LONG-TERM IMPLICATIONS OF GNSS DISPOSAL STRATEGIES FOR THE SPACE DEBRIS ENVIRONMENT

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ABSTRACT

Current situation derived from space object density is a concern in the Low Earth Orbit and Geosynchronous Orbital regimes. The large number of active and inactive objects in these regions has led to the creation of space debris mitigation guidelines, which attempt to limit the future growth of the population by defining the procedures that should be followed when decommissioning spacecraft. In the LEO regime, re-entry disposal strategies are often applied, ensuring that objects remain in orbit less than 25 years once the operational lifetime is finished. On the contrary, GEO objects are normally put in the so-called graveyard orbit, out of the GEO band, ensuring they will not enter into the GEO protected region in the medium term.

The current situation in the Medium Earth Orbit (MEO) has not yet required defining mitigation measures. But with the increase in the number of objects in this regime, coming from the deployment of several constellations devoted for global navigation systems, an increasing interest exists in analysing the need of disposal strategies and the identification of the most appropriate disposal approach.

The MEO region will be populated with four complete navigation systems, all of them in relatively close orbital altitudes: The American GPS, Russian GLONASS, European Galileo and Chinese BeiDou. Considering these constellation satellites, the mission related objects derived from their launches and the de-commissioned satellites, disposal approaches shall be defined in order to avoid jeopardizing the altitude band suitable for such constellations.

Because of their distances to Earth, ordinary disposal manoeuvres leading to a direct or delayed re-entry due to atmospheric drag are not feasible, as they require unrealistic fuel budgets. The dynamics of MEO orbigs suggest two feasible approaches for such disposal activities: disposal to stable graveyard orbits, or disposal to eccentricity build-up orbits.

For the first case, a minimum safe distance to the active constellation altitude is desired to be kept for 200 years after the disposal, and thus very stable orbits need to be achieved.

The eccentricity build-up strategy makes use of resonance effects between the Earth's geopotential, the Sun and the Moon. Depending on the orbit's initial conditions, a large eccentricity build-up takes place, which can lead to a re-entry of the satellite on the long term.

This paper summarises the results from simulating the commissioning and maintenance of the four aforementioned constellations, and the complete space debris population over 200 years. Three different disposal strategies were simulated for the four constellations: One business-as-usual scenario, in which the disposal is performed as currently envisaged, one graveyard disposal scenario, and one eccentricity disposal scenario. The Delta-V cost of the disposal manoeuvres is computed for all the simulated navigation satellites. The results are assessed in terms of spatial density increases as well as collision risk and to-be expected manoeuvre rates for both navigation satellites and typical satellites missions in LEO and GEO.

The results of these simulations show that the lowest risk for the constellation satellites can be achieved by disposing to stable orbits. Nevertheless, the overall collision risk from disposed navigation satellites and upper stages in these orbits is very low compared to typical LEO and GEO risks in all simulated scenarios. Similar, in the time frame considered, the effect of disposed navigation satellites in LEO and GEO is almost negligible.

Key words: GNSS; MEO; Long-term evolution.

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1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) are considered a critical asset by all major powers in the world. The availability and reliability of GNSS is currently critical for the world economy. Apart from this, and because of their potential use for military applications, major powers strive to control and operate a navigation system. At this point, four GNSS systems are deployed or in deployment phase: GPS (Global Positioning System), GLONASS (*Globalnaya Navigatsionnaya Sputnikovaya Sistema*). Galileo and BeiDou. All these systems rely on a constellation of satellites distributed in several orbital planes in the MEO region. The BeiDou system, as well as some regional augmentation systems rely on additional geostationary and/or geosynchronous, that are not the focus of this study.

As mentioned above, the four GNSS systems are in different phases of deployment. The study presented here was carried out between 2014 and 2015, and reflects the status and predicted evolution of the constellations at that time. At that time, both GPS and GLONASS were at operational phase, while Galileo and BeiDou were in their initial deployment phases.

For the four GNSS we simulated the future evolution of the constellation (in terms of launch and decommissioning rates) for 200 years, and considered three different overall approaches for the end-of-life disposal: A baseline scenario, based on what is currently being done, a graveyard scenario, in which all disposed satellites are placed in a long-term stable orbit, and an eccentricity growth scenario, in which the chosen disposal orbit is chosen to leverage the orbital perturbations happening in the MEO region, with the objective of making the disposed spacecraft re-enter the Earth after a long period.

Several resonant perturbations related by the combined effect of the Sun, the Moon and the Earth's gravitational potential belonging to the inclination dependant resonances exist. These are described in [1].Rossi [2] determined that, for MEO orbits, several combinations of the Ω and ω of a disposed satellite lead to such a large long-term increase in the eccentricity that would allow a satellite to re-enter the Earth. We attempt to minimise this effect in the graveyard scenario, and to maximise it in the eccentricity growth one.

Results from the same study were already published in [3] and [4].

