GALILEO CONSTELLATION END-OF-LIFE DISPOSAL: ORBIT STRATEGY AND APPLICATION TO FIRST SATELLITE DECOMMISSIONING

Lukas Steindorf(1)**, Ruben Castro**(1)**, Riccardo Di Corato**(1)**, and Jose Manuel Sanchez Perez**(2)

(1)*ESTEC, European Space Agency, Noordwijk, The Netherlands, Email: {Lukas.Steindorf, Ruben.Castro, Riccardo.Di.Corato}@esa.int*

(2)*ESOC, European Space Agency, Darmstadt, Germany, Email: Jose.Manuel.Sanchez.Perez@esa.int*

ABSTRACT

This paper presents the Galileo Constellation Disposal Orbit Strategy and its application to the first disposal operations of an operational Galileo satellite. As a Medium Earth Orbit GNSS constellation serving as critical public infrastructure, a safe, robust, and reliable disposal strategy is key to achieve several objectives:

- Ensuring the long-term exploitability of GNSS constellation orbits
- Compliance with Space Debris regulations, in line with ESA's "Zero Debris" strategy

On this basis, ESA has developed a Disposal Orbit Strategy based on the usage of stable disposal orbits with minimum eccentricity growth. The strategy consists in transferring satellites at end-of-life to stable orbits located at least 300 km above the Galileo constellation. By optimising the eccentricity vector of such orbits, it is possible to achieve no crossing with the Galileo operational altitude for a long-time interval (typically hundreds of years).

The operational implementation of such strategy (both with impulsive and low-thrust manoeuvres) and the problem of performing satellite tank depletion whilst minimising perturbations to the disposal orbit is addressed. Low eccentricity growth orbits are also used as disposal orbits for the upper stages that launched the Galileo satellites: this paper describes the approach followed to achieve these orbits and the current status after thirteen Galileo launches.

An alternative satellite disposal strategy, outside the current baseline, is also analysed: by performing larger disposal manoeuvres (feasible with low-thrust propulsion available in Galileo second generation), it is possible to target unstable orbits that maximise the eccentricity growth, such that an atmospheric re-entry can be achieved after around 100 years. A trade-off of this strategy against the baseline stable disposal orbit strategy is presented.

Finally, this paper describes the specific strategy adopted for the disposal of the first Galileo operational satellite: by making use of remaining on-board propellant at start of the disposal campaign it has been possible to achieve a stable orbit 700 km above the Galileo constellation altitude.

Keywords: Galileo; Disposal; Graveyarding; Minimum Eccentricity Growth; Stable Orbits.

1. INTRODUCTION

Galileo is Europe's Global Navigation Satellite System (GNSS) and the world's most precise satellite navigation system, delivering sub metre-level positioning accuracy to around four billion users worldwide. The satellite constellation in Medium Earth Orbit (MEO) is being actively maintained and will keep improving in the foreseeable future without an operational end date. As a result, the constellation's end-of-life disposal strategy is of utmost importance, not only to Galileo itself, but to all active MEO constellations of the present and future to guarantee maximum exploitability of this orbit regime. With the first Galileo satellites reaching their design end-of-life age this paper discusses the Galileo satellite disposal strategy and the first graveyarding of a Galileo satellite.

International and European Space Debris Mitigation (SDM) standards, e.g. ISO [1] adopted in ECSS [2], demand the removal of spacecraft and launch vehicle orbital stages from protected orbital regions after the end of their mission. In the aforementioned standards, protected regions are limited to Low Earth Orbit (LEO) and Geostationary Orbit (GEO). The ESA Space Debris Mitigation Requirements [3] extend this to a general Earth orbit clearance requirement respecting not only LEO and GEO regions, but also the regions utilised by known constellations at fixed operational altitudes, which includes GNSS constellations. Therefore, for the two Galileo end-of-life MEO disposal orbit strategies presented in this paper - stable and unstable disposal orbit - the SDM requirements are derived from [1, 2, 3]. Please note that disposal obit stability is defined as no interference in terms of the

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Table 1. GNSS constellation altitudes and LEO/GEO protected orbital regions.

Region	Constellation	Altitude [km]
LEO	-	0 - 2000
MEO	GLONASS	19122
	GPS	20182
	BeiDou	21528
	Galileo	23222
GEO	-	35786 ± 200

disposal orbit apogee/perigee altitude crossing with any protected region, or in other words defined as small eccentricity growth of the disposal orbit. The requirements are as follows:

- If a stable disposal orbit is targeted (see Section 2.1), such orbit shall neither interfere with any protected region (LEO, GEO) nor with the orbits of known constellations for at least 100 years from end of mission.
- If an unstable disposal orbit is targeted (see Section 2.2), a satellite that has not been operated in LEO shall re-enter in the Earth atmosphere within 100 years from end of mission, and spend less than 25 years [3] in the LEO protected region.
- In either case, the cumulative collision probability with space objects larger than 1 cm shall be below 10^{-3} for the first 100 years from end of mission.

