EUROSTAR 2000 DISPOSAL ON A GRAVEYARD ORBIT: ORBIT CONTROL STRATEGY AND OPERATIONAL IMPLEMENTATION

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ABSTRACT

In agreement with the Inter-Agency Space Debris Coordination Committee recommendations, some EADS ASTRIUM spacecraft have been recently disposed of on a graveyard orbit at the end of their operational life.

This paper presents in details the rationale of the operations design from a Flight Dynamics standpoint.

The sequence of orbital manoeuvres was selected so as to achieve the highest possible graveyard orbit, while fulfilling a set of constraints relating to different domains: AOCS (Attitude and Orbit Control System), propulsion, operational workload, orbital events, ground station link availability.

One challenge was to maximize the chance of reaching the final target orbit, in spite of the decreasing probability level, as tanks are getting close to empty, to be able to realize the full amplitude and efficiency of the programmed thruster burns.

A recent example of such operations with a EUROSTAR 2000 geostationary satellite is described in this paper, based on in-orbit data.

1. POST-MISSION OPERATIONS : THE INTERNATIONAL RECOMMENDATIONS

1.1 The Inter-Agency Space Debris Coordination Committee (IADC) recommendations (2002)

Two specific regions of outer space are of particular interest for space missions and must be protected :

- the Low Earth Orbit (or LEO) Region, a spherical region that extends from the Earth's surface up to an altitude of 2 000 km
- the Geosynchronous (GEO) Region, a segment of the spherical shell defined by the following:
- $Z_{GEO} - 200$ *km* $\leq$ *altitude* $\leq Z_{GEO} + 200$ *km*
- *-15 degrees* $\leq$ *latitude* $\leq$ *+15 degrees*

with Z_{GEO} = geostationary altitude = 35 786 km

IADC provided recommendations to operators of existing space systems for post-mission disposal : all on-board sources of stored energy of a space system, (residual propellants, pressurant, batteries, payload, …) should be depleted or saved when they are no longer required.

For the GEO region**,** so as not to cause interference with space systems still in GEO orbit and not to bother the Geosynchronous Transfer Orbits, it is recommended to increase the perigee altitude Zp at the end of re-orbiting till a minimum value that ensures no descent of the space-system below the upper altitude of the protected region (Z_{GEO} + *200 km*) under the effects of the main perturbations :

- the luni-solar and geopotential perturbations; their impact shall be accounted for through an allocation of a 35 km margin (upper altitude becomes then Z_{GEO} + *235 km*),
- the solar radiation pressure, impacting the orbit eccentricity; when the eccentricity at the end of the post-mission operations is null, its impact may be bounded by $1000 \cdot C_R \cdot A/m$ (where C_R is the Solar radiation pressure coefficient, and A/m the aspect area to dry mass ratio).

Remaining propellant estimations before EOL shall enable reaching this objective with a 99 % probability.

Two terms "*re*-orbitation" and "*de*-orbitation" are introduced later on : they mean that the satellite is respectively above and below the geostationary orbit.

For the LEO Region, spacecraft should be either de-orbited (direct re-entry) or manoeuvred into an orbit where lifetime is limited to 25 years under the main effect of the atmospheric drag.

1.2 Application to Eurostar 2000 re-orbitation

The Eurostar 2000 spacecraft considered in this paper has achieved more than 10 years of its telecommunication mission. A re-orbitation was decided according to the remaining propellant in tanks, although

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the platform was still fully operational. The provision for the re-orbitation, decided before launch and considered for the operations, was a tangential delta-V (DVt) of 6 m/s with an estimated probability higher than 99%.

This enables an increase of the perigee altitude at EOL of 165 km if a null eccentricity is targeted. This is below the recommended altitude of Z_{GEO}+200 km, without even considering the impact of the different perturbations. The available DVt at 99% was thus a limiting point to fulfil the IADC recommendations. The main adapted objectives set for the re-orbitation were therefore :

- To maximise the perigee altitude by selecting an elliptic graveyard orbit with an optimised eccentricity,
- To passivate battery on a long-term basis,
- To definitively switch the satellite off and prevent any future radio-frequency emission and hinders with other satellites.

