# CLUSTER: MISSION OVERVIEW AND END-OF-LIFE ANALYSIS


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## ABSTRACT


The Cluster mission is part of the scientific programme of the European Space Agency (ESA) and its purpose is the analysis of the Earth's magnetosphere. The Cluster project consists of four satellites. The selected polar orbit has a shape of 4.0 and 19.2 Re which is required for performing measurements near the cusp and the tail of the magnetosphere. When crossing these regions the satellites form a constellation which in most of the cases so far has been a regular tetrahedron.

The satellite operations are carried out by the European Space Operations Centre (ESOC) at Darmstadt, Germany.

The paper outlines the future orbit evolution and the envisaged operations from a Flight Dynamics point of view. In addition a brief summary of the LEOP and routine operations is included beforehand.


## LAUNCH AND EARLY ORBIT PHASE [1]

In June 1996 the first attempt to launch the four Cluster satellites failed as the test launch of Ariane 5 exploded after 37 sec. During the following years the satellites were rebuilt and called Cluster II. In fact for one satellite (Flight Model 5, called Phoenix, Cluster 1) the spare parts of the 1996 manufacturing and testing phase could be used, the other 3 ones (FM 6, 7 and 8) contain only new parts.

The Cluster satellites were launched in Summer 2000 with Soyuz rockets from Baikonour into a highly eccentric orbit. The two launches occurred on:

| | |
|---|---|
| 16. July 2000 | Cluster 2,3 renamed as Salsa, Samba, respectively |
| 9. Aug 2000 | Cluster 1,4 renamed as Rumba, Tango, respectively. |

They were injected into highly eccentric orbits with heights of 240 and 17090 km, inclination of 64.9 degrees and lines of apsides near the equator.

In order to reach the final configuration with heights of 26197 km (4.0 Re) and 124368 km (19.2 Re), an inclination of 89.6 degrees and an argument of perigee of 4.2 degrees, a series of four apogee raising manoeuvres and a large inclination change manoeuvre were required for each spacecraft. They were executed during the following period:

| | |
|---|---|
| from 17. to 21. July 2000 | for Cluster 2,3 |
| from 10. to 13. August 2000 | for Cluster 1,4 |

The final manoeuvres for reaching the proper constellation were performed around 26. August 2000.

The satellites were injected with an attitude close to the perigee velocity vector and an initial spin rate of 5 rpm, which was increased to about 15 rpm shortly afterwards. The attitude had to be changed several times due to the different modes of orbit manoeuvres (apogee raising with positive declination and inclination change with negative declination).

At the end of November 2000 after the wire boom deployment the spacecraft were manoeuvred into the operational attitude (close to normal to ecliptic, negative declination) with the following constraints:

| | | |
|---|---|---|
| 93.5 | < SAA | < 95.9 degrees |
| 13.5 | < Spin rate | < 16.5 rpm. |

## HISTORY OF OPERATIONS UP TO SUMMER 2007 [2] [3]

The key activity within the Flight Dynamics area is the planning and execution of the manoeuvre sequences for achieving the required constellations. Because of the orientation of the orbit in space (ascending node around 160 degrees initially) and the location of the constellation near apogee the tail crossing occurs around the autumn equinox and the cusp crossing around the spring one. Hence the manoeuvring activities fall into the following months:

May/June/July for the preparation of the tail crossing.
Nov./Dec. for the preparation of the cusp crossing.

A full constellation change manoeuvre sequence typically consists of a sequence of burns with axial oriented thrusters near apogee and perigee, and with radial thrusters within the ascending and descending part of the orbit. The entire sequence is repeated for trim purposes. In order to have a stable constellation over several orbital revolutions the satellites must all have the same orbital period.

As the angle between the spin axis of the satellite and the Sun direction has to be slightly above 90 degrees, attitude slews are required about every 3 months. In some cases a subsequent orbit correction manoeuvre is needed as the applied $\Delta v$ compensation mode has still some residual effects on the orbit.

In addition to these manoeuvre activities routine monitoring of orbit and attitude (including generation star mapper commands) is performed.

The Cluster operations have been carried out successfully at ESOC for the past 7 years. The nominal mission lasted up to end 2003. In Febr. 2002 an extension of the Cluster mission (up to end 2005) was approved together with the increase in data coverage which implied the use of a second ground station (see Table 2). In Febr. 2005 a second extension of the Cluster mission (2 times 2 years, i.e. up to end 2009) was approved. However, the subsequent description of the operations is not broken down according to mission extension phases but primarily to tetrahedra set-up, see Table 1 as well as Figure 1.

a) Two tetrahedra, twice per year

At the beginning of the mission dedicated constellations were established for the dayside cusp crossing and for the nightside tail crossing. In between a full constellation manoeuvre sequence had to be performed. The strategy for the year 2001 is shown in Figure 2 and Figure 3. For the cusp crossing period two tetrahedra were put at the north and the south cusp with true anomalies of 131 and 228 degrees, respectively, see Figure 4. Analogue to the cusp methodology the two tetrahedra for the tail were established at true anomalies of 170 and 190 degrees, see Figure 5. At the two regular tetrahedra all lines go through one common intersection point. Obviously the formation is degrading to elongated tetrahedra at other parts of the orbit.

