaining risks were assessed and the Go-Ahead given for the start of the activity.

## VI. The Orbit Lowering Strategy

### A. The Deorbiting Maneuver Concept

The first two descending phases of the deorbiting period were followed by a third phase for final passivation of the satellite.

- 1) In *Phase 1* maneuvers would be performed in pairs at opposite positions in the orbit (PSO) to decrease the semi-major axis and maintain a circular orbit. The duration of individual burns was limited to 300 seconds to al-

low operations with both the “mono-gyro” and as backup the “gyroless” mode<sup>3</sup>. Goal was to lower the semi-major axis by at least 100 km (to less than 700 km altitude).

2) In *Phase 2* pairs of maneuvers would be performed as in *Phase 1*, however the duration of individual burns would be gradually extended as the thrust level decreased with the tank pressure so that the magnitude of the  $\Delta v$  remained in the order of 2 m/s.

3) *Phase 3*, the *Passivation Phase*, would start once depletion of the fuel was considered possible. A reference orbit with a ground track cycle of about 1 day would initially be acquired. Then a series of long burns was planned until tank depletion. Each of these burns would be performed in a section of the orbit that offers maneuver monitoring via extended ground station coverage. This series of visibilities was achieved daily, because the last maneuvers of *Phase 2* were designed such as to achieve a 15 orbit repeat cycle. The passivation burns alternatively lowered and raised the orbit so that actual orbit conditions remained close to the reference orbit. A series of 8 burns were prepared; the first 2 with duration of ca. 25 minutes and all the subsequent with a duration of ca. 40 minutes each.

The two descending phases were sorted into 7 blocks of maneuvers performed over a period of 48 days, interrupted each by 2 or 3 days due to moon blinding conditions. In addition these breaks were needed for new orbit determination and predictions as well as maneuver preparations by the FDS team.

1. Block 1: July 6th to 8th, Moon < 35 deg to s/c x-axis (up to 300s thrusts)
2. Block 2: July 12th to 16th, around full Moon (up to 300s thrusts)
3. Block 3: July 20th to 24th, Moon > 145 deg to s/c x-axis (up to 300s thrusts)
4. Block 4: July 27th to 31st, around new Moon (up to 300s thrusts)
5. Block 5: August 3rd to 7th, Moon < 35 deg to s/c x-axis (up to 400s thrusts)
6. Block 6: August 11th to 14th, around full Moon (up to 440s thrust)
7. Block 7: August 18th to 22nd, Moon > 145 deg to s/c x-axis (up to 480s thrusts)

The individual thruster activations were located close to the equator, which excluded the Sun in DES FOV at that time of the year. This also allowed to exclude interferences by the Moon in the DES FOV over full or new Moon periods. Assuming a maximum satellite yaw depointing of 25 degrees in case of faulty thrusts and with the DES FOV being a cone of half-angle 60 degrees around the satellite X-axis, periods had to be identified where the Moon to spacecraft X-axis angle was below 35 degrees or higher than 145 degrees (in the range from 0-180 degrees). Outside these periods no maneuvers were planned.

The durations of individual maneuvers and their frequency were sized so that spacecraft acquisition by the (few) ground stations would be ensured in all cases. Ground stations relied on accurate orbit prediction to acquire the spacecraft at the beginning of passes. Large in-plane maneuvers could have resulted in large differences between the actual orbit and the orbit predictions used at the ground station (e.g. due to poor burn performances or burn interruptions). The consequences were block-wise fixed thrust durations (from 300 to 480 seconds), corresponding to  $\Delta v$  values between 1.50 m/s and 2.00 m/s. This guaranteed controlled Time Offset Values (TOV) evolution at the ground stations of less than 2 seconds over a maneuver block (max 3% performance error), maximal event time deviations w.r.t. initial planning of 60 seconds over a maneuver block and thrust durations to fit within a single ground station pass.

