# EFFECTIVENESS OF THE DE-ORBITING PRACTICES IN THE MEO REGION

**A. Rossi**[1], **L. Anselmo**[1], **C. Pardini**[1], **and R. Jehn**[2]

[1]*ISTI–CNR, Via Moruzzi 1, 54124, Pisa, Italy*
[2]*ESA-ESOC, Robert Bosch Str.5, 64293 Darmstadt, Germany*

## ABSTRACT

The Medium Earth Orbit (MEO) region is becoming increasingly exploited as the number of navigation constellations grows with the advent of the European GALILEO and the Chinese COMPASS systems. There is the need for an effective disposal strategy of satellites at end-of-life able to prevent any possible damage of operational satellites. This strategy has to take into account the known instability of nearly circular disposal orbits in MEO. These orbits show an increase of the eccentricity that could lead to dangerous crossings of the operational orbits.

The nature of this instability, linked to luni-solar resonances, is briefly recalled. Then the effect of different disposal strategies on the long term evolution of the MEO environment is analyzed. It is shown how the disposal of satellites at end-of-life into well separated storage zones, above the constellations operational orbits, is capable of limiting the collision risk for operational satellites to very low values for long time spans (200 years). Moreover, a disposal into eccentric orbits not only keeps the collision risk to very low values, but also has the advantage of reducing the lifetime of the disposed satellites, thus freeing the orbital environment from the uncontrolled spacecraft.

## 1. INTRODUCTION

The Medium Earth Orbit (MEO) region, home of the navigation constellations, is becoming more and more exploited with the future advent of the European GALILEO and the Chinese COMPASS constellations.

The sensitive applications of the navigation constellations and the absence of any natural sink mechanism, such as the atmospheric drag, call for a careful debris prevention policy able to preserve the MEO environment, avoiding the future problems now already faced by the Low Earth Orbit (LEO) and the Geostationary Orbit (GEO) environments [4]. As a matter of fact, since several years the GPS satellites adopt a debris prevention policy. In particular, as proposed for the geostationary ring, the GPS satellites are moved to a disposal region, at least 500 km above the operational orbit, at the end-of-life.

The disposal zone is, in principle, well separated both from the GPS operational orbit and from the GALILEO planned orbit. Unfortunately the picture is more complicated. In a number of recent papers (e.g. [2] [5] [12]) the instability of the navigation constellations disposal orbits, showing an increase of the eccentricity that could lead to dangerous crossings of the operational orbits, was studied. Figure 1 shows the eccentricity evolution over 100 years, for a GPS like orbit propagated with increasing sophisticated dynamical models, from a simple case with only the gravity monopole term, plus luni-solar perturbations, to a full model with Earth gravity harmonics up to degree and order $10$ and luni-solar perturbations. The first long term effects of the $2:1$ geopotential resonance (due to the fact that the orbital period of the navigation constellations equals approximately half a sidereal day) appear when the harmonics up to $\ell = 3$ and $m = 3$ are included (see e.g. [12]). The real striking change in the pace of the eccentricity growth happens when a full model including Earth gravity harmonics and luni-solar perturbation is assumed. The eccentricity undergoes a very long term (quasi-secular) perturbation that, at the end of the 100-year time span, leads to a value more than $3$ times larger than in the case without luni-solar perturbations. This is due to a so-called *luni-solar resonance*. Moreover, it is worth noting how, in the case where a full dynamical model is applied (including luni-solar perturbations), the eccentricity growth drops significantly going from the case where a $3 \times 3$ gravity field is used (the uppermost red curve) to a $4 \times 4$ gravity field (the top magenta line) and then to the full model with a $10 \times 10$ field. This, most probably, means that the shape of the ellipsoid, represented by the simple spherical harmonics expansion up to degree and order three, undergoes a stronger resonance with the Sun and the Moon perturbations. The caveat that should be taken by this example is that simulating, or analytically calculating, an approximate problem with few harmonics might overestimate the perturbation effect. The FOP orbital propagator [13] used in this paper takes into account this fact.

