ABSTRACT

When a satellite reaches its nominal lifetime, the entire mission changes its character. Basic elements like fuel, electrical power, orbit maintenance, pointing stability are no longer self-evident and are beginning to reveal their mission limiting character and have to be analysed and carefully budgeted in order to achieve the longest possible lifetime, unless the unforeseen would happen. This is another thread to a mission, which comes into its years. Any anomaly to come might be more severe and more impacting than earlier ones. Comparing to its predecessors ERS1&2, fuel appears to be the most precious consumable on-board of ENVISAT. A strategy to optimize its usage will therefore form a central part of the present Post Launch Support Office (PLSO) study. Since ENVISAT flight hardware is, at this moment, in excellent shape, and given the fact that PLSO was able to preserve valuable industrial engineering expertise, another key-factor for a long duration mission, the perspective for the ENVISAT mission is very positive.

1.1. Mission limiting factors

Mission limiting factors are those, which can change the character of the mission or even lead to termination.

Considering the technical status of the payload, certain instruments may fail after some time. In consequence, related data products and services cannot be continued any longer. The mission as a whole could be continued but depending on which instrument failed, it would be substantially reduced. This is a situation, which has to be realistically considered.

Another critical point is space-ground communications, which consists of either command and control of the spacecraft, but also on-board data storage and downlink capabilities. Whereas command and control of a spacecraft is extremely robust (and therefore unlikely to fail), data storage may become an issue. Consequences could be even more pronounced as for a single instrument failure, because more than one payload instrument might suffer from it.

More critical are failures in the attitude and orbit control system (AOCS). Usually they go along with a reduction of pointing quality, which may be tolerable, but could also make certain data products meaningless. But worst case, the control over the spacecraft and therefore the spacecraft itself may be lost.

Failures in the electrical power system (solar array and battery) can be as critical. Usually, the efficiency of the solar panel is decreasing with time as the battery storage capacity, which usually is the dominant effect. As a consequence, less power is available for the payload and therefore might be a constraint for instrument operations. Also, major failures cannot be excluded which could be equivalent to mission termination.

Finally, there is the fuel factor. Propellant is needed for all orbit control manoeuvres (in and out of plane), but also for emergencies like collision avoidance manoeuvres or highly consumptive platform safe-modes. As its amount is limited, this is the truly deterministic factor, which will say: Even if all systems...
would remain operational, the moment all fuel is exhausted, the mission will be finished.

1.2. ENVISAT current budgets

After 5 years of operation, the whole payload is operational and with good performance. Of course, there are signs of ageing and degradation (e.g. reduction of throughput in optical systems), but all in all the engineering parameters are better than expected. For a few instrument modules, redundancies had to be applied in this period, which makes their situation a bit tenser compared to those, which still have their full redundancies available. The current and expected performances of ENVISAT are summarized by tab. 1.

<table>
<thead>
<tr>
<th>ENVISAT mission elements</th>
<th>Current Perf.</th>
<th>Exp. Evolution</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASAR</td>
<td>Good</td>
<td>Fair</td>
<td>Data subsystem on redundant side, 18 T/R modules not available</td>
</tr>
<tr>
<td>MERIS</td>
<td>Excellent</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>AATSR</td>
<td>Excellent</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>RA-2</td>
<td>Good</td>
<td>Fair</td>
<td>S-Band redundant failed</td>
</tr>
<tr>
<td>MWR</td>
<td>Good</td>
<td>Fair</td>
<td>Degradation of 36.6 GHz channel</td>
</tr>
<tr>
<td>DORIS</td>
<td>Excellent</td>
<td>Fair</td>
<td>Instrument on redundant side</td>
</tr>
<tr>
<td>SCIAMACHY</td>
<td>Excellent</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>MIPAS</td>
<td>Good</td>
<td>Fair</td>
<td>Degraded interferometer (currently improving)</td>
</tr>
<tr>
<td>GOMOS</td>
<td>Good</td>
<td>Fair</td>
<td>Instrument on redundant side</td>
</tr>
<tr>
<td>Payload Equipment Bay</td>
<td>Excellent</td>
<td>Good</td>
<td>Small degradation only</td>
</tr>
<tr>
<td>Service Module</td>
<td>Excellent</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>Propulsion &amp; Hydrazine</td>
<td>Good</td>
<td>Fair</td>
<td>Main limiting factor</td>
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Looking into these figures, it becomes clear that the inclination manoeuvres consume most of the fuel, nominal operations considered. It is about 85% of the annual budget, which is used to maintain the ground track inside a dead band of ± 1 km. As a consequence, the mean local solar time (MLST) is kept constant around its nominal 10:00 at descending node crossing (DNX). Another important amount has to be allocated for satellite disposal, in order to free the ENVISAT orbit for other polar orbiting missions. Right now, it is assumed to lower the altitude about 25 km, which would cost about 50 kg of fuel, a considerable amount which is equivalent to even more than one year of nominal operations. This amount seems to be not usable for operations, which is a great pity.

