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THE END-OF-LIFE DISPOSAL OF THE ITALIAN GEOSTATIONARY SATELLITES

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ABSTRACT

To date, four Italian satellites have been launched in geostationary orbit: SIRIO, Italsat 1, Italsat 2, and SICRAL. Of these, only the latter is still operational: SIRIO was abandoned close to the geopotential equilibrium point at 75° E in 1985; Italsat 1 was re-orbited above the geosynchronous altitude at the beginning of 2001; and Italsat 2 was moved, due to a malfunction, in July 2002, below the geosynchronous altitude. This paper reviews how the strategy for the end-of-life disposal has evolved over the last twenty years, due to the growing concern regarding the possible overcrowding of the geostationary ring. The Italian experience is revisited, in order to show the lessons learned in the context of the new international awareness of the space debris problem at the geosynchronous altitude, which has led to the endorsement of a specific disposal strategy by the Inter-Agency Space Debris Coordination Committee (IADC). Long-term orbital propagation is used to assess the impact and relative effectiveness of different disposal scenarios, employing the Italian geostationary satellites as test cases.

THE ITALIAN GEOSTATIONARY SATELLITES AND THEIR EVOLVING DISPOSAL STRATEGY

To date, four Italian satellites have been placed in Geostationary Orbit (GEO): SIRIO, Italsat 1, Italsat 2 and SICRAL 1.

SIRIO, managed by the National Research Council (CNR), was designed in the early 1970's to perform propagation experiments in the SHF radio frequency band over the North Atlantic. Launched from Cape Canaveral on 25 August 1977, the spin-stabilized cylindrical satellite (diameter: 1.4 m; height: 2.0 m; on-station mass: ~ 200 kg), with an Earth-pointing despun antenna, easily outperformed its intended nominal lifespan of two years at 15° W, and in 1983 was moved to a new longitude slot at 65° E. This was done in order to carry out propagation and telecommunications tests with the Chinese Academy of Space and Technology (CAST). Having successfully completed its extended mission and running low in fuel (hydrazine) for orbital and attitude control, SIRIO was moved, in 1985, close to the GEO stable equilibrium longitude at 75.1° E (Foni et al., 1986). During the maneuver sequence, the residual propellant, the amount of which was only approximately known, was exhausted, but the intended station change was completed anyway using the additional small thrust provided by the pressurant gas (nitrogen) contained in the hydrazine tanks.

The decision to put SIRIO, at end-of-life, close to the eastern longitude equilibrium point in GEO (75.1° E) was motivated by its proximity to the last operational longitude (65° E), by the small amount of ΔV still deliverable by the on-board propulsion system (< 3 m/s, including the thrust of the pressurant gas) and with a view to resuming periodic contact with the spacecraft, from the San Marco ground station in Malindi, Kenya, in order to perform technological tests. This was achieved in 1987 (Trumpy and Foni, 1987) and 1989 (Foni et al., 1990), when two series of attitude maneuvers were completed to test the satellite systems and the sensor performances more than ten years after the launch. In addition, in 1987 a small orbital trim maneuver was executed in order to reduce the oscillation around the stable equilibrium longitude to less than 0.3°.

Italsat was an advanced telecommunications project of the Italian Space Agency (ASI), operating at high frequencies (uplink at 30 GHz, downlink at 20 GHz) with digital technology. A telemetry beacon at 20 GHz and propagation beacons at 40 and 50 GHz were also included. Two satellites were built by Alenia Spazio and launched from Kourou, Italsat 1 on 15 January 1991 and Italsat 2 on 8 August 1996. Each tri-axially stabilized spacecraft consisted of a box-shaped bus (2.3 m × 2.7 m × 3.5 m) and two solar panels with a total span of 21.8 m. The on-station mass was ~ 900 kg. Italsat 1 operated for ten years at the longitude of 13.2° E. At the beginning of 2001, an end-of-life re-orbiting was attempted, according to the Inter-Agency Space Debris Coordination Committee (IADC) recommendations (IADC, 2000). However, due to a substantial underestimation of the residual propellant available on-board, it was possible to raise the semimajor axis by only 80 km above the geostationary altitude. However, the final trajectory was close to circular and the spacecraft passivation – to avoid an eventual future explosion – was successfully completed.

