ENVISAT PLATFORM OPERATIONS: PROVIDING A PLATFORM FOR SCIENCE

D. Milligan(1), L. Ventimiglia(2), Y. Eren(3), D. Mesplés(1), F. Diekmann(1), D. Kuijper(4), M. Garcia-Matatoros(1)

(1) ESA-ESOC, Robert Bosch Str5, 64293 Darmstadt, Germany. 
Emails: david.milligan@esa.int, daniel.mesplés@esa.int, frank.diekmann@esa.int, marco.antonio.garcia.matatoros@esa.int
(2) Science Systems, c/o ESA-ESOC, Robert Bosch Str5, 64293 Darmstadt, Germany. Email: Luca.Ventimiglia@esa.int
(3) LSE SG, c/o ESA-ESOC, Robert Bosch Str5, 64293 Darmstadt, Germany. Email: Yusuf.Goeksel.Eren@esa.int
(4) LogicaCMG, c/o ESA-ESOC, Robert Bosch Str5, 64293 Darmstadt, Germany. Email: Dirk.Kuijper@esa.int

ABSTRACT
The ENVISAT satellite, launched on March 1st 2002, is controlled from the European Space Operations Centre (ESOC) in Darmstadt, Germany. This paper presents a summary of the Envisat orbit maintenance strategy and some in-flight enhancements promoting longer battery lifetime. The orbit control strategy is described in detail, and it is shown to be the likely lifetime limiting factor for Envisat. Regular orbit maintenance manoeuvres are required to maintain ground track control to within +/-1km. Envisat orbit maintenance manoeuvres are of two basic types. In-plane manoeuvres are used to correct ground track drift mainly around the equator, which is caused by the effect of air-drag. These are performed relatively frequently; typically 1-2 months apart. The second basic type of manoeuvre is an out-of-plane correction. This is applied to correct ground track drift at high latitudes (close to the poles). Such manoeuvres are relatively infrequent (2-3 per year), but are dominant in terms of propellant use. A review of the orbital strategy was carried out in 2005, which identified an efficiency improvement which has been applied since January 2006. A fuel efficient manoeuvre strategy is described allowing interferometry for international polar year.

1. INTRODUCTION
Envisat was developed with the primary objectives being the continuity of ERS1&2 data1,2. Envisat was launched in March 2002 on an Ariane V from Kourou in French Guyana into a sun-synchronous low earth orbit with the following orbital characteristics:
- semi-major axis= 7159.5 km,
- inclination= 98.55 deg,
- mean-local solar time= 10:00 A.M. (at the descending node)
- repeat cycle of 35 days (or 501 orbits) with 14 11/35 orbits/day.

During the Launch and Early Orbit Phase ENVISAT was manoeuvred to phase with the orbit of ERS-2 (Envisat being 30 minutes ahead). The Envisat system, satellite and ground segment are described in detail in 3,4,5 & 7.

2. ORBIT CONTROL STRATEGY
The most likely subsystem to encounter end of life conditions first, is the onboard propulsion subsystem, which will reach end of life at hydrazine depletion. The major use of on-board hydrazine is for periodic orbit maintenance. A summary of the general strategy is given below; for a more detailed description see Rudolph et al.3.

- Gravitational forces by sun and moon
- Air drag
- Solar radiation pressure

The orbit control strategy therefore aims at compensating the effect of these forces. The major effect of solar gravity perturbations is a secular decrease in inclination, with the Moon inducing additional periodic perturbations on the inclination with a period of half a month. The rate of inclination change depends on the Sun-Earth distance. As the Earth moves closer to the Sun (closest distance during wintertime) the torque on the orbital plane increases and therefore increases the inclination change rate. Figure 2 illustrates the effects of these forces on the orbital plane. Shown are the actual deviations of the ground track, from the reference ground track, at the northern-most point on the orbit. The perturbations can be seen as a gradual drift toward the pole (increase in y-axis value) of the ground track, with the manoeuvres seen as sharp decrease (in y-axis value) away from the pole, of the ground track. The seasonal effect is also evident in the varying rate of ground track drift. The area highlighted shows when the perturbing effect from the sun is smallest.