**Table 1 Summary of constellations**

| Const. no. | Manoeuvre Period | Constellation Type: Regular Tetrahedron | Multiscale | ΔPos(3,4) |
|---|---|---|---|---|
| **a)** | **Two tetrahedra, twice per year** | | | |
| 1 | -> 01.Dec. 2000 | March 2001 cusp 600 km | | |
| 2 | 10.May -> 05.June 2001 | Sept. 2001 tail 2000 km | | |
| 3 | 06.Jan. -> 08.Febr.2002 | March 2002 cusp 100 km | | |
| **b)** | **Two tetrahedra, once per year** | | | |
| 4 | 16.June -> 22.July 2002 | Sept. 2002 tail 3810 km<br>March 2003 cusp 5000 km | | |
| 5 | 04.June -> 12.July 2003 | Sept. 2003 tail 200 km<br>March 2004 cusp 261 km | | |
| 6 | 02.May -> 20.June 2004 | Sept. 2004 tail 1000 km<br>March 2005 cusp 1280 km | | |
| **c)** | **Phasing strategy, twice per year** | | | |
| 7 | 26.May -> 06.July 2005 | | Sept. 2005 tail | 1200 km |
| 8 | 02.Nov. -> 19.Nov. 2005 | March 2006 cusp 9300 km | | |
| 9 | 19.May -> 28.June 2006 | Sept. 2006 tail 9960 km | | |
| 10 | 01.Nov. -> 07.Dec. 2006 | | March 2007 cusp | 650 km |
| 11 | 24.May -> 04.July 2007 | | Sept. 2007 tail | 40 km |