Italsat 2 was stationed initially at 13° E and later moved to 16.2° E for its operational telecommunications mission. Unfortunately, in July 2002, due to a series of anomalies with the propulsion and attitude control systems, the satellite expended most of the remaining propellant, preventing the implementation of the planned end-of-life disposal procedures. At that point, the only option left was to move the satellite as far as possible below the geostationary altitude (Portelli, 2002).

SICRAL 1, built by Alenia Spazio for the Italian Ministry of Defense, was developed from the Italsat series and launched from Kourou on 7 February 2001. Stationed at 16.2° E, the spacecraft is equipped with transponders in the SHF, UHF and EHF bands, to guarantee secure communication between military forces and command and control centers. At the end of its planned operational life (10 years), the satellite will be re-orbited at least 400 km above the geostationary altitude.

Even though the Italian satellites launched in geosynchronous orbit account for less than 0.6% of the total (~ 700 at present), the post-mission disposal strategy has evolved over the time according to the growing international concern over the possible overcrowding of this precious region of space. When SIRIO reached the final stages of its extended mission, there was still no common internationally accepted technical position on the subject. The disposal strategy chosen was driven by the limited amount of residual propellant available for maneuvers and with a view to continuing the use of the satellite for technological and scientific (optical tracking for long-term geopotential study) purposes.

The Italsat project was conceived in the 1980's. At that time the orbital debris problem was just starting to emerge and the preliminary analyses and discussions on the subject were still restricted to a small community of specialists. Therefore, no substantial orbital increase or passivation measure was envisaged for the end of the mission and even after the launch of Italsat 1 and 2 the Comsat consultants deemed an end-of-life re-orbiting of 50 km to be more than sufficient.

However, in 1998 the Italian Space Agency (ASI) gained admittance to the IADC, which previously had recommended a minimum re-orbit altitude for satellites in GEO at the end of their operational life. Specifically, the recommended perigee of the disposal orbit was stipulated to be higher than the geostationary altitude by an amount ΔH (km) given by

$$\Delta H = 235 + C_r \times 1000 \times A / M \tag{1}$$

where A is the satellite average cross-sectional area (m^2), M is the satellite mass (kg) and C_r is a radiation pressure coefficient, typically between 1 and 2, which specifies the amount of solar radiation transmitted, absorbed and reflected by the spacecraft (IADC, 2000). In addition, ASI participated in drawing up the European Space Debris Safety and Mitigation Standard (EDMSWG, 2002) and the IADC Space Debris Mitigation Guidelines (IADC, 2002), both adopting the IADC recommendation for the end-of-life disposal of GEO satellites.

For these reasons, ASI decided to apply the IADC recommendation to both the Italsat satellites and promoted the development of the proper re-orbit and passivation procedures. Unfortunately, the residual propellant on Italsat 1 revealed itself to be insufficient in attaining the required perigee altitude increase (298 km above GEO) and the spacecraft was left, passivated, some 80 km – on average – above the geostationary altitude. Italsat 2, on the other hand, operated nominally until July 2002, when spacecraft control was compromised by an unexpected failure.

The SICRAL project, being finalized in the 1990's, was the first to include end-of-life disposal from the beginning of the mission design phase and should be the first Italian geostationary spacecraft able to fully implement the IADC recommendation.

THE LONG-TERM ORBITAL EVOLUTION OF THE ABANDONED SPACECRAFT

To assess the future environmental impact of the Italian satellites abandoned in or near GEO, the recent orbital elements of SIRIO, Italsat 1 and Italsat 2 were propagated for one century using a high accuracy numerical integrator based on Cowell's method (Kwok, 1987; Pardini and Anselmo, 1994). The analysis included the zonal and tesseral harmonics of the Earth's gravity potential, up to the 16^{th} degree and order, the luni-solar gravitational attraction and the solar radiation pressure.

