GALILEO FIRST FOC LAUNCH: RECOVERY MISSION DESIGN

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Abstract: *Galileo Full Operational Capacity (FOC) first two satellites were launched from Kourou on a Soyuz ST-B equipped with a Fregat-M upper stage on 22 August 2014. After separation, the acquisition of the signals already showed that the achieved orbit was far from a nominal injection. This was clearly confirmed by several orbit determinations done by ESOC Flight Dynamics. Analysis of the achieved orbit indicated that Fregat had performed its second burn in a direction about 35 degrees away from the nominal direction. As a result, the satellites were left in a non-nominal orbit, out of the specifications of the launcher, and out of the range of orbits that the satellites could recover using their own propulsion system. Under these circumstances, the nominal mission was not possible, and the redesign of a recovery mission started. This paper presents the mission analysis for the recovery mission to a non-nominal orbit, taking into account the known capabilities of the satellites (propulsion, avionics, etc.), and operational constraints. Given the high eccentricity and low perigee of the orbit, the mission drivers for this recovery were:- Reduce the power dynamic range; reduce Doppler, increase visibility from receiver, and reduce operational burden on the Earth Sensors; reduce exposure to the Van Allen belts; and improve contribution to the global constellation performance in case the satellites could be introduced in the Galileo navigation service.*

Keywords: *Galileo, Fregat, launch failure, mission recovery.*

1. Introduction

Europe's Galileo satellite navigation system – currently being built up – will provide high-quality positioning, navigation and timing services to users across the whole world. Galileo's Full Operational (FOC) constellation will consist of 24 operational satellites plus six spares orbiting Earth in three circular medium-Earth orbits, at an altitude of 23222 km and 56 degrees inclination. Galileo is an endeavour of the European Commission, with the European Space Agency as Design Authority in charge as well of its implementation.

The first two FOC satellites, GSAT0201 and GSAT0202, manufactured by the OHB/SSTL consortium, were launched by Arianespace from Guiana Space Centre on a Soyuz ST-B equipped with a Fregat-M upper stage on 22 August 2014.

As planned, 3.8 hours after lift-off, the two satellites separated from Fregat, and their signals were acquired by the TTC antennas of the LEOP network managed by a joint CNES/ESOC team. An initial orbit determination was done by the ESOC Flight Dynamics team, based on angular and ranging S-band data, and clearly showed that the satellites' orbits were far from the expected nominal injection orbits. Analysis of the achieved orbit indicated that Fregat's second burn, nominally a circularisation manoeuvre from an elliptical transfer orbit to the final one, was performed with the correct magnitude but about 35 degrees away from the nominal direction. This last manoeuvre not only did not circularise the final orbit, leaving the eccentricity at 0.233 and semi-major axis 3700 km below the nominal value, but it also reached the final orbital plane with about 12 degrees error (13.2 degrees in RAAN and 5.35 degrees in inclination). Such orbits were out of the range of orbits that the satellites could recover using the amount of propellant budgeted for a nominal mission, and therefore reaching the nominal orbit in the Galileo Constellation was not possible. In addition, due to the low perigee, the satellites could not be able to maintain Earth pointing attitude with the accuracy needed for payload operations and navigation service provision since its main attitude sensor, the Infrared Earth Sensor, could not operate at those low altitudes (13700 km) . Unfortunately, that meant that the satellite could not be used as part of the nominal Galileo constellation under these circumstances.

Nevertheless, work at the Galileo Project Office (GPO) was started right away to design a recovery mission. The objective was to define a so-called recovery orbit that could allow the satellite to provide added value to the Galileo System. The analysis also included the manoeuvre strategy to achieve the recovery orbits and its later evolution.

This paper presents the mission analysis performed at GPO in collaboration with ESOC, CNES and DLR/GfR. The mission design took into account the known capabilities of the satellites (avionics, propulsion constraint, available propellant and the needed reserves for later routine operations, etc.), and operational constraints (non-nominal Earth pointing procedures, station visibility, manoeuvre timing).

Given the high eccentricity and low perigee of the orbit, the mission drivers for this recovery orbit, aiming to provide navigation signal in space, were:

- Reduce the L-band power dynamic range between apogee and perigee
- Reduce Doppler as to facilitate L-band ground receivers to lock the signal.
- Increase visibility time for receiver
- Reduce burden on the Earth Sensors operation
- Reduce exposure to the Van Allen belts, and, therefore, reduce satellite equipment degradation
- And, finally, improve contribution to the global constellation performance in case the satellites could be introduced in the Galileo navigation service.

2. The Launch Failure

FOC first two satellites were launched from Kourou on a Soyuz ST-B equipped with a Fregat-M upper stage. Times for Lift-off (22/08/2014 12:27:11 UTC) and injection (22/08/2014 16:15:08) matched the nominal ones.

After injection and acquisition of signal, a preliminary orbit determinations were done by Flight Dynamics, based on angular and ranging data, clearly showing an orbit far from the nominal injection. Analysis of the achieved orbit indicates that Fregat performed its second burn in a direction about 35 degrees away from the nominal direction. As a result, the satellites were left in a non-nominal orbit, out of the specifications of the launcher, and out of the range of orbits that the satellites could recover using their own propulsion system. The final consolidated OD estimating the injection parameter was performed on 23 August 2014 around 06:00 (see data Tab. 1 and Tab. 2; in J2000, epoch 22nd Aug 2014 16:15:08.0 UTC).

