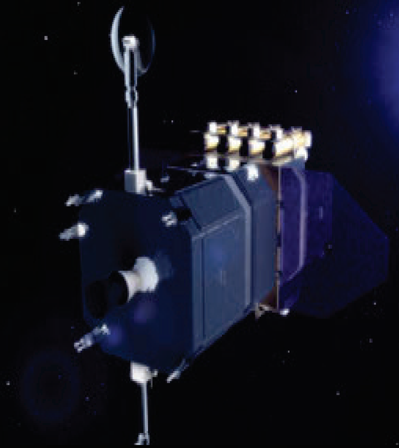
END-OF-LIFE DISPOSAL IN INCLINED GEOSYNCHRONOUS ORBITS



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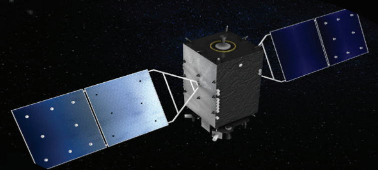

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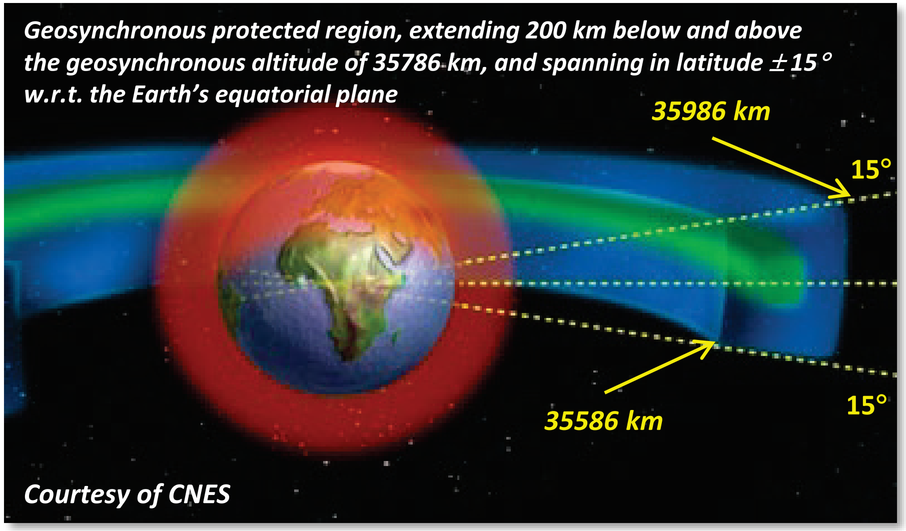
Introduction

With the goal of preserving the utilization of the geostationary orbit, the IADC Space Debris Mitigation Guidelines:

1) Defined a toroidal protected region

2) Introduced a formula for the appropriate end-of-life disposal of GEO spacecraft and orbital stages to no further long-term interference with the geosynchronous protected region for at least 100 years



The IADC end-of-life disposal formula requests the fulfillment of the following two conditions for a successful disposal orbit above the geosynchronous protected region:

1. A minimum increase of the perigee altitude h_p of

$$\Delta h_p\ [km] \geq h_0 + (1000 \cdot C_R \cdot A/M)$$

C_R is the solar radiation pressure coefficient, A is the average aspect area (in m^2) of the re-orbited object, and M its mass (in kg). h_0 is set equal to 235 km, representing the sum of the upper limit of the protected region (+ 200 km) and of the maximum descent of the re-orbited object due to luni-solar & geopotential perturbations (+ 35 km)

2. An initial eccentricity $e_0 \leq 0.003$

Introduction

- The IADC disposal guideline was developed when the geosynchronous region was mainly used to host geostationary satellites, maintained close to the Earth's equatorial plane during the mission, and displaying, once abandoned, a periodic evolution of the orbit plane, with a period of ~ 53 years and a maximum inclination of ~ 15°, in consequence of the concurring action of geopotential and luni-solar perturbations

- Highly inclined geosynchronous orbits are now considered for various applications