The main features of the long-term trajectory evolution of satellites abandoned in, or near, the geostationary orbit have been described in detail elsewhere (see, for instance, Van der Ha, 1980, and Fenoglio and Flury, 1987). In the present study the attention was focused on the specific long-term "dynamical interference" of the Italian abandoned satellites with the geostationary ring, where most of the operational spacecraft are maintained, and with the geosynchronous protected region, the latter defined in EDMSWG (2002) and IADC (2002) for orbital debris mitigation purposes. The GEO ring was defined as the volume of space centered on the geostationary orbit (mean altitude of 35,786 km, zero inclination), ± 75 km in altitude and ± 0.1° in declination. For the geosynchronous protected region, the excursion in altitude and declination was ± 200 km and ± 15°, respectively.

The long-term interaction of the abandoned satellites with the GEO region may be easily understood by plotting the instantaneous radius vector at the nodal crossings (ascending and descending), when the objects intersect the (equatorial) plane of the geostationary orbit. Figures 1, 2 and 3 show the altitude at which such nodal crossings occur, with respect to the average geostationary height, for SIRIO, Italsat 1 and Italsat 2, respectively.

The case of SIRIO is quite interesting. Even though no orbit raising maneuver was carried out at the end-of-life, in the next century the satellite will cross the geostationary ring, where most of the operational spacecraft are concentrated, for only four relatively short periods, spanning about 17% of the time. Moreover, during all these periods the orbit will be characterized by an inclination equal to or greater than 10°, implying a far shorter time spent by the abandoned spacecraft in the GEO ring. In other words, if the initial orbit of SIRIO has been correctly identified, over the next century only about 17% of the revolutions will cross the geostationary ring, sometimes once, more often twice. However, the time spent there will be less than 0.1% of the total (~ 36 days in 100 years).

The situation is very different for Italsat 1. Even though the mean altitude has been raised about 85 km above GEO, the satellite will continue to cross the geostationary ring at least once per orbit. Regarding Italsat 2, whose final mean altitude at the end-of-life was more than 140 km below GEO, about 75% of the orbits will continue to intersect the geostationary ring – once per revolution – during the next century.