Table 1. Assessment of GSAT0201 orbits at injection

GSAT0201	Target		Final estimation and assessment		
Orbital Parameters J2000	Nominal	REQ 3σ accuracy	Estimated	Difference with respect to Target	Approx. sigma
Semi-major axis [km]	29912.3	100	26197.6	-3715	111-sigma
Eccentricity	0.00027	0.001	0.232	0.23	698-sigma
Inclination [dig]	55.12	0.12	49.77	-5.35	134-sigma
RAAN [dig]	100.66	0.12	87.47	-13.19	330-sigma
Arg. Latitude [dig]	241.98	-	249.77	7.79	-
Arg. Perigee [dig]	-	-	24.73	-	-

Table 2. Assessment of GSAT0202 orbits at injection

GSAT0202	Target		Final estimation and assessment		
Orbital Parameters J2000	Nominal	REQ 3σ accuracy	Estimated	Difference with respect to Target	Approx. sigma
Semi-major axis [km]	29887.7	100	26181.3	-3706	111-sigma
Eccentricity	0.00056	0.001	0.233	0.23	698-sigma
Inclination [deg]	55.12	0.12	49.77	-5.35	134-sigma
RAAN [deg]	100.66	0.12	87.48	-13.18	329-sigma
Arg. Latitude [deg]	241.98	-	249.76	7.78	-
Arg. Perigee [deg]	-	-	24.88	-	-

The orbit where the satellites were injected was far away from the nominal. The Period, perigee and apogee altitude for these orbits were as shown in Tab. 3:

Table 3. Assessment of GSAT0202 orbits at injection

Perigee altitude [km]	13796
Apogee altitude [km]	25848
Period	11h 43min

Figure 1 and Fig. 2 show the nominal and the current orbits in space to have a clear picture of the difference between the nominal Galileo orbit and the anomalous injection orbit.

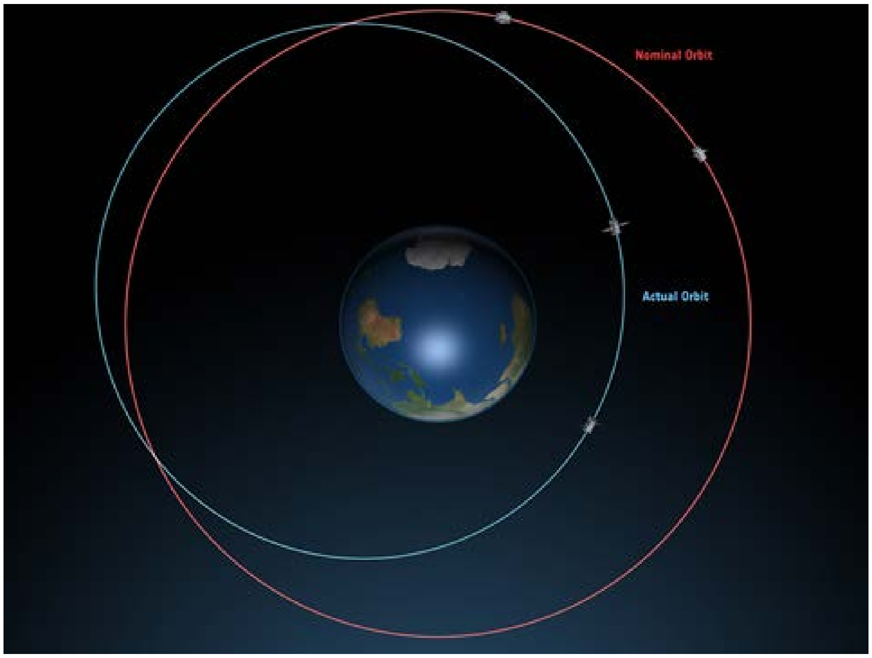

Figure 1: Bottom view from orbital plane of nominal and injected orbit
[© ESA – P. Carril]

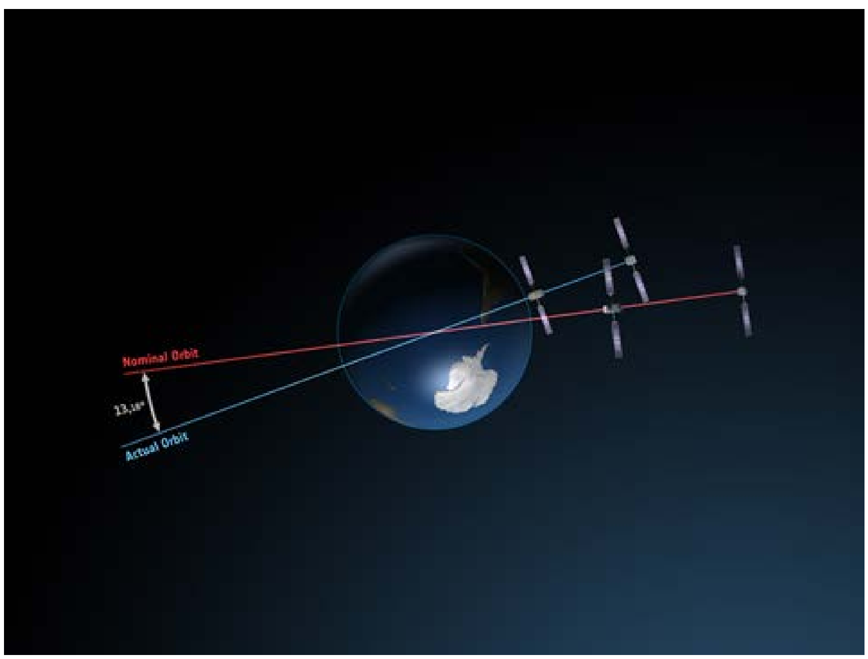

Figure 2: Side view of nominal and injected orbit
[© ESA – P. Carril]