As mentioned above, the cause of the long term eccentricity growth is a resonance condition resulting from the third body and the geopotential perturbations, arising when the secular motions of the lines of apsides and

*Proc. '5th European Conference on Space Debris', Darmstadt, Germany*
*30 March – 2 April 2009, (ESA SP-672, July 2009)*

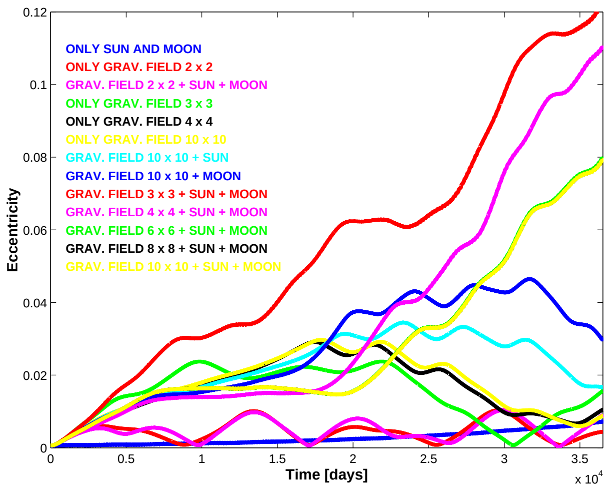


*Figure 1. Resonance onset. Long term evolution of the orbital eccentricity for a GPS like orbit with increasingly complex perturbative models.*

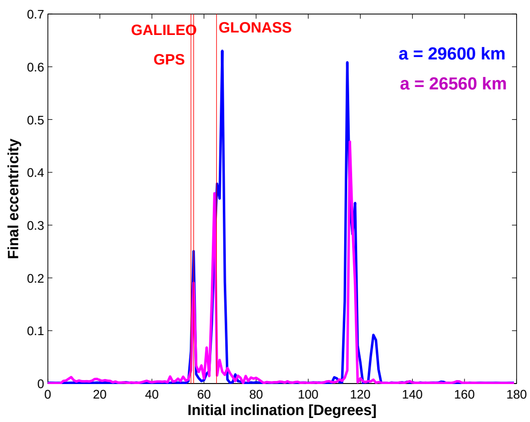


*Figure 2. Maximum eccentricity growth after 200 years as a function of initial inclination for GALILEO-like (blue line) and GPS-like orbits (magenta line).*

nodes become commensurable with the mean motion of the Sun and the Moon. In particular, it turns out that the navigation constellations are located in a so-called *inclination dependent luni-solar resonance*, where the resonance condition is dependent only on the satellite's orbital inclination [3]. This is clearly noticeable in Fig. 2, where the maximum eccentricity growth after 200 years is shown for a set of GALILEO-like orbits with inclination varying from $0°$ to $180°$ (blue line). The magenta line refers to set of orbits having initial semimajor axis equal to the GPS one. The peaks corresponding to the inclination dependent resonances clearly appear in the plot. In particular the peak at $56°$ is nearly coincident with the nominal GALILEO inclination. It can be noticed how the resonance appears for both the orbits, almost independently from their altitude, as predicted by [3] [12]. The inclination resonances are classified [3] by 3 commensurability conditions involving the argument of

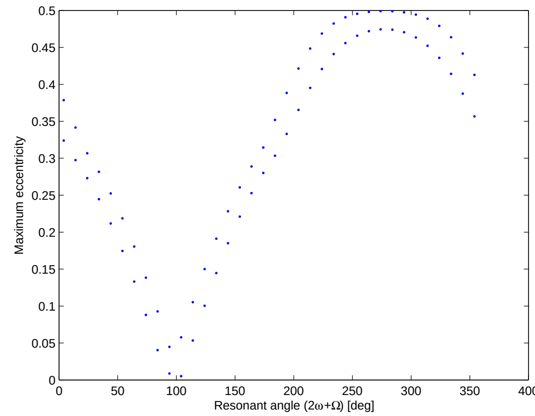


*Figure 3. Maximum eccentricity growth, as a function of initial resonant argument $2\omega + \Omega$, for a GPS disposal orbit.*

perigee, $\omega$, and the right ascension of ascending node, $\Omega$: $i)$ $\dot{\Omega} \approx 0$ (polar orbits), $ii)$ $\dot{\omega} \approx 0$ (critical inclination at $i = 63.4°$) and $iii)$ $\alpha\dot{\omega} + \beta\dot{\Omega} \approx 0,\ \beta > 0$, where $\alpha$ and $\beta$ are mutually prime integers. For the orbits of the navigation constellations, different resonant arguments become important (i.e., nearly vanish), giving way to very long period effects in the eccentricity. In particular, for the GPS-II, $(2\dot{\omega} + \dot{\Omega}) \approx 0.0046$ per day; for GALILEO, $(2\dot{\omega} + \dot{\Omega}) \approx 0.0002$ per day; for GLONASS and GPS-I (near the critical inclination), $2\dot{\omega} \approx 0.002$ per day.