Figure 1. Envisat launch (left) and an artist’s impression in orbit (right)
Air drag has a significant influence on spacecraft flying at low altitude. At the altitude of Envisat, variations in air density, of a factor 1000, can take place in short periods of time, which makes this force an unpredictable one. Figure 3 illustrates the effect of air drag on the satellite orbit in terms of deviation of altitude (vertical axis) and cross-track position (horizontal axis) relative to the reference orbit. At an altitude above nominal, the satellite has a westward drift, as seen at the ascending node crossing. The rate of this drift slowly reduces as the altitude decays due to air drag, until nominal altitude is reached, below which the drift reverses and becomes easterly. As the easterly limit is approached an orbit raising manoeuvre is necessary. The cause of these drifts is the change in altitude, which also affects period, and the sun-synchronicity of the orbit.

**2.1. Orbit Control Performance**

To date, a total of 16 OCMs (which are responsible for 95% of hydrazine consumption) have been performed. Fuel consumption at the time of writing is 154 kg (of the initial 314 kg – see figure 4).
Out of plane manoeuvres, for reasons of orbital efficiency, are centred as far as possible, around the ascending node crossing (or ANX, see equation 1 and figure 6). The amount of ΔV applied is of the order of 2.3 m/s, to produce a 2000m change in ground track at high latitudes. The thrust to mass ratio dictates the length of burn required to achieve such a ΔV. As the upstream pressure in the hydrazine subsystem falls with propellant usage, so does the effective thrust delivered, requiring the burn to be lengthened, which reduces the efficiency of the manoeuvre due to spread losses (see equation 2).

Manoeuvres must sometimes also be offset, since the position of the eclipse with respect to the ANX varies throughout the year. When the thrust duration exceeds a certain threshold, it becomes necessary to offset the burn centre with respect to the ascending node crossing to maintain the manoeuvre inside the eclipse. In such cases the losses described by equation 1 are also incurred. The desirability to operate efficiently leads us to try to minimise the losses, which are found by the summation of the offset loss, spread loss and slew loss.

\begin{align}
\Delta I &= \frac{\cos(\alpha) \Delta V}{V} \\
\eta &= \frac{\sin \beta - \sin \alpha}{\beta - \alpha}
\end{align}

(1)
(2)

Where,
- η is the efficiency c.f. an impulsive manoeuvre
- ΔI is the inclination change
- TA is the offset with respect to the ANX
- α and β are the angles between which the thrust is applied (for a ANX centred manoeuvre α=β)

The eclipse duration for Envisat varies between 31.5 and 33.7 minutes, depending on the time of the year. In addition to the increasing losses incurred, due to increasing burn time, there is also a hard constraint - a point at which the manoeuvre fills the entire eclipse, and further increases in burn time are not possible. At this point it becomes necessary to split the manoeuvre. At the beginning of the mission, slew losses dominate, which leads us to try to minimise the manoeuvre frequency. The deadband requirement means that we must perform at least 2.78 manoeuvres per year (otherwise the spacecraft would pass outside the +/- 1km limit of the reference track, a limit set for Science data quality reasons).

With the constraint that the slews and thrust must be performed inside an eclipse, analysis shows7 that for tank pressures above around 9bar, the minimum number of manoeuvres per year is constrained by the deadband requirement. Below around 9bar, the manoeuvre frequency per year increases because the ‘burn plus slews’ duration exceeds the eclipse duration (which has the side effect of narrowing the deadband control). The manoeuvre types switch from ‘deadband constrained’ to ‘eclipse length constrained’. This means that once the tank pressure drops below around 9bar, we have to increase the frequency of the manoeuvres, to keep them inside the eclipse. Since the slew loss is the dominant loss in the first part of the mission, swapping to eclipse constrained manoeuvre types too early reduces manoeuvre efficiency, impacting hydrazine consumption rate and therefore feasible lifetime extension. Allowing the slews to be performed outside of the eclipse, allows us to increase manoeuvre frequency only when this is required by efficiency considerations, rather than eclipse length.

Figure 7 shows the losses associated with a 2000m deadband correction (i.e. ΔV fixed at 2.34 m/s), for the cases with the slews inside and outside of eclipse. The x-axis, required thrust time, is a function of upstream hydrazine tank pressure, and since pressure drops with time, this can also be thought of as ‘time into the mission’, with beginning of life on the left. Two cases of one burn solutions are shown, one performed at the optimum season (ANX centred), and one performed at the worst case season (23.5deg eclipse offset included). The one performed at the ANX is always the most efficient since there are no offset losses. Initially there is no difference with the manoeuvre performed with a 23.5deg eclipse offset, since the manoeuvre is short enough to still be centred at the ANX. As the thrust time increases, the manoeuvre starts to fill the eclipse and must be offset, ultimately up to a maximum offset of 23.5deg. The one burn solutions are only possible up to a point (for the slews in eclipse), as eventually the manoeuvre fills the entire eclipse. At this point the manoeuvre must be split, and two burn solutions become necessary to impart this ΔV (also shown on the figure).