After the first converged Orbit Determination done by Flight Dynamics, an investigation of the potential causes of the injection failure was done. Several failures scenarios were analysed to check whether they explained the current orbit of the satellites. After isolating the most probable cause in accordance with the orbit, it was concluded that the first Fregat burn had been executed nominally, but that the 2nd burn had presented some anomaly. Using the available data, it was possible to estimate the magnitude and direction of the Fregat 2nd burn in a way that fitted Fregat ballistic trajectory between the 1^{st} and the 2nd burns and the orbit after the 2nd burn (provided by ESOC Flight Dynamics orbit determination process).

Table 4. Fregat 2nd burn performance, in orbital frame

Delta-V	Nominal	Actual	Difference
Radial [m/s]	-28	-663	-635
Along [m/s]	1456	1135	-321
Cross [m/s]	108	637	529
Magnitude [m/s]	1459	1460	1

Table 5. Fregat 2nd burn performance

Difference in Magnitude [m/s]	1
Difference in angle [deg]	35.3

These results presented in Tab. 4 and Tab. 5 show that Fregat burn was as expected in magnitude (1460 m/s) but wrong in direction, about 35 degrees away from the nominal direction. Since the projection in the velocity was lower than nominal, the achieved semi-major axis was underperformed. In addition the direction of the burn had components in the radial direction, towards the Earth, thus the strong eccentricity, and finally out of plane, thus the errors in inclination and RAAN, as shown by Tab. 1 and Tab. 2.

3. Implications of the Faulty Injection Orbit

This section presents the implications at satellite level of the orbit where the L3 satellites were injected.

3.1. Earth Sensor

The Galileo satellites embark two (prime and redundant) Selex ES IRES N2 Earth sensors. The operational altitude range of the sensor, as specified in the user manual for nominal Pitch and Roll outputs, is between 18.000 km and 53.000 km due to the apparent size of the Earth (as see by the spacecraft) with respect to the field of view of the Earth Sensors infrared detectors, see Fig. 3. Out that range, the output from the sensor would not be interpreted correctly by the satellite, triggering a transition to Safe Mode. The injection orbit had a perigee altitude of 13713 km, so it was foreseeable that the Earth Sensor will not work for the whole orbit.

The workaround for this issue is to inhibit the Earth Sensor by telecommand when the satellite is flying below 18000 km, enable the Earth Sensor afterwards. During the time the Earth Sensor is inhibited, the FOC spacecraft use only the gyros to controlled its attitude. As it is shown in the next section, this requires some extra care for the current orbit.

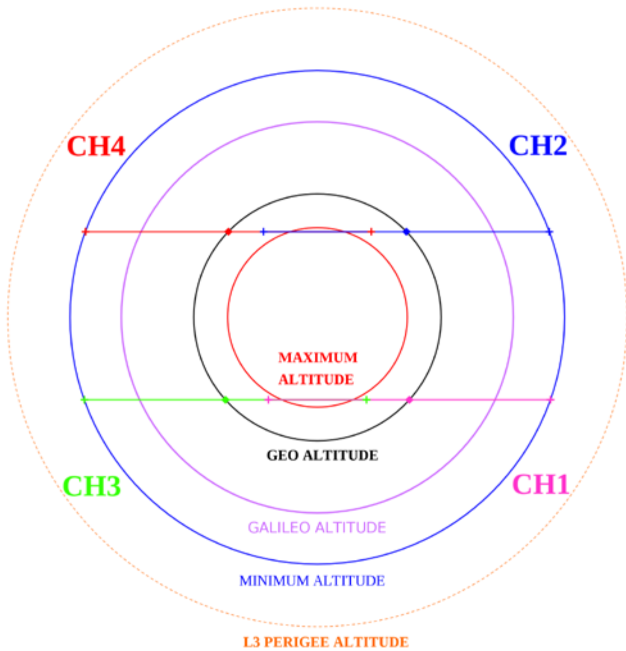

Figure 3. Apparent Earth size in relation to Earth Sensor field of view, for different altitudes

3.2. Gyroscopes

The gyros per se are not affected by the anomalous orbit, but the avionics SW compensate the orbit rate using a simplified expression that is only valid for circular orbits, shown in Eq. 1:

$$\dot{\theta} = \sqrt{\mu/r^3} \tag{1}$$

While the correct expression is, taking into account non-circular orbits, is as per Eq. 2:

$$\dot{\theta} = \frac{\sqrt{\mu a(1-e^2)}}{r^2} \tag{2}$$

When the satellite crosses the perigee region, the orbit rate is higher than what the Avionics SW computes. Since the Earth Sensor is inhibited, and the gyros are compensated with the wrong information, the satellite attitude will start diverging away from nadir-pointing due to this error (see Fig. 4). If the Earth Sensor is inhibited when altitude is lower than 18000km, the nadir-pointing error can grow up to 12 degrees. Under this circumstances, when the satellite raises through 18000 km, the Earth sensor cannot generate Earth pointing measurements, and the satellite will trigger a transition to Safe Mode.