As an example, the dependence of the eccentricity growth, in the case of the GPS constellation, from the angle $(2\omega + \Omega)$ is shown in Fig. 3, where a set of GPS disposal orbits with initial orbital elements $a = 27060$ km, $e = 0.005$, $i = 55°$, $\Omega = 154°$ and $\omega$ varying from $0$ to $360°$, are integrated for 200 years and the maximum eccentricity is recorded. The maximum values of the eccentricity are reached whenever the angle equals $\approx 270°$, so that $\sin(2\omega + \Omega) \approx -1$. This plot clearly highlights the possibility to properly select the angular arguments, $\Omega$ and $\omega$, of a disposal orbit to prevent large long term growth of the eccentricity.

The eccentricity growth may represent an hazard for the long term disposal of the spent satellites and upper stages, since they can re-enter the operative zone, if the disposal orbit is not stable. On the other hand, the operational satellites can perform avoidance maneuvers if the projectile is large enough to be tracked from the ground. A potentially even more dangerous problem can arise from the accumulation, in the graveyard zones above the constellations, of non-operational spent spacecraft, unable to perform avoidance maneuvers. If a fragmentation would ever happen in the orbits of the navigation constellation, the resulting cloud of debris would be very difficult to track from the ground sensors, due to the large distance, and would therefore represent a serious hazard for all the spacecraft in the region [11].

The long term evolution of the collision risk in the MEO region was analyzed by means of the SDM 4.0 model [13]. SDM 4.0 is the latest evolution of the software suite [9] [1] [10] for the modeling of the long term evolution of the space debris population, developed in Pisa under European Space Agency contracts. Thanks to a new extremely accurate orbital propagator and to a very detailed traffic model (specially tailored for the MEO and GEO regions), complex evolution scenarios in any orbital regime can be simulated.

For the current study we envisaged a number of scenarios to analyze the stability and the effectiveness of the proposed navigation constellations disposal zones. The long term interaction of the disposed spacecraft with the operational ones, and within the disposal region, was studied, under different disposal options. The effectiveness of a strategy involving a “dilution” of the collision risk [6], i.e. exploiting the initial disposal eccentricity and the dynamical instability at MEO altitude to place the disposed spacecraft in highly eccentric orbits, was investigated too. In this respect, the possible interaction of the disposed MEO spacecraft with the GEO (and LEO) protected region was analyzed and discussed.

## 2. LONG TERM EVOLUTION STUDIES

The initial population adopted in all the scenarios described in this Section is MASTER 2005. The EVOLVE 4 explosion and collision models [7], and the CUBE collision probability algorithm [8] were used. The orbits were propagated with FOP [13]. The lower limit for the particles included in the simulations was 10 cm. The default explosion scenario includes an average number of 4.6 explosions per year, in all the circumterrestrial space, from 2005 to 2024. In 2025 a suppression of in-orbit explosion was assumed. The number and the type of the events are taken from an analysis of the past 5 years.

The following scenarios were simulated:

- Business As Usual (BAU), with the following traffic assumptions for the 4 different navigation constellations:
  - in the NAVSTAR GPS constellation, 2 launches per year, carrying one satellite each, are simulated. The upper stage is left in an elliptic orbit until the year 2020. After this epoch no upper stage is added;
  - in the GLONASS constellation, 2 launches per year, carrying 3 satellites each, are simulated. The upper stage is left in a circular orbit slightly below the orbit of the satellites until the year 2050. After this epoch no upper stage is added;
  - the actual building of the GALILEO constellation is supposed to start in the year 2012. In the building period of the constellation 6 launches per year, carrying one satellite each, are simulated, until the total number of 30 satellites is reached. Then, in the maintenance period, one launch per year, carrying one satellite, is simulated. The upper stage is left in a circular orbit below the orbit of the satellites for all the time span of the simulation;
  - the actual building of the Chinese COMPASS constellation is supposed to start in the year 2007. In the building and maintenance period of the constellation, 1 launch per year, carrying one satellite each, is simulated, until the total number of 30 satellites is reached . The upper stage is left in a circular orbit below the orbit of the satellites for all the time span of the simulation.

  In the BAU scenario no satellite is re-orbited at end-of-life.

- Mitigation 1 (MIT1): the difference with respect to BAU is that all the satellites in the 4 navigation constellations are reorbited at end-of-life into a circular ($e \leq 10^{-3}$) disposal orbit approximately 500 km above the operational one (starting from the beginning of the simulation), without any targeting of the argument of the perigee ($\omega$). Moreover, all the upper stages are not left in orbit, starting from the year 2010.