On the right of figure 7 are the losses when slews are allowed outside eclipse. The most notable difference is that one burn solutions are possible to the end of mission, and that the efficiency of the worse-case-season burns are markedly increased. This is because an extra 600s is effectively gained by allowing the slews to go outside the eclipse, and this can be used to reduce the offset of the burn in non-optimal seasons. It can be seen that removing the constraint that slews must be
performed inside eclipses is clearly advantageous in terms of minimising hydrazine loss. The left of Figure 7 demonstrates that when hydrazine consumption forces the burn time to exceed around 1200s, it is no longer possible to impart a 2000m ground track correction at high latitude with a single burn. At this point the minimum loss per manoeuvre jumps from 1.25 to 1.67kg; an extra loss of 420g per manoeuvre, caused by the forced manoeuvre split. Allowing slews outside eclipse however, requires a change of one of the operational constraints.

2.2. Analysis of illuminated Slews

With mission extension foreseen, and the benefits of altering the eclipse thrusting constraints clear, the impacts of allowing slews to be performed outside eclipse needed to be assessed. During the slew the attitude is non-nominal (up to 90deg bias around the z-axis), but is returning to the nominal pointing within 5 minutes, such that the thermal impact is not dramatic. Analysis focussed on stray light in sensitive optics, with the main areas being addressed:
- The Star Trackers
- The Earth sensor
- Possible Surveillance Triggering
- Instruments sensitivity

An analysis of the star trackers showed that the margin between sun vector and SST field of view is always greater than 47deg, which is well within specification. Similar analyses were performed for other light sensitive equipment, such as the Earth sensor and payload instruments. Several of the payload instruments have optical protection (i.e. a shutter) or a safe position for the optics (such as the mirror position in GOMOS). A system level review found there were no show stoppers in allowing the slews to take part outside of eclipse, only procedural changes were necessary. The affect on Earth sensor masking was also analysed and the result incorporated in the altered OCM strategy. With propellant savings evident, the decision was taken to alter the manoeuvre constraints and allow slews to take place in sunlight. The first such manoeuvre took place in January 2006.

2.3. Projected Hydrazine Consumption

A best case projection of hydrazine consumption is shown in figure 9, together with a case where 7kg/yr margin is taken. Margin may be used when on-board surveillances trigger which invoke AOCS back-up modes requiring thruster use. Such a back-up mode has been used just once in the mission so far.

![Figure 7 Estimated hydrazine loss per 2km ground track change (slew in eclipse – left, slew outside eclipse –right)](image)

![Figure 9 Historical and Projected hydrazine use on Envisat (top) and comparison of Envisat and ERS-2 fuel use (below)](image)
2.4. Special Manoeuvres for Interferometry

Since beginning of 2007 a new orbit maintenance strategy has been put in place for Envisat with the following characteristics:
- Out of plane manoeuvres (to control orbit inclination) are performed in phase, every other repeat cycle (i.e. every 70 days);
- A small Out of Plane manoeuvre is introduced during Northern Summer to introduce the correct phase;
- In plane manoeuvres (to control semi-major axis) are performed with a ground track control of +/-200 meter at the equator (with respect to the reference orbit) at the start of every cycle, with an occasional touch up in between.

The extra manoeuvres to control the semi-major axis can be accommodated with negligible fuel penalty, but for inclination control (which accounts for 95% of all fuel use), a phased approach was selected to minimise fuel impact (see figure 10). By phasing the manoeuvres at integral repeat cycles, a very small deadband is achieved for a given day in alternate repeat cycles (starts of repeat cycles are marked in figure 10). This strategy allows the interferometry goals of international polar year to be achieved with a low additional fuel cost (estimated ~1kg extra).

3. ENHANCED BATTERY PROTECTION

3.1. Power Subsystem Description

A brief summary of the Envisat power subsystem is given below, for a more detailed description see 7. An Si solar array provides ~7kW of power in sunlight, with 8 NiCd batteries providing power in eclipse. The main power bus is unregulated, in that the main bus voltage follows the state of charge of the batteries, with power users designed to accept a range of input voltages (24-37V).