2. SELECTION OF THE GRAVEYARD ORBIT

2.1 Orbit raising targeting a null eccentricity

To perform the orbit-raising from the on-station position to the graveyard orbit, a <u>first approach</u> consists in increasing the perigee altitude at EOL till its maximum value by means of the available amount of DVt. Perigee altitude is given by: $Zp = a\,(1-e) - r_E$, a being the semi-major axis, e the eccentricity and r_E the Earth radius. Increasing Zp in an optimal way means getting a larger and larger till its EOL value a_{EOL}, while keeping e close to zero.

In this approach, a *circular* graveyard orbit shall thus be selected. However, the eccentricity vector $\vec{E} = (e_x, e_y)$ (vector with modulus equal to the eccentricity and argument equal to the direction of the Earth-perigee in the inertial frame) evolves in time, due to the solar radiation pressure (Fig. 1.). It remains roughly on a circle of radius $Er = 0.0115 \cdot A/m$ in a one-year periodic motion (Fig. 2). The centre of circle C is such that $\overrightarrow{CE} = Er \cdot \vec{u}_{Earth \rightarrow Sun}$ where $\vec{u}_{Earth \rightarrow Sun}$ is the unit vector in the Earth→Sun orientation (hence function of the epoch).

Consequently, targeting the null eccentricity vector at EOL leads 6 months later to an eccentricity of $2 \cdot Er$ (Fig. 2). This induces a descent of the perigee altitude of $a_{EOL} \cdot 2 \cdot Er \sim 975 \cdot C_R \cdot A/m$, matching the value $1000 \cdot C_R \cdot A/m$ proposed in the IADC formulation. In this first approach, IADC recommended perigee altitude at EOL is 235 + $1000 \cdot C_R \cdot A/m$ = 285 km, requiring a DVt of <u>10.4 m/s</u>.

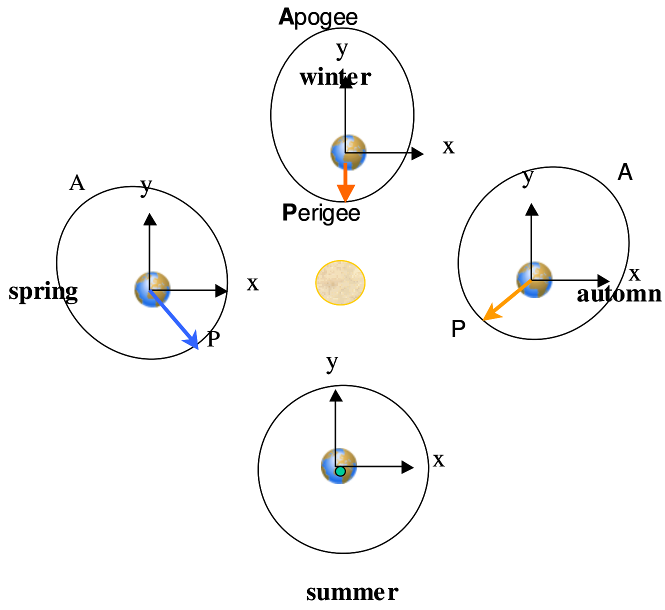

Figure 1. Perigee evolution during one year

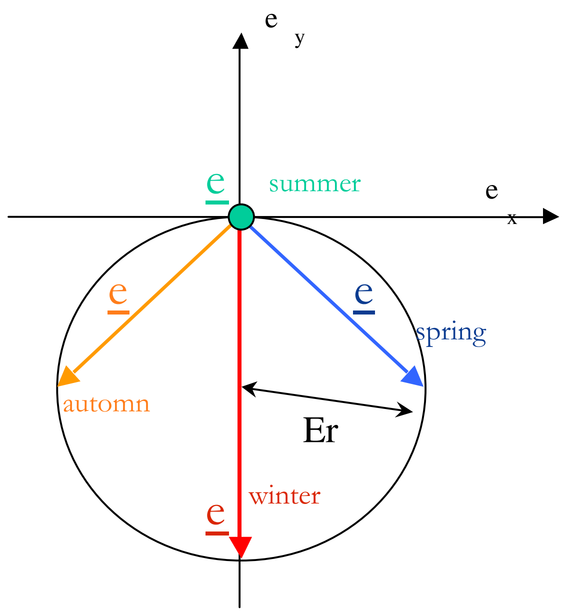

Figure 2. Eccentricity vector evolution during one year

2.2 Optimisation of the target in eccentricity

A <u>second approach</u> consists in anticipating the impact on the perigee altitude of the solar radiation pressure by targeting the eccentricity vector at EOL such as its evolution over one year fits the natural eccentricity circle centred on zero.