Table 1 summarizes the orbital altitudes of the protected regions including other GNSS constellations in MEO applicable to the disposal strategy of Galileo. Given that Galileo has the highest altitude of the current operational GNSS constellations, the chosen default approach to comply with the above mentioned requirements is to achieve a stable disposal orbit altitude between 300 km to 1000 km above the Galileo operational altitude. The characteristics of the targeted final disposal orbit have to be designed such that its natural orbit evolution limits eccentricity growth such as to delay crossing either the Galileo operational altitude, as well as the MEO and GEO region above, for at least 100 years from end of mission. An alternative strategy consists of achieving the exact opposite, high eccentricity growth, thriving for a quick orbital decay. The characteristics and trade-offs of both strategies are discussed in the following sections.

The following widely accepted symbols will be used across the document to refer to the Keplerian orbital elements: a for semi-major axis (SMA), e for eccentricity, i for inclination, Ω for right ascension of ascending node (RAAN), ω for argument of perigee (AoP), and f for the true anomaly. Additionally, the change in semi-major axis with respect to the reference Galileo altitude is represented by Δa, while the argument of latitude is defined as $\theta = \omega + f$. Finally, the quantity $\vec{e} = (e_x, e_y)^{\mathrm{T}}$ represents the eccentricity vector, where $e_x = e \cdot \cos\omega$ and $e_y = e \cdot \sin\omega$.

2. ECCENTRICITY GROWTH OF THE INCLINED NEAR-CIRCULAR GALILEO ORBIT

This section introduces the dynamics governing the eccentricity growth of quasi-circular orbits at MEO altitude. In this orbital regime, eccentricity growth is caused by resonance of the perturbing force from Earth's shape of its gravity field, especially J_2, and the third body attractions by both the Sun and the Moon, and is presented in closed-form in [4] by performing a first averaging of the equations of motion over the satellite's orbital period, and a subsequent averaging over the orbit period of the third body, referred to as doubly-averaged. Evaluated at Galileo's nominal orbit inclination of $i = 56$ deg the eccentricity growth becomes

$$\begin{aligned}\frac{de}{dt} = &- (15/8)e\gamma s[-0.0077\sin 2(\omega - \Omega) \\ &- 0.1334\sin(2\omega - \Omega) - 0.5240\sin 2\omega \\ &+ 0.4719\sin(2\omega + \Omega) - 0.0962\sin 2(\omega + \Omega)],\end{aligned} \tag{1}$$

where $\gamma = n_3^2 R_m/n$, $s = (1 - e^2)^{0.5}$, n the mean motion of the satellite orbit, n_3 is the mean motion of the third body, and R_m is the mass ratio ($R_{\mathrm{m}} = 1$ for solar perturbation, $R_{\mathrm{m}} = 182.3$ for lunar perturbation) [4]. For Galileo the secular rates of the coefficients in Eq. (1) are shown in Table 2. It can be seen that the term $2\omega + \Omega$ shows the smallest secular rate of all terms, and hence the initially achieved value of $2\omega + \Omega$ once a disposal orbit has been acquired has the dominant impact on the eccentricity evolution, amplified by its large coefficient of 0.4719. In fact, selecting

$$2\omega + \Omega = 90\,\mathrm{deg}, \tag{2}$$

leads to minimised eccentricity growth, while

$$2\omega + \Omega = 270\,\mathrm{deg} \tag{3}$$

leads to maximised eccentricity growth.

This property can be used to get an approximate target ω of the disposal orbit for either of the two strategies for any given Ω of a satellite in one of the constellation planes. However, since it does not capture the full dynamics, numerical computations are needed to determine the actual optimal value.

Table 2. Secular rates due to J_2 and Sun-Moon perturbations for the Galileo orbit [4].

Term	Expression	Secular rates [deg/day]
	ω	$+0.0132$
	Ω	-0.0262
1^{st}	$\omega - \Omega$	$+0.0394$
2^{nd}	$2\omega - \Omega$	$+0.0526$
3^{rd}	2ω	$+0.0264$
4^{th}	$2\omega + \Omega$	$+0.0002$
5^{th}	$\omega + \Omega$	-0.0130

2.1. Low Eccentricity Growth Strategy

The aim of the Low Eccentricity Growth (LEG) strategy is to manoeuvre the satellite into a graveyard orbit that minimises the eccentricity build-up in order to ensure that it will not cross the operational altitude for at least 100 years. This is achieved by targeting $\Delta a = +300$ km above the nominal Galileo altitude, a small initial eccentricity and a mean argument of perigee that utilises the resonance effect of the fourth term in Eq. (1) to minimise the eccentricity growth, as per Eq. (2). To assess the analytically derived strategy, a parametric analysis considered the following initial conditions:

- $\Delta a = +300$ km
- $e = 0.0025$
- $54\,\text{deg} \leq i \leq 58\,\text{deg}$ (5 steps)
- Any value of initial Ω (15° steps) and ω (10° steps)
- Initial epoch [2020, 2028] – Starting at January 1^{st}
- Propagation period: 200 years

The stability of each initial orbit is characterised by looking at the time needed to interfere with the Galileo nominal orbit, i.e. the time that the perigee stays above the Galileo altitude. The result for the initial epoch at 56 deg inclination is shown in Figure 1. For any given Ω one can identify two values of ω separated by approximately 180 deg which lead to minimal eccentricity growth and which are in close agreement with Eq. (2). The impact of inclination is shown in Figure 2, where it can be seen that vertical stability bands appear for both higher and lower inclinations than 56 deg which guarantee 200 years clearance for any initial value of ω. Furthermore, the results for a given inclination shift with the disposal epoch (see Figure 3), while there always remain two values of ω for which long-term stability is guaranteed.