In sunlight conditions the current input to the bus is controlled by the solar array junction shunt regulator (RSJ). The battery charging is controlled partly by hardware and partly by software. In the early sunlight period battery charging is under hardware IL, or current limit law. In this case the maximum current that can be delivered to the batteries is capped, if the power balance allows high charge currents to be reached. As the battery voltage (and therefore bus voltage), rises with charge state, eventually the voltage limit is reached, and voltage limit law V_L is applied by the hardware. In voltage limit the current delivered to the batteries is controlled to stop the battery voltage rising above V_L. At this point the delivered charge current tends to taper down (see figure 11).

In parallel to the hardware control a software battery charge algorithm runs, which integrates the total ampere-hours delivered and received by the batteries. When the desired input-output balance of charge is reached (known as the k-factor) the on-board software sends a command to the power subsystem that initiates trickle charge (see figure 11 (below)). In trickle charge mode the current input to the batteries is reduced, and set to exactly offset the natural internal losses, so that no net charge is added.

3.2. Power FDIR Software Enhancement

The timing of the trickle charge command has a significant effect on the k-factor applied to the batteries. In certain failure cases the battery algorithm in on-board software is stopped by the autonomy. In such cases trickle charge is not applied and a net overcharge is observed. Overcharging batteries can
lead to damage, and in severe cases even loss of batteries.

Even though subsystem performance had so far been excellent, with no triggering of any power surveillances to date, it was decided to enhance the power FDIR software to limit the number of cases in which the battery recharge algorithm can become disabled. A new subset of failures cases was identified for which it would be possible to keep the algorithm enabled.

With such changes foreseen, a full version upgrade of the CFS (Central Flight Software) was planned. This was designed and tested by industry using the test bench, which includes flight hardware for the DHS (Data Handling Subsystem). After validation of the new software version by industry, the software upgrade was delivered to ESOC, where it was further validated using the ESOC simulator, which includes an emulation of the CFS processor hardware. The new CFS version was uplinked to the spacecraft in July 2005, and has been operationally active ever since.

3.3. Safe Mode Fast-track recovery

In certain circumstances, the upgrade of CFS will have no effect in limiting battery overcharge. The most important such case is satellite safe mode. Envisat has so far never undergone transition to safe mode, but if this were to happen, all major functions of the CFS are disabled; including battery charge management. Recovery from safe mode requires substantial ground intervention. When we consider that there are usually only around 10 minutes available every 100 minute orbit for commanding, the recovery duration can easily become extended to the order of days. With this in mind the safe mode recovery procedures were extensively reviewed, to identify safe and robust ways of accelerating to recovery of the charge control algorithm. The result produced a new system level procedure ‘Safe Mode Fast-track Recovery’. This procedure a priori selects a safe and robust hardware configuration for recovery, which is considered to have the highest probability of success. Extensive training of SPACONS and expert engineering on-call support was also performed once the new procedure was in place. Recovery to activation of battery charge algorithm, under optimum conditions, can now be achieved in 3-4 passes.

4. CONCLUSION

Envisat has now surpassed its design lifetime of 5 years and with excellent, high-quality science data being returned on a daily basis, mission extension to 2010 has been approved. The extent of the possible mission extension depends upon maintaining robust performance and safely decreasing the rate of usage of life limiting consumables. After a review of the service module, work has focused on enhancing the Envisat Power FDIR (Failure Detection Isolation and Recovery) software and on modifying the orbit control strategy. After analysis of the orbit control efficiency was performed, it was seen that relaxing a pre-launch orbit manoeuvre constraint would lead to substantial savings in hydrazine. An analysis was performed to asses the impact of the constraint change, which involved allowing the spacecraft to slew to non-nominal attitudes in sunlight, and ultimately led to the constraint being relaxed. The first such manoeuvre was implemented in flight in January 2006. The hydrazine consumption has been projected forward and shown to allow a mission extension until end 2010, including a small margin. An efficient strategy has been developed that allows the Interferometry goals of international polar year to be achieved with minimal additional fuel cost.

An analysis on the power subsystem led to enhancements being made to the Power FDIR software to reduce the number of failure cases that could lead to battery overcharge. A CFS update was performed including enhanced power FDIR functionality and a review of ground procedures led to the creation of a ‘Fast-track’ safe mode recovery procedure.

5. Acknowledgements

The Authors would like to acknowledge the excellent work and inputs of the Flight Control and Flight Dynamics Teams at ESOC, and industry and project experts in ESTEC and at Astrium Toulouse.

6. References

1. M.Rosengren, Orbit Control of ERS-1, ERS-2 and ENVISAT to support SAR Interferometry, Paper presented at the ERS and Envisat Symposium, Gothenburg, 16-20 October 2000.