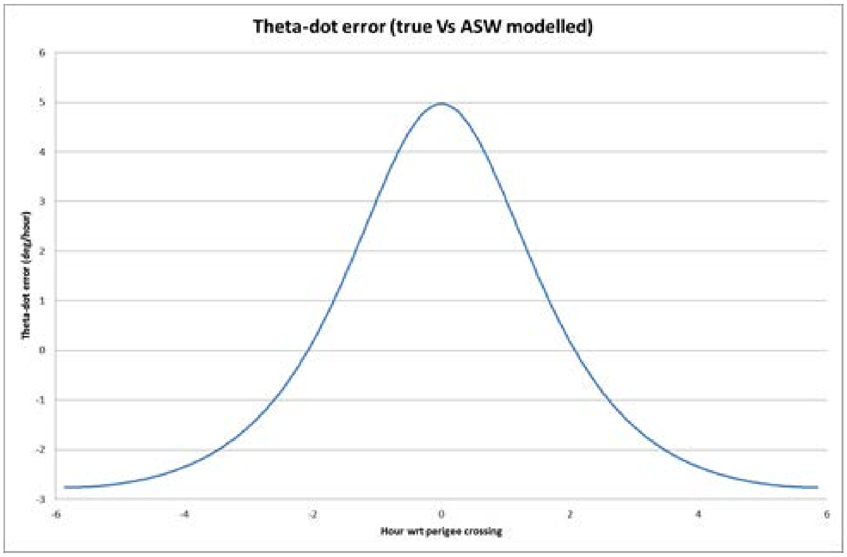

Figure 4. Error on the On-board computed orbit rate due to Eq. 1 for the injection orbit

4. Reassessment of DV budget

The satellite mission was originally designed for a direct injection onto the MEO, not further than 400 km from the nominal altitude. Other delta-V budget items were designed for orbit maintenance, relocation within the same orbital plane and graveyarding. A total of 170 m/s was budgeted for a whole nominal mission. This meant that the amount of propellant present on the satellites was not enough to correct the anomalous orbit, neither to circularise it.

In order to consider alternative orbits, a new delta-V budget had been put together to assess the amount of propellant available for recovery the mission, increasing the limit as much as possible after careful analysis of these budgets.
Some amount of propellant were reserved for the routine mission, i.e. activities after the recovery manoeuvres. The USM (ultimate safe mode, a thrusters based reorientation to the Sun direction) reserve for a maximum number of expected Safe Modes and one planned SW upload (current design, major SW upload require a reorientation to the Sun). The Station Keeping reserve is to correct the amount of perturbation introduced by the USM and SW upload. Collision avoidance reserve is a best guess based on the number of times these manoeuvre will be done and the warning time. With all these considerations, the available delta-v was the following, see Tab. 8:

Table 6: Available propellant mass and DV for recovery manoeuvres.

	GSAT0201	GSAT0202
Delta-V for manoeuvres [m/s]	165	165

This delta-V is longitudinal and impulsive. However, due to the eccentricity of the orbit, the gravity loses are not negligible. Other inefficiencies due to manoeuvre timing accommodation to operational constraint will also affect the actual equivalent “impulsive” delta-V. For the analysis, it was decided to use 160 m/s as “impulsive” delta-V to account for these effects.

5. Mission drivers for the orbit recovery

The mission drivers for the recovery orbit, aiming to provide navigation signal in space, were:

- Reduce the L-power dynamic range between apogee and perigee
- Reduce Doppler as to facilitate L-band ground receivers to lock the signal.
- Increase visibility time for receiver
- Reduce burden on the Earth Sensors operation
- Reduce exposure to the Van Allen belts, and, therefore, reduce satellite equipment degradation
- And, finally, improve contribution to the global constellation performance in case the satellites could be introduced in the Galileo navigation service.

6. Recovery Orbits

With the amount of 160 m/s, a parametric analysis of potential target orbit has been done. The simplest manoeuvre scenario for a recovery is to perform a series of manoeuvre in the apogee to raise the perigee altitude. Alternatively some of the (lasts) manoeuvres can be done at the perigee to target a given orbital period that will provide a ground track repeat pattern.

6.1. Parametric Analysis

The running parameter is the percentage of the DV of 160 m/s that is used in manoeuvres at the apogee (the rest of the DV is used at the perigee). The Keplerian elements are those of the orbit after the manoeuvres. Table 7 provides the result of the parametric study for the identified candidates only.

Table 7. Current amount of propellant and equivalent delta-V

% of DV done at Apogee	Semi-major Axis [km]	Eccentricity	Radius Perigee [km]	Radius Apogee [km]	Altitude Perigee [km]	Altitude Apogee [km]	Candidate
0.0%	23752	0.154128	20091	27413	13713	21035	
22.0%	24614	0.152841	20852	28376	14474	21998	Safe Orbit
68.3%	26573	0.151120	22557	30588	16179	24210	2 rev / 1 day
88.2%	27485	0.150815	23340	31630	16962	25252	19 rev / 10 days
98.7%	27978	0.150766	23760	32196	17382	25818	37 rev / 20 days
100.0%	28043	0.150765	23815	32271	17437	25893	Max perigee altitude

From these orbits, some present certain interest for a redefined mission. The following four candidates are identified (but only two will be retained):

- Galileo Safe Orbit
- 2 rev / 1 day Resonant Orbit

- 19 rev / 1 day Resonant Orbit
- Maximum perigee altitude Orbit

The first two candidates can be discarded for the reasons explained hereafter:

The 'Galileo Safe Orbit' has an apogee below the Galileo nominal constellation. The orbital parameters are chosen such that the crossing with Galileo altitude is avoided for at least 200 years, see Fig. 5, while maximizing the amount of DV used at the apogee. Doing manoeuvre at the apogee is more efficient; in addition doing manoeuvre at the perigee when the perigee is low (14474 km for this orbit) may not be possible due to the limitations of the Earth sensor at low altitude. Because of that limitation, this orbit might not be feasible. This also presents problems of radiation dose.