As it turns out, fuel will be the main limiting factor.

2. FUEL STRATEGIES

Before any fuel strategy can be developed, a proper budget of resources is needed, which is listed in tab. 2.

<table>
<thead>
<tr>
<th>Table 2: ENVISAT Fuel Budget</th>
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<tbody>
<tr>
<td>Mass [kg]</td>
</tr>
<tr>
<td>Available fuel (Jan. 2007)</td>
</tr>
<tr>
<td>Available fuel (Jan. 2009) (expected)</td>
</tr>
<tr>
<td>Total consumption per year</td>
</tr>
<tr>
<td>OCM/Inclination per year</td>
</tr>
<tr>
<td>SFCM/altitude per year</td>
</tr>
<tr>
<td>Required for disposal</td>
</tr>
</tbody>
</table>

Taking all these figures into account, and considering nominal operations with all inclination and altitude maintenance manoeuvres performed, it is clear that in 2010, no fuel will be left, which automatically means the end of mission. So, the only way to achieve any extension of the ENVISAT mission is to reduce the fuel consumption which must mean to touch the manoeuvring strategy. This of course will also have an impact on the mission character, which needs to be assessed carefully. Additionally, one might look for ways to take advantage of the fuel budget, allocated to dispose ENVISAT into a lower orbit.

2.1. General considerations

What compromises would have to be made if the manoeuvring strategy is modified? Generally, it is not too difficult to predict what happens to the orbit, if a certain type of manoeuvre would not be performed any longer, especially when first concentrating of the fuel budget.

Beginning with the so called spacecraft fine control manoeuvres (SFCM), these are regularly performed to maintain the altitude. Generally, performing no or less altitude corrections will let the repeat cycle change in an uncontrolled way. This will have severe impacts on mission planning relevant software, which would need quite some adaptation in order cope with a drifting altitude. Also, a considerable amount of operations parameter updates and their verification has to be considered (e.g. for limb sounding instruments, but also ASAR). Finally, when looking to the amount of
fuel, which could be saved by a reduction of this type of manoeuvre (it is only about 15% of the annual consumption, see tab. 2), it is probably not the most effective way to save fuel.

What would happen, if the inclination drift is not corrected? First of all, this will make the inclination drift from its current 98.5 degrees towards the pole. Accordingly, the mean local solar time (MLST), another very important mission parameter, will change. The further the inclination is away from sun synchronous conditions, the faster the MLST will change (quadratic with time). However, the requirements on the accuracy of this value are less constraining compared to the repeat cycle. MLST is allowed to vary by as much as ±5 minutes around the nominal 22:00 at ANX. Secondly, the inclination drift happens to be quite slow such that a 5 minutes drift in MLST is more than a year of operations. However, once the MLST has left the allowed corridor, it can’t be brought back to its nominal value without manoeuvring, i.e. consuming fuel. Bearing in mind that a nominal inclination manoeuvre requires in the order of 5 to 7 kg already, which is needed to correct a few seconds of MLST drift, it becomes clear that the benefit of a drifting inclination orbit is timely limited.

What happens, if the orbit is changed to a lower altitude? Besides the fuel needed, it changes the repeat cycle. But it also moves the inclination angle, for which this new orbit would be sun synchronous, closer to the pole. This effect can effectively be used to optimize ENVISAT’s fuel consumption over time.