The comprehensive analysis shows that for any initial epoch, inclination and Ω, there are always two values of ω

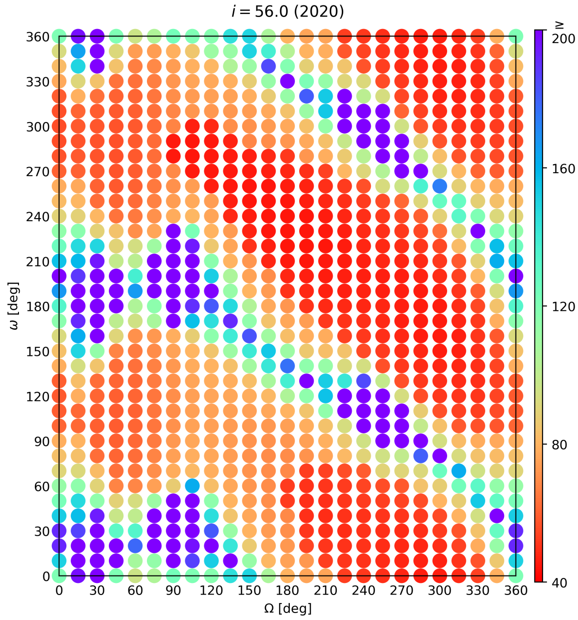

Figure 1. Years to cross the Galileo altitude as a function of initial ω and Ω, for $\Delta a = +300$ km, $e = 0.0025$, $i = 56$ deg, and T_0 at 1^{st} January 2020.

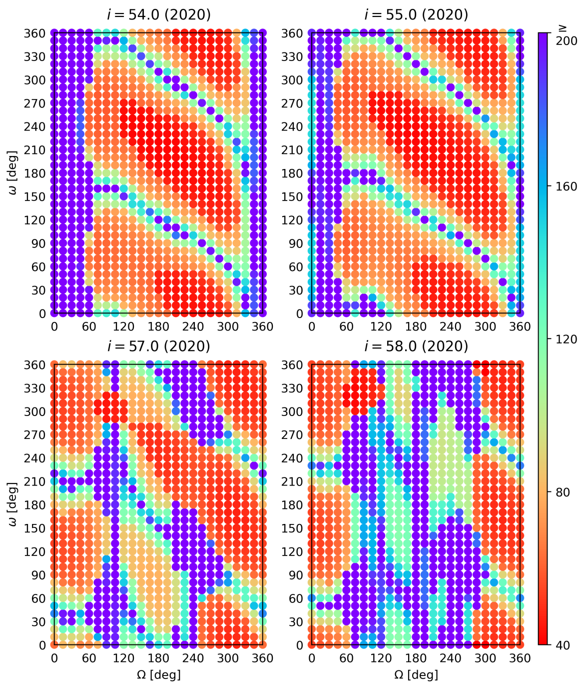

Figure 2. Years to cross the Galileo altitude as a function of initial ω and Ω, for different values of inclination, $\Delta a = +300$ km, $e = 0.0025$, and T_0 at 1^{st} January 2020.

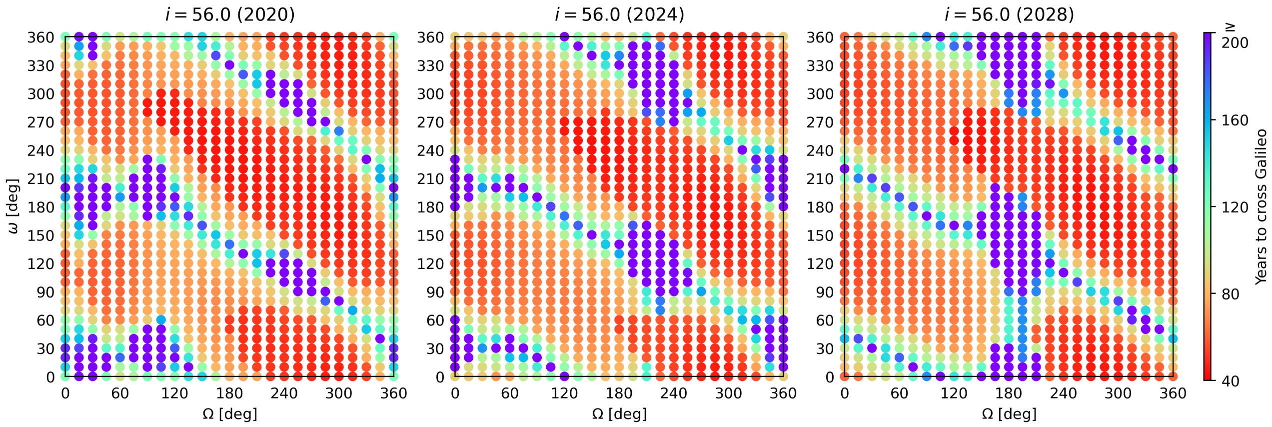

Figure 3. Years to cross the Galileo altitude as function of initial ω and Ω, for different values of initial epoch T_0, $\Delta a = +300$ km, $e = 0.0025$, and $i = 56$ deg.

that lead to minimal eccentricity growth with guaranteed 100 years clearance of the Galileo altitude. In general, more than 200 years clearance should also be achievable, while interference with the LEO and GEO protected regions will occur in a time frame longer than 200 years. This result is confirmed by independent analysis in [5].