- Mitigation 2 (MIT2): differently from MIT1, the satellites in the 4 navigation constellations are reorbited at end-of-life into an upper circular disposal orbit targeting a particular value of $\omega$. In this case $\omega$ is chosen in order to minimize the long term eccentricity growth of the disposed satellite. This is obtained by choosing $\omega$ in such a way that $\sin(2\omega + \Omega) \simeq +1$, that is $(2\omega + \Omega) \simeq 90°$ (see Fig. 3).

- Mitigation 3 (MIT3): the satellites in the 4 navigation constellations are reorbited at end-of-life into an elliptic orbit, with an initial eccentricity of $\simeq 0.022$ and apogee on the operational orbit. The elliptic disposal orbit is reached with a single maneuver to lower the perigee with a $\Delta V$ of $\approx 40$ m/s, of the order of the $\Delta V$ required to rise the satellites to the circular disposal orbits of the MIT2 case. As in MIT1 and MIT2 all the upper stages are not left in orbit, starting from the year 2010.

All the navigation constellations are supposed to have a lifetime covering the whole simulated time span.

## 3. SIMULATION RESULTS

The four scenarios described in the previous section were simulated with SDM 4.0 over 200 years, starting in 2005. Each case was modeled with 40 independent Monte Carlo runs. In the following, the plots show the average from all

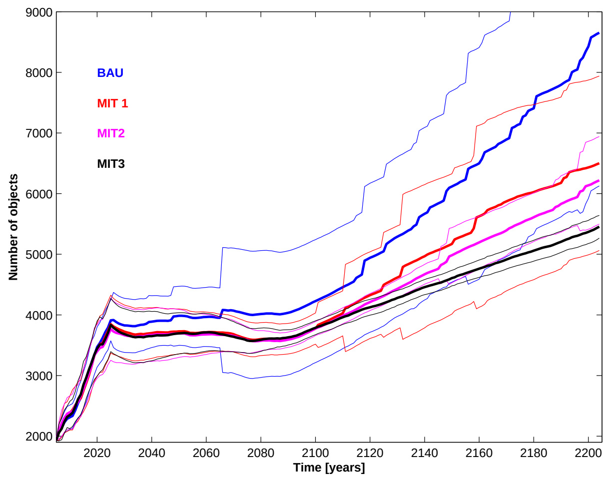


*Figure 4. Effective number of objects larger than 10 cm in the BAU (blue line), MIT1 (red line), MIT2 (magenta line) and MIT3 (black line) cases in the MEO region. The thin lines are the plus or minus $1\sigma$ limits.*

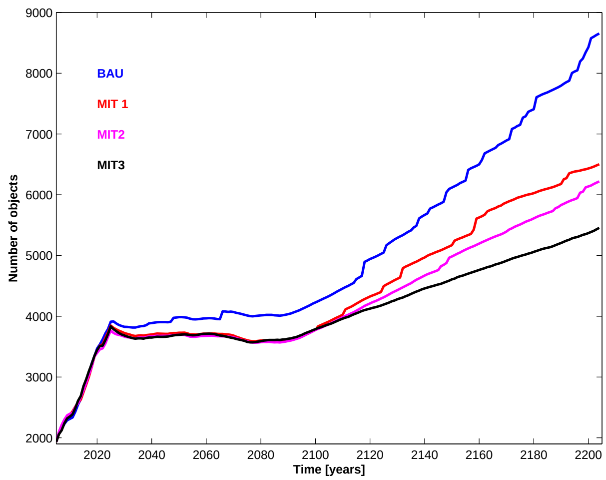


*Figure 5. As in Fig. 4, but showing only the average values of the 40 Monte Carlo runs.*

the Monte Carlo runs, along with one standard deviation from the mean, where applicable.

In Figs. 4 and 5 the effective number of objects larger than 10 cm in the MEO region (i.e., between $10\,000$ and $30\,000$ km of altitude) is shown. The effect of the mitigation measures is clearly visible in the reduction of about 25 % in the number of objects between the BAU case and the MIT1 or MIT2 cases. The MIT3 case displays a significantly lower number of objects: this is partly due to the fact that the elliptic disposal orbits spend just a fraction of their orbital period in the selected MEO shell, whereas the circular disposal orbits spend all their orbital period in the shell. The change of slope around the year 2025 is mainly due to the stop of in-orbit explosions.
Looking at the density of objects in Figs. 6 and 7, a number of considerations can be made. First, in all the cases an increase of a factor about 10 with respect to the initial