## **B. The Ground Segment**

During the routine operations phase, housekeeping telemetry acquired during the part of the orbit not covered by S-Band ground stations could be routed via the X-Band downlink. Since the payload operations were terminated during the de-orbiting activities, this option was no longer available. It was therefore necessary to plan the burns in visibility of S-Band ground stations. The available ground station network (see Fig.2) for the first two descent phases included the ESA stations in Kiruna (Sweden) and the near-equatorial station in Kourou (French Guyana) as well as Malindi (Kenya). The latter was made available by the Italian Space Agency (ASI). Following an analysis of the work-plan of the operational team at ESOC and the availability of both ground stations, it was decided that the first burn of a daily maneuver pair was performed in visibility of Kourou in the ascending orbit arc around midnight, and the second in visibility of Malindi in the descending arc in the morning. The Norwegian KSAT supported local nighttime passes via Svalbard and similarly post-burn monitoring via Troll at the Antarctic. Advanced and careful planning of the equatorial stations was necessary to minimize conflicts with other mission bookings (e.g. XMM-Newton station bookings of Kourou). In particular for Kiruna ERS-2 had complete priority over all other flying ESA missions for the prime 15m antenna. The ground station tracking times were in addition artificially increased to op-

timally support orbit determination activities. The numbers of all ground station passes for ERS-2 during all three deorbiting phases are summarized in Table 2.

**Table 2. Number of ground station passes for ERS-2 deorbiting operations.**

Station	Number of Passes since the Start of De-orbiting
Kiruna (ESA)	681
Kourou (ESA)	43
Maspalomas (ESA)	8
Perth (ESA)	2
Svalbard (KSAT)	217
Troll (KSAT)	89
Malindi (ASI)	35
Katsuura (JAXA)	8
<b>Total</b>	<b>1083</b>

mally supporting other Earth Observation missions at ESOC and training them during the ERS-2 re-orbiting operations in February 2011, in order to provide a 7-day support over a longer period of time. An upgrade of the command and AOCS monitoring software had to be implemented which supported the “connected tank systems” configuration chosen for the final mission phase. The repeat pattern of the maneuver planning, execution and assessment activities made it possible to set up a shift pattern and generate all Flight Dynamics products required by the FCT and the station scheduling office over the whole time period of two months in time and with the usual quality. The actual performance of the maneuvers during phase 1 and 2 made it necessary to adjust the maneuver planning at the end of phase 2 so the correct orbit altitude could be acquired at the start of the passivation phase.

The complete set of maneuvers for phase 1 and 2 was pre-planned before starting the de-orbiting. During the two descent phases, the plan was checked before each block of maneuvers to assure no thresholds were violated and maneuvers were executed within visibility of the stations. In the first phase, the size of the burns was kept and only the timing of the maneuvers was adjusted when needed. This procedure was also followed in the second phase, but this had to be adjusted towards the end of that phase to ensure the defined 1-day repeat orbit could be acquired. A so-called *coarse orbit determination* was executed after each burn and a complete *fine orbit determination* was run following each maneuver block.

## VII. Timeline and Performance of Descent Phases

The nominal ERS-2 science mission was formerly ended on 4. July 2011 by switching off all payload instruments. They were however left in a mode where heating was still activated to ensure a stable thermal environment for the platform. The ground configuration and all onboard functions were reviewed and the go-ahead for the deorbiting given in a formal Go/NoGo meeting.

The first maneuver week was organized as a LEOP-like operations activity at ESOC including full on-site support of the FCT, the FDS and the ground segment teams. Specialists from industry and the PLSO were on-call during the entire period. Daily maneuver briefings and de-briefings during block 1 were relaxed to weekly meetings during the remaining maneuver blocks.

Only a very limited debris collision avoidance support by the ESOC Space Debris Office was possible during the descent phases. Reasons were the expected maneuver errors (approximately 1s along-track or >100m radial) and the fact that coarse orbit determination after each burn did not allow to have accurate pre- and post-maneuver trajectories available. In addition, calibrated orbits between maneuver blocks were not valid for long enough before the first maneuver of the next block in order to enable the normal procedure for debris screening after the maneuvers.

Since the launch of Envisat, the ERS-2 orbit was synchronized with the one of Envisat in a 35 days repeat cycle and a ca. half an hour difference in PSO. As a consequence of the orbit lowering of Envisat<sup>8</sup> by ca. 17.4 km in 2010 this synchronicity was lost. Periods of short overlapping ground station passes between ERS-2 and Envisat were introduced with the risk of RF interferences between the two satellites, which were equipped with S-Band transponders of identical frequencies. In case of separation angles of < 1.4 deg tracking, telemetry and commanding (loss of uplink lock) of one or both satellites could be affected and required special procedural precautions. In order to put in place these measures, an accurate prediction of separation was required. A new FDS product to predict these RF interferences was defined and introduced for both missions. Avoiding this way critical interference periods ERS-2 was not affected by any RF interference effects until its end of mission.