2.2. High Eccentricity Growth Strategy

An alternative strategy [6] is concerned with High Eccentricity Growth (HEG). This strategy foresees achieving unstable orbits for which the orbital resonance increases the eccentricity such that atmospheric re-entry occurs within 100 years. As a first guess, this is again achieved by employing the fourth term of Eq. (1), this time targeting for a maximum change in the eccentricity growth as per Eq. (3).

For the HEG strategy another important factor besides the choice of ω is the available delta-v for the disposal campaign as it directly impacts the time to atmospheric re-entry. The parametric study performed in [5] concludes in the case of Galileo that with a 100 m/s allocation to lower the initial perigee altitude, re-entry may happen even after 200 years, while an initial inclination of 56 deg ensures largest re-entry opportunities. In fact, a minimum of 180 m/s are required to guarantee re-entry from any of the three Galileo orbital planes [7].

Furthermore, with this disposal strategy, the disposed satellite will be crossing both the LEO and GEO protected regions. The stay in LEO will be typically limited in time (in the order of 10 years for a 100 years re-entry trajectory [7]), so compliance with the 25 years SDM requirement should be generally achievable, but it would need to be verified for each specific case. On the other hand, as the eccentricity grows, the apogee will reach the altitude of the GEO protected region much earlier after 40 to 60 years for a 100 years re-entry trajectory [7]. Specific analysis will be required to assess the degree of interference with the GEO protected region and with the four GNSS operational constellations, and to quantify the associated cumulative risk of close approach with space objects as described in ESA's Space Debris Mitigation Compliance Verification Guidelines [8].

Comparing the two presented strategies, HEG reduces the collision risk of disposed satellites amongst each other as each of the disposed satellite orbits will be unstable and vary quickly in eccentricity. On the other hand, HEG increases the collision risk with active satellites not only with Galileo, but all active GNSS constellations, though overall the combined collision risk is reduced with respect to LEG [6]. Furthermore, it can be noted that collision risk of disposed satellites to a LEG graveyard orbit pose a threat to such a stable disposal shell as it is containing decommissioned satellites which are unable to perform avoidance manoeuvres in case of collision risk. Additionally, eccentricity growth in a LEG orbit is only delayed such that eventually after more than 100 years disposed objects will start crossing the nominal Galileo altitude, and later other GNSS constellations or protected regions. HEG will interfere with all operational GNSS constellations shortly after the disposal.

One of the main challenges of the HEG strategy is its large delta-v requirement. The delta-v required to guarantee a 100 year re-entry is around 200 m/s, considerably higher than the approximately required 18 m/s for the LEG strategy. Thus, from an operational perspective considering the G1 space system design, implementing the LEG strategy is always feasible, for any initial epoch, orbital plane and inclination, guaranteeing 100 years no interference with the operational Galileo altitude.

After trading off the discussed advantages and disadvantages of both the LEG and HEG strategies, as well as the SDM requirements, the current baseline for Galileo was selected to be the LEG strategy, which is within the scope of satellite design (including qualification evelope and propellant budget). However, future Galileo satellite design may be compatible with HEG thanks to the higher

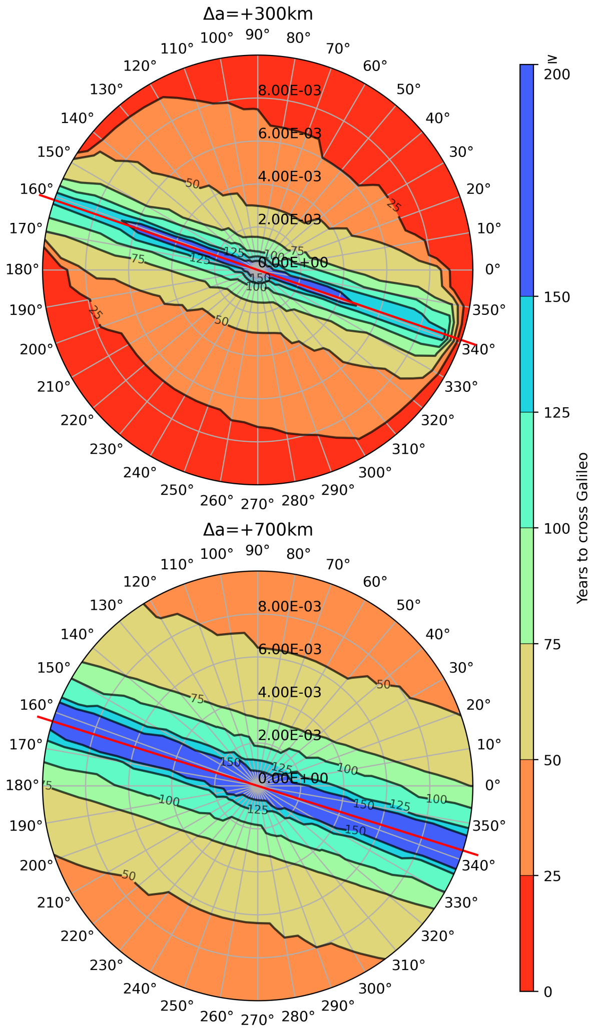

Figure 4. Years to cross Galileo altitude for graveyard orbits with $\Delta a = +300$ km (top), and $\Delta a = +700$ km (bottom). The radial variable is e, while the angular variable is ω. Stable direction of $\vec{e}$ marked with a straight red line.

specific impulse of electric propulsion thrusters, and assessment of the optimal disposal strategy will remain an ongoing field of study.