  Satellite navigation systems
  - Inclined Geosynchronous Orbit (IGSO) component of the Chinese Beidou ($i = 53°$- $58°$)
  - Indian Regional Navigation Satellite System (IRNSS) ($i = 28°$- $30°$)
  - Japanese Quasi-Zenith Satellite System (QZS) ($i = 40°$- $45°$)

  Science
  - IUE, SDO

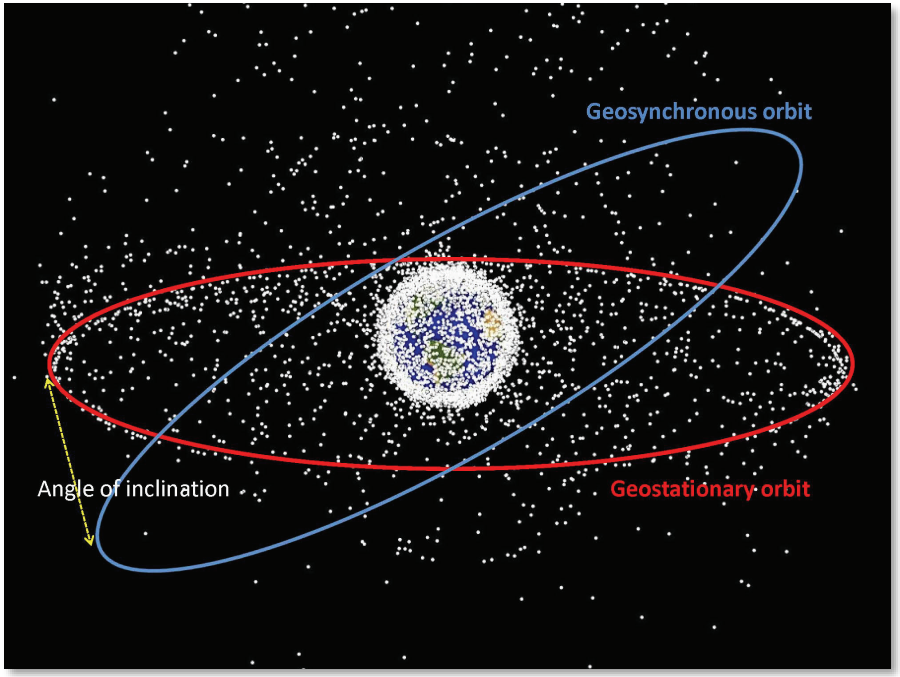
  Telecommunications & Intelligence
  - Syncom 2

- At the beginning of 2020, 24 objects were in a Highly Inclined Geosynchronous Orbit (HIGSO) with $i > 25°$: 12 Beidou, 5 IRNSS, 3 QZS, 1 active scientific spacecraft (SDO), 2 abandoned spacecraft, and 1 mission related object

- They still represented < 2% of the objects known in the geosynchronous region

Stability vs. instability of nearly circular geosynchronous orbits

- The orbital plane and eccentricity evolution of nearly circular geosynchronous orbits have been deeply investigated over many years
- The possibility of eccentricity instability for some inclinations had already been pointed out in the early '60s (Allan & Cook, 1964)
- The Lidov-Kozai mechanism, discovered first for satellites by Mikhail L. Lidov in 1961, and rediscovered for asteroids by Y. Kozai in 1962, consists in a perturbation of the orbit of a satellite by the gravity of another body orbiting farther out



- Due to the Lidov-Kozai effect, all satellites inclined by more than ~ 40° with respect to the generalized Laplace plane would experience a considerable growth of the eccentricity, accompanied by librations of the argument of perigee around either 90° or 270°
- In consequence of this, the eccentricity of high inclination near-geosynchronous orbits might grow significantly, irrespective of its initial value