2. SIMULATION

In order to assess the impact of the growth of the aforementioned constellations, it was necessary to simulate both the whole near-Earth environment itself (without the GNSS satellites), and the four GNSS constellations for 200 years. This was carried out with the Long-Term utility for Collision Analysis (LUCA) ([5]), that produces space debris populations. These populations were later processed and converted to probability density tables that were used within ESA MASTER-2009 [6]. Finally, collision risk was assessed with the Assessment of Risk Event Statistics (ARES) tool ([7]), which is a part of the ESA Debris Risk Assessment and Mitigation Analysis (DRAMA) suite ([8]). For the collision risks, average cross section areas for all the involved objects were computed by gathering their geometry information from disparate sources and by using the CROC (CRoss Section Of Complex bodies) tool, also from the ESA DRAMA suite ([9]).

For the four constellations, their nominal orbital configuration (as shown in 1) was chosen. The drift rate of the orbital planes for each constellation was determined with FLORA, whereas the initial location of the planes was deduced for constellations which were active at the moment of performing the study (GPS and GLONASS) and set to arbitrary values for Galileo and BeiDou.

For each of the simulated constellations, an station-keeping plan was devised. These plans were devised to keep the RAAN of each individual satellite within the nominal bounds of its constellation. This does not necessarily match the station-keeping plans of current GNSS constellations.

2.1. Launch rates

The four GNSS constellations were simulated by assuming a constant lifetime for each individual spacecraft. Therefore, whenever any spacecraft reached its end-of-life, its disposal was simulated, and a new spacecraft was inserted into the simulation in order to replace the former one. The lifetime was determined by comparing the advertised and actual lifetimes for old GPS and GLONASS satellites. Then, a factor comparing the average lifetime against the advertised one was determined for each constellation. This average lifetime factor was determined to be 2 for GPS and 1.9 for GLONASS. In order for the simulation to be conservative, these factors were reduced to 0.75 times their computed values. For Galileo and BeiDou, there were no decommissioned satellites at the time of the study, so this factor could not be computed. Therefore, the same value as for GPS was chosen. Table 1 shows the final average lifetimes.

At the time of performing the simulations, GPS and GLONASS were already in operational state, therefore, we just needed to simulate the replacement of spacecraft once they were decommissioned. For Galileo and BeiDou, however, we had to assume a build-up phase (until year 2020) and then a maintenance phase. The year 2020 was chosen, as the operators of both constellations claimed, at the time of the study, that they would reach a fully operational status by that date.

Table 1. Nominal simulation parameters for all the constellations

Param.	GPS	GLONASS	Galileo	BeiDou
# planes	6	3	3	3
a (km)	26560	25508	29600	27906
e (-)	0.0088	0.0012	0.001	0.0023
i (deg)	54.82	64.8	56	55.13
life (yr)	22.5	14.5	18	7.5
sats/yr	1.3	2.1	1.7	3.6

Table 2. Nominal simulation parameters for all the mission-related Rocket Bodies

Param.	GPS	GLONASS	Galileo	BeiDou
sats/RB	1	6,2	2	4
$h_a (km)$	22005	20349 19694	23600	21591
$h_p (km)$	20352	19924 19280	23470	180

2.2. Mission-related objects and mission profiles

In order to correctly assess the impact of deployment of GNSS constellations in the near Earth environment, it is also necessary to consider all the mission-related objects. For the simulations, we assumed the following launcher configuration and satellites per launch.

- GPS: We assume that future launches will be performed at a rate of 1 satellite/launch.
- GLONASS: 50% of the launches performed with Soyuz (2 satellites/launch) and 50% of the launches performed with Proton (6 satellites/launch).
- Galileo: For Galileo, we were able to perform the simulations with some information provided by ESA. For the build-up phase (2013-2020), we assumed the satellite launches were split equally between Ariane 5 and Soyuz-Fregat. After the build-up phase, all launches were done assuming Soyuz-Fregat ant 2 satellites/launch.
- BeiDou: We assumed 2 satellites/launch during the build-up phase (2013-2020), and 3 satellites/launch during the maintenance phase.

Table 2 shows the detailed orbital parameters assumed for each of the simulated cases. All the simulated SMAs were dispersed around the nominal parameters listed in the table. Inclination and RAANs were initially set equal to those of the related GNSS vehicles. The AoP and True anomalies were randomly chose for each individual rocket body.

2.3. Spacecraft and cross sections

We have considered the cross sections for all the past GNSS satellites models for accurately modelling the collision risks. All new launches have been assumed to be of the latest spacecraft types of each constellation. Figures 1 and 2 show two examples, as well as the computed cross section from any aspect angle. Table 3 shows all the computed cross section areas.