3. DISPOSAL ORBIT ACQUISITION AND TANK DEPLETION STRATEGIES

This section analyses the necessary operations to achieve the graveyard orbit, using the baseline LEG strategy, which entails mainly two stages; orbit raising to graveyard orbit, and tank depletion.

For the orbit rasing, the orientation of the target eccentricity vector $\vec{e}$, defined by ω, is found by performing a parametric analysis of mean absolute eccentricity and ω identifying regions of stability as shown in Figure 4. Both the top and bottom plot show the years to cross Galileo altitude for the same specific Ω, in this case Galileo satellite GSAT0104, at the same epoch in April 2024 for two different altitudes $\Delta a = +300$ km and $\Delta a = +700$ km, respectively. As expected, it can be seen that the shape outlines of constant perigee decay times to Galileo altitude are aligned with two values of ω separated by 180 deg, which are marked with a straight red line that satisfies Eq. (2), and thus mark the stable direction of $\vec{e}$. From comparing both cases, one can infer that this stable direction does only vary to a negligible degree with increasing Δa, and is mainly a function of Ω and epoch as shown in section 2.1. However, there is an absolute eccentricity limit which indeed depends on Δa, above which the chosen ω does no longer guarantee LEG. Similarly, it can be inferred that with increasing Δa there develops an absolute eccentricity limit - that can be operationally achieved - below which the argument of perigee can be freely chosen without any penalty in crossing time below 200 years.

Therefore, targeting a higher Δa is advantageous as the requirements on the final eccentricity vector become more relaxed with both the range of stable ω and the allowed e increasing. However, at the same time it is desirable to constrain disposal orbit altitudes to limit the extension of the Galileo graveyard region. Therefore, in general, the mean disposal orbit shall satisfy all of the following:

- An altitude satisfying $+300\,\text{km} \leq \Delta a \leq +1000\,\text{km}$ with respect to the nominal Galileo altitude,
- an absolute eccentricity below 0.001, and
- ω aligned with one of the stable directions.

Once the target graveyard orbit altitude and corresponding $\vec{e}$ have been identified a manoeuvre campaign has to be established achieving said orbit with the space system in use. Here, attention to the discerning difference of the first and second Galileo generations with respect to their propulsion systems is highlighted. In either case the remaining delta-v at the beginning of the disposal campaign provides the range of Δa between 300 km to 1000 km. As mentioned previously, a higher Δa is recommended whenever possible to achieve a longer time to crossing the Galileo altitude. However, in case two satellites of the same orbital plane are graveyarded simultaneously or within a short time frame, it is recommended to separate them at least by $\Delta a = 150$ km in a to avoid risk of collision in the short term, and at the same time target different inclinations such that both satellites experience a relative orbital plane drift with respect to each other to avoid risk of collision in the medium term.

For Galileo First Generation (G1) which utilises chemical propulsion a succession of Hohmann transfers is recommended. The two burns of each Hohmann sequence, which occur in opposite locations of the orbit, shall be aligned with the stable direction in $\vec{e}$ and therefore centred at $\theta = \{\omega_{\text{target}}, \omega_{\text{target}} \pm 180°\}$. The number of Hohmann sequences depends on the desired Δa, while

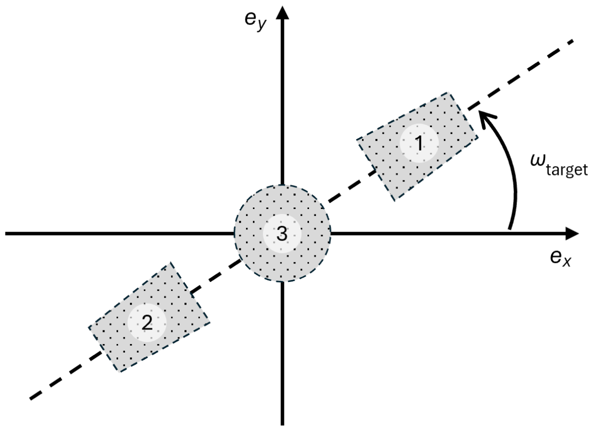

Figure 5. Eccentricity vector plane showing the stable target ω direction, and respective $\vec{e}$ target areas (1, 2, 3) for intermediate burns of a disposal campaign.

the planned delta-v should decrease from one Hohmann sequence to the next, such that a stable intermediate orbit is reached quickly, and to avoid long manoeuvres towards the end of the graveyarding campaign when potentially coping with low pressure in the propellant tanks. Two or three such Hohmann sequences are usually sufficient, and a final single correction manoeuvre can be implemented to correct previous misperformances decreasing the eccentricity and/or improving the orientation of $\vec{e}$.