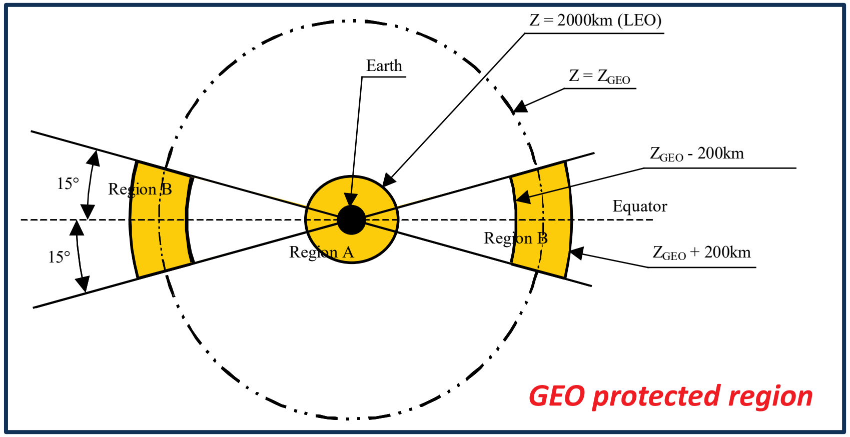
Stability vs. instability of nearly circular geosynchronous orbits

- In the real world the picture is much more complex: luni-solar perturbations also give rise to resonances depending only on inclination, as well as others related to semi-major axis, eccentricity and inclination (Cook, 1962; Hughes, 1980 and 1981)
- For nearly circular geosynchronous orbits, the following applies
  - If the initial inclination $i_0 \leq 30°$, the Lidov-Kozai effect does not affect the orbit, and also luni-solar resonances are not met during the long-term evolution of the orbit plane
  - The eccentricity displays periodic variations with amplitude depending on the initial conditions, but remains in any case bounded for a very long time, with no significant systematic growth
  - For $i_0 > 30°$, certain combinations of the initial conditions lead to a considerable eccentricity growth, often with a complex interplay between resonances depending only on inclination and resonances depending on semi-major axis, eccentricity and inclination (Bordovitsyna, Tomilova, & Chuvashov, 2014)

- If $i_0 \leq 30°$, it is always possible to avoid a significant eccentricity growth over 200 years, irrespective of the other initial conditions (i.e. epoch, right ascension of the ascending node and argument of perigee)
- If $i_0 > 30°$, only specific initial conditions would be able to guarantee a relative stability of the eccentricity

A possible extension of the IADC formula

- In addition to the initial inclination, the eccentricity evolution of nearly circular geosynchronous orbits depends as well on the relative positions of the Sun and the Moon
- In order to investigate the stability of the eccentricity, the full range of initial conditions relative to the Sun, the Moon, the right ascension of the ascending node and the argument of perigee was explored (Anselmo & Pardini, 2017) using two orbit propagators: the CNES semi-analytic propagator STELA and the ISTI/CNR numerical propagator SATRAP
- The IADC formula (with $h_0 = 235$ km) and any possible extension were tested over a time interval of 200 years, assuming $e_0 = 0.003$ and $C_R\, A/M = 0.1$ m^2/kg
- It was found that the IADC guideline would be able to guarantee no further interference with the geosynchronous protected region over 200 years, irrespective of initial Sun and Moon position, ascending node and argument of perigee, only for initial disposal inclinations $i_0 \leq 2°$
- With $i_0 > 2°$ this would be no longer guaranteed, even though the applicability of the IADC formula might be extended up to $i_0 \leq 10°$, for any initial condition, if sporadic crossings of the geosynchronous protected region by ~ 10 km were deemed acceptable



A possible extension of the IADC formula

- Concerning still higher initial inclinations, up to $i_0 = 30°$, where the amplitude of the eccentricity oscillations progressively increases, but remains anyway upper bounded, a relationship as the IADC formula might be maintained by just increasing the value of h_0

Modification of the parameter h_0 in the IADC formula, as a function of the initial disposal inclination i_0, to guarantee no further interference with the geosynchronous protected region over 200 years, irrespective of initial Sun and Moon position, ascending node and argument of perigee

h_0 (km)	i_0
235	$\leq 2°$
285	$\leq 18°$
300	$\leq 20°$
350	$\leq 26°$
400	$\leq 28°$
500	$\leq 29°$
550	$\leq 30°$

