GIOVE-A'S FREGAT DISPOSAL ASSESSMENT

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ABSTRACT

Galileo will be Europe's own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. Following the approval of Galileo in 1999, a demonstration element was added – the Galileo System Test Bed (GSTB) with the GIOVE-A and GIOVE-B satellites – to allow early experimentation with the navigation signals and services before committing to the final constellation design.

GIOVE-A (launched on 28 Dec 2005) and GIOVE-B (launched on 26 April 2008) were injected in the Galileo operational orbit (semi-major axis 29600 km, circular orbit, inclination 56 degrees) by direct injection with Soyuz/FREGAT launch vehicle.

In order to mitigate future collision risks at Galileo altitudes, it was decided that all injected objects (FREGAT, and GIOVE/Galileo satellites at end-of-life) would be placed in higher-altitude disposal orbits.

After separation from the GIOVE satellites, in both cases, FREGAT performed manoeuvres to move to a disposal orbit with a higher altitude. The disposal orbit was targeted as to minimize eccentricity growth and therefore maximize time for FREGAT to cross the operational orbit altitude.

The objectives of this paper are:

- To present an assessment of the FREGAT graveyarding actual manoeuvres with respect the target disposal orbit.
- To present an assessment of the FREGAT actual disposal orbit evolution based on long-arc TLE fitting, taking into account accuracy of the fitting and of very long-term predictions.

1. INTRODUCTION

Galileo will be Europe's own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. Galileo is a Global Navigation Satellite System composed of 30 navigation satellites and a ground infrastructure with the main control centres in Europe and a network of dedicated stations deployed around the world. The Galileo constellation is defined as a Walker 27/3/1 and is composed of 3 equally-spaced orbital planes with a nominal inclination of 56 degrees and a semi-major axis of 29,600 km. Each plane will contain nine equally-spaced satellites plus a spare satellite. The first launches are foreseen in 2010, with the full constellation deployed by end 2013.

Following the approval of Galileo in 1999, a demonstration element was added – the Galileo System Test Bed (GSTB) with the GIOVE-A and GIOVE-B satellites, whose mission was:

- To secure use of the frequencies allocated by the International Telecommunications Union (ITU) for the Galileo system.
- To verify the most critical technologies of the operational Galileo system, such as the on-board atomic clocks and the navigation signal generator.
- To characterise the novel features of the Galileo signal design, including the verification of user receivers and their resistance to interference and multipath.
- To characterise the radiation environment of the Medium Earth Orbit planned for the Galileo constellation.

Those two satellites have been launched into orbits in the same altitude as Galileo using a Soyuz launcher enhanced with a FREGAT module for direct injection.

Following a programmatic decision to create a graveyard orbit above the Galileo altitude in order to mitigate future collision risks, the FREGAT module was programmed to inject itself, after separation from GIOVE-A, in an circular orbit at about 210 km above the Galileo altitude.

The major problem with this kind of graveyard orbit is that the eccentricity growth is not bounded as in geostationary altitudes. Therefore, there is a risk that the eccentricity of the disposed object's orbit grows enough that the perigee altitude ends up crossing the operational altitude.

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

According to numerical research performed in the past [1], [2], for the region of Galileo (semi-major axis 29600 km, inclination 56 deg) a small eccentricity would make the eccentricity grow slowly. If, in addition, the initial argument of perigee is carefully chosen, the growth can be further slowed down to the point of guaranteeing that the crossings take place a few hundreds of years after the disposal.

This paper will, first, present a short analysis of the selected graveyard orbit elements for GIOVE-A's FREGAT. Second, based on long-arc TLE fit, a set of orbit vectors and their accuracy are obtained and used for analysing the evolution of the achieved disposal orbit.

2. FREGAT MISSION DESCRIPTION

GIOVE-A (launched on 28 Dec 2005) was injected in the Galileo operational orbit (semi-major axis 29600 km, circular orbit, inclination 56 degrees) by direct injection using a combination of SOYUZ and FREGAT [3].