### C. Flight Dynamics

For the de-orbiting and passivation operations the existing Flight Dynamics Team was increased by including staff nor-

**A. Phase 1 : Descent Phase 1**

The first 36 maneuvers of the first descent phase were executed without any problems. Gyro6 was used for piloting, Gyro4 configured for potential Safe Mode cases and Gyro3 was switched on, but not used for piloting. First signs of increasing gyro noise became immediately obvious<sup>3</sup>. 65.8 kg of hydrazine were spent for a total semi-major axis change of 110.9 km (see Table 3 for a performance summary). These fuel quantity estimates resulted from on-ground book-keeping propagated since launch and were affected by accumulated inaccuracies.

**Table 3. ERS-2 deorbiting Phase 1 performance summary.**

Block	Period	Number of burns	Total burn duration (s)	Total Delta V (m/s)	Average Delta V per burn (m/s)	Total Fuel Consumption (kg)	Fuel left onboard (kg)	Semi-major Axis decrease (km)
1	6.7.-8.7.	6	1782	-10.44	-1.74	11.7	148,5	19.9
2	12.7.-16.7.	10	2978	-16.79	-1.68	18.9	129.6	32.1
3	20.7.-24.7.	10	2987	-15.98	-1.60	18.1	111.5	30.3
4	27.7.-31.7.	10	2986	-15.23	-1.52	17.1	94.4	28.6

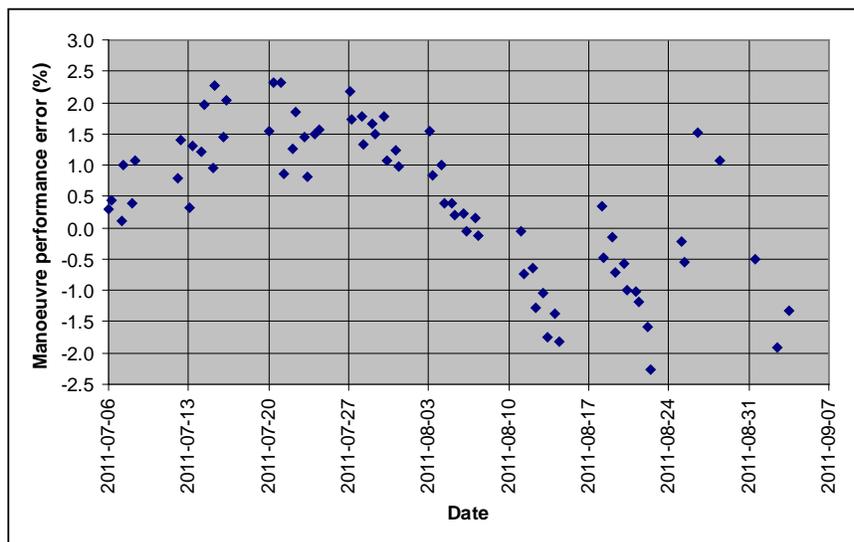
**B. Phase 2 : Descent Phase 2**

The three blocks of Phase 2, consisting of 28 individual burns, are summarized in Table 4. The burn durations were increased to compensate for the decreasing thrust levels. An estimated amount of 60.1 kg of hydrazine was consumed, leaving ca. 34.3 kg onboard. All onboard systems showed a nominal performance with continuously increasing noise levels for Gyro3. The maximum absolute wheel rates were always well within the wheel capacity for all axis.

**Table 4. ERS-2 deorbiting Phase 2 performance summary.**

Block	Period	Number of burns	Total burn duration (s)	Total Delta V (m/s)	Average Delta V per burn (m/s)	Total Fuel Consumption (kg)	Fuel left onboard (kg)	Semi-major Axis decrease (km)
5	3.8.-7.8.	10	3889	-18.67	-1.87	21.0	73.4	34.9
6	11.8.-14.8.	8	3348	-15.07	-1.88	16.9	56.5	27.7
7	18.8.-22.8.	10	4189	-19.69	-1.97	22.2	34.3	36.4

The total lowering of the semi-major axis in Phases 1 and 2 was 209.9 km. The maneuvers were slightly overperforming in Phase 1 as depicted in Fig.1, causing ERS-2 to reach the 1-day repeat orbit altitude sooner than in the nominal plan. It was therefore modified to reach the ground track providing the required visibility for the passivation phase at the start of that phase. This was achieved by dropping the originally planned maneuvers for the 15<sup>th</sup> of August and allowing a drift of ERS-2 at the end of block 7 towards the desired ground track. To acquire the orbit for the



**Figure 1. Maneuvre performance errors during de-orbiting phases 1**

passivation phase, the sizes of the drift stop maneuvers (DS1, DS2, see Table.5) were adjusted accordingly.