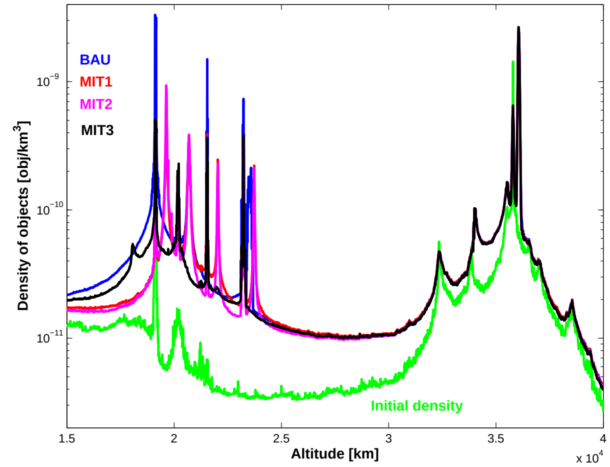


*Figure 6. Density of objects larger than 10 cm in the BAU (blue line), MIT1 (red line), MIT2 (magenta line) and MIT3 (black line) cases, in the MEO and GEO region in the year 2205. The green line shows the initial (year 2005) density.*

density is observed. The peaks of densities coincide with the navigation constellations operational orbits and with the disposal region. It can be noticed how in the BAU case (blue line), the highest peaks are reached in the operational orbits, whereas in the MIT1 and MIT2 cases the highest peaks pertain to the circular disposal orbits. The density in the MIT3 case (black line) shows a broader distribution, thanks to the imparted initial eccentricity (that is further growing during the simulation time span). Note anyway that the density evolution in the GEO region is basically unaffected by how the navigation constellations are managed.

Fig 8 shows the average eccentricity of all the disposed GALILEO satellites in the 40 Monte Carlo runs. It can be noticed how in the MIT2 scenario, where a particular value of the argument of perigee $\omega$ is targeted, the average eccentricity remains below $0.01$ for about 130 years and is below the MIT1 value for all the simulated time span. On the other hand, it should also be noticed how the average eccentricity, after a long time, tends anyway to grow, even in the case where a stable orbit was targeted. This might be partly due to dynamical effects, moving the satellites from the stable orbit after a long time, but also to long term numerical instability related to the choice of the internal accuracy of the orbital propagator [13].

Fig. 9 shows the cumulative number of fragmentations, averaged over the $40$ Monte Carlo runs, involving at least one object coming from the MEO region (i.e., whose semimajor axis is below $30\,000$ km, which means that collisions in the GEO region are not considered here). In Fig. 10 the expected cumulative number of collisions in the MEO region between objects larger than 10 cm is shown. As it is well known, the two plots show basically the same quantity, where Fig. 9 handles discrete collision events and Fig. 10 is based on the direct output of the collision probability evaluation algorithm (CUBE) at

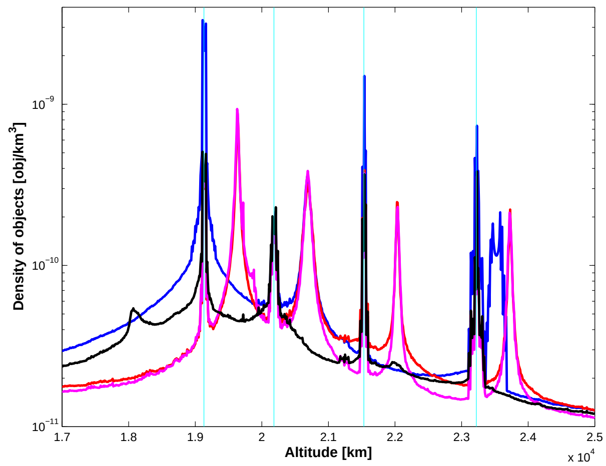


*Figure 7. Detail of the density of objects larger than 10 cm in the BAU (blue line), MIT1 (red line), MIT2 (magenta line) and MIT3 (black line) cases, in the MEO region, in the year 2205. The thin vertical lines mark the operational orbits of the navigation constellations (from left to right: GLONASS, GPS, GALILEO, COMPASS).*