The mission is separated into three phases as shown in Fig. 1:

1. Ascending trajectory: using a Soyuz launch vehicle for a ballistic ascending trajectory, the Nose Module, i.e. the assembly of GIOVE-A and FREGAT, was left on a ballistic trajectory.

2. FREGAT, using its thrusters, propelled the Nose Module to a transfer orbit and then to the final orbit.

3. After separation from GIOVE-A, FREGAT performed one manoeuvre in order to raise its semi-major axis (red dashed circle in Fig. 1) and a second manoeuvre (blue discontinuous circle in Fig. 1) to raise its semi-major axis again and to target the desired values of eccentricity and argument of perigee (see next section).

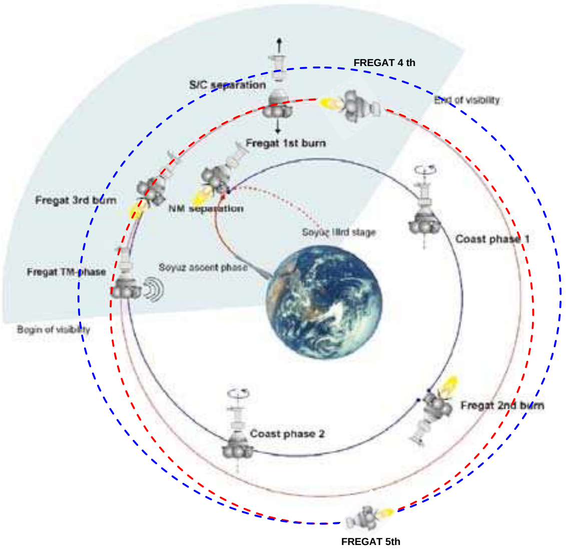


Figure 1: GIOVE-A's SOYUZ/FREGAT mission phases.

3. FREGAT DISPOSAL TARGET ELEMENTS

The selection of the FREGAT disposal orbit was done with the goal of placing FREGAT above the operational Galileo altitude and minimizing the eccentricity growth in order to maximize the time for the perigee to decrease down to the Galileo altitude (what we would call "crossing time"). As mentioned earlier, past studies have shown that, a small eccentricity and an optimized combination of right ascension of the ascending node and argument of perigee could delay considerably the eccentricity growth, and thus delay the crossing time. In particular, solutions where $2\omega+\Omega=90°$ *deg* (with Ω *the* right ascension of the ascending node and ω the argument of perigee) were found to be suitable in the range of Galileo orbital parameters.

Additional numerical simulations, done in the frame of the Galileo Project [4], provided regions of Ω and ω for a given initial eccentricity where the eccentricity growth was small enough to allow for crossing times later than 200 years after disposal. Figure 2 shows a preliminary selection for the FREGAT disposal orbit (tagged as "PMA report" in Fig. 2) that, according to those numerical simulations, was not optimal. Taking into account the range of argument of perigee achievable by FREGAT for the disposal orbit, a range of Ω values were chosen.

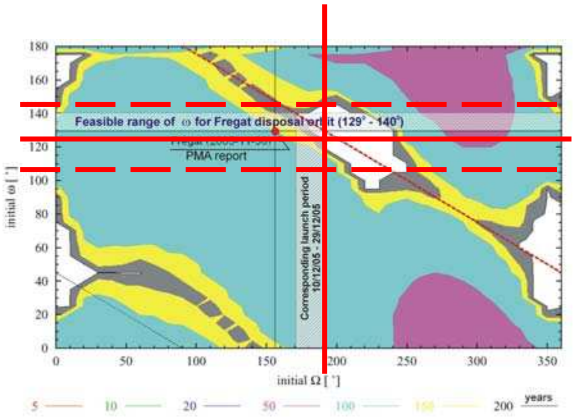


Figure 2: GIOVE-A FREGAT Time to cross Galileo Orbit as a function of RAAN and Argument of Perigee.