One difficulty with this strategy is to keep $\vec{e}$ aligned with the target direction after each of the respective circularisation burns of a given Hohmann sequence, as ω becomes more unstable the more circular an orbit is. Generally, this does not pose a problem as for such a circular orbit the eccentricity evolution is stable (see Eq. (1)). However, in the presence of uncertainties or imperfections in either manoeuvre execution or navigation solution one could obtain an $\vec{e}$ which does not provide the desired stability improvement of the intermediate orbit. Thus, an alternative strategy for G1 consists of a series of manoeuvres which keep raising the current perigee above the current apogee altitude effectively becoming the new apogee by skipping the intermediate circularisations. This way, achieving the desired orientation of $\vec{e}$ of the intermediate orbits is generally easier. Finally, only the very last burn of the graveyarding campaign would seek to circularise the orbit in this strategy.

Figure 5 helps to visualise both aforementioned strategies as it shows ω_{target} in the eccentricity vector plane and potential target regions in $\vec{e}$ for each burn of the graveyarding campaign. When selecting the strategy consisting of a series of Hohmann sequences, which is the current baseline, every second burn (i.e. the circularisation burns) would target $\vec{e}$ to be in the area denoted with "3" in the figure, while each apogee raising burn would target either area "1" or "2". However, the alternative strategy skipping the intermediate circularisations will only target area 3 with the last burn of the campaign, while all intermediate eccentricity vectors will alternate between areas "1" and "2", ensuring that $\vec{e}$ remains aligned with ω_{target} throughout the campaign for increased operational robustness and orbit stability.

For Galileo Second Generation (G2) utilising electric low-thrust propulsion, the satellite will spiral up to the selected altitude in a continuous long duration burn. The recommended strategy is to keep the maximum eccentricity during the entire transfer below 0.001 such that in case of a platform failure during the orbit raising the final eccentricity is guaranteed below this threshold. Gauss's variational equations are derived in [9], and considering only tangential thrust producing an acceleration u_{t}, the eccentricity changes according to

$$\frac{de}{dt} = \frac{(p+r)\cos f + re}{h} \cdot u_{\text{t}}, \tag{4}$$

where p is the orbital parameter, r is the orbital radius, and h is the angular momentum. As a result, the low-thrust transfer shall commence close to $f = 90°$ such that the eccentricity benefits from initially being reduced in the first half orbit of the transfer, as the sign of the cosine is negative for $90° \leq f \leq 270°$. Since this method does not actively control the eccentricity and instead bounds it to the initial eccentricity at start of transfer, it could end up close to 0.001 which is the maximum allowable eccentricity of an operational Galileo satellite. For low disposal orbits in the vicinity of the lower altitude threshold, this can lead to a violation of the 100 year stability requirement and in such cases, further improvements should be employed. Potential improvements include

- aiming for a higher Δa (still within the 1000 km limit),
- reducing the final eccentricity by stopping the transfer close to the target altitude at $N + 0.5$ revolutions (assuming the transfer had been commenced at $f = 90$ deg),
- a final circularisation campaign, and
- controlling the argument of perigee to a stable direction.

Finally, applicable to both G1 and G2, SDM guidelines mandate to passivate the space system and to deplete the propellant tanks to prevent future break-up or explosion. The recommendation for the depletion of the propellant tanks, whenever possible, is to implement out-of-plane manoeuvres such as to produce, in the ideal case, no perturbation to $\vec{e}$. When possible, the out-of-plane depletion manoeuvres shall be planned such to change the inclination in the direction that improves even further the stability of the orbit for the given epoch as found by parametric analysis. The number of manoeuvres for depletion should be minimised, but it will generally depend on the amount of remaining propellant, and operational and space system constraints limiting the duration of each

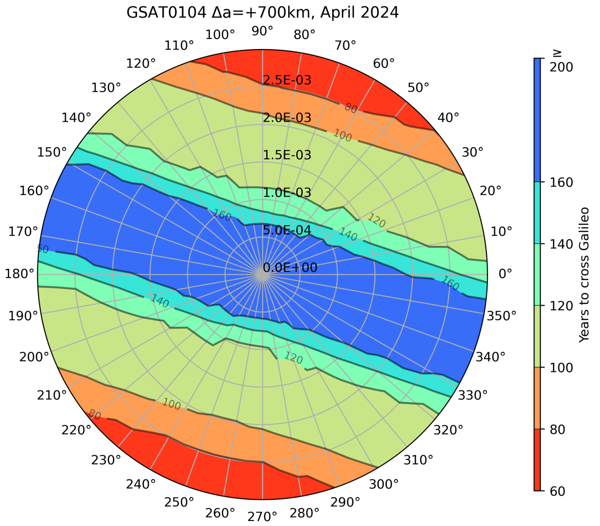

Figure 6. Years to cross the Galileo altitude for the GSAT0104 disposal case as a function of initial $\vec{e}$. The radial variable is e, while the angular variable is ω.

burn. It should be noted that in the case of G2 the remaining propellant can be depleted via the cold gas thrusters providing a very low specific impulse, hence providing low disturbance to the orbit, and an effective means for operations in terms of time allocation.

4. FIRST SATELLITE DISPOSAL AND CURRENT ORBIT STABILITIES

Not only Galileo satellites nearing their end-of-life need to be disposed of, but also the launcher upper stages need to stay clear of GNSS constellations after they have delivered the satellites to space. This section shows the implementation of the strategy discussed so far in this paper on the first graveyarding of an operational Galileo satellite, GSAT0104, and the status of the launcher upper stages used so far with respect to their predicted interference with GNSS constellations.