### VIII. The Passivation Phase

Deorbiting Phase 3, the Passivation Phase, was started when the 570 km reference orbit was reached after the two drift-stop maneuvers (DS1, DS2) and about 34 kg of fuel remaining on-board. With this fuel estimate tank depletion was considered possible already during the first passivation burn due to the assumed error of the pulse counting method (-30kg / +15kg). At the altitude reached after Phase 2 it was possible to acquire an orbit with a ground track repeat cycle of exactly 15 revolutions in 24 hours. This meant a daily repetition of the ground station coverage, a huge benefit for planning and implementing under tight control an open ended passivation process. The ground station network was extended for the Passivation Phase, now also including the ESA station at Maspalomas (Canary Islands) and Katsuura (Japan, operated by JAXA). With these ground stations, good coverage of the passivation burns was achieved with overlapping passes at Kiruna/Svalbard and Maspalomas/Kourou and short telemetry gaps between Katsuura and Svalbard and between Kiruna and Maspalomas (Fig.2). Two initial maneuvers with duration of 25 minutes each were scheduled together with a subsequent set of 6 maneuvers of 40 minutes. The maneuvers in Phase 3 alternatively raised and lowered the orbit so that actual orbit remained close to the reference orbit. The maneuver characteristics are summarized in Table 5.

The payload instruments were switched off from their respective Heater Modes on 24<sup>th</sup> August. As some of the platform sensors are located on the payload module it was decided to maintain a stable thermal environment by using hardware-controlled heating lines instead. In this mode the heating is continuously provided, which leads to a DoD of ca. 17% (only 9% in payload Heater Mode used prior to switch-off). To reduce this rather high discharge of the battery the so-called “Day/Night Logic” was enabled during the last 15 minutes in eclipse just before the burns. The logic disables heating during the absence of the Sun signal.

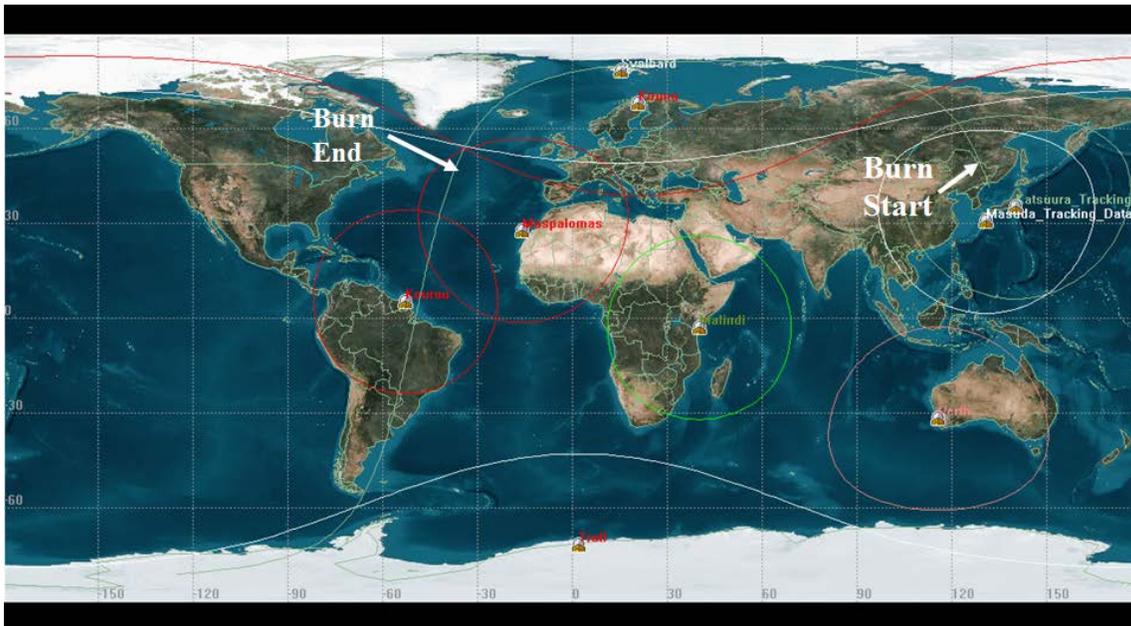


Figure 2. Network of ground stations during passivation maneuvers.