The orbit perigee remains Sun pointed (Fig. 3) mainly due to the solar radiation pressure, the eccentricity vector follows the natural circle and the eccentricity is quite stable (Fig. 4.).

With such a strategy, the perigee altitude is now stable regarding the solar radiation pressure and defined by $a_{EOL}(1-Er)-r_E$. The graveyard orbit is slightly *elliptic*.

In this second approach, the perigee increase constraint becomes *Zp > 200 + 35 km* to cope with only the luni-solar and geopotential perturbations. This 235 km threshold is reachable with a DVt of 9.5 m/s. The second approach is less demanding regarding the propellant consumption. It was thus preferred.

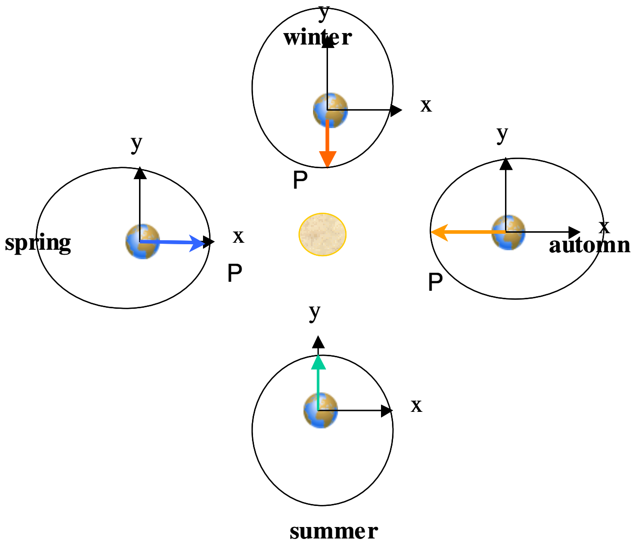

Figure 3. Perigee evolution during one year

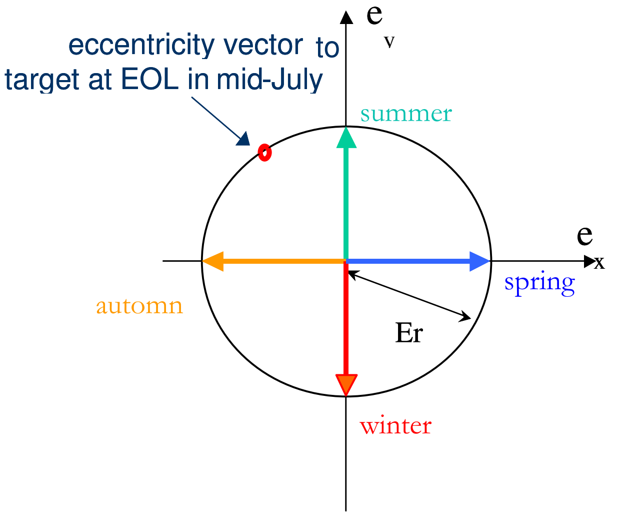

Figure 4. Eccentricity vector evolution during one year

The selected manoeuvre plan consists in performing orbit control manoeuvres in Station-Keeping Manoeuvre mode (also called SKM) with thruster 4 to achieve positive DVt (Fig. 6) and thus increase the semi-major axis ($\Delta a \sim 27.425 \cdot \Delta Vt$, with Δa in km) while controlling the eccentricity vector around the optimised target in eccentricity (Fig. 7).

3. THE EUROSTAR 2000 RE-ORBITATION

3.1 The Eurostar 2000 platform

The ASTRIUM Eurostar 2000 platform features an AOCS based on a so called "0 Degree of Freedom" onboard angular momentum stabilization: an on-board momentum wheel provides stability to the spacecraft and is also used for pitch control. The attitude is controlled using solar arrays (Astrium patented Solar Sailing (SOSA) concept) and bi-liquid thrusters. The sensors used in the control loop are the spacecraft body mounted Earth sensors, the gyroscopes and the Sun sensors mounted on the Solar Arrays (SA).