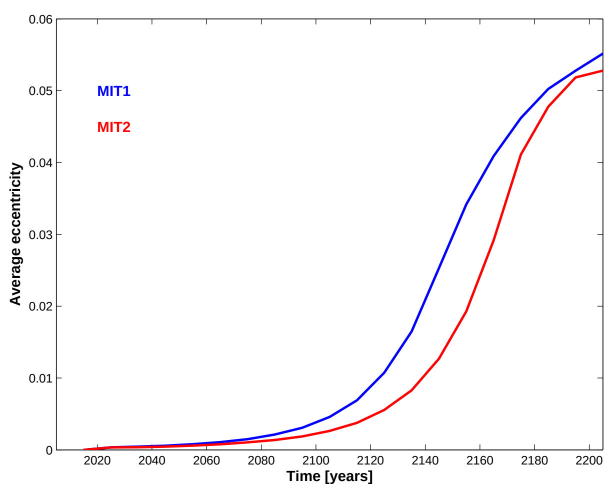


*Figure 8. Time evolution of the average eccentricity of the orbits of all the disposed GALILEO satellites, from all the 40 Monte Carlo runs. The blue line refers to the MIT1 scenario and the red line to the MIT2 scenario.*

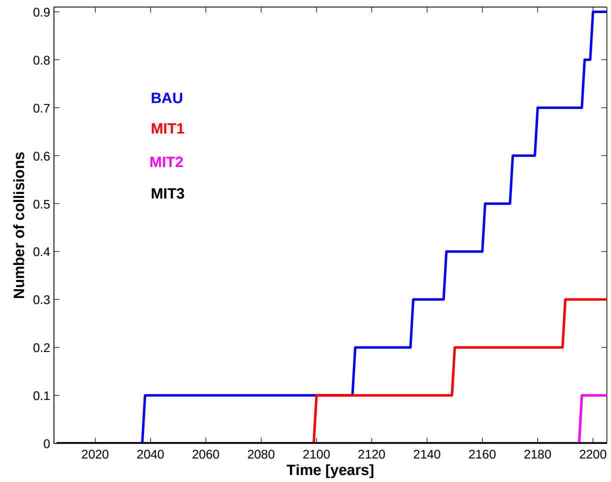


*Figure 9. Cumulative number of fragmentations, averaged over* 40 *Monte Carlo runs, in the BAU (blue line), MIT1 (red line), MIT2 (magenta line) and MIT3 (black line) cases, in the MEO region.*

each evaluation step. It can be noticed how the mitigation measures seem able to keep the collision rate in MEO at a negligible level, whereas the BAU scenario yields an average of about one collision in the investigated time span.
The location, in an Earth centered reference system, of all the collision induced breakups is shown in Fig. 11.

Fig. 12 shows how the majority of the fragmentation events involving MEO objects happen around the GLONASS orbit. It can be noted that all the 4 constellations suffer at least one collision in the BAU scenario. The most affected are GPS and GLONASS (mainly due to the large number of GLONASS spacecraft presently in space). 29 fragmentations involving non-operational GLONASS spacecraft and one collision between an operational and a non-operational GLONASS spacecraft are recorded. One collision between a non-operational GLONASS and a non-operational GPS is recorded too. A collision between two non-operational GALILEO spacecraft is also recorded and the proximity between GALILEO and COMPASS leads to a collision between an operational COMPASS spacecraft and a non-operational GALILEO satellite. One collision between an upper stage in GTO and a GEO operational spacecraft is recorded too. As a comparison, note that, in the 40 Monte Carlo runs of the MIT 1 case, 11 fragmentations involving MEO objects were recorded. Out of these, 3 collisions were between upper stages in GTO and uncontrolled GEO satellites, 3 were between non-operational GLONASS satellites, 1 was between an upper stage in GTO and an upper stage in GEO, 1 was between two GTO upper stages, 1 was between non-operational GPS satellites, one between an operational and a non-operational COMPASS satellite and the last 2 between non-operational COMPASS satellites. In the MIT 2 case only 6 fragmentations involving MEO objects were recorded. Out of these, 2 collisions were between upper stages in GTO and uncontrolled GEO satellites, 2

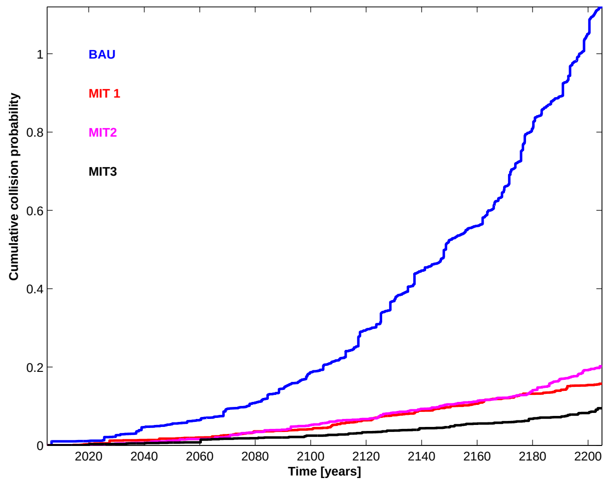


*Figure 10. Expected cumulative number of collisions in the BAU (blue line), MIT1 (red line), MIT2 (magenta line) and MIT3 (black line) cases, in the MEO region.*