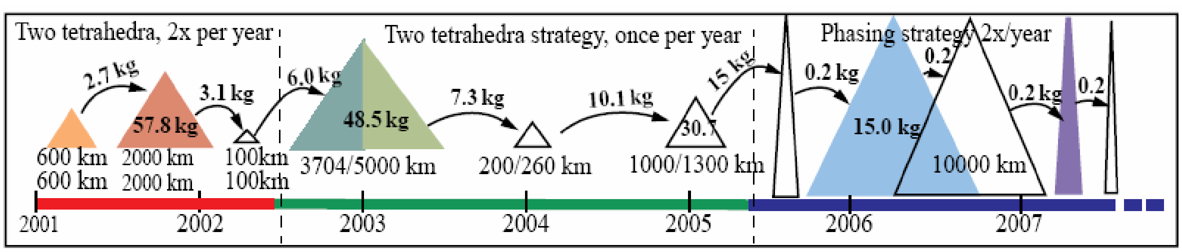


**Figure 1 Overview of constellations**

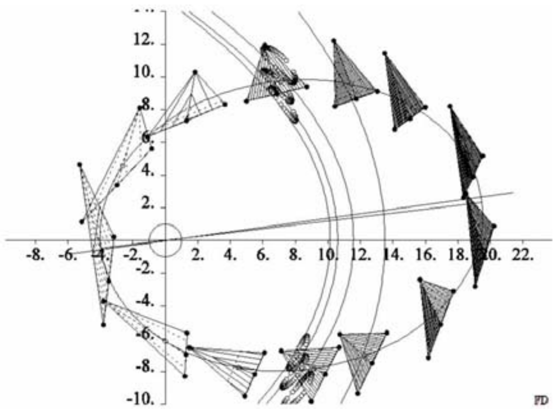


**Figure 2 Cusp crossing constellation March 2001**

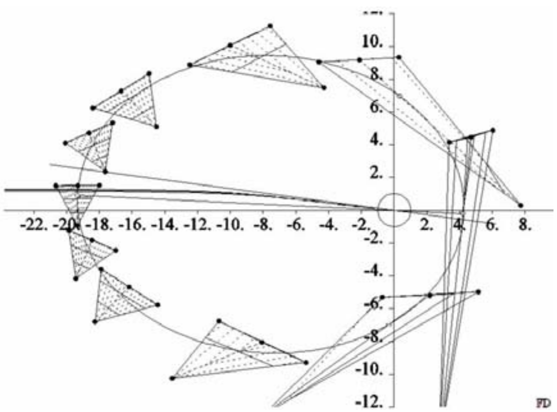


**Figure 3 Tail crossing constellation Sept. 2001**

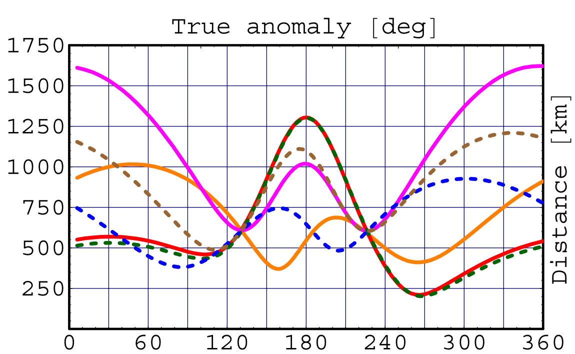


**Figure 4 S/C interdistance plots. March 2001**

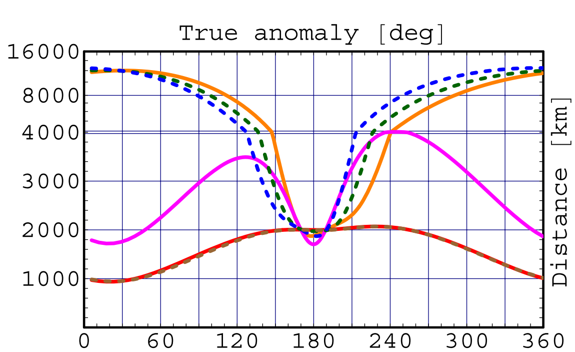


**Figure 5 S/C interdistance plots. Sept. 2001**

b) Two tetrahedra, once per year

Already half a year before the end of the nominal mission the constellation strategy was changed for reasons of fuel saving. The compromise was to focus on the northern cusp only and to give up the southern cusp one. This tetrahedron was instead placed at the orbit position of the tail crossing. Since the positions of the tetrahedra are quite different w.r.t. the symmetry axis of the orbit (true anomalies of 128 and 170 degrees, see Figure 6) the ratio of the sizes of the two tetrahedra became 5000:3704.

Giving up the perfect tetrahedron around the southern cusp was eased by the fact that the perturbing forces lead to a natural drift (increase in argument of perigee) which moved the orbit into less interesting regions exterior to the south cusp. The drift in argument of perigee of nearly one year was corrected in summer 2004 which explains the higher fuel consumption of 10.1 kg in 2004 for the moderate change of the tetrahedron size from 200 to 1000 km (see Figure 1).

Another advantage of saving one constellation change per year was the increase of the science return since the instruments have to be switched off for a while around each manoeuvre during the 4-6 weeks of the constellation change.

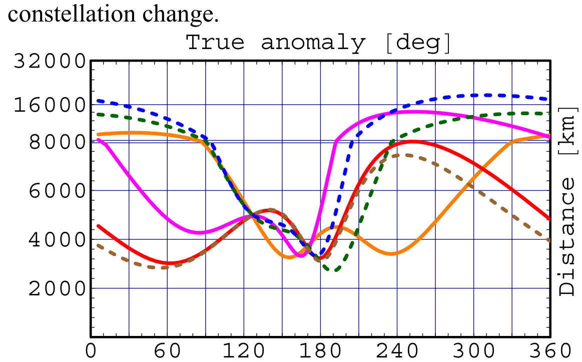


**Figure 6 S/C interdistance plots. Sept. 2002**

c) Phasing strategy, twice per year

Due to the uniqueness of the Cluster mission there has been a big interest by the scientists to achieve another extension of the mission. Four requirements could be mentioned for the new constellations: large tetrahedron (10000 km) for the cusp crossing 2005, lifetime extension until beginning of 2010, possibility to form multi-scale constellations and keeping enough fuel for orbit and attitude maintenance. Multi-scale configuration is a constellation where two satellites (S/C 3 and 4) are close together (less than 1000 km) and form a triangle (10000 km) with the remaining two satellites within the surface of interest. Fortunately, for that new extension period (2 times 2 years) the desired orbital position of the tetrahedron is almost identical for the dayside crossing of the bowshock/magnetopause and for the nightside crossing of the tail half a year later. A very interesting possibility is the phasing of the satellites (primarily intermediate changes in semi-major axis). Satellites 3 and 4 were put into almost identical orbits such that they can be phased to any desired distance. However, special attention had to be paid for the 40 km separation case for reasons of collision exclusion. A strategy has been chosen where the satellites have all around the orbit either a radial or an out of orbital plane separation such that the margin against collision due to any $\Delta v$ is above 20 cm/s. This figure is one order of magnitude higher than the observed unplanned velocity increases resulting from outgassing after cracking of batteries. The phasing of the other two satellites is done in such a way that three satellites cross a certain surface at the same time. Several alternations between tetrahedron and multi-scale constellation have been established so far as listed in Table 1 above.

Table 2 provides some additional information concerning the orbit evolution (Cluster 1 taken as example) and the station usage.

## CONSTELLATION CHANGE IN NOV./DEC. 2007

The goal of the upcoming constellation change manoeuvre sequence in Nov./Dec. 2007 is manifold. Apart from establishing the cusp constellation for March 2008 the major goal was the reduction of eclipses, i.e the number of individual eclipses and duration of overall eclipse season for the remaining two years of the extended mission. In addition the lifetime of Cluster 2 was desired to be extended in order to extend the operations to end of 2010. The current situation concerning remaining fuel, battery status and perigee height evolution is given below in Table 3.