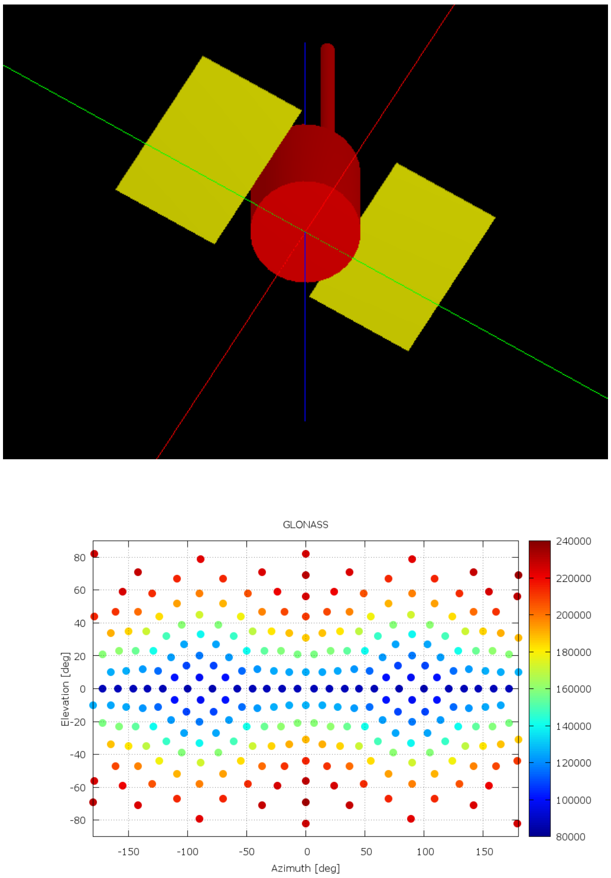

Figure 1. GLONASS model and cross sections from different aspect angles (cm^2)

2.4. Disposal strategies

Two different approaches for the future disposal strategies have been considered, along with a third one (referred to as the *business as usual* scenario).

The *graveyard* scenario assumes that each disposed satellite is displaced to an orbit that guarantees long-term stability. The criterion chosen was to ensure that the

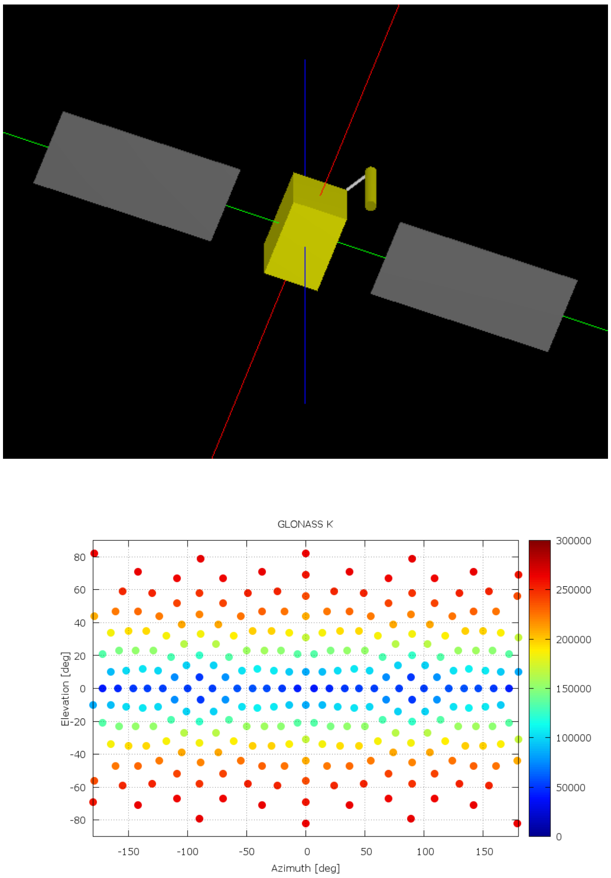

Figure 2. GLONASS-K model and cross sections from different aspect angles (cm^2)

minimum distance between each disposed satellite and the nominal operational orbit of its corresponding GNSS constellation is always larger than a per-constellation selected limit.

The *eccentricity growth* scenario assumes that, for each disposed satellite, a decommissioning manoeuvre that maximises the eccentricity growth and a re-entry after at most 200 years is sought.

In the no *disposal scenario*, we simulated the behaviour we have observed from GPS and GLONASS operators. For GPS, we determined that end-of-life disposal manoeuvres have been carried out. Most of them involved a moderately large increase in the semi-major axis ($1100km$ in average). For GLONASS, we observed that, apparently. no end-of-life disposal manoeuvres were done in the past. For Galileo and BeiDou, as there were no disposed satellites in the moment of writing this work, we did some assumptions. We assumed for Galileo a similar behaviour as GPS (disposal to a graveyard orbit with no particular effort for ensuring long-term stability). In the Galileo case, the simulated semi-major axis increase was between $300km$ and $400km$. Finally, for BeiDou, there was little information available at the time of the study. Therefore, the simplest approach (no disposal manoeuvre) was selected for BeiDou.

Table 3. Collision cross sections for all simulated GNSS spacecraft types (m^2)

Type	Average cross section (m^2)
GPS Block I	5.496
GPS Block II and II-A	9.219
GPS Block IIR and IIRM	11.422
GPS Block IIF	15.973
GPS Block III	22.843
GLONASS	15.837
GLONASS-M	23.046
GLONASS-K1 and K2	16.674
GIOVE-A	7.123
GIOVE-B	7.564
Galileo-IOV	11.612
Galileo-FOC	16.875
BeiDou-M	12.575

2.5. Disposal orbits and decommissioning manoeuvres

Decommissioning is simulated as a set of manoeuvres that are performed when each of the active satellites in the simulation reach their end-of-life (Table 1). For each satellite and strategy, we had a decommissioning requirement (long-term stability for the graveyard scenario or eventual reentry for the eccentricity growth scenario). Therefore, a disposal orbit is required for each simulated satellite. In order to evaluate if that disposal is correct, it would be necessary to propagate it for 200 years, in order to verify that it is stable, or it allows re-entry. The aforementioned approach would require a huge computational effort. In order to perform an adequate simulation with a modest computational effort, we limited the number of initial disposal orbits by means of pre-computed evolution maps.