Figure 5. Eurostar 2000 platform, artist view

3.2 Orbital manœuvre sequence

The sequence of orbital manoeuvres was selected so as to fulfil a set of constraints relating to different domains: AOCS (no Earth sensor blinding during manoeuvres – sensor used for Earth pointing -, no eclipses during operations – Sun pointing required in safe mode -), propulsion (limitation on the thrust duration to avoid emptying the propellant management device, 3 hours minimum between two consecutive manoeuvres to fill it up again), mission, Telemetry/Telecommands (TM/TC) link, ground crew workload management.

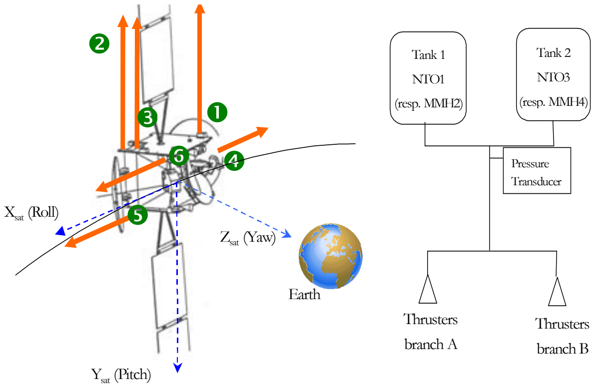

Figure 6. (left) satellite in Earth-pointed attitude, (right) liquid feedlines for a pair of tanks (NTOx or MMHy)

The manoeuvre plan was then divided into 2 parts :

- a *deterministic phase* defined as the phase whose probability was greater than 99% to have enough propellant to perform the orbit control manoeuvres (no bubbles in the propellant lines). The orbit control manoeuvres to increase perigee altitude are performed at high pace : series of 4 orbit control manoeuvres per day, regularly spaced out to turn around the target in eccentricity (Fig. 7),
- a *random phase* where probability to ingest bubbles is higher. Series of 2 orbit control manoeuvres per day are foreseen to maximise the chance of crossing the final target in eccentricity in case of sudden unexpected stop of operations (Fig. 7).

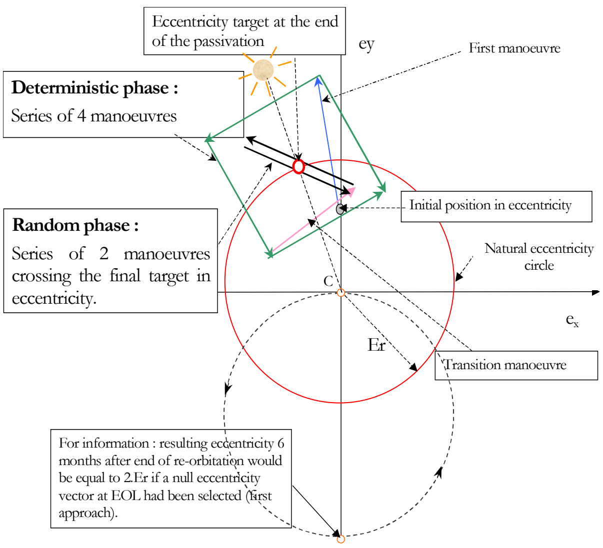

Figure 7. Manoeuvre sequence and strategy for control in eccentricity

3.3 Re-orbitation sequence

The re-orbitation operations (Fig. 8) are divided into 3 parts:

- *Preparation phase* - After the payload switch-off, a specific thermal configuration is set, on one hand to maintain the TM/TC and AOCS equipments at operational temperature, on the other hand to decrease the tank temperature to condensate the vapour and to maximise the available propellant in liquid phase.
- *Orbit raising* – The manoeuvre plan is achieved and reviewed in real-time as function of events. For one propellant (NTO or MMH). The tank the most likely full is used in order to delay as much as possible the potential ingestion of bubbles.
- *Electrical passivation* - This operation starts either in emergency mode after loss of attitude due to bubbles in the lines or from a ground action in Earth pointed attitude. This phase has two aims: the battery passivation and the switch-off of the satellite.