The following aspects had to be taken into account for the optimisation of the manoeuvre sequence:

- Eclipses:

  As already mentioned above the major goal of this constellation change was to reduce the number of eclipses during 2008 and 2009. Detailed studies were done on the relation between perigee height and number of eclipses. The prime results are listed below in Table 4. In fact the table is based on an eccentricity change only, i.e. the apogee height is reduced by the same amount as the perigee height is increased. It was also checked whether the apogee height could be left unchanged. This would mean an increase of the orbital period by 1.2 hours (from 57.1 to 58.3 hours). The influence on the ground based observations would be minor as the obtained average distribution of visibility from Earth is comparable. However, it had to be rejected due to a less favourable evolution of the orbital elements over the remaining two years which would lead to 4-5 eclipses more on S/C 1, 3 and 4. The major

**Table 2 Cluster 1 orbit evolution and station allocation**

| Const. no. | Date | Cluster 1 Orbital Parameters | | | | | Station Allocation | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $h_p$ | $h_a$ | $i$ | $\Omega$ | $\omega$ | Maspa-lomas | Villa-franca | Perth |
| 1 | 2000/12/01 | 18050 | 119730 | 89.5 | 161.2 | 359.2 | | 1,2,3,4 | |
| 2 | 2001/06/05 | 20710 | 117090 | 88.9 | 161.9 | 2.6 | | 1,2,3,4 | |
| 3 | 2002/02/08 | 21410 | 116320 | 89.1 | 162.6 | 7.6 | | 1,2,3,4 | |
| 4 | 2002/07/22 | 23910 | 113860 | 90.1 | 163.6 | 10.5 | 3,4 | 1,2 | |
| 5 | 2003/07/12 | 21840 | 115890 | 88.6 | 164.4 | 17.3 | 3,4 | 1,2 | |
| 6 | 2004/06/20 | 22570 | 115200 | 89.6 | 166.4 | 19.0 | 3,4 | 1,2 | |
| 7 | 2005/07/06 | 23670 | 114100 | 93.2 | 171.9 | 22.2 | 3,4 | 1,2 | |
| 8 | 2005/11/19 | 21780 | 116020 | 93.7 | 172.8 | 24.8 | 3,4 | 1,2 | |
| 9 | 2006/06/28 | 18950 | 118850 | 95.2 | 174.8 | 27.1 | 3,4 | | 1,2 |
| 10 | 2006/12/07 | 16290 | 121530 | 96.5 | 176.5 | 28.8 | 3,4 | | 1,2 |
| 11 | 2007/07/07 | 13300 | 124640 | 99.3 | 179.4 | 30.2 | 3,4 | | 1,2 |

**Table 3 Current situation**

| | | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|---|---|---|---|---|
| **Fuel (kg)** | | 14.46 | 14.67 | 17.66 | 15.17 |
| **Oxidant (kg)** | | 26.21 | 31.73 | 36.03 | 26.42 |
| **Battery (Ah)** | | 12.4 | 34.4 | 25.3 | 37.3 |
| **Perigee height (km)** | **2008/01/01** | 10400 | 10580 | 9300 | |
| | **2009/01/01** | 5480 | 5140 | 4190 | |
| | **2010/01/01** | 2150 | 940 | 945 | |
| | **2011/01/01** | 1800 | re-entered[1] | 1100 | |

[1] In case no perigee raising would be carried out for Cluster 2, this satellite would re-enter during spring 2010.

contribution comes from the inclination which would increase by one degree more. In Autumn 2009 the inclination will reach a critical value so that a small change in combination with the low perigee height will have a significant influence on the number of eclipses.

- Lifetime:

There is a strong desire to extend the Cluster mission up to the end of 2010. Because of the gravity of the Moon the perigee height will reach a minimum during mid 2010. Although Cluster 2 has currently the highest perigee altitude compared to the other Cluster satellites, the earlier re-entry during spring 2010 is primarily caused by the orientation of the orbit, i.e. inclination and argument of perigee.

A significant perigee height increase will satisfy all three goals, reduction of individual number of eclipses, reduction of overall eclipse season and extension of lifetime, and also a reduction of radiation as a by-product.

The established manoeuvre sequence will be conducted from 30. Oct. to 13. Dec. 2007 and will consist of 32 manoeuvres in total. The orbital changes as well as the remaining fuel are listed below in Table 5.

The fuel consumption is in the order of 6 kg. The fuel reserve for Cluster 3 is higher compared to the other ones because some further additional large attitude slews are planned for that satellite for scientific reasons during 2008.

Table 6 below provides the evolution of the orbit for the next two years.

The different evolution of the individual Cluster orbits will obviously degrade the constellation. The separation between the orbits is given in Figure 7 and Figure 8 below. The separation between the orbits is expressed as distances of the S/C as they would be if one could remove the along track differences of the S/C all around the orbit. Only the true anomaly interval from 100 to 180 degrees is shown as the observations of the cusp and the tail are taken within that range