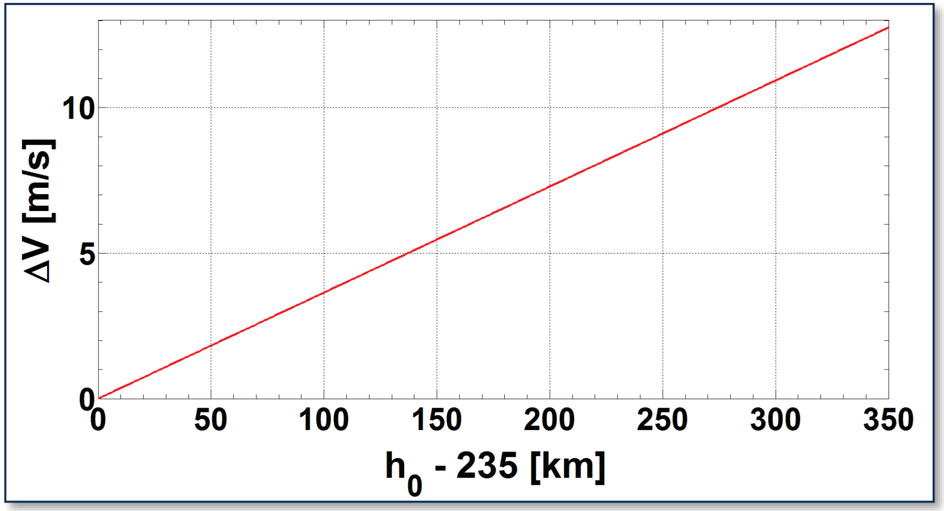
- It cannot be excluded that choosing appropriate initial conditions, smaller values of h_0 exist to avoid the long-term crossing of the protected region for a given value of i_0
- But this should be checked case by case, being not a general result valid for any possible combination of the initial conditions

- With $i_0 > 30°$ the eccentricity may grow to quite large values, for certain initial conditions, due to resonances and/or the Lidov-Kozai mechanism. Consequently, it is not possible to define end-of-life disposal strategies being simple, universal and inexpensive at the same time

A possible extension of the IADC formula

- The additional ΔV needed to implement the extended IADC formula was computed as follows:

$$\Delta V_{+}\ [km/s] \approx 3.646 \times 10^{-5}\,(h_0[km] - 235)$$

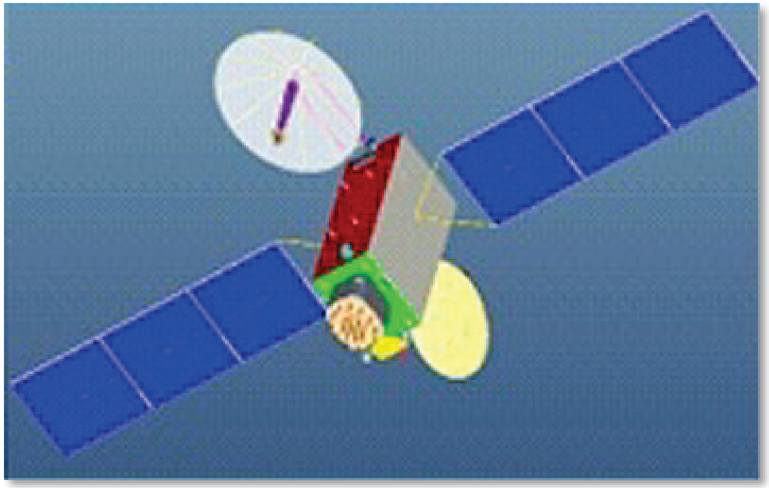


- For $h_0 = 550$ km, i.e. the maximum value applicable for $i_0 \leq 30°$, it was found a $\Delta V_{+} = 11.5$ m/s, i.e. an additional velocity variation equivalent to that needed to re-orbit, with $e_0 = 0$, a spacecraft with $C_R A/M = 0.08$ m^2/kg, using the original IADC formula with $h_0 = 235$ km