For each simulated GNSS constellation and disposal strategy, we considered only disposal orbits with a fixed increase in the semi-major axis, and fixed initial eccentricities, and a small set of initial inclinations. With these orbital elements fixed, the choice of a disposal orbit is limited to selecting a pair of values for the RAAN and AoP. Figure 3 depicts an example of this for the Galileo eccentricity growth. A single evolution map per simulated year was computed.

Table 4 shows the fixed orbital elements for each constellation and disposal scenario. The requirement of minimum distance to the nominal constellation (for the graveyard scenario) and the maximum time to re-entry (for the

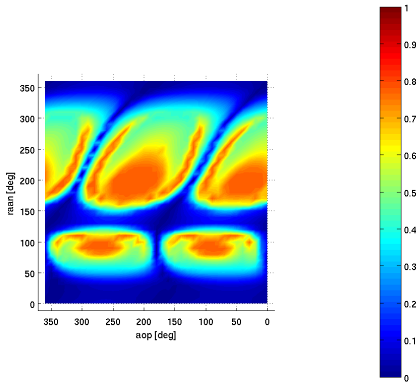

Figure 3. Maximum eccentricity (in 200 years) for Galileo disposal orbits. Simulation year 2020, inclination 55^o, eccentricity growth scenario

Table 4. Disposal orbits for graveyard (first block) and eccentricity growth(second block)

	GPS	GLONASS	Galileo	BeiDou
$\Delta a(km)$	$+800$	$+500$	$+350$	$+500$
$ecc(-)$	0.001	0.001	0.001	0.001
Dist (km)	550	100	100	100
$\Delta a(km)$	$+1100$	$+500$	-500	-500
$ecc(-)$	0.02	0.01	0.01	0.01
Time (yr)	200	200	200	200

eccentricity growth scenario) are also shown.

When considering the disposal of a particular satellite, all the available evolution maps are used for choosing a disposal orbit are retrieved. Then, a set of inclination, RAAN and AoP is chosen from them. The choices are further limited to those disposal orbits that can be reached from the initial orbit with a ΔV expense smaller than $0.6km/s$. The ΔV required is computed with a Hohmann transfer to achieve the increase in SMA listed in Table 4, and a combined RAAN/inclination manoeuvre afterwards. Notice that this approach is an approximation that does not take the changes of eccentricities into account, nor yields an optimised manoeuvre. We allowed disposal manoeuvres up to $0.6km/s$ (a relatively large value) in order to compensate for the lack of optimisation in the disposal manoeuvres.

The ΔV finally constraints the range of possible inclination, RAAN and AoP to a subset of all those that existed in the evolution maps. The finally chosen disposal orbit is the one that allows to fulfil the disposal scenario requirement with the minimum ΔV expense. In case no valid disposal orbit is found within the fixed ΔV limit, the chosen disposal manoeuvre is the *best effort* one. The disposal orbit that comes closer to the fixed requirement of minimum distance or time to reentry is selected.

3. RESULTS OF THE LONG-TERM SIMULATIONS

In order to be able to compute the contribution of GNSS satellites and related objects to the overall population, the overall population itself had to be simulated.This population included clouds from explosions and collisions, new (non GNSS) launches, based on ESA MASTER future launch projections, all GNNS launches and related objects, and additional space debris sources. For each disposal scenario, 48 Monte-Carlo runs were executed, and their results averaged. Figures 4 and 5 show the evolution of the simulated GNSS populations.

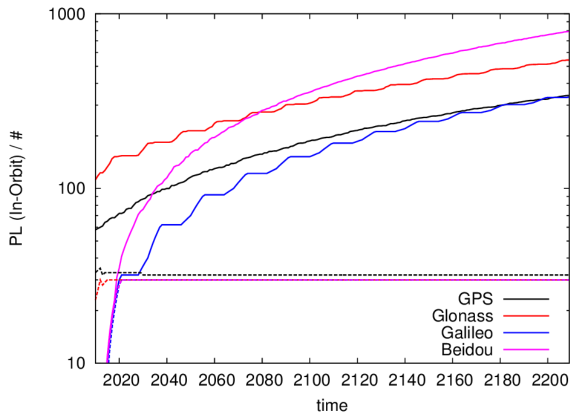

Figure 4. Number of simulated satellites in the simulations. Dashed lines correspond to active satellites, and solid lines to the overall. These number are identical for all the Monte-Carlo runs and all the scenarios