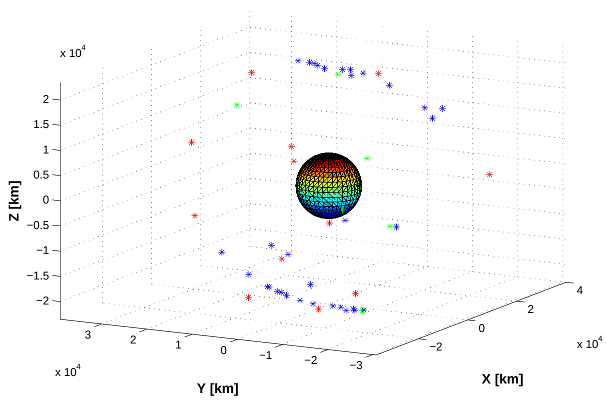


*Figure 11. Location, in Earth centered Cartesian coordinates, of the collision induced breakups recorded in 40 Monte Carlo runs, involving at least one MEO object: BAU (blue asterisks), MIT1 (red asterisks), MIT2 (green asterisks).*

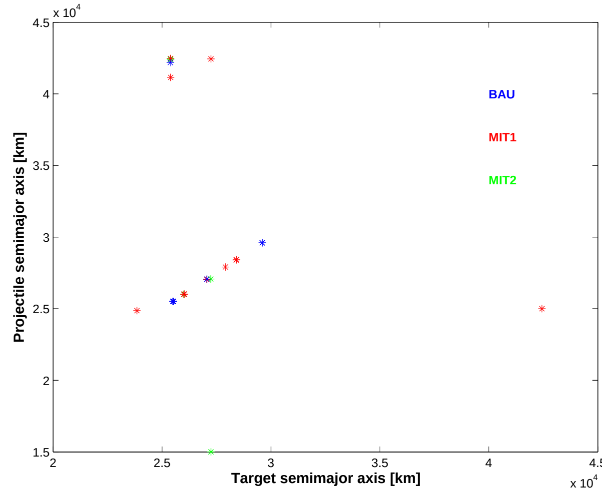


*Figure 12. Semimajor axis of the targets and projectiles involved in all the MEO fragmentations recorded in the 40 Monte Carlo runs of the 4 cases. Note that, as explained in the text, no collision involving MEO objects is recorded in the MIT3 case and that several occurrences in the BAU case appear superimposed in the plot, around the GLONASS orbit semimajor axis.*

were between non-operational GLONASS satellites, one was between a GTO upper stage and a non-operational GPS satellite and the last one was between a GTO upper stage and a navigation constellation upper stage. In the MIT 3 scenario no fragmentation was recorded in MEO in all the 40 Monte Carlo runs.

As a conclusion, it can be stated that an accurate management of the MEO region, with de-orbiting of upper stages and re-orbiting of satellites at the end-of-life, can guarantee a long term stability of the environment with very low collision risk, compatible with the delicate mission of the navigation constellations satellites. On the other hand, it should be stressed that, similarly to the LEO region, the non disposal of the upper stages significantly increases the long term growth of the collision risk in the region. Moreover, from a collisional risk point of view, the disposal on moderately eccentric orbits, with initial perigees at lower altitude with respect to the operational height, appears slightly favorable and has no negative influence on the collision risk in the GEO protected region. In addition, as seen in Fig 13, after about 80–100 years, the satellites disposed on unstable eccentric orbits start to reenter into the atmosphere, thus reducing the number of objects in Earth orbit. It should be noticed that these reentering satellites spend a negligible part of their lifetime in Low Earth Orbit and, therefore, do not increase in any significant way the overall collision risk in LEO [4]. The instability of the MEO disposal orbits, while possibly problematic from the operational point of view, apparently does not pose a sensible collision risk on the active navigation satellites.