The selection strategy of the argument of perigee for the FREGAT orbit presents one additional complication: the FREGAT flight program is normally frozen some time before the launch such as to allow enough time for validation of the programme.

Due to GIOVE-A thermal constraints, FREGAT has to fly with a specific solar aspect angle. Since the flight programme is frozen (in practice, this means that ω is fixed), this solar aspect angle is achieved by using the only degree of freedom available, i.e. by selecting the lift-off time, depending on the launch date. As a consequence, for each launch date, a different value of Ω is required, always within the range of values selected from Fig. 1. The targeting of the ω value in the flight programme has to be done for a nominal day, assuming that delays may happen, and that FREGAT may not achieve the optimized ω corresponding to the actual Ω.

As can be observed in Fig. 2, the target values (continuous red lines) for the GIOVE-A actual launch date were still optimal (white zone, crossing with Galileo altitude in more than 200 years). These elements are shown in Tab. 1. In particular, for these values, the eccentricity will stay small for longer than 400 years.

Epoch: 2005/12/28-13:39:57.540		
Semi-major Axis:	29772.3	km
Eccentricity:	0.00196	
Inclination:	56.0	deg
RAAN:	190.55	deg
Arg. of Perigee:	125.6	deg
True Anomaly:	29.27	deg

Table 1: GIOVE-A's FREGAT disposal target values.

In addition to the fact that the optimal combination of Ω and ω might not be achieved, a relatively small deviation in the actual argument of perigee due to trajectory dispersion would make the crossing time earlier (see horizontal dashed lines in Fig. 2, and perigee evolution for different amount of deviation of argument of perigee in Fig. 3). A deviation in the eccentricity would have a similar consequence (Fig. 4).

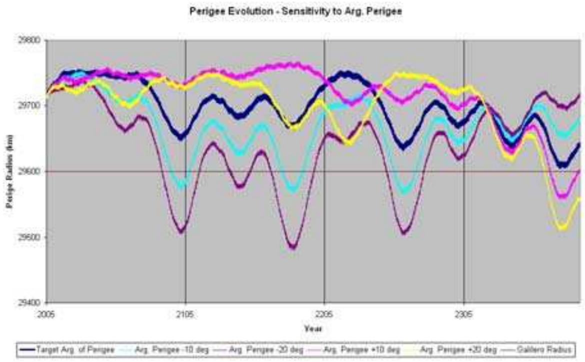


Figure 3: Evolution of perigee due to deviations in argument of perigee.

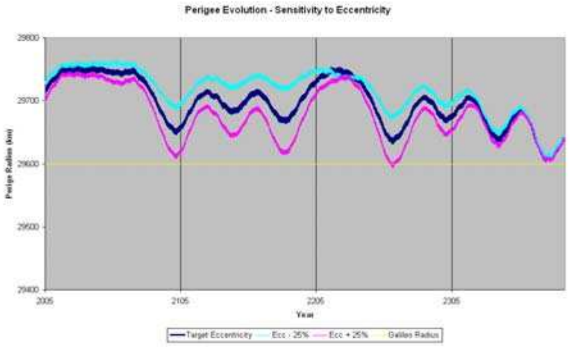
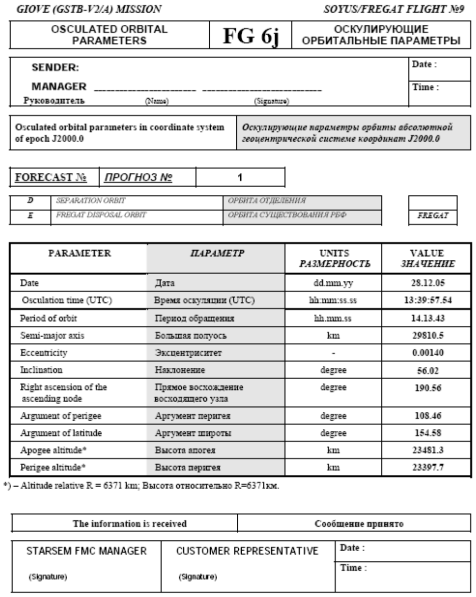


Figure 4: Evolution of perigee due to errors in eccentricity.