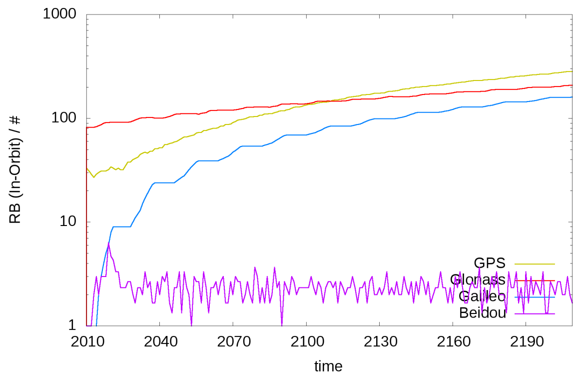

Figure 5. Number of simulated GNSS-related rocket bodies in the simulations

In the no disposal scenario, there was not a single catastrophic collision involving the GNSS objects. There was, however, a non-catastrophic collision that happened in a single Monte Carlo, between a GLONASS payload and a small simulated mission related object (diameter slightly above $5cm$).

In the eccentriciy growth scenario, one catastrophic collision happened between an old GLONASS-related rocket body (launched in 1990) and a simulated SL-16 rocket body.

Finally, in the graveyard scenario: in one Monte-Carlo run, two disposed BeiDou satellites collided in 2085, and in another run, two disposed GLONASS objects collided in 2182.

4. EVOLUTION OF DISPOSAL SCENARIOS AND COLLISION RISKS

The simulated scenarios were executed assuming the same set of disposal rules for all the constellations at once. Therefore, we can see the effect of the disposal policy of each constellation on itself and the environment, and also some interactions that might arise between objects from different constellations. Figure 6 shows an overview for the four scenarios.

4.1. Effects on the nominal GNSS constellations

The graveyard and eccentricity growth strategies remove the disposed satellites from the nominal altitudes, thus the risk on active satellites caused by disposed satellites is zero initially.

For eccentricity growth the risk turns to non-zero levels when the eccentricity buildup reaches levels where the altitudes covered by the orbit reach the altitude band of the operational constellation. This risk may be damped by the differential drift in RAAN between the disposed spacecraft and the plane it was disposed from. For graveyard orbits the risk should remain non-zero for a long time.

In this respect the no disposal case should be in between these scenarios since some objects end in orbits with a relatively large eccentricity growth and some with small. Additionally, for the cases without any altitude change (GLONASS and Beidou) an overlap in altitude is present from the beginning leading to a non-zero risk.

Disposed satellites can pose a threat not only to the constellation they came from, but also to the other GNSS constellations. In this document, we call this cross-effect. Cross-effects can be two-fold:

- A direct cross effect happens when a constellation disposes its satellites near the nominal altitude of other constellation. When this scenario happens, the target constellation starts seeing risk coming from the chasers very soon, unless the eccentricity growth of the chasers is well constrained.

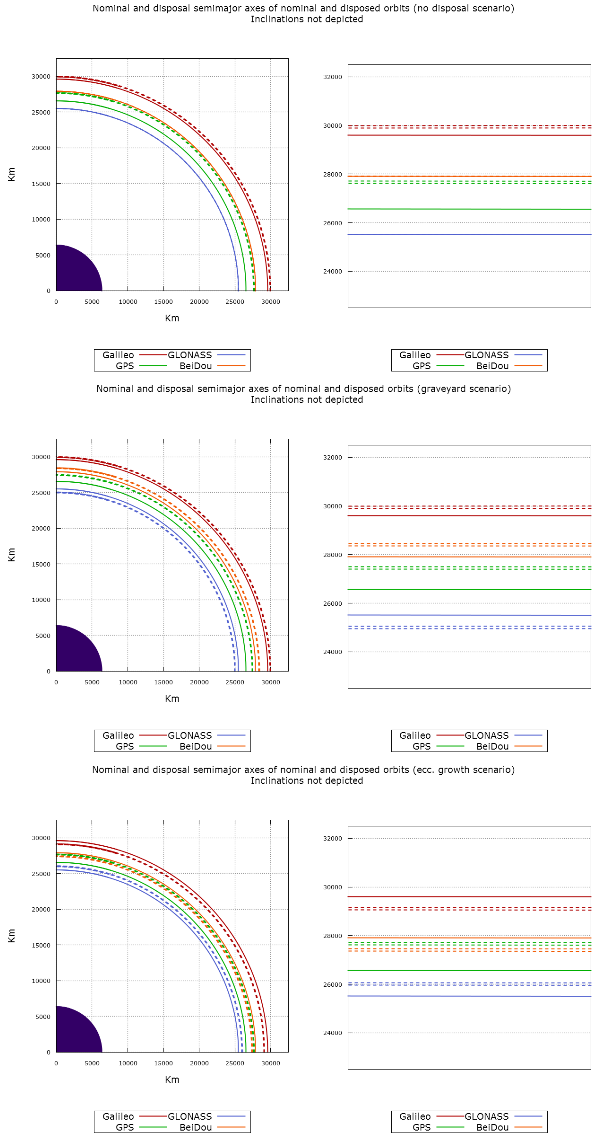

Figure 6. Representation of nominal (solid) and initial disposal orbits (dashed, interval) for the no disposal, graveyard, and eccentricity growth scenarios

- An indirect cross-effect happens when a constellation sees risks from satellites from other constellations, which were disposed far away. Given enough time, the eccentricity growth allows them to reach the nominal altitude of the “victim” constellation.Due to the long times required for eccentricity to build-up (particularly, if this effect was not sought), and the differential drift of orbital parameters, a slight and late influence is expected from this effect.