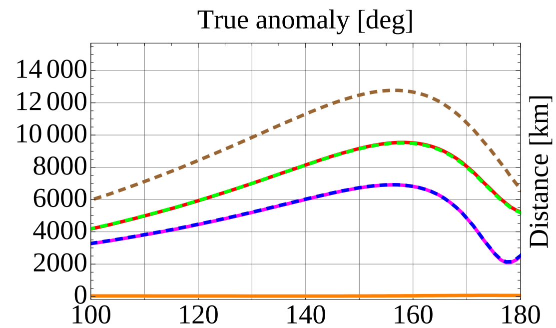


**Figure 7 Separation between orbits in Autumn 2008**

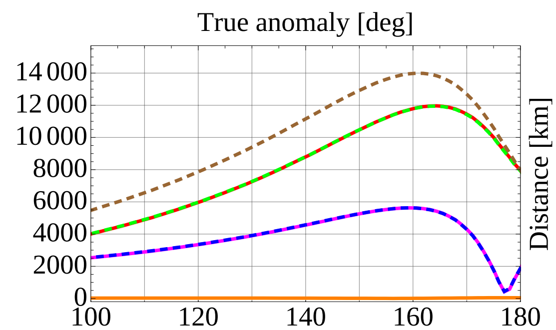


**Figure 8 Separation between orbits in Autumn 2009**

**Table 4 Number of eclipses**

| S/C | Perigee height increase on 1. Dec. 2007 | Number of revolution with eclipses | | | | |
|---|---|---|---|---|---|---|
| | | Spring 2008 | Autumn 2008 | Spring 2009 | Autumn 2009 | Sum 2008 and 2009 |
| 1 | 0 km | 26 | 7 | 41 | 29 | 103 |
| | 2188 km | 21 | 6 | 33 | 15 | 75 |
| 2 | 0 km | 23 | 6 | 39 | 14 | 82 |
| | 2263 km | 20 | 5 | 31 | 9 | 65 |
| 3/4 | 0 km | 26 | 8 | 47 | 30 | 111 |
| | 2765 km | 21 | 7 | 35 | 19 | 82 |

**Table 5 Post manoeuvre status**

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|---|---|---|---|
| **Change in $h_p$ (km)** | 2188 | 2263 | 2765 | 2765 |
| **Change in $i$ (deg)** | 0.322 | 0.428 | 0.082 | 0.074 |
| **Change in $\omega$ (deg)** | -0.653 | -1.035 | -0.972 | -0.972 |
| **Remaining fuel (kg)** | 9.4 | 9.2 | 11.3 | 9.3 |

## LONG TERM ORBIT EVOLUTION

As mentioned in the previous chapter the manoeuvre sequence in Nov./Dec. 2007 has the goal to reduce the eclipses and to extend the lifetime for Cluster 2 up to the end of 2010. In order to provide the possibility to operate the satellites into the year 2011, a further perigee raising would be required for Cluster 2. In principle this manoeuvre could already have been included in the Nov./Dec. 2007 sequence. However, it was not done for the following two reasons. First, for reasons of efficiency. The later the manoeuvre is executed the more efficient it becomes. Second, it remains to be seen, whether the necessity will arise after all the eclipses up to the end of 2010. A perigee raising manoeuvre of about 15 m/s (requiring less than 1.5 kg of fuel) is introduced around the beginning of July 2010. With this manoeuvre size the perigee height will not fall below 350 km which is required for minimizing the air drag influence.

The stability of a highly eccentric orbit is primarily determined by the evolution of the perigee altitude. The prime cause for the variation of the perigee height for the Cluster satellites comes from the gravity of the Moon, the gravity of the Sun introduces a further oscillation. The evolution of the perigee height can easily be followed with the help of the stroboscopic method [4], where the mass of the perturbing body is equally distributed along its orbit. The influence (change/revolution) of the mass ring on the orbit of the satellite can be expressed as:

$$\Delta h_p = f(a) e \sqrt{1-e^2} \sin^2 i \sin 2\omega$$

The angles of the S/C orbit inclination and argument of perigee have to be expressed in the orbital plane of the perturbing body.

Table 7 below provides the long term evolution of the orbits including the local minima of the perigee height. It should be noted, that the orbits of the satellites 3 and 4 are slightly different and will drift apart towards the end of their lifetime, however, for reasons of simplicity these differences are ignored in here. Figure 9 provides the evolution in graphical form.