4.1. First Galileo Satellite Graveyarding Implementation

The first satellite graveyarding campaign of an operational Galileo satellite, GSAT0104, has been performed in April 2024. Based on remaining propellant reserves at start of the disposal campaign a target altitude of 700 km above the Galileo altitude has been selected. To analyse the long-term stability for the graveyard orbit a parametric study in $\vec{e}$ has been performed for this altitude and the specific epoch, respecting the applicable orbital plane and inclination of GSAT0104. Figure 6 shows the result for the specific GSAT0104 case analysed at the insertion epoch in April 2024. The main focus of the manoeuvre campaign was not only to achieve a final $\vec{e}$ with low absolute eccentricity to comply with the 100 year requirement, but to also to obtain safe intermediate orbits throughout the disposal campaign. A secondary focus was to align $\vec{e}$ with the stable directions. Based on the results in Figure 6 the following objectives for $\vec{e}$ of the final and intermediate orbits have been selected:

- A mean argument of perigee either within $[158, 168]$ or $[338, 348]$.
- A mean absolute eccentricity below 0.001 for the final orbit, which corresponds to a difference of 60 km between apogee and perigee, not posing an operational challenge.

Table 3. GSAT0104 graveyarding manoeuvre plan consisting of three Hohmann transfer sequences. Showing the commanded delta-v vs. achieved mean orbital elements after each manoeuvre.

Seq. ID	commanded dV [m/s]	a [km]	e [-]	ω [deg]
1	13.09	29839	0.0072	159.7
	13.36	30072	0.0007	
2	5.50	30168	0.0036	341.5
	6.61	30281	0.0001	
3	0.69	30293	0.0003	342.3
	0.50	30301	1.63e-5	

Table 3 shows the manoeuvre plan for the graveyarding of GSAT0104, as planned and implemented by the Galileo Service Operator (GSOp). Three Hohmann sequences were planned in total with decreasing delta-v allocation from one sequence to the next. The table also shows achieved mean orbit elements after each of the performed manoeuvres. It can be seen that ω after each apogee raising manoeuvre is well within the target direction for $\vec{e}$. This strategy allows to modify the initially developed manoeuvre plan throughout the operations campaign adjusting to thruster misperformances to keep ensuring that the final target can still be achieved with precision.

Figure 7 shows the perigee altitude evolution of each of the intermediate orbits of the disposal campaign for a propagation period of 300 years. After the 1st manoeuvre the perigee evolution is already keeping clear of the Galileo constellation altitude for more than 100 years even though after this apogee raise a high intermediate eccentricity is established. This is achieved by targeting $\omega = 159.7°$ as identified by the parametric analysis in Figure 6, proving the desired robustness of the graveyarding strategy. Each subsequent manoeuvre extends the duration to when the perigee altitude will cross any of the GNSS constellations. The final orbit's ω (and of the intermediate circularised orbits) does not strictly need to be aligned with the target direction given the low eccentricities of these orbits. The final achieved orbit has

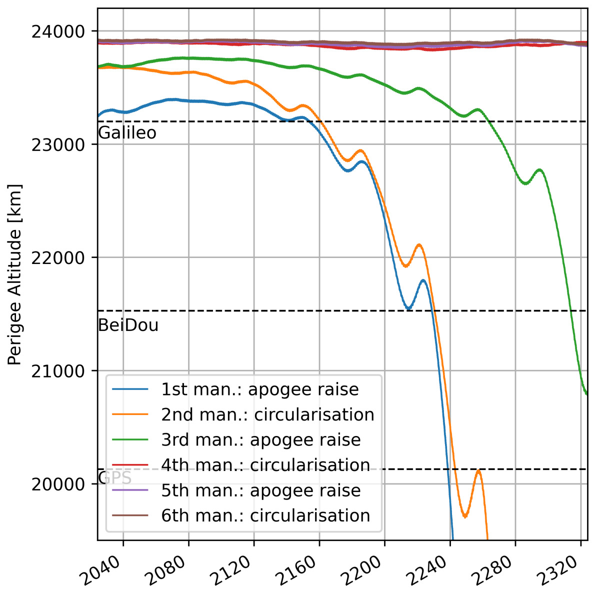

Figure 7. 300 year propagation of GSAT0104's perigee altitude after each manoeuvre execution of its graveyarding campaign (see Table 3).

$\Delta a = 701.4$ km, with $e = 1.63\text{e-}5$ which is well within the eccentricity limit of 0.001.

4.2. Galileo Launcher Upper Stages Orbit Stabilities

With respect to Galileo launch vehicle upper stages, efforts have been made together with the launch service providers for the design of injection and passivation strategies such that the achieved orbit stability guarantees staying clear of the GNSS MEO operational altitude for an objective of 100 years from end of mission. The challenge for a rocket upper stage to achieve an accurate and stable $\vec{e}$ may come from various limitations concerning its guidance system, the on-board task schedulers, battery lifetime, minimum impulse, engine shutdown transients, performance accuracy and more. As a result, a robust approach was required with as few upper stage engine relights as possible.

For G1, the disposal of the upper stage comprises passivation and a graveyard orbit with

- a final $|\Delta a| = 300$ km above or below the nominal Galileo altitude, and
- a final eccentricity as small as possible.