- Therefore, even assuming the most unfavorable initial conditions, an extension of the IADC formula might be practicable up to $i_0 = 30°$, with a maximum ΔV penalty of 11.5 m/s
- This, of course, would have a not negligible cost, but could be economically affordable and technically feasible
- Moreover, as already pointed out, much less expensive solutions, in terms of additional ΔV, would be often available for appropriate combinations of orbital and celestial initial conditions

Very high initial inclinations

- When i_0 > 30° a significant growth of the eccentricity cannot be avoided without a careful selection of initial conditions
- A simple and universal end-of-life re-orbit strategy with a varying value of h_0 is no longer applicable
- Taking as an example the IGSO component of the Chinese Beidou navigation system ($i = 53°$-58°), the long-term eccentricity behavior is extremely sensitive to the initial conditions at a given epoch, in particular the right ascension of the ascending node Ω_0
- For the Beidou IGSO-1 spacecraft, assuming no further orbital control after 7 June 2013, it would have been possible to maintain a small eccentricity
  - for nearly 3 centuries with $\Omega_0 = 0°$
  - for just 1 century with $\Omega_0 = 30°$
  - for < 25 years with $\Omega_0 = 120°$ or $\Omega_0 = 225°$



- Selecting the initial ascending node in the intervals $90° \leq \Omega_0 \leq 180°$ or $210° \leq \Omega_0 \leq 250°$ would have led to a growth of the eccentricity above 0.83, causing the reentry of the satellite into the atmosphere after an interval of time ranging from several decades to a few centuries (Zhao et al., 2015)
- A case by a case analysis is needed to assess the long-tem evolution of very high inclination orbits

Very high initial inclinations: the Lidov-Kozai effect

- The Lidov-Kozai effect is a consequence of the hierarchical and restricted three-body approach
- In the real world, adding to the Moon the Earth's oblateness, the Sun, other relevant perturbations as direct solar radiation pressure, and the intricate web of luni-solar resonances, the simple pattern of the classical Lidov-Kozai mechanism no longer occurs
- Examples of such behaviors are provided by a couple of long-term propagations carried out with the ISTI/CNR numerical propagator SATRAP, taking into account all relevant perturbations and including the atmospheric drag for perigee altitudes below 1000 km

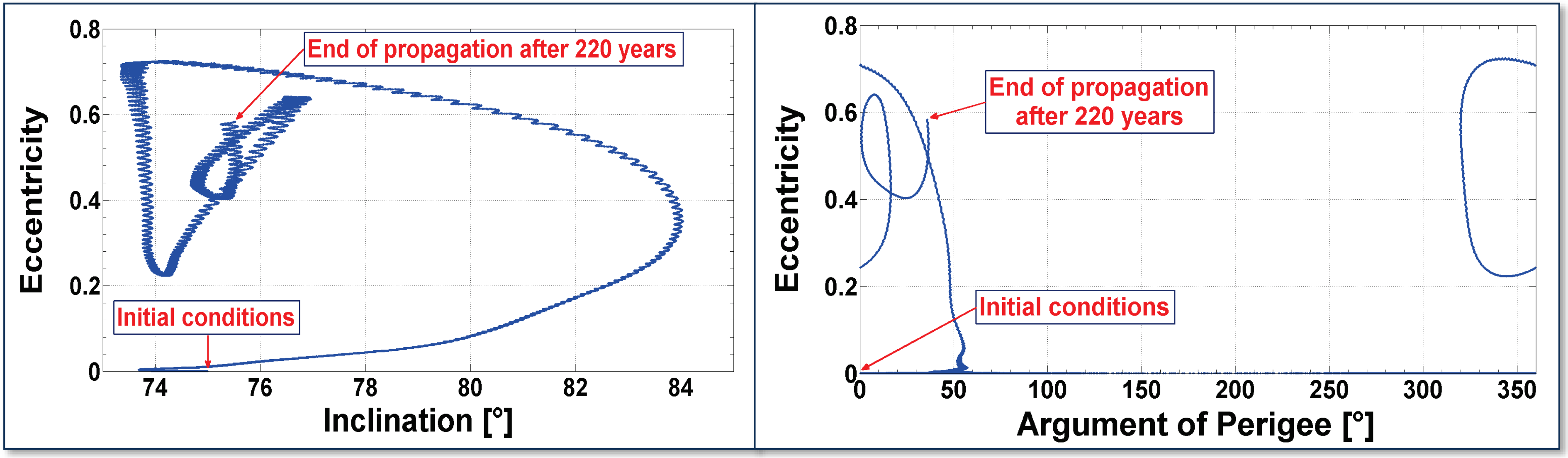
> Satellite $C_R\,A/M = 0.05\ m^2/kg$
> Initial semi-major axis $a_0 = a_{GEO}$ and inclination $i_0 = 75°$
> Initial epoch: 20 March 2019, 00:00 UTC
> Propagation duration: > 200 years
> Moon longitude of ascending node ≈ 13°
> Moon inclination w.r.t. the Earth's equator ≈ 22°