4. FREGAT Measured elements

On the launch date, once GIOVE-A was injected in its nominal orbit and FREGAT in its disposal orbit, the launcher authority (i.e., STARSEM) provided a set of measured orbital elements based on the FREGAT telemetered inertial platform data and additional tracking from Russian stations (see Fig. 5).



GIOVE (GSTB-V2/A) MISSION *SOYUS/FREGAT FLIGHT №9*

OSCULATED ORBITAL PARAMETERS	FG 6j	ОСКУЛИРУЮЩИЕ ОРБИТАЛЬНЫЕ ПАРАМЕТРЫ

SENDER:
MANAGER ____________________ ________________________
Руководитель (Name) (Signature)
Date :
Time :

Osculated orbital parameters in coordinate system of epoch J2000.0	*Оскулирующие параметры орбиты абсолютной геоцентрической системе координат J2000.0*

FORECAST №	*ПРОГНОЗ №*	1

D	*SEPARATION ORBIT*	*ОРБИТА ОТДЕЛЕНИЯ*
E	*FREGAT DISPOSAL ORBIT*	*ОРБИТА СУЩЕСТВОВАНИЯ РБФ*

FREGAT

PARAMETER	*ПАРАМЕТР*	UNITS *РАЗМЕРНОСТЬ*	VALUE *ЗНАЧЕНИЕ*
Date	Дата	dd.mm.yy	28.12.05
Osculation time (UTC)	Время оскуляции (UTC)	hh:mm:ss.ss	13:39:57.54
Period of orbit	Период обращения	hh.mm.ss	14.13.43
Semi-major axis	Большая полуось	km	29810.5
Eccentricity	Эксцентриситет	-	0.00140
Inclination	Наклонение	degree	56.02
Right ascension of the ascending node	Прямое восхождение восходящего узла	degree	190.56
Argument of perigee	Аргумент перигея	degree	108.46
Argument of latitude	Аргумент широты	degree	154.58
Apogee altitude*	Высота апогея	km	23481.3
Perigee altitude*	Высота перигея	km	23397.7

*) – Altitude relative R = 6371 km; Высота относительно R=6371км.

The information is received	Сообщение принято

STARSEM FMC MANAGER	CUSTOMER REPRESENTATIVE	Date :
(Signature)	(Signature)	Time :

Figure 5. Values provided by STARSEM

Long-term propagation of those elements showed that FREGAT would cross Galileo orbit in about 260 years (see Fig. 6). This was due to an error in the achieved argument of perigee of -17 degrees, falling in the blue region of fig. 2. Fortunately, the achieved eccentricity was lower than the target one, and it compensated partially for the error in the argument of latitude.

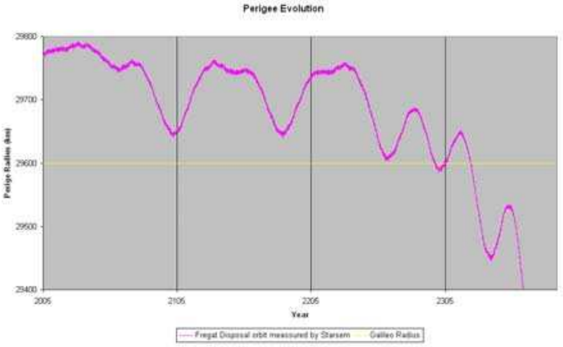


Figure 6: Evolution of perigee due to errors in eccentricity (STARSEM-provided orbit).