Another potential threat of disposed satellites on active constellation is via fragments: In the event of a fragmentation (for example, a collision between two objects in a graveyard orbit), all the resulting fragments could pose a risk to virtually every object in the GNSS constellations (provided there is enough time for the eccentricity to build up).

GPS faces low risks, as seen in Figure 7. This is due to the fact that satellites are removed from the nominal constellations in all three scenarios, and the overall number of satellites in orbit is low (because of the large lifetimes assumed). In addition to this, in the no disposal and graveyard scenarios, other constellations do not dispose satellites near the GPS constellation. Therefore, the cross effects are slight and delayed in time. In eccentricity growth, GLONASS satellites are put near GPS nominal orbit, thus the sudden increase of the blue curve around 2060, forty years after the disposal operations began.

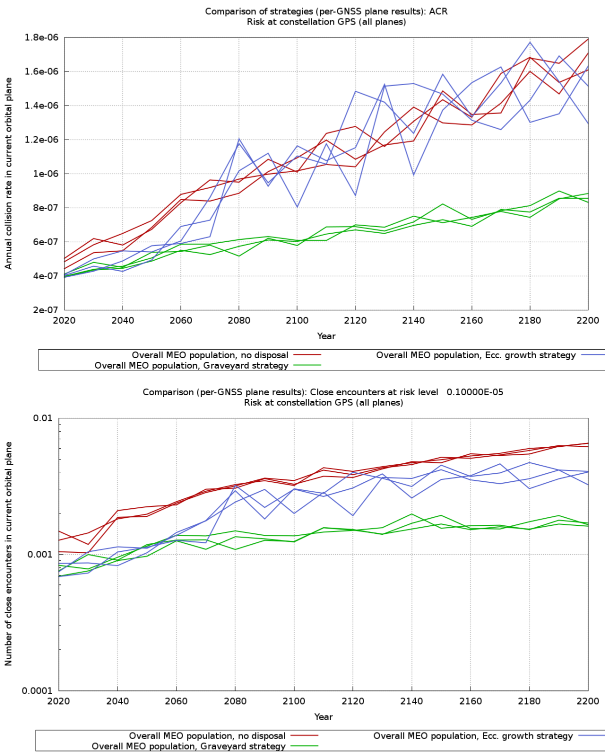

Figure 7. Comparison of annual collision risks and close approaches on the nominal GPS constellation on three orbital planes for all the disposal scenarios

GLONASS (Figure 8) faces higher risks than GPS. The constellation is partly penalised by old GLONASS satellites which have already been left drifting in the past, and are present in all the studied scenarios. No cross effects are noticeable. This is due to the GLONASS constellation being at one edge of the ring formed by MEO constellations (see Figure 6). In all scenarios, disposed GPS satellites (the nearest constellation) are displaced far from GLONASS constellation. In addition to this, the nominal inclination of the GLONASS constellation is quite different from the inclinations of the rest of the constellations, thus greatly reducing the likelihood of close encounters with object from the other constellations.

For **Galileo**, Figure 9 shows that the number of encounters per year increases with time. Also, for Galileo, the

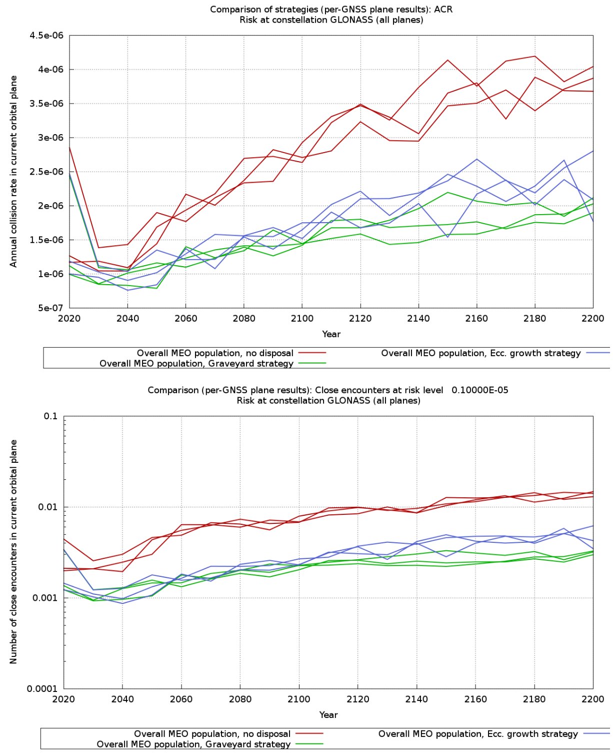

Figure 8. Comparison of annual collision risks and close approaches on the nominal GLONASS constellation on three orbital planes for all the disposal scenarios

adoption of eccentricity growth strategy implies results slightly better than the no disposal case. We determined that, until the simulation year 2120, practically all the computed risks (and close approach rates) were caused by Galileo-related objects. From the year 2120 onwards, disposed objects from other constellations started contributing to the risks faced by Galileo. For the no disposal and eccentricity growth scenarios, up to half the total risk is due to foreign constellation objects at the end of the simulation time frame. On the other side, the graveyard strategy is successful in keeping decommissioned satellites far from the nominal orbit and therefore those objects don't contribute significantly to the overall collision risk. Therefore, the graveyard strategy is the most successful in keeping decommissioned satellites far from the nominal orbit.