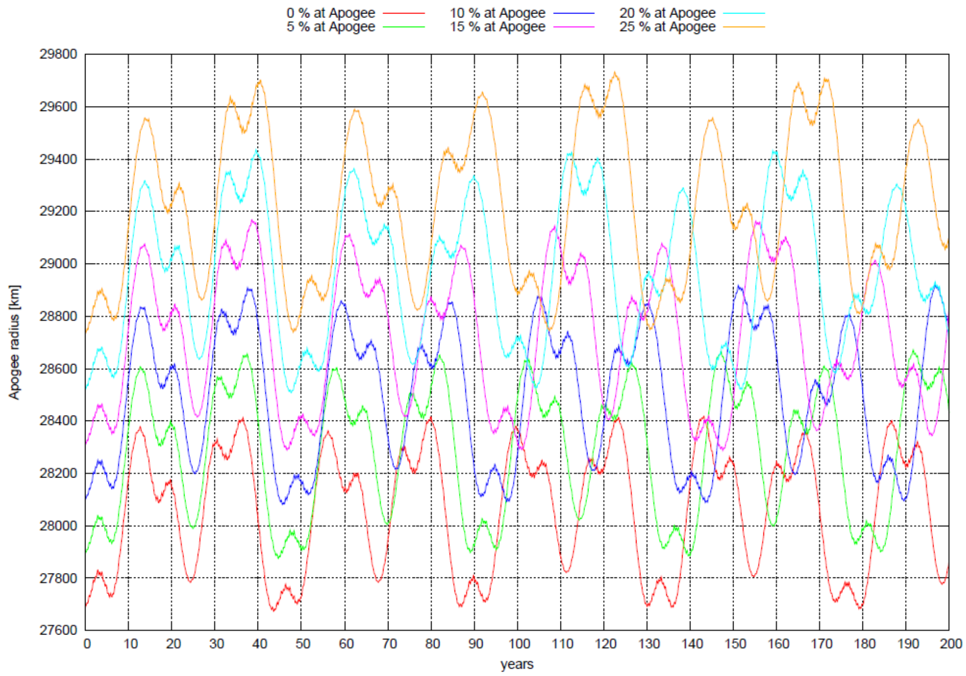

Figure 5. Apogee altitude evolution for different recovery orbit candidates.

The 2 revolutions / 1 day Resonant Orbit presents some interesting properties for navigation and for operations planning. The satellites ground track repeat every day, so the visibility is well known in advance. This orbit is resonant with GPS (2 rev / 1 day) and with Galileo (17 rev / 10 days). Figure 6 shows the ground-track of this orbit (red colour) during 10 days, and the orbit of a nominal Galileo satellite (blue colour).

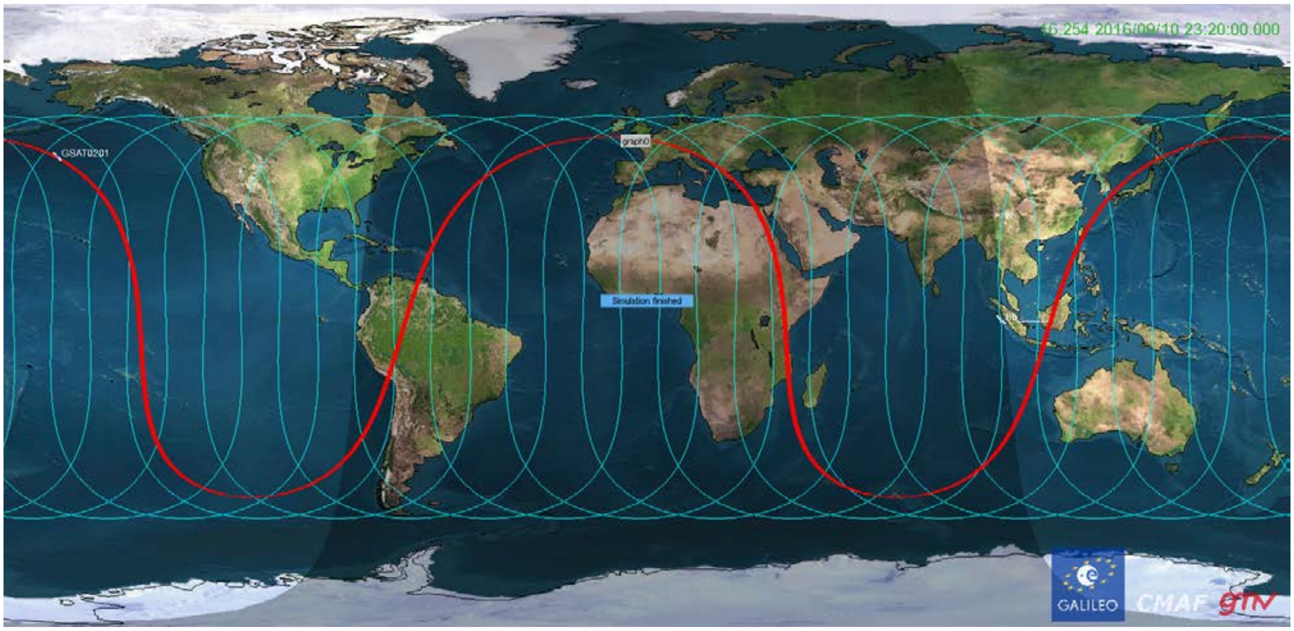

Figure 6. Ground track comparison between resonant orbit (2 rev / 1 days) and nominal Galileo orbit (17 rev / 10 days)