On 26<sup>th</sup> August the first long passivation burn was executed without any noticeable change in on-board conditions. In fact, no depletion of the tanks was reported by telemetry in the first 5 maneuvers. The initial 34.3 kg of fuel at the beginning of the Passivation Phase estimated by the pulse counting method already reached the zero limit after the fourth burn. This confirmed the conservative nature of this method and proved the better suitability of the PVT method towards tank depletion.

The noise of Gyro3 steadily increased during the deorbiting phases and reached a maximum on 28<sup>th</sup> August. It provided meaningful measurements for an additional day until 30<sup>th</sup> August, when the Gyro3 output was constantly

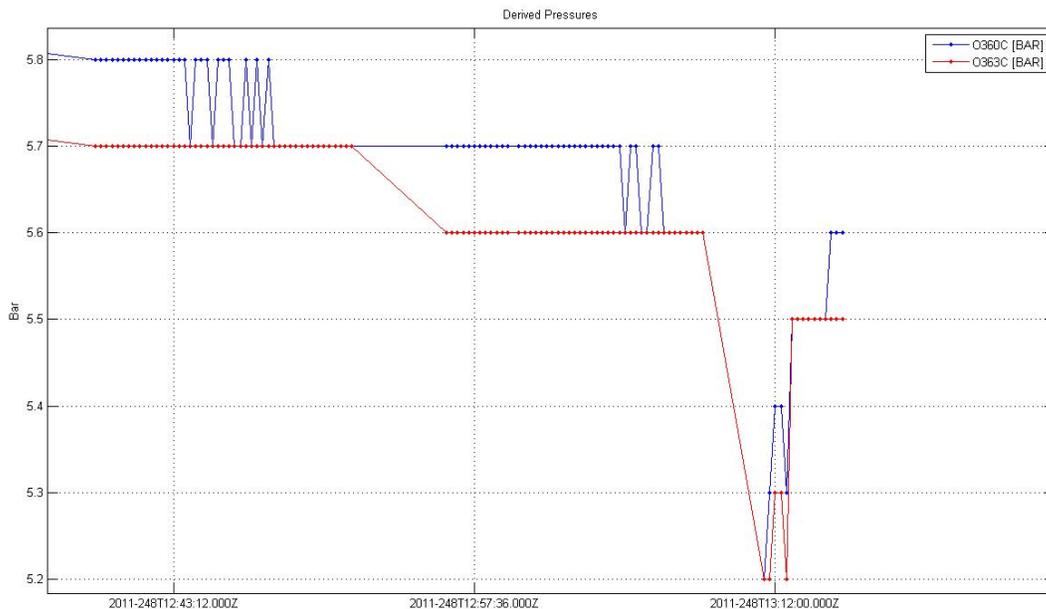
null indicating a failure of the unit. A power cycling was attempted to recover the unit, but the output remained null showing that the unit had permanently failed. Gyro3 was not selected for on-board control and consequently its failure had no direct impact.

No sign of depletion was observed during the first ground stations of Passivation maneuver P6 on 5<sup>th</sup> September until the loss of signal from Kiruna, (91% within the burn). After the ground station gap between Kiruna and Maspalomas, the final 48s of the burn could still be monitored. Depletion was then identified during this short period without doubt from 2 independent observables:

- During the telemetry gap, there was a significant drop from both propulsion pressure sensors. In less than 3 minutes, the pressure had decreased from 5.6 down to 5.2 bars (Fig.3). The pressure criteria to send the passivation time tag command sequence was either a drop on both sensors > 0.1 bar within 1 minute or a pressure of less than 5.5 bar reported via telemetry.
- Gyro outputs clearly showed an increase in the spacecraft rates that was characteristic of irregular thrust levels.