### 2.2 An Optimization

Fig. 1 shows the principle of how the ENVISAT fuel budget could be optimized. In black, the nominal inclination manoeuvre strategy is shown.

Keeping the altitude fixed (i.e. maintaining the repeat cycle of 501 orbits in 35 days), the manoeuvre sets the inclination back slightly above the sun synchronous angle of 98.5 degree. At the same time, the MLST stays almost constantly at 22:00 ANX\(^1\). This aspect is covered by the lower part of fig. 1.

As explained in section 2.1 already, it would be possible to give up inclination manoeuvres at some time in the mission. The greenish curves show the general progression of both, the inclination angle (upper part) and MLST (lower part). Still, the orbit has a nominal repeat cycle, i.e. the altitude manoeuvres would still be performed. After 13 month of operations, the lower MLST limit would be reached, and bringing it back to 22:00 would require more fuel than what is available at that time.

If, at the moment the lower MLST limit is reached, the altitude would be changed to a lower orbit, the repeat cycle, but also the inclination angle, under which the orbit would be sun synchronous, would change. Anticipating an orbit which is 25 km lower than the current one, this angle would be such, that the actual value would still be way above. As a consequence, the MLST will drift from its current, lower limit to almost its upper limit. Only once the new sun-synchronous inclination angle is passed, it will start drifting downwards again. As can be seen in fig. 1, the resulting mission extension depends on when exactly the altitude would be lowered. But another 32 to 44 months extra seem feasible (see also fig. 2).

One of the most attractive side effects of this approach is that the fuel, needed to lower the altitude by 25 km, is coming from the reserve taken into account to dispose ENVISAT into another orbit, once its operational life would be reached. To say it in other words: The idea is to lower the current ENVISAT orbit at a certain time and to continue the operation until the fuel, necessary to control the satellite altitude, gets completely exhausted.

Of course, lowering the orbit by 25 km would change the repeat cycle, requiring several changes in planning software, but also measurement parameters. However, these modifications would have to be made only once. As soon as the new orbit is reached, the altitude could be kept constant again, i.e. the altitude manoeuvres could be maintained.

\(^1\) The amplitude of MLST variation in case of nominal inclination manoeuvres is even smaller than depicted. The plot in this part aims to show the qualitative MLST variation more than the absolute.
2.3 Different Operational Scenario

Considering the different ideas, which were presented before, there are three principal ways of how the ENVISAT mission could be continued. Its benefits in terms of mission end date are depicted in fig. 2.

Scenario 1: Continue as today, i.e. proceed with all altitude and inclination manoeuvres, ensuring continuity and stability of orbital parameters, and especially repeat cycle and MLST. Taking into account a 50 kg fuel margin to release the ENVISAT orbit at the end of operational life (which would be equivalent to the end of fuel), mission can continue until end of 2010.

Scenario 2: Similar to scenario 1, it is again considered releasing the ENVISAT orbit at the end of its operational life/at the end of fuel. But the inclination control is discontinued, about 13 month before the orbit release manoeuvre (see section 2.2). Consequently, it would be possible to continue the mission with current orbit performance until autumn 2010, which would be a little bit less than scenario 1. But saving the inclination manoeuvres from that moment would extend the overall mission until orbit release until the end of 2011. One has to keep in mind that in this last phase, the current altitude will still be maintained. It would only be the MLST, which would drift to its lowest, tolerable value.

Scenario 3: This scenario takes full advantage of the fuel optimization, presented in section 2.2. Its main difference to the previously mentioned scenario is the following: The ENVISAT orbit is released before the end of its operational life, such that the lower orbit and its closer to polar sun synchronous inclination will over-compensate for the inclination drift of the original orbit. In order to maximize the mission duration, orbit control will therefore have to change in three phases. Up to the end of 2009, the control would be as today, i.e. both, inclination and altitude are controlled. In the second phase, starting approximately at the end of 2009, the inclination control discontinues, until the MLST reaches its lower limit. At that time, the orbit altitude will be lowered by 25 km using the budget, foreseen to release the ENVISAT orbit, which is the begin of a third phase. Again, the inclination is kept floating. But due to the selected orbit and its new sun synchronous inclination, the MLST will drift from its lower to its upper limit and back again. The altitude will still be controlled. Depending on the date, the orbit altitude is reduced the third phase could last between 32 and 44 months. At the end of this phase, i.e. when finally no propellant is left to control the altitude, an even further reduced mission could be thought of.