This orbit has two disadvantages:

- The perigee is not as high as for the retained candidates (16000 km versus 16800 km of the 19 rev / 10 day candidate),
- Due to the low repeat cycle (2 revolutions) the effect of the "deep resonance" with the Earth gravity field (2:1). This is a problem present in GPS, which has to be manoeuvres every 18 months approximately to correct resonance-induces semi-major axis growth, and for early Galileo semi-major axis (5 revolutions / 3 days) that were definitely discarded in favour of the final baseline of 17 revolution / 10 days.

As a consequence the two first candidates are dropped, and only the 19 rev / 10 days and 37 rev / 20 days resonant orbits and the maximum perigee altitude orbit are retained for the rest of the analysis.

6.2. Resonant Orbit: 19 revolutions / 10 days

This orbit is especially attractive for Galileo mission. The repeat ground-track of 19 revolutions in 10 days is very close to the nominal one of Galileo, 17 revolutions in 10 days. This will allow to optimise the position of these two satellites so coverage gaps can be minimise, and that optimisation stays constant cycle after cycle (something that can only be done because of this repeatability). In addition, this orbit is achieved by doing a large percentage of manoeuvres at the apogee, which is optimal from an operational/visibility and manoeuvre efficiency. The perigee altitude is increased enough as to facilitate the operations of the Earth sensor and to reduce radiation dose. The eccentricity is also reduced to values that will allow receiver to operate efficiently.

Figure 7 shows the ground-track of this orbit (red colour) during 10 days, and the orbit of a nominal Galileo satellite (blue colour).

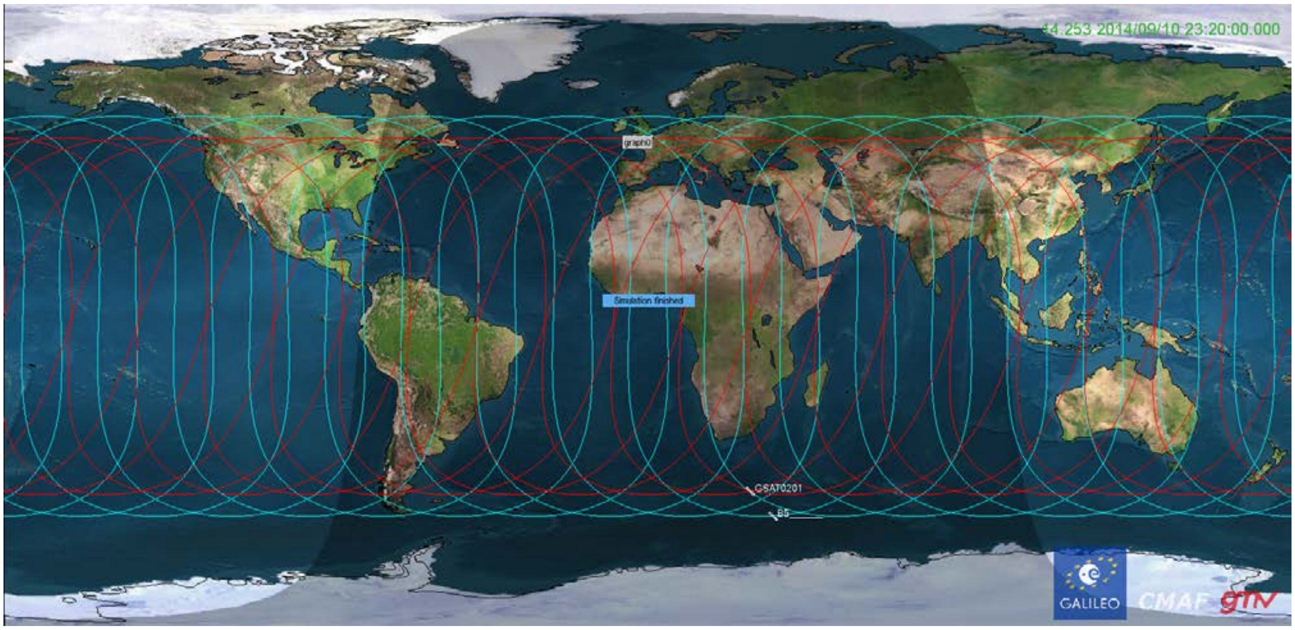

Figure 7. Ground track comparison between resonant orbit (19 rev / 10 days) and nominal Galileo orbit (17 rev / 10 days)

6.3. Resonant Orbit: 37 revolutions / 20 days

This orbit is especially attractive for Galileo mission as well. The repeat ground-track of 37 revolutions in 20 days with both satellite separated 180 degrees of mean anomaly, the ground track repeats every ten days with swapping satellites. Together with the same advantages described for the 19 rev/ 10 days, this orbits adds that it has a higher perigee.

After consideration in the Galileo Project, the 37 rev/ 20 days orbit was chosen as target for the recovery mission.