**Table 5. Passivation phase performance summary.**

Maneuver	Date	Mid Thrust Time (UTC)	Duration (s)	Delta V (m/s)	Fuel Consumption (kg)	Total Fuel Spent
DS1	25/08/2011	01:26:00	168	-0.68	0.773	126.6
DS2	25/08/2011	08:38:11	168	-0.68	0.771	127.4
P1	26/08/2011	12:57:30	1498	-6.10	6.769	134.2
P2	28/08/2011	12:51:00	1448	6.07	6.282	140.4
P3	31/08/2011	12:51:10	2243	+9.19	9.501	149.9
P4	02/09/2011	13:01:00	2396	-9.10	10.033	159.9
P5	03/09/2011	13:00:06	2453	-8.98	9.970	169.9
P6	05/09/2011	12:52:47	2335	+8.19	~9 (no TM available)	178.9



**Figure 3. Derived ERS-2 tank pressure (in Bar) during maneuver P6.**

Considering the risk of a return to thruster controlled modes with possibly not sufficient fuel to perform the required attitude convergence and station keeping, it was decided at this point to execute the final spacecraft passivation. The corresponding sequence was commanded shortly after the successful termination of the burn and the related platform mode change at 13:14z via Maspalomas. The disconnection of the first set of 3 batteries was confirmed by telemetry. Then the (unused) transponder B emitter was switched off. The ground station operator confirmed the loss of downlink after the switch off of transponder A and the disconnection of the last battery was commanded in the blind (i.e. after the definitive loss of telemetry). Absence of downlink was finally confirmed in the subsequent Kourou and Kiruna passes. The Keplerian elements of the disposal orbit were determined later as and are summarized in Table 6.

**Table 6. ERS-2 Final Orbit following Passivation.**

<b>Epoch</b>	2011/09/06-00:00:00.0
<b>Semi-major axis</b>	6941.123 km
<b>Eccentricity</b>	0.002382
<b>Inclination</b>	98.516 deg
<b>Right Ascension of Ascending Node</b>	326.675 deg
<b>True Anomaly</b>	283.933 deg

## IX. Conclusion

On 5<sup>th</sup> Sept 2011 at 13:16 UTC the ERS-2 deorbiting phase was successfully concluded after sending the last commands for switching off the two transponder-emitters and disconnecting the four batteries. Shortly before, just at the end of the 6<sup>th</sup> passivation maneuver, first clear indications for tank depletion were obvious from on-board pressure readings. The deorbiting period started two months before on the 6<sup>th</sup> July. 66 orbit-lowering and 6 passivation maneuvers were necessary to reach the final target altitude of ca. 570 km and to nearly empty the tanks. A re-entry of ERS-2 is expected in about 15 years. Almost 20 kg more hydrazine was consumed until tank depletion than originally expected at the beginning of the deorbiting using the pulse counting (book keeping) method. With these results, all objectives of the ERS-2 deorbiting phase were fully achieved. Apart from the late failure of the backup Gyro3, which had no impact on the overall activity, all subsystems on-board performed perfectly. There were also no problems with any of the hardware or software elements on-ground or the ground stations availability and support.

## Appendix A Acronym List

AMI	Active Microwave Instrument
ASI	Agenzia Spaziale Italiana
DES	Digital Earth Sensor
DoD	Depth of Discharge
ESA	European Space Agency
ESOC	European Space Operations Center
ESRIN	European Space Research Institute
ESTEC	European Space Technology Center
EO	Earth Observation
FCT	Flight Control Team
FDS	Flight Dynamics System
FOV	Field Of View
GOME	Global Ozone Monitoring Experiment
IADC	Inter-Agency Debris Coordination Committee
JAXA	Japan Aerospace Exploration Agency
KSAT	Kongsberg Satellite Services AS
LEOP	Launch and Early Operations Phase
PLSO	Post Launch Support Office
PVT	Pressure, Volume, Temperature
PSO	Position Sur Orbite
RF	Radio Frequency
SAR	Synthetic Aperture Radar
TOV	Time Offset Value
XMM-Newton	X-Ray Multi-Mirror

## Acknowledgments

The authors would like to thank the experts of the industrial team at Astrium SaS for their support and contribution to the success of the ERS-2 deorbiting activities. Our particular gratitude goes to M. Horblin from Astrium for his invaluable advice and support for so many years. The authors also thank the Norwegian, Italian and Japanese Space Agencies for providing ground station support during critical maneuver phases. Finally, our highest appreciation to the members of all previous flight control and support teams who took care of the satellite since launch.

And to our colleague Hugues Dufort, whom we will always remember.

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