- Two sets of initial conditions were assumed

1. $e_0 = 0.0001$ $\Omega_0 = 180°$ $\omega_0 = 0°$ [descending node and apogee towards the Sun]
2. $e_0 = 0.001$ $\Omega_0 = 0°$ $\omega_0 = 0°$ [ascending node and perigee towards the Sun]

Very high initial inclinations: first example

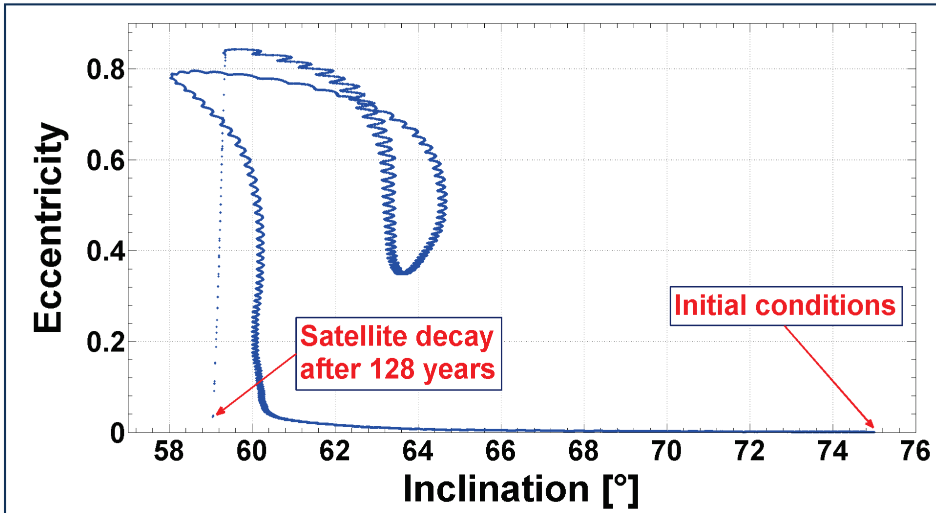
First case with $i_0 = 75°$, $e_0 = 0.0001$, **descending node and apogee towards the Sun**