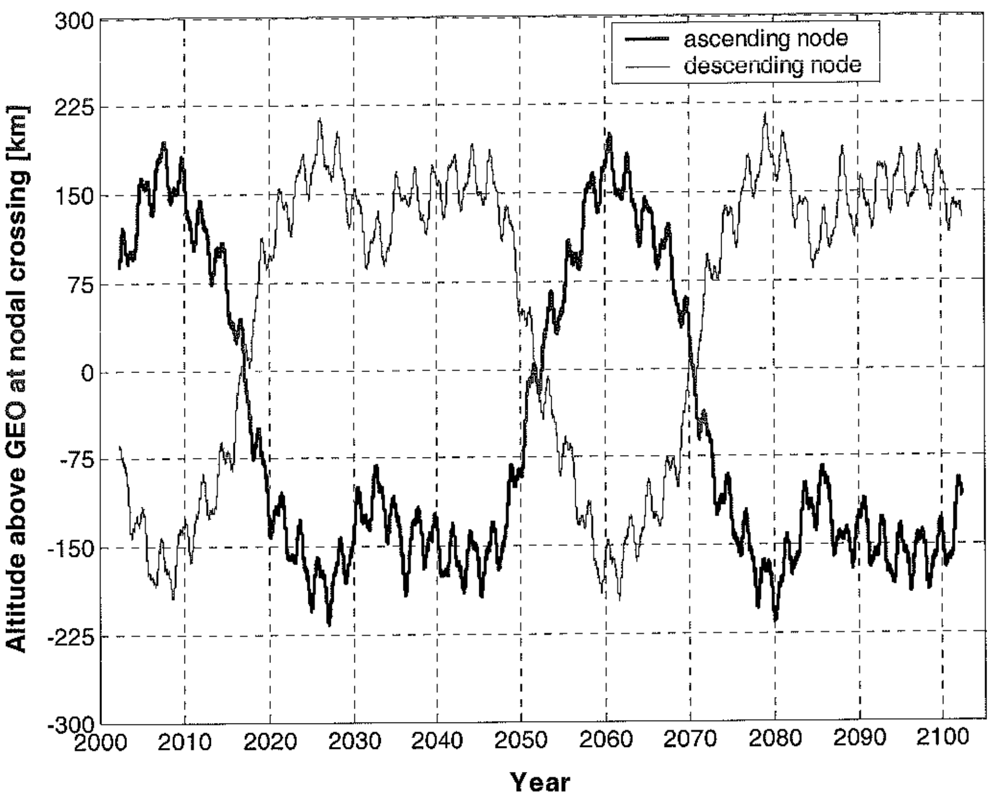

Fig. 1. SIRIO: Altitude above, or below, the geostationary orbit at the satellite nodal crossings.

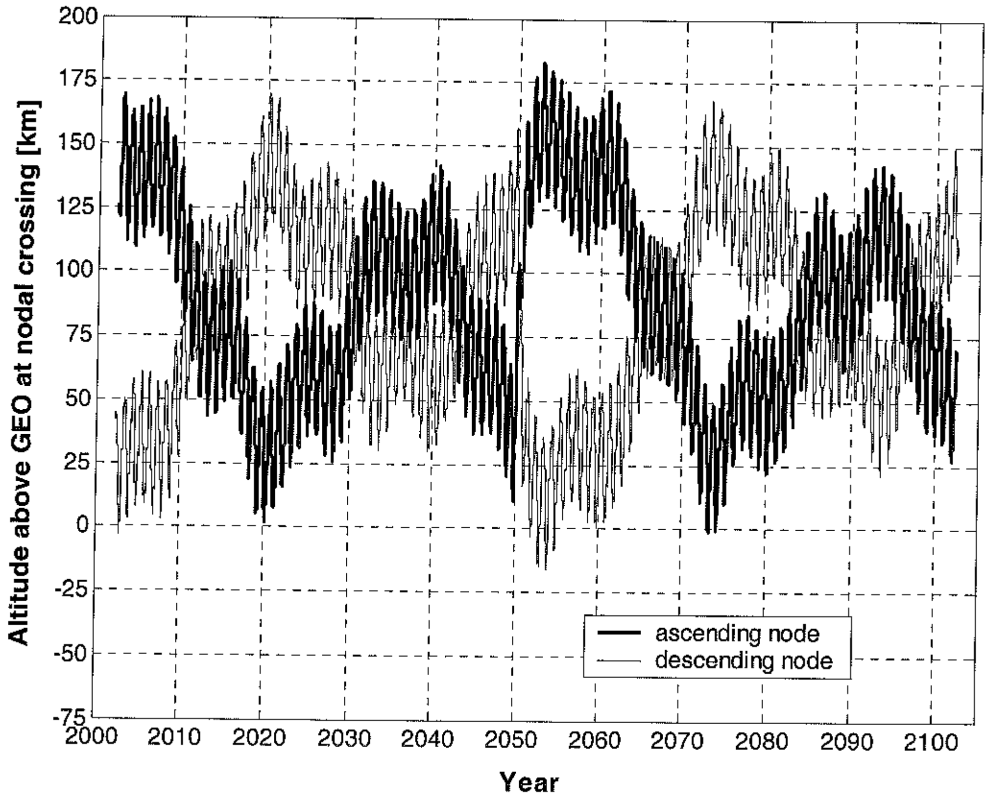

Fig. 2. Italsat 1: Altitude above, or below, the geostationary orbit at the satellite nodal crossings.