Considering the accuracy of Galileo orbit determination, and assuming that debris objects are tracked with covariances as per CDM (Conjunction Data Message), it is possible to predict the number of close encounters at certain collision probability levels, as shown in Figure 9. The number of close encounters increases steadily with time, and is similar for all strategy types (although the graveyard strategy is safest).

BeiDou (Figure 10) faces the highest risks of all constellations. In this case, the small lifetime we selected for the simulations leads to a large number of disposed satellites, and thus an increased risk. In the no disposal scenario,

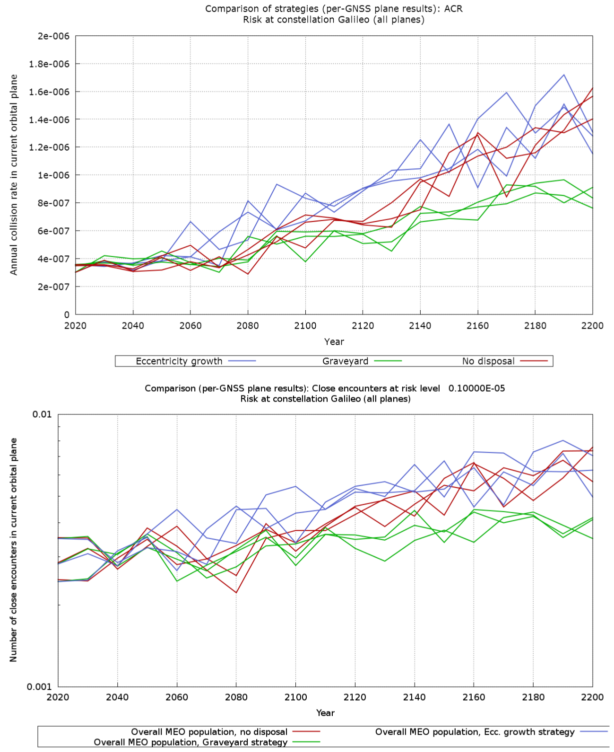

Figure 9. Comparison of annual collision risks and close approaches on the nominal Galileo constellation on three orbital planes for all the disposal scenarios

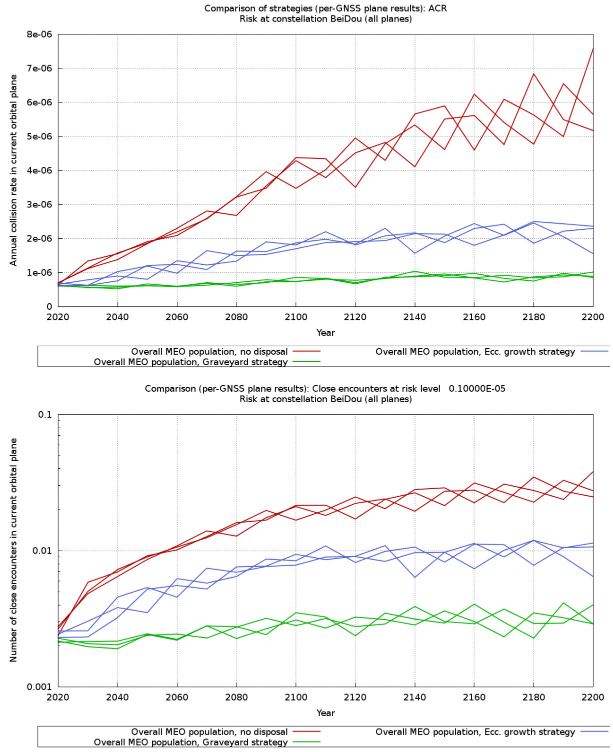

Figure 10. Comparison of annual collision risks and close approaches on the nominal BeiDou constellation on three orbital planes for all the disposal scenarios

two effects show up: Disposed BeiDou satellites are assumed to be left to drift, and a cross effect from GPS satellites, which are disposed into an orbit 250 km away from the BeiDou nominal altitude. In this case, up to 0.03 encounters per plane and year can be expected. The graveyard scenario behaves quite similarly to the other constellations. As for eccentricity growth, it is also penalised by the large number of disposed satellites.

4.2. Effects on the LEO and GEO regions

One of the proposed scenarios, the eccentricity growth, aims at achieving the passive re-entry of disposed objects by means of an increase of the eccentricity until its perigee is within the Earth atmosphere. This happens during a long period, and there will be a period of time in which the perigee will be within the protected LEO region and the apogee within the altitudes considered for the GEO region. Therefore, a non-zero risk may exist related to these objects. We observed that, in these cases, the eccentricity growth made them reach, on the first place, the nominal altitudes of nearby constellations, then the GEO region and, in the last place, the LEO region. As we had aimed for a re-entry after 200 years, the arrival at the LEO region happened approximately after 200 years simulated time.