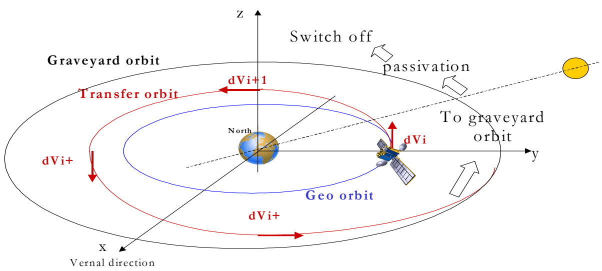

Figure 8. Re-orbitation sequence

4. AOCS STRATEGY FOR ORBIT RAISING

4.1 AOCS objectives

At AOCS level, objectives were the followings :

- To adapt the Station-Keeping Manoeuvre mode to End of Life configuration so that it can support in particular wheel off-loading and orbital oscillator updating (operations usually performed during inclination corrections), in different thrust modes : pulsed or continuous (see below).
- To try to keep the Earth pointing attitude as long as possible to enable to shut down equipment from ground (availability of TM/TC); and to ensure a safe behaviour of the AOCS during orbit raising despite erratic behaviour of thrusters as tank ran out of fuel, with bubbles appearance.
- To define a strict sequence for AOCS switch-off to prevent from self restart hazards, in particular trying to set an on-board automatic AOCS switch-off sequence robust to any loss of attitude or TM/TC link.

From the existing design, new functions have been developed to accommodate theses objectives, as well as others (using the available memory space for additional software...).

4.2 Fixed Momentum Wheel off-loading

The orbit control manoeuvres are long and can create some deposit of ice and un-burn propellant on the reflector in front of one of the thruster (#4). When the reflector is illuminated by the Sun, a sublimation phenomenon takes place and creates a pitch torque that is compensated by the wheel.

Based on in-flight observations, wheel variation due to sublimation was predicted (-14.1 Nms) and a strategy of wheel off-loading in Station-Keeping Manoeuvre mode was elaborated.

4.3 Orbital Oscillator Updating

During re-orbitation, semi-major axis increase induces a decrease of the orbital angular frequency. Solar Array rotation is controlled at orbital frequency, as computed on-board by the orbital oscillator.

Analyses showed it was better to take into account the longitude drift for the orbital oscillator to have correct orbital period on-board and keep Solar Arrays Sun pointed.

4.4 Earth sensor performance

When altitude increases, the Earth radius seen by the Earth sensor decreases. This can alter the computation, based on the Earth↔space transitions, of roll and pitch measurements. Analyses showed it was worthless to calibrate the Earth Sensor with altitude since its performances were only marginally affected.

4.5 Selection of the thrust mode

Two thrusters control modes are available:

- The so-called continuous mode ; spreading a set of small burns over a long time interval.
- The so-called pulsed mode using a single pulse over a control period.

On-station, orbit control manoeuvres were performed in continuous mode, with N=3 and duty-cycle α=20% (Fig. 9). During the deterministic phase of the re-orbitation, a pulsed mode was proposed since more efficient in terms of ratio DVt /used propellant. This efficiency is improved because actuation time t_{on} are longer (Fig. 10).

However, the pulsed mode introduces a delay in the control chain, inducing a low gain (K) on the 3 axes. This can degrade the pointing performance.

To maintain a sufficient attitude control performance in pulsed mode, the duty-cycle α was chosen low enough (13%), according to relationship :

$$\text{depointing} \sim \frac{\alpha . C_{pert}}{K} \qquad (1)$$

where C_{pert} is the error on the prediction of the perturbing torques.

In the random phase, gains must be higher to get a reactive control able to restore the proper attitude in case of bubbles appearance; a continuous mode was hence used.

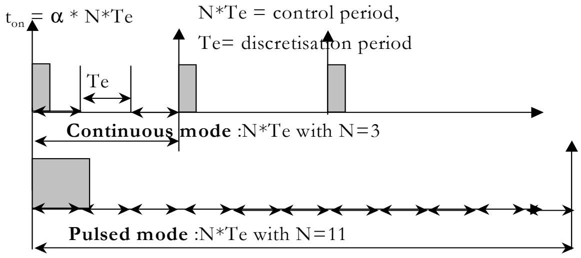

Figure 9. Thrust modes, continuous and pulsed

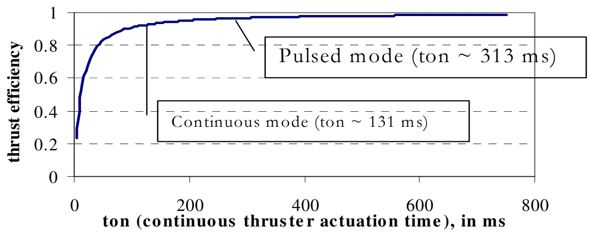

Figure 10. Thrust efficiency as function of actuation time

4.6 Earth pointing

To keep Earth pointing as long as possible, it was proposed first to limit the risk of on-board anomaly detection by relaxing the monitoring of attitude (thresholds increased on Earth sensors, on gyro monitoring, …) then to implement a process that allows to keep Earth pointing while bubbles appear in the lines.