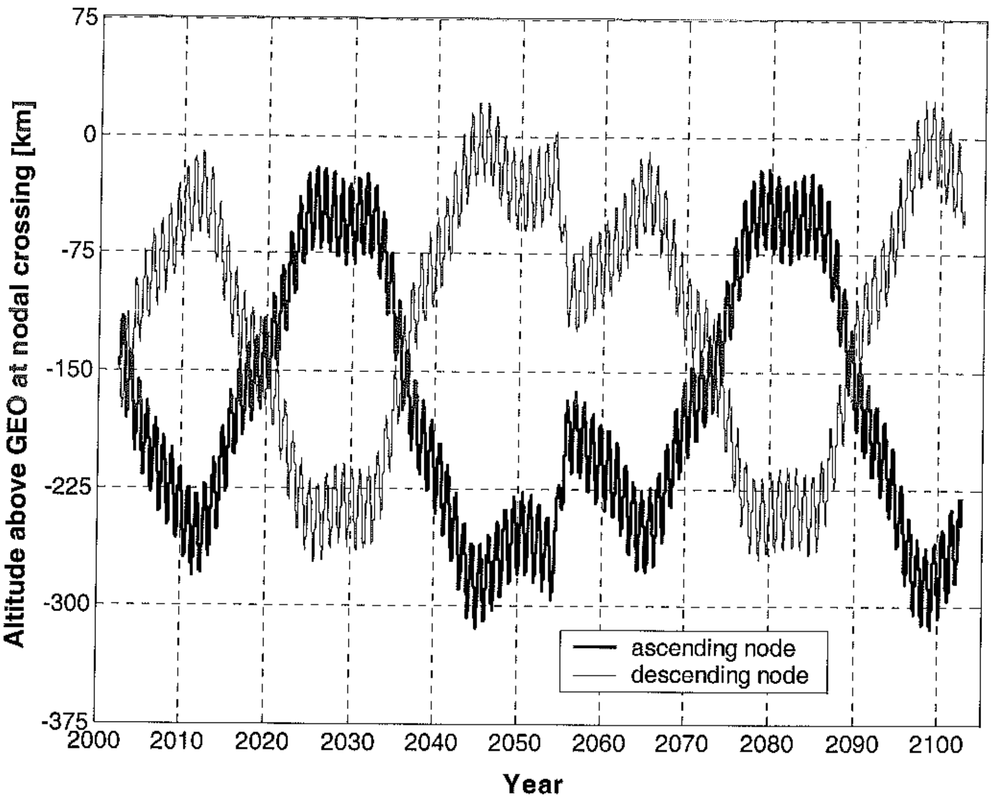

Fig. 3. Italsat 2: Altitude above, or below, the geostationary orbit at the satellite nodal crossings.

THE SIRIO IDENTITY

The initial state vector of SIRIO used in the study was derived from the two-line elements provided by NASA. However, the orbit obtained at the initial epoch considered (24 May 2002) differed from that propagated using the last state vector determined by the Lario tracking station in 1987 (Trumpy and Foni, 1987) by an amount roughly equivalent to a maneuver of 25 m/s. A series of attitude maneuvers was actually carried out after the last orbit determination from Lario (Foni et al., 1990), but the net orbital effect was negligible. Moreover, there was no known energy source on board able to produce the observed orbital change, including the residual pressurant gas. In addition, by analyzing the historical two-line element sets for SIRIO, kindly provided by NASA, a state vector discontinuity was discovered on 3 December 1999. At that epoch the two-line elements recorded an abrupt orbital plane change corresponding to a ΔV of about 21 m/s, which, if real, was very similar to the observed discrepancy between the current two-line elements and the orbit propagated using the last state vector determined in Italy.

A possible solution to the puzzle could come from an object exchange in the catalog maintained by USSPACECOM. As a matter of fact, during the second half of the 1980's, the orbit and in particular the orbital plane of SIRIO was very close to that of Cosmos 1366 and Ekran 9. It is therefore possible that during or after the series of maneuvers performed to modify its station longitude in GEO, SIRIO was exchanged by USSPACECOM for one of the Soviet satellites, most probably Ekran 9. If this were the case, the event recorded on 3 December 1999 would have affected Ekran 9, while the current SIRIO state vector should be searched for in the two-line elements attributed to the Soviet satellite. In addition, the current state vector of Ekran 9 is quite close to that obtained by propagating the last orbit of SIRIO determined by the Lario tracking station, contributing to the plausibility of this scenario. Other possible explanations could be: (1) the event recorded in the two-line elements was spurious, i.e. not real; (2) the satellite was hit by a piece of orbital debris, capable of inducing the observed velocity variation. However, there is no evidence in the data at present to support the first scenario, while the second is deemed extremely improbable (overall probability ~ 10^{-8}), implying – for example – the collision with an object of more than 5 kg at a relative velocity of 800 m/s, or of more than 1 kg at 4 km/s.