For the LEO region, our simulations shown that the simulated GNSS payloads started arriving at the LEO region at year 2200 (as we had aimed for a 200-year re-entry time). The effect we observed in the spatial density in LEO was of around $4 \cdot 10^{-14} (1/km^3)$, which is several orders of magnitude below the normal contributions from other sources. It must be borne in mind that, apart from the relatively low number of GNSS objects in LEO (compared with the contributions from LEO objects themselves), the objects in an eccentricity growth orbit spend only a small fraction of their orbital periods within the LEO region, therefore their contribution to the spatial density there is also minimised.

The effect of disposed satellites in GEO is very faint, because satellites which eventually reach the GEO ring reach it with a high inclination (the one they had at disposal time, accounting for its drift). Thus, the overlapping region between the GEO ring (0^o nominal inclination) and disposed satellites is small. In addition to this, disposed satellites are spread in a large region, thus reducing the overall spatial density. The case with the largest influence in the GEO region is the eccentricity growth. In this case, our simulations shown that the spatial densities caused by the GNSS-related objects at GEO altitudes are around $3 \cdot 10^{-14} (1/km^3)$. In this case, the effect of these objects is observed from the year 2120 onwards (well before any object arrives at the LEO altitudes). We simulated the annual collision risks of three typical operative GEO satellite against the disposed GNSS objects, and found them to be exactly zero until simulation year 2180. However, the ACRs after that date are of the order of $1 \cdot 10^{-9}$ at most. This is well below what is encountered routinely, and shows that the contribution of disposed GNSS objects to the risks in GEO is basically negligible.

There is a more relevant contribution to the risks in the LEO and GEO regions, which is the one from the mission-related rocket bodies. Table 2 shows an overview of how these objects were simulated. In LEO, we observe an initial spike of spatial density caused by GNSS-related rocket bodies, lasting until year 2040, followed by an almost constant contribution. The initial spatial density spike was of about $1.5 \cdot 10^{-11}(1/km^3)$, and the constant contribution of about $5 \cdot 10^{-12}(1/km^3)$. These contributions are overall small, but several orders of magnitude larger than those related to the GNSS vehicles themselves. They also appear in all the scenarios. It is worth noting that the contribution in LEO is mostly related to the BeiDou rocket bodies. We simulated the BeiDou rocket bodies with a low perigee (180 km) that leads to a re-entry a few years after. The initial spike we observed was related to the simulated build-up phase for BeiDou, when all the rocket bodies related to that phase re-entered, a steady state was reached, with the new BeiDou launches adding to the sum, and the re-entering ones removing from the sum. It is also likely that rocket bodies from the other constellations might have contributed to the spatial densities in LEO and GEO. As they are subject to the same perturbations, they might have undergone an eccentricity growth similarly to the disposed GNSS vehicles. When setting the initial orbits of the rocket bodies, this effect was neither sought nor avoided. However, in view of the previous results, it is expectable that the contributions from non-BeiDou rocket bodies to the risk in LEO and GEO is negligible.

5. CONCLUSIONS

From the results presented here, the following conclusions can be reached:

- When considering the long-term behaviour of disposed satellites in the MEO region, it is necessary to consider the long-term eccentricity growth effect. A suitable propagator which includes the relevant perturbations must be used for this. Moderately long propagation times must be considered.
- The absolute levels of the collision risk induced by the disposed objects are very small for all disposal scenarios. The choice of the disposal strategy will thus have a small effect on the operational need for collision avoidance manoeuvres in the GNSS and MEO region, and an almost negligible effect in the LEO and GEO regions.
- When considering the disposal of GNSS satellites, the disposed vehicles have the largest influence on the active GNSS satellites themselves.
- The lowest flux (and therefore the lowest risk) on the active GNSS is achieved by means of a graveyard disposal that ensures a long-term stability (i.e, negation of the eccentricity growth).
- The largest fluxes (and the largest risks) on the active GNSS spacecraft happen with the eccentricity growth strategy. The collision risks found in this case are nevertheless small.
- The graveyard approach leads to an accumulation of inactive spacecraft on the graveyard orbits. A future large scale adoption of this approach for disposal would need to consider this to prevent collisions between disposed objects.
- When disposing to a graveyard orbit, the altitudes of all other active GNSS constellations should be avoided.
- The study shows that, assuming a fixed eccentricity and SMA increase for the initial orbital elements of the disposal orbit, it might not be feasible to achieve a graveyard orbit or/and an eccentricity growth orbit. Particularly, this depends on the initial plane from where the disposal is taking place. Thus:
  - When intending to remove a satellite from orbit, a study tailored for that satellite has to be performed
  - Constellation operators could consider a mixed approach for disposal (i.e., perform graveyard or eccentricity growth disposal depending on the initial conditions at the decommissioning date)
  - Operators can also consider delaying the end-of-life disposal manoeuvre. This study has shown that the feasibility of disposal manoeuvre changes with time (particularly, with the position of the Sun-Earth-Moon plane)

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