3. EXPECTATIONS FOR EXTENDED MISSION

Of course, there is a lot more to talk about than just fuel. As mentioned in the introduction, other elements like AOCS, electrical power or the payload in general, may show degradation and abnormal behaviour, enforcing some critical decisions in the future.

Starting with the AOCS system, consisting of gyros, wheels, star- and earth sensors, it is, after 5 years of nominal mission, still fully intact. This is of course the best starting position. Also, its design, especially the gyros, is already more robust than its ERS-2 predecessors. And in the unlikely case of severe gyro degradation or even failure, corrective actions in form of software patches could be put in place, helping to avoid fuel consuming safe modes. This could be learned also from ERS-2. Additionally, after one sporadic ENVISAT event in 2006, countermeasures have been installed to avoid fuel consuming FAM2 mode in case of further anomalies of the digital earth sensor.

![Figure 2: Benefits as they can be expected from the different strategies.](image)
which already showed difficulties during their nominal mission lifetime are more likely to run into problems. Here GOMOS and MIPAS have to be mentioned. In case of GOMOS even a redundancy had to be activated, making any follow-on problem way more critical. MIPAS did suffer from degradation in non-redundant parts involved in the mechanical control of its interferometer slides. Both instruments are still operational and working with stable performance, although restrictions had to be made compared to their initial mission design. So, both instruments have a fair to good perspective. However, after a phase of intensive care, the MIPAS performance regarding its interferometer control is even improving again.

But whatever the problem might be, the ENVISAT post launch support team (PLSO) is fully committed to take care and bring any instrument back to operations. The team, which consists of a number of experienced payload engineers, is closely working together with ESOC and ESRIN as well as industry, most of them having participated in the ENVISAT C/D phase.

4. CONCLUSIONS

Generally, the pre-condition for a successful mission extension are given. For a platform having reached its nominal lifetime already, the whole equipment is still in excellent technical condition.

Fuel turns out to be the most limiting resource amongst the mission critical elements and will, presuming no major anomaly, determine the end of ENVISAT’s operational life. If the current orbit manoeuvre strategy would be maintained, this date will be sometime in 2010.

The paper could show that there are principal ways optimizing the fuel consumption and allowing an extension of the mission into 2013 or even beyond. This would be achieved mainly on cost of inclination control. But also the orbit altitude would have to be lowered at least once. However, a number of open points need to be clarified before any decisions can be taken.

At first, a trade off between the different types of operations

A. Nominal repeat cycle, nominal orbit control
B. Nominal repeat cycle, inclination drifting
C. Lower orbit/new repeat cycle, inclination drifting

has to be carried out per instrument. Questions like which data applications would be influenced by the different operational scenario, have to be carefully addressed. Especially the requirements on MLST need to be checked carefully. It should be investigated, too, whether it could be relaxed even beyond the 5 minute requirement, as it contains potential for even longer extensions.

Secondly, the exact altitude of the lower orbit deserves optimization, too. Self speaking, sufficient fuel needs to be allocated for the manoeuvre. But the exact altitude will also have an influence on the amount of fuel which could be saved, the repeat cycle as well as the global coverage of the individual instruments, which could be expected from this new orbit.

At third, from a more operational point of view, it needs to be investigated which mission planning and observation related parameters would need to be changed in order to support type B or C operations.

In shorter words, the best possible mission compromise needs to be found, which – taking into account ENVISAT’s complexity – is not an easy task. Once the strategy is decided, all necessary modifications still have to be implemented into the ground and space segment to allow continuation beyond 2010.

It has to be kept in mind that any change in the key assumptions (technical or non-technical) will lead to a re-assessment of the strategy.