Assuming that the two-line elements of Ekran 9 refer instead to SIRIO, the Italian satellite will cross the geostationary ring more often than presented in Figure 1, as shown in Figure 4: about 47% of the orbits will in fact intersect the GEO ring in the next century.

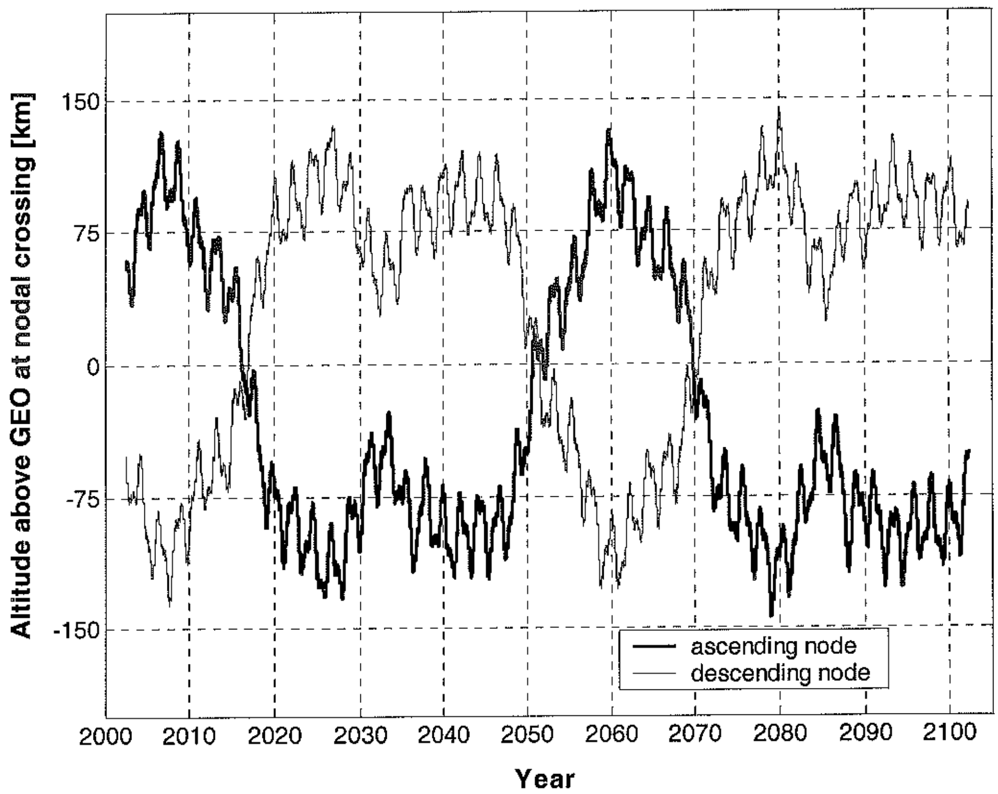

Fig. 4. Altitude of the nodal crossings if SIRIO had been exchanged for Ekran 9 in the USSPACECOM catalog.

CONCLUSIONS

For different reasons, all three Italian geostationary satellites that have concluded their operational life remained in the geosynchronous protected region, as defined in EDMSWG (2002) and IADC (2002). However, while the SIRIO disposal was accomplished according to the final project plan, the two Italsat satellites had to be re-orbited following the IADC recommendation, even though a series of problems prevented the achievement of a positive result.

Concerning the long-term interaction of the abandoned Italian spacecraft with the geostationary ring, where most of the operational satellites are maintained, the results obtained were quite surprising. SIRIO in fact, despite being abandoned at GEO altitude, will cross the geostationary ring over the next century much less often than each of the two Italsat satellites, whose mean altitude was significantly altered at their end-of-life. This conclusion would basically be confirmed even if SIRIO had been exchanged for Ekran 9 in the USSPACECOM catalog.

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