Figure 8 shows the apsidal evolution (apogee and perigee altitudes) of the upper stages used to launch Galileo satellites up to and including launch 12, depicting as well the altitude where other GNSS MEO constellations are placed. Note that Galileo's third launch is missing in this overview as the launcher upper stage experienced an in-flight anomaly and did non achieve target orbit [10, 11]. The following can be inferred:

- Two upper stages cross the Galileo altitude between 50 and 100 years from their respective end-of-mission.
- Nine upper stages cross the Galileo altitude after more than 150 years from their respective end of mission.
- No upper stage crosses any other GNSS constellations altitude before 150 years from their respective end of mission.

For G2, the disposal orbit of the launcher upper stage after passivation is different as the satellite injection altitude is expected around 7000 km. At that altitude, the launcher is unlikely able to reduce the perigee in order to achieve Earth re-entry within an acceptable time frame. Therefore, the aim will is similar to the baseline Galileo satellite disposal strategy, which is to not only avoid crossing protected regions for more than 100 years, but to further leave the upper stage in a very stable orbit such that it does not pollute different altitudes. This will be achieved by targeting a low eccentricity (compatible with the accuracy of the launcher upper stage GNC), similar to the approach described above for the G1 launcher upper stages.

5. CONCLUSIONS

This paper has presented a baseline Galileo disposal orbit strategy which mitigates collision risks with protected orbit regions including other GNSS MEO constellations, ensuring that GNSS operational orbits remain usable in the long term. The strategy consists of selecting a graveyard orbit that minimises the eccentricity build-up to ensure that disposed satellites do not interfere for at least 100 years with the Galileo altitude, other GNSS constellations or other protected orbital regions. This is achieved by targeting an altitude at least 300 km above the nominal Galileo altitude, a small initial eccentricity and a mean argument of perigee that ensures minimum eccentricity growth. Analysis demonstrates that it is always possible to determine a disposal orbit compliant with the 100 years clearance requirement (more than 200 years is generally achievable), regardless of initial orbital plane, epoch, or inclination. A small amount of delta-v (18 m/s as minimum) is required by this strategy, with limited impact on the satellite mass budget.

An alternative strategy employing maximal eccentricity growth alongside a trade-off between both strategies with their respective challenges as well as advantages has been presented. The optimal disposal strategy for the Galileo constellation is anticipated to remain an ongoing field of study and may evolve with the space system capabilities.

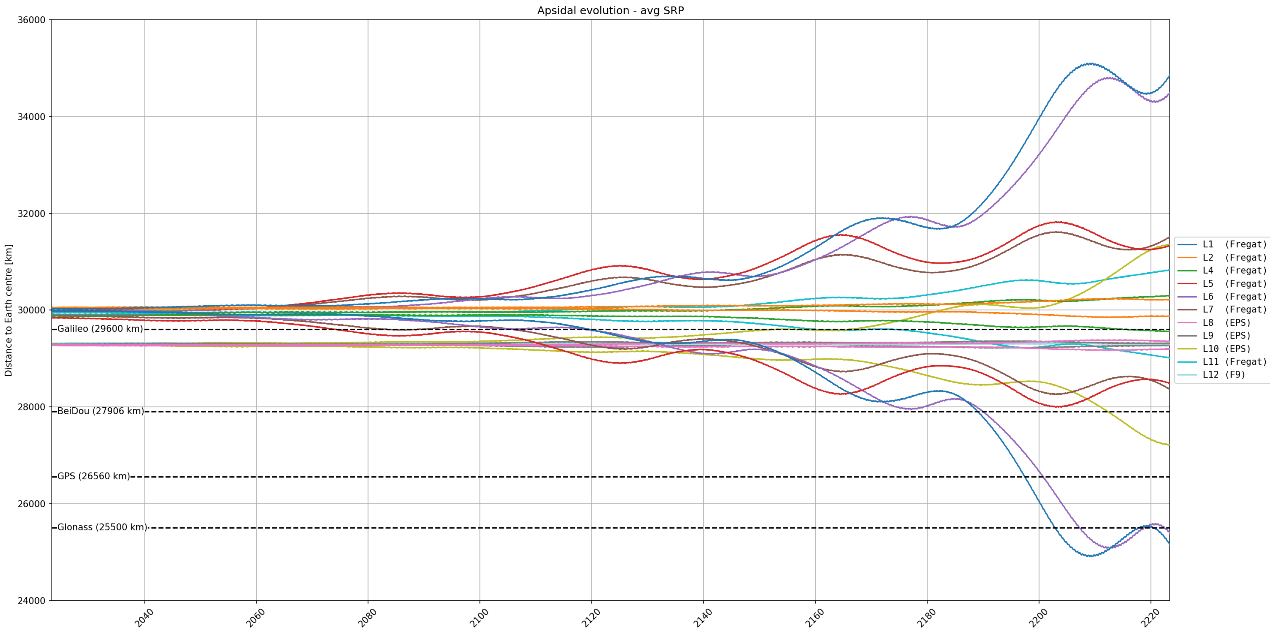

Figure 8. Apsidal evolution of upper stages used in Galileo launches compared to GNSS MEO constellation altitudes.

Finally, the first operational experience of the graveyarding strategy to an operational Galileo satellite has been summarized with respect to its compliance to SDM requirements. In addition, it has been shown that the Galileo launcher upper stages do not interfere with the operational altitude for more than 100 years in the vast majority of cases.

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