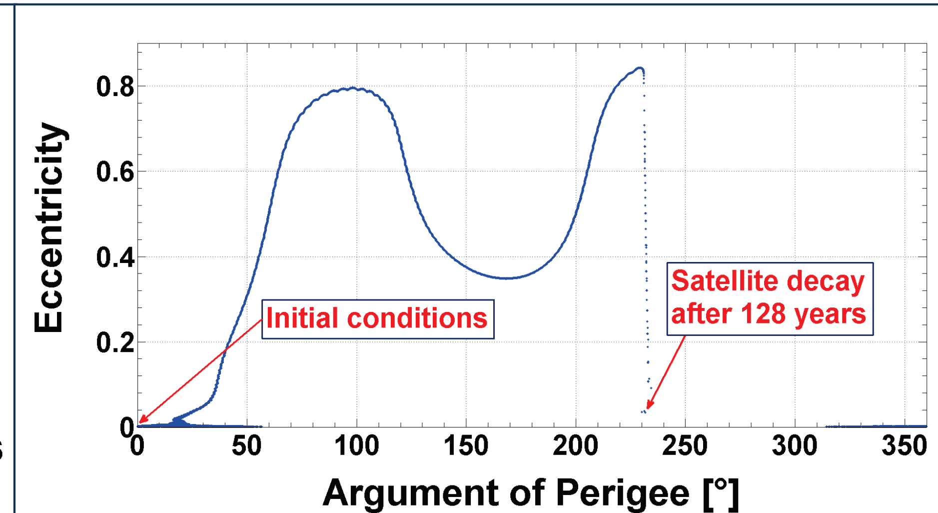


- The inclination increases up to 84° and the eccentricity exceeds 0.7, but the satellite is still in orbit after 220 years
- As in the classical Lidov-Kozai effect, the eccentricity growth and its successive large amplitude oscillation is accompanied by a libration of the perigee around a “stable” value. However, such a value is neither 90° nor 270°, but ~ 0°

Very high initial inclinations: second example

Second case with $i_0 = 75°$, $e_0 = 0.001$, ascending node and perigee towards the Sun





- The eccentricity growth is so large to induce satellite decay after 128 years
- Concerning the coupled evolution of eccentricity and argument of perigee, the simple pattern of the classical Lidov-Kozai effect is not observed, and no libration around a specific value of the argument of perigee occurs
- During the first 100 years, when the eccentricity is small and the inclination decreases, the perigee librates around the ascending node (0°)
- When the eccentricity starts to grow, the perigee starts an anti-clockwise precession
- The satellite decay occurs when the eccentricity rebounds from 0.35 to 0.84

Conclusions

- The original IADC guideline for the end-of-life re-orbiting of spacecraft and orbital stages above the geosynchronous altitude resulted strictly valid, irrespective of the orbital and celestial initial conditions, for $i_0 \leq 2°$, and applicable in most cases for $i_0 \leq 10°$

- The potential growing use of geosynchronous orbits with higher inclinations has raised the problem of what strategy to adopt at the end-of-life for these new classes of objects

- For $i_0 \leq 30°$, it was shown that an extension of the IADC formula would be possible by just increasing the value of h_0 as a function of i_0, with a maximum of 550 km for $i_0 = 30°$

- This possibility arises from the fact that, despite the complexity of the perturbations acting on such orbits, the eccentricity would remain bounded to sufficiently low values for at least 200 years, irrespective of the orbital (Ω_0 and ω_0) and celestial (Sun and Moon position) initial conditions

- With $i_0 = 30°$ and $h_0 = 550$ km, no crossing of the geosynchronous protected region would occur, over 200 years, even in the less favorable combinations of initial conditions

- However, very often it would be possible to avoid any further long-term interference with the protected region also adopting significantly lower values of h_0, being these obtained in order to guarantee the fulfillment of the IADC guideline even with the worst initial conditions

Conclusions

- The cost of implementing the extended IADC formula, in terms of additional ΔV to be delivered by the propulsion system and mission impact, would be not negligible, but affordable
- With $i_0 = 30°$, the maximum additional ΔV penalty would be 11.5 m/s, approximately doubling the cost currently incurred to apply the original IADC formula to nearly geostationary satellites

- **For geosynchronous satellite systems operating at very high inclinations**

- Usually it is not possible to avoid a significant increase of the eccentricity, and no general and cost-effective end-of-life disposal solution can be recommended for the re-orbiting of near circular geosynchronous objects with $i_0 > 30°$
- However, for specific initial conditions, it might be possible
  - To constrain the eccentricity growth from several decades to a few centuries
  - To induce an eccentricity growth able to cause orbital decay in several decades
  - To exploit the perturbations in order to cause the emergence of a dynamical protection mechanism of the geosynchronous protected region, effective at least for several decades