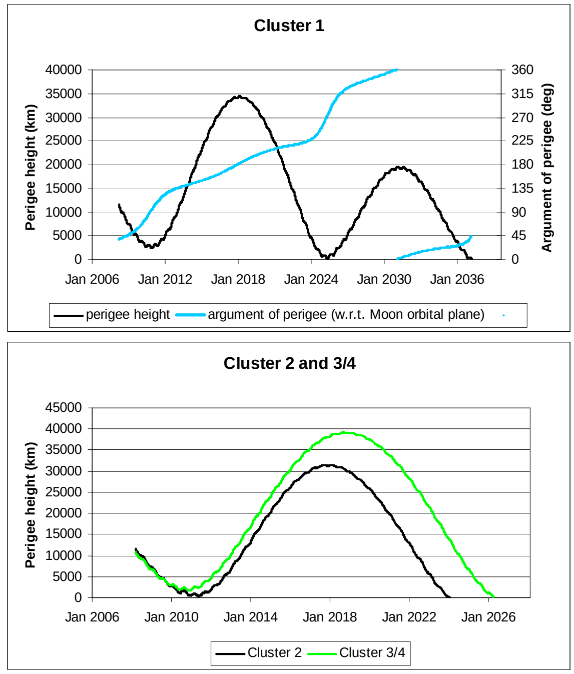


**Figure 9 Perigee height long term evolution**

**Table 6 Evolution of orbital parameters for the years 2008/2009**

| Date | Cluster 1 | | | | Cluster 2 | | | | Cluster 3/4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $h_p$ | $i$ | $\Omega$ | $\omega$ | $h_p$ | $i$ | $\Omega$ | $\omega$ | $h_p$ | $i$ | $\Omega$ | $\omega$ |
| **2008/01/01** | 12600 | 102.4 | 182.5 | 30.4 | 12820 | 96.6 | 175.2 | 29.0 | 12090 | 99.7 | 179.3 | 33.7 |
| **2008/07/01** | 9850 | 105.7 | 185.8 | 31.4 | 9920 | 99.3 | 177.8 | 29.9 | 9210 | 103.8 | 183.4 | 34.9 |
| **2009/01/01** | 7510 | 110.2 | 190.4 | 32.5 | 7300 | 103.1 | 181.4 | 30.5 | 6760 | 108.2 | 188.2 | 35.6 |
| **2009/07/01** | 5380 | 115.7 | 196.2 | 34.3 | 4840 | 107.7 | 185.9 | 31.1 | 4570 | 114.0 | 194.8 | 37.1 |
| **2010/01/01** | 3720 | 122.4 | 204.5 | 37.7 | 2690 | 113.9 | 192.6 | 32.4 | 2920 | 121.0 | 204.0 | 40.3 |

**Table 7 Long-term evolution of orbital parameters**

| Date | Cluster 1 | | | | Cluster 2 | | | | Cluster 3/4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $h_p$ | $i$ | $\Omega$ | $\omega$ | $h_p$ | $i$ | $\Omega$ | $\omega$ | $h_p$ | $i$ | $\Omega$ | $\omega$ |
| **2010/01/01** | 3720 | 122.4 | 204.5 | 37.7 | 2690 | 113.9 | 192.6 | 32.4 | 2920 | 121.0 | 204.0 | 40.3 |
| **2010/11/25** | 2400 | 136.3 | 229.7 | 54.8 | | | | | 1680 | 135.1 | 232.2 | 58.4 |
| **2010/12/20** | | | | | 490 | 130.6 | 217.0 | 45.1 | | | | |
| **2011/06/01** | | | | | 370 | 138.4 | 237.7 | 61.4 | | | | |
| **2015/01/01** | 22770 | 135.6 | 322.4 | 136.5 | 19980 | 132.4 | 324.2 | 139.6 | 23720 | 133.2 | 322.4 | 133.1 |
| **2020/01/01** | 29990 | 135.5 | 342.2 | 188.1 | 25860 | 132.3 | 341.6 | 189.0 | 37390 | 132.2 | 340.7 | 181.1 |
| **2024/12/15** | 690 | 153.5 | 73.5 | 291.3 | | | | | | | | |
| **2025/01/01** | 780 | 153.1 | 76.2 | 294.2 | | | | | 6630 | 144.5 | 9.0 | 224.3 |
| **2030/01/01** | 17390 | 99.4 | 146.2 | 359.8 | | | | | | | | |
| **2035/01/01** | 8120 | 104.6 | 160.6 | 29.7 | | | | | | | | |
| **Re-entry** | March 2037 | | | | January 2024 | | | | April 2026 | | | |

Two remarks have to be added following the figures of Table 7. Cluster 1 is an outstanding satellite within the Cluster family not only for the reason as it was re-built from spare parts following the 1996 launch but also for (a) it is the oldest satellite and has the longest lifetime and (b) it will return to an almost nominal orbit configuration in 2030 with a polar inclination and a line apsides near the equator. It should be added that the inclination will reach its maximum of 150 degrees towards the end of 2024 and its minimum of 98 degrees in the years 2030/2031.

The Cluster satellites will stay in orbit for another 20-30 years. No particular attention has to be paid concerning the collision risk as for these types of orbits the population is not dense. However, the satellites will cross the geostationary ring (42164 ± 100 km). Figure 10 provides the distances at ascending and descending node crossings.

All the crossings, except those in 2016/2020, will actually occur within 1-2 revolutions, hence the risk is very low.