However, it was suspected that the measured elements could have some estimation errors that would invalidate this long-term propagation. So the question was whether more accurate orbit values could be obtained to perform the long-term propagation and perigee evolution analysis.

5. TLE-based orbit accuracy

Since FREGAT is a passive object, no active tracking data can be obtained in order to estimate the actual orbital elements. The only orbital information publicly available is contained in Two Line Elements (TLE) for GIOVE-A's FREGAT provided by USSTRATCOM (GIOVE-A's FREGAT NORAD number is 28923). More than 3 years of TLEs (around 1100 sets) are available for this FREGAT vehicle.

These TLEs were used to generate orbits that in turn were transformed to XYZ pseudo-observations used in a long term orbit determination (OD) estimating the initial state vector and the solar radiation pressure (see Tab. 3).

TLE-fit-based FREGAT Kepler elements (J2000)		
Semi-major Axis:	29813.2	km
Eccentricity:	0.002	
Inclination:	56.07	deg
RAAN:	191.15	deg
Arg. of Perigee:	136.3	deg
True Anomaly:	18.29	deg

Table 3: FREGAT Elements Based on TLEs

The internal consistency of this method was checked by comparing the estimated Kepler elements from 6 consecutive orbit determinations of 6 months based on pseudo-observations in each OD (see Fig. 7). The results can be found in Tab. 4.

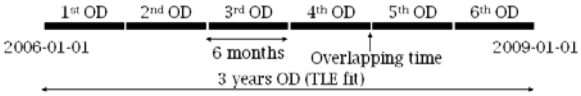


Figure 7.Schematic of the TLE fit methodology.

Semi-major Axis:	0.001	km
Eccentricity:	1.14E-05	
Inclination:	0.00034	deg
RAAN:	0.0049	deg
Arg. of perigee	0.788	deg
Arg. of latitude:	0.0038	deg

Table 4: RMS of estimated Kepler elements consistency at overlapping points.

Note that due to the very long arcs used in the orbit determination, the semi-major axis is determined with high accuracy. The inaccuracy of other elements, such as RAAN and argument of latitude, translates in position errors of 2.5 km. The highest inaccuracy is in the argument of perigee but, as seen in Fig. 2, this is quite small compared with the actual dispersion of the actual disposal orbit (see Tab. 1 and Tab. 3). This can nevertheless produce discrepancies in the results if not interpreted with care. Figure 8 shows the perigee evolution for two different TLE-fits. Even though the evolution in both cases is practically the same, one crosses the 29600 km Galileo radius, and the other one misses it by 2 km. This has an implication on how the actual crossing time is defined in terms of threshold around the Galileo radius based on the long-term propagation accuracy.

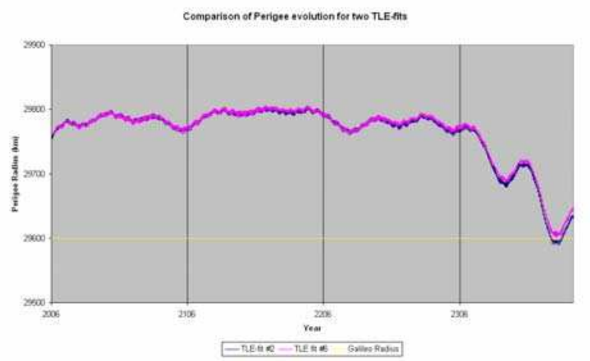


Figure 8: Comparison of Perigee evolution between TLE-fits orbit.

6. Long-term propagation of TLE-fit orbit

Once a set of orbital parameters has been obtained by long-arc TLE fitting, and its accuracy assessed, a new long-term propagation can be done in order to verify the crossing time. The solar radiation pressure coefficient estimated as part of the TLE-fit orbit determination was also used for the propagation.