Of course, the picture might change if a considerably higher traffic will take place in the future exploitation of

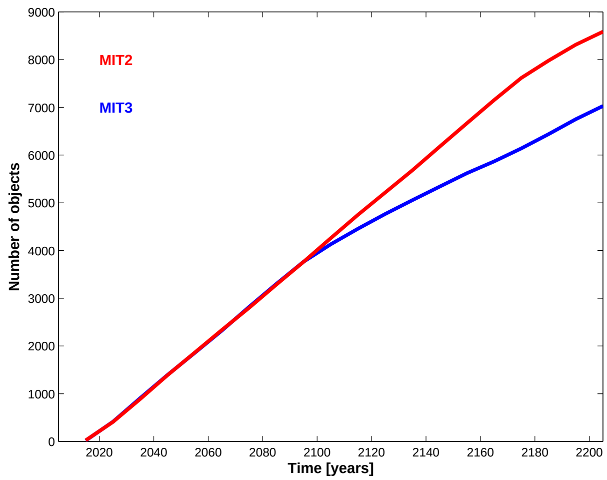


*Figure 13. Number of disposed GALILEO satellites present in space as a function of time, in the MIT2 (red line) and MIT3 (blue line) cases, in all the 40 Monte Carlo runs. Note how, after about 80–90 years from the beginning of the simulation, the two lines start to diverge due to the reentry of the satellites disposed on initially eccentric orbits.*

the MEO region.

## 4. ACKNOWLEDGMENTS

The work described in this paper was carried out in the framework of the European Space Agency ESOC Contract No. 18423/04/D/HK to ISTI/CNR.

## REFERENCES

[1] Anselmo, L., Cordelli, A., Farinella, P., Pardini, A. & Rossi, A. (1996). Final Report, Study on Long Term Evolution of Earth Orbiting Debris, ESA/ESOC Contract No. 10034/92/D/IM(SC), Consorzio Pisa Ricerche, Pisa, Italy.

[2] Gick, R.A. & Chao, C.C. (2001). GPS disposal orbit stability and sensitivity study, *Advances in the Astronautical Sciences*, **108**, 2005–2018.

[3] Hughes, S. (1980). Earth satellite orbits with resonant lunisolar perturbations. I. Resonances dependent only on inclination, *Proc. R. Soc. Lond. A.*, **372**, 243–264.

[4] Jehn, R., Rossi, A., Tim, F. & Navarro, D. (2009). Reorbiting of Satellites in High Altitudes. In Proc. $5^{th}$ European Conference on Space Debris (Ed. H. Lacoste), ESA SP-672 (CD-ROM), ESA Publications Division, European Space Agency, Noordwijk, The Netherlands.

[5] Jenkin, A.B. & Gick, R.A. (2003). Collision Risk Posed to the Global Positioning System by Disposal Orbit Instability, *Journal of Spacecraft and Rockets*, **39** (4), 532–539.

[6] Jenkin, A.B. & Gick, R.A. (2005). Dilution of disposal orbit collision risk for the medium Earth orbit constellations. In Proc. of the Fourth European Conference on Space Debris (Ed. D. Danesy), ESA SP-587, Darmstadt, Germany, 18–20 April 2005, pp. 309–314.

[7] Johnson, N.L., Krisko, P.H., Liou, J.C. & Anz-Meador, P.D. (2001). NASA's New Breakup Model of EVOLVE 4.0, *Adv. Space Res.*, **28** (9), 1377-1384.

[8] Liou, J.-C. (2006). Collision Activities in the Future Orbital Debris Environment, *Adv. Space Res.*, **38**, 2102–2106.

[9] Rossi, A., Cordelli, A., Pardini, C., Anselmo, L. & Farinella, P. (1995). Modelling the Space Debris Environment: Two New Computer Codes, paper AAS 95-186, In Spaceflight Mechanics 1995, *Advances in the Astronautical Sciences*, **89**, Univelt Inc., San Diego, California, pp. 1217 – 1231.

[10] Rossi, A., Anselmo, L., Pardini, C. & Valsecchi, G.B. (2004). Final Report, Upgrade of the Semi-Deterministic Model to Study the Long Term Evolution of the Space Debris. ESA/ESOC Contract No. 15857/01/D/HK(SC), ISTI/CNR. Pisa, Italy.

[11] Rossi, A.,Valsecchi, G.B. &. Perozzi, E. (2004) Risk of collision for the navigation constellations: the case of the forthcoming GALILEO, *The Journal of the Astronautical Sciences*, **52**, 455-474.

[12] Rossi, A. (2008). Resonant Dynamics of Medium Earth Orbits: space debris issues, *Celestial mechanics and Dynamical Astronomy*, **100**, 267-286.

[13] Rossi, A., Anselmo, L., Pardini, C. & Valsecchi, G.B. (2009). Final Report, Semi-Deterministic Model. ESA/ESOC Contract No. 18423/04/D/HK, ISTI/CNR, Pisa, Italy.