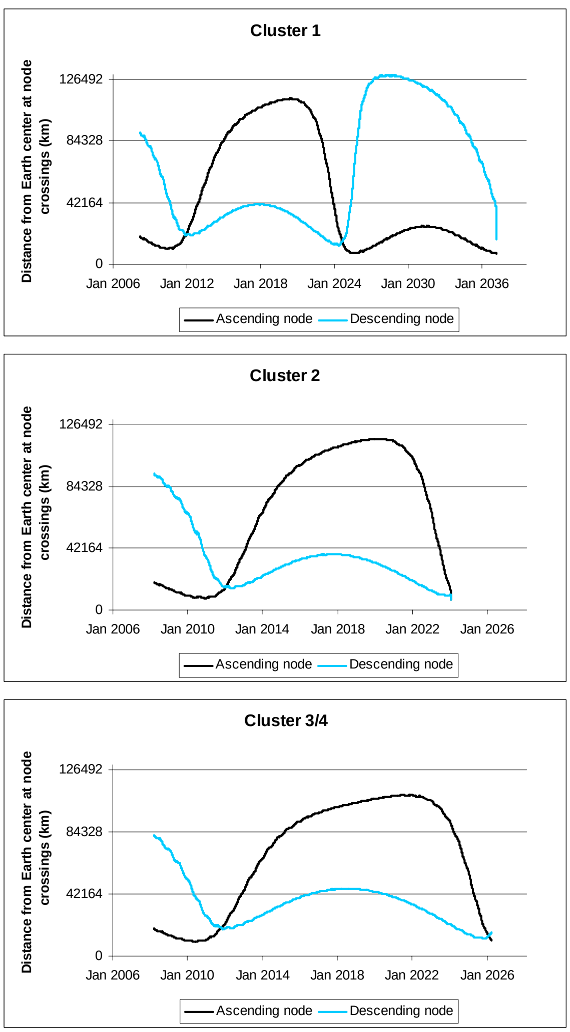


**Figure 10 Distance from Earth centre at node crossings**

During the period 2016/2020 the descending node crossing will approach the geostationary ring from inside. There is no problem at all for Cluster 1 and 2 as the maximum distances from Earth are 41100 km (Febr. 2018) and 38200 km (Aug. 2017), respectively. However, Cluster 3 and 4 will cross the geostationary ring, in July 2016 (upwards) and in July 2020 (downwards), the maximum distances will be 45800 km (Sept. 2018). As the slope is not so steep as compared to the other crossings, the passing through the geostationary ring will last about 4-6 revolutions, which is still not considered critical.

## SELECTING END-OF-LIFE ATTITUDE

The change in spin direction for cluster is mainly caused by the gravity gradient. The gravity gradient torque for a spinning satellite averaging over one orbit and assuming a spherical Earth is given in [5] (eqn. 17-44).

From that equation it can be seen that the spin axis will drift on a cone around the orbit normal. Comparing determined attitude drift for a three-month period between attitude manoeuvres has shown good agreement with the prediction using the equation hence confirming that the gravity gradient is the main disturbance torque for cluster spin axis.

The above method has been used to predict the spin axis movement during the last 14 years from around the end of nominal operations in 2010 to the re-entry time of the first spacecraft in 2025. Figure 11 shows the movement of the orbital normal (dashed blue) during this period in a frame with the ecliptic plane having $\phi$=0 and with the ecliptic South Pole located at $(\phi,\theta)$=(90, 0) degree.

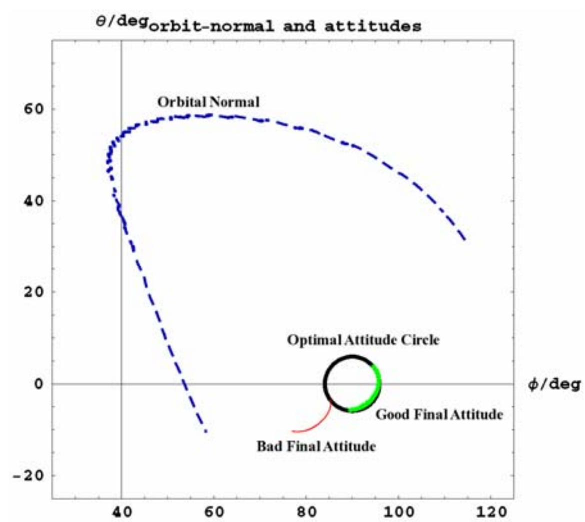


**Figure 11 Orbit normal and attitude paths**

The thick black circle is all the optimal attitudes for spacecraft 1, 2 and 4 being tilted by 5.9 degree from the ecliptic south. An optimal attitude is in this respect an attitude which ensures that the angle between the spin axis and the spacecraft-to-sun direction is staying between 93.5 and 95.9 degree for about a three month period. The thick green and thin red curves show the attitude drift of two examples of such initially optimal attitude selected for respectively 2010/07/01 and 2011/01/01. Both attitudes move on a curved path caused by the orbit-normal motion around the ecliptic South Pole. All other optimal attitudes have similar drift patterns since the distance between the attitudes is small compared to the distance to the orbit-normal. What can be observed from Figure 11 is that the motion of the thick green attitude profile nearly overlaps part of the optimal attitude circle while the thin red attitude profile drift further away from the ecliptic South Pole. This means that the resulting angle between the spin axis and the sun (the solar aspect angle, SAA) in the thick green case stays closer to the nominal range, which is between 93.5 and 95.9 degree. However, since the attitude drift is very slow (period >>1 year) the SAA will be in the entire range 90±tilt-angle in degree. The consequence is that it is nor possible to avoid time intervals where the booms and spacecraft will shadow each other (SAA in interval 90±3.2 degree) neither to avoid illumination of the top of the spacecraft (SAA<90 degree), but it is indeed possible to choose an end-of-life attitude that results in a decade long attitude profile (thick green) with solar aspect angle in a semi-nominal range near 90±6 degree. This will hence ensure the power supply and a near nominal thermal condition. In that respect the thick green and thin red curves in Figure 11 represent near best and worst case attitudes and their predicted solar aspect angles between 2011 and 2025 can be seen in Figure 12. It shows that the thick green curve is never more than approximately 6 degree from the 90 degree, while the thin red curve is up to about 15 degree away.