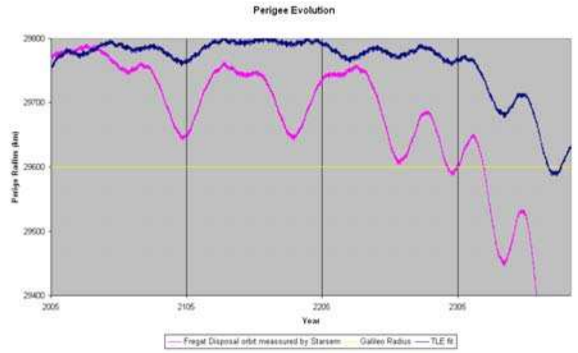


Figure 9: Comparison of Perigee evolution between orbit provided by STARSEM and TLE fit orbit.

Figure 9 shows orbits propagated with both STARSEM measured values and the TLE-fit. The perigee evolution is clearly quite different, and the crossing time is still above 290 years.

Not surprisingly, the crossing time is much longer for the TLE-fit than for STARSEM-provided orbit, since its argument of perigee falls to the "right" side of the target value (see Fig. 2).

Once again, this shows that relatively small deviations in the argument of perigee can change drastically the evolution of the perigee. Fortunately enough, for GIOVE-A's FREGAT, this did not decrease the crossing time too dramatically.

7. FUTURE STUDIES

Motivated by the results presented in this paper, a subsequent analysis of GIOVE-B's FREGAT disposal orbit will be made in the future once sufficient TLE data is available (GIOVE- B was launched April 2008).

Having seen that disposal orbits are very sensitive to the actual achieved eccentricity and argument of perigee, further studies on the probability of having early crossing times will be carried out taking into account available data on the dispersion of FREGAT disposal for other missions.

Finally, once again, this shows that relatively small deviations on the initial argument of perigee can change drastically the evolution of the perigee. Luckily enough, for the GIOVE-A's FREGAT, this did not decrease the crossing time too dramatically.

The use of long-arc TLE fit for passivated objects will be further assessed for its use in collision risk assessment in case it can be used for the Galileo orbital regions.

8. CONCLUSIONS

The study presented here shows that the low eccentricity growth strategies for disposal at GNSS altitudes may be difficult to implement because of the sensitivity of the results to the initial argument of perigee and eccentricity. In the case of GIOVE-A's FREGAT disposal, the target argument of perigee may not be optimal due to a launch date different from the nominal one for which the argument of perigee has been optimized.

In addition, since FREGAT follows a frozen flight program, dispersions in the trajectory may not be fully corrected resulting in a further sub-optimal argument of perigee.

GIOVE-A's FREGAT is a clear example, a lucky one nevertheless, since the deviation ocurred in a favourable direction so it did not shorten the crossing time. However, had the deviation been in a "wrong" direction, the crossing time could have been much shorter. One way of avoiding this would be selecting a higher disposal orbit as to provide some margin. The Galileo graveyard orbit will be nominally 300 km above the operational one.

Finally, long-term TLE-fit of passive elements such a disposed FREGAT has shown to provide good results. This could be due to the well known dynamics at GNSS altitudes. Other uses of such long-term fit, as collision risk assessment, need to be studied in the future.

REFERENCES

[1] Chao, C.C. “MEO disposal orbit stability and direct reentry strategy”. AAS Paper No. 00–152, AAS/AIAA Space Flight Mechanics Meeting, Clearwater, FL, January 23–26, 2000.

[2] Saunders, C.J., Martin, C.E., Lewis, H.G. (2005). Disposal Orbit Characteristics for Galileo Including Orbit Propagation Techniques. In Proc. 4th European Conference on Space Debris. SP-672 ESA Publications Division, European Space Agency, Noordwijk, The Netherlands.

[3] STARSEM. (2005) GIOVE-A Launch Kit. Available on http://www.starsem.com/news/kits.htm.

[4] Merz, K. (2004). “Investigation of possible Disposal Orbits for GNSS”. ESA Internal document MAO Working Paper No. 471 Issue 1, Rev. 0. July 15, 2004