Figure 8 shows the ground-track of this orbit (red colour) during 20 days, and the orbit of a nominal Galileo satellite (blue colour).

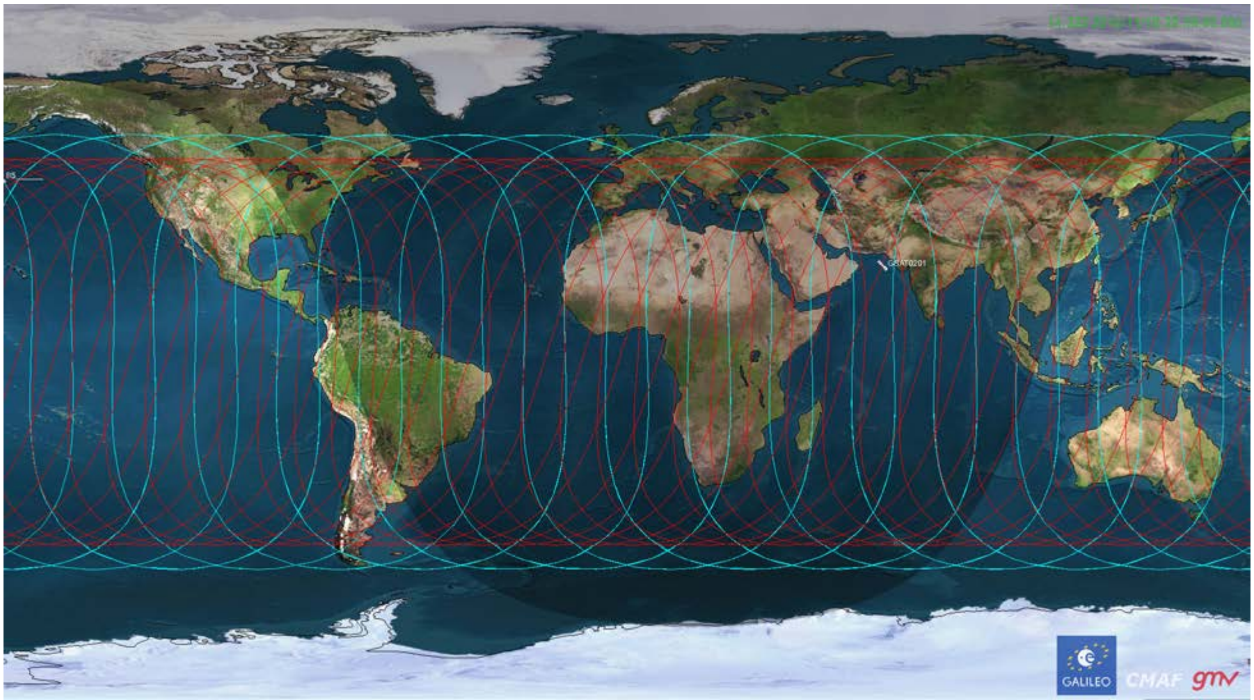

Figure 8. Ground track comparison between resonant orbit (37 rev / 20 days) and nominal Galileo orbit (17 rev / 10 days)

7. Target Recovery Orbit (37 rev / 20 days)

The starting point to define the Station Keeping strategy is to use the Galileo Strategy [1] based on setting orbit element bias to the orbit corrected after LEOP so that the future known perturbation are counteracted. Unknown perturbations, such as those coming from thrusting during transition to ultimate Safe Mode, will be corrected with the SK item allocated in new delta-V budget.

The recovery strategy was based on circularising the orbit by raising the perigee as much as possible and achieving a resonant orbit of 37 revolutions in 20 days, i.e. mean semi major axis around 27977.9 km (Galileo reference is 17 orbits in 10 days). In addition, the phase between both satellites shall be 180 degrees at the relative opposed apsides.

No corrections on the out-of-plane parameters (inclination and RAAN) were considered for achieving the target orbit. Therefore these elements came from the natural evolution along the strategy. In a similar way, corrections in the argument of perigee were not foreseen.

On the other hand, the semi-major axis to get a resonant orbit depends on the rates of change of: RAAN, perigee and mean anomaly; caused mainly by Earth potential and in lesser extent by the third body. These drifts depend at the same time on the semi-major axis as well as on the inclination and eccentricity.

Whereas secular drifts analytical expressions provides an accurate first order approximation of the drifts from current values, the long term natural evolution of the orbit modify these drifts.

Therefore an iterative process based in long term propagation was needed to find out the optimum semi-major axis which minimise the long-term departure of the ground-track from the required resonant orbit.

The target semi-major axis was set after this iterative process, including ESOC Flight Dynamics in the loop, using the mathematical models of the spacecraft and minimising the drift of the longitude of the ascending node based on actual orbital elements.

It should be noted that the target orbit was always optimised and given at perigee as the most constringent point.

The optimisation was performed one satellite after the other. Once the first satellite is optimised its apogee passing time is taken as the second satellite perigee crossing time and the optimisation process is set. Note that the orbit of the spacecraft were similar but not the same, so the optimum osculating semi-major axes were close but not equal (difference of meters)

The target true anomaly is a degree of freedom that in principle could be selected such way that minimise the probability of collision risk. The consequence would be the need of introduce free drift days in the manoeuvre strategy plan. However analyses show that there is not a true anomaly interval which minimise this probability. This is not a concern since the collision risk probability is extremely low as discussed in L3 Mission Analysis recovery.