Further optimisation of the final end-of-life attitude will be depending on exact trade-offs between experimental and operational requirements and on the required duration in which the SAA has to stay within the defined limits.

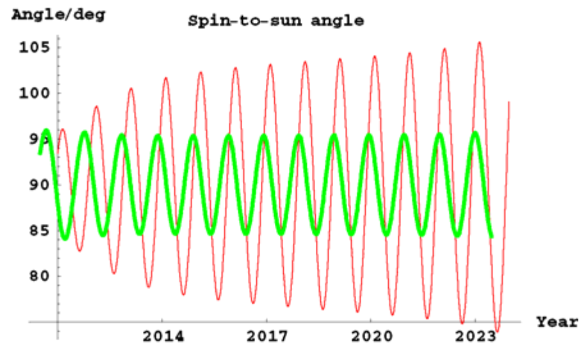

**Figure 12 Solar aspect angle development**

## ENVISAGED END-OF-LIFE ACTIVITIES

The end-of-life activities cannot be specified in a precise manner as there are a few uncertainties concerning the actual end of the mission and hence the remaining fuel. For the considerations in here a continuation of the operations and an end of mission around mid 2011 has been assumed, by that time the power provided by the solar arrays reduces to 200 W level which is the minimum power required to operate the payload. Based on that supposition the derivation of the remaining fuel for mid 2011 is given in Table 8.

Two points should be noted. First, there is more oxidant available than required. Second, a fuel uncertainty of about 3.0 kg has to be taken into consideration, which represents about 1.2% of the initial fuel of about 400 kg at launch. Hence the remaining fuel for Cluster 2 could be very low.

**Table 8 Remaining fuel for mid 2011 (kg)**

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|---|---|---|---|---|
| **Remaining fuel on Jan 2008** | 9.4 | 9.2 | 11.3 | 9.3 |
| **Remaining oxidant on Jan 2008** | 18.4 | 23.3 | 26.3 | 17.3 |
| **Required oxidant on Jan 2008** | 14.5 | 14.2 | 17.3 | 14.4 |
| | | | | |
| **Orbit and attitude maintenance** (see Table 9) | 4.0 | 4.0 | 4.0 | 4.0 |
| **Special attitude slews during 2008** | | | 1.5 | |
| **Orbit correction during 2010** | | 1.5 | | |
| | | | | |
| **Remaining fuel around mid 2011** | 5.4 | 3.7 | 5.8 | 5.3 |

**Table 9 Fuel requirements for standard orbit and attitude maintenance (kg)**

| | Attitude (0.1 kg/man) | Orbit (0.2 kg/man) | Total |
|---|---|---|---|
| **2008** | 0.5 | 0.5 | 4.0 |
| **2009** | 0.6 | 0.5 | |
| **2010** | 0.7 | 0.5 | |
| **Half of 2011** | 0.4 | 0.3 | |

In general, the following end-of-life activities could be envisaged from a Flight Dynamics point of view:

- Reduce Cluster 1 lifetime:
  In order to advance the re-entry date from 2037 to 2025/2026 a perigee lowering manoeuvre would be needed requiring a $\Delta v$ of about 65 m/s corresponding to 6 kg of fuel. This is slightly higher than the fuel book keeping figure.

- Re-entry of Cluster 2 in June 2011:
  The minimum perigee height of 370 km will be reached at the beginning of June 2011. The re-entry cannot be initiated later when the perigee height will increase again.

- Increase separation between Cluster 3 and 4:
  Currently Cluster 3 and 4 have almost the same orbit. In order to avoid any collision an increase of the separation between the planes and the phases could be carried out.

- Crossing of geostationary ring:
  During the period 2016 to 2020 some crossings of the geostationary ring with lower slopes will occur. The remaining fuel could be used to improve the situation, either to remove the crossing or to increase the slope which reduces the duration of the individual crossing.

Considering the various options the sequence of activities could be envisaged:

- Slew to end-of-life attitude and keep the spin rate.

- Deplete the remaining fuel according to the passivation procedures. The depletion should be combined with some of the orbit aspects mentioned above. With the measurable effects on the orbit the fuel book keeping can be verified. As this activity should be carried out in steps sufficient time should be allocated for the entire activity.

Of course, a detailed breakdown of the individual tasks would have to be done nearer to the end-of-mission event when remaining fuel and intentions are better known.

## ORBITAL ELEMENT ACRONYMS

| | |
|---|---|
| $a$ | semimajor axis |
| $e$ | eccentricity |
| $i$ | inclination |
| $\Omega$ | right ascension of the ascending node |
| $\omega$ | argument of perigee |
| $h_p$ | perigee height |
| $h_a$ | apogee height |

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