4.7 Contingency cases

An on-board AOCS process would automatically switch the satellite off a few hours after a loss of attitude and a loss of TC link.

5. OPERATIONS

Actual flight operations occurred from the 19th of June to the 24th of July 2003. At the end of the thermal configuration (7th of July), temperatures of the AOCS equipments were still within operational range. 19 orbit control manoeuvres were carried out.

5.1 The deterministic phase

The deterministic phase included 13 manoeuvres, all performed with enlarged monitoring thresholds, in branch B, with tanks MMH4 coupled with NTO 1 and NTO 3 alternatively, in pulsed mode. Only ORBIT CONTROL MANOEUVRE #13 was a continuous one. All orbital control manoeuvres were performed nominally with correct pointing performances (depointing lower than 0.25 deg on each axis).

5.2 The random phase

During the random phase, the continuous mode (N=3) was used with a duty cycle α=20%. Pointing performances were correct. Two tanks were emptied : MMH2 was emptied after orbit control manoeuvre #17, MMH4 after orbit control manoeuvre #19.

At the end of orbit control manoeuvre #19, the eccentricity vector was reaching the target. An additional manoeuvre could have lead to a loss of attitude, and was not very interesting in terms of perigee altitude increase (the gain in semi-major axis would have been compensated by an eccentricity vector more distant from its target). Start of passivation was hence decided.

5.3 AOCS management

Fixed Momentum Wheel off-loading management. To prevent too large pitch depointing due to wheel off-loading at the beginning of the pulsed orbit control manoeuvres, off-loading was realised over a manoeuvres series. Observed wheel variation was –8.2 Nms to be compared to a –14.1 Nms predicted level. A good pointing behaviour during manoeuvres was observed (less than 0.25 deg of depointing).

SOSA & Oscillator Update. The orbital oscillator was regularly updated during the orbit control manoeuvres. Pointing performances in SOSA were correct.

Final AOCS switch off. As the spacecraft was still Earth pointed after the electrical passivation, the AOCS switch-off was performed from the ground. Thanks to the TM/TC link availability, the switch-off was confirmed by observations.

5.4 Anomaly

During orbit control manoeuvre #18, an anomaly was detected on the thrusters actuation monitoring. The emergency control mode succeeded in keeping the Earth pointing.

The explanation for the anomaly was that some bubbles were still present in lines after orbit control manoeuvre #17, inducing transient lacks of thrust. Then the AOCS, as attitude change was too small, commanded greater actuations than the expected ones leading to overcome the monitoring threshold on "thrusters on" time duration.

6. CONCLUSION

At the end of passivation, the perigee altitude was 243.5 km above the geosynchronous altitude Z_{GEO} ; it was achieved with a tangential delta-V of 9.79 m/s. This achieved DVt is above the original target of 6 m/s at 99% probability. This was made possible thanks to the extra fuel provision made to conservatively cover the uncertainty in the fuel level gauging.

The eccentricity vector had reached its target despite some erratic manoeuvres at the end of operations due to bubbles appearance in the propellant feeding lines. It ensured that the perigee altitude would be quite stable with regard to the solar radiation pressure effect. The perigee altitude was 247.3 km above Z_{GEO} three months after EOL and 257 km above Z_{GEO} 6 months after EOL (source : NORAD).

The perigee altitude of 235 km when solar radiation pressure effect is anticipated was thus fulfilled, in the spirit of the IADC recommendations. Two tanks were emptied (MMH2 and MMH4) and the satellite conveniently switched-off.

This in-flight experience fully validated the proposed re-orbitation strategy, developed for the end-of-life management of the Eurostar 2000 platform. In particular, the adequate selection of the graveyard orbit, of the eccentricity management during re-orbitation and of the AOCS analyses was demonstrated.

References

1. IADC Steering Group (12 April 2002). *IADC Space Debris Mitigation Guidelines*, IADC-02-01, version produced during IADC-20 meeting.