7.1 Requirements in the target orbit

Three requirements were imposed for achieving the target orbits at perigee crossings:

- Each spacecraft shall be within 95 meters from its resonant semi-major axis.
- The difference in semi-major axis between the two spacecraft shall be less than 76 meters.
- The difference in anomaly between the two spacecraft shall be 180 degrees with a tolerance of 2 degrees.

In this way the departure from a reference ground-track in the ascending node is less than 4 degrees in 6 years, and the difference between satellites anomalies at any moment is at least 135 deg during 6 years, and therefore the satellites can be tracked separately.

As said before, no manoeuvres were foreseen in out-of-planes parameters and argument of perigee, but they should be kept as closest as possible between both satellites.

7.2 Target Orbit long-term characterization

The evolution of the RAAN can be approximated linearly by -0.03990505 deg/day, and the evolution of the argument of perigee can be approximated linearly by 0.03383184 deg/day.

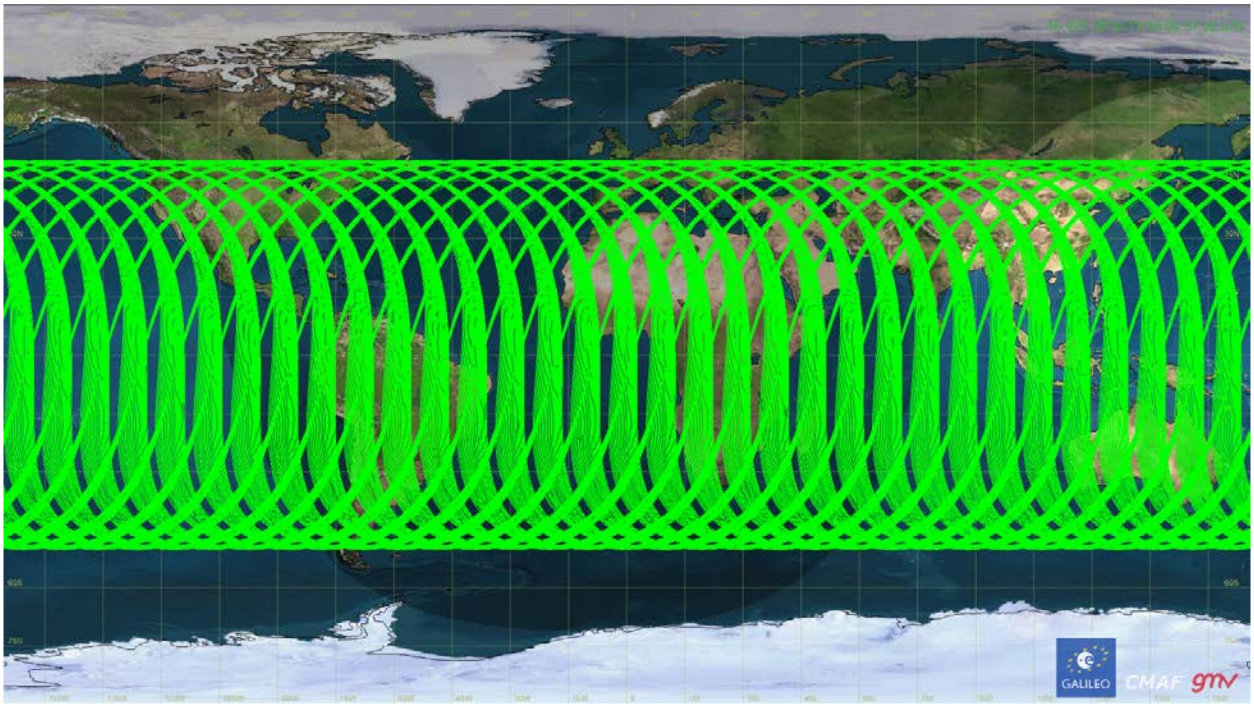

Figure 9. Ground-track after two years

Due to the drift on the argument of perigee, the ground track evolves even if the ascending nodes are kept within boundaries. Nevertheless, the ground track is constrained and in the North hemisphere the departure minimised.

The repeatability of ~20 days give certain synchronism with the Galileo Reference (10 days). It should be also noticed that every 10 days, half of the cycle period, each L3 satellite has the ground-track position that the other L3 satellite had 10 days earlier, since they are located 180 degrees apart in anomaly. Therefore, the ground track repeatability is 20 days per satellite but 10 days per L3 couple, increasing this synchronism with the Galileo Reference.

Of course the relative position of these two satellites with respect to the reference Constellation will differ with time. The different RAAN and perigee drifts (with resultant resonant semi-major axis, period) makes the latitude crossing time drift away with respect to the one of the reference Constellation. But in batches of few cycles the relative positions can be considered similar for certain applications.

8. Realization of the orbit achievement

The manoeuvre operation set-up was following the same scheme described in [2], with a combined CNES and ESOC team (CNESOC) taking responsibility for the Flight Dynamics inputs from ESOC in Darmstadt (Germany). DLR GfR, from GCC in Oberpfaffenhofen (Germany), was taking responsibility for Satellite operations, especially for the computations of TC to be uploaded for inhibit the Earth Sensor and correcting gyro compensation (more details can be found in a paper to be presented in this Symposium [3]). For the satellite contacts, the Galileo ground network was used complemented with stations from the CNES TTC network.

8.1 Iterative Target Orbit Computation

As explained in section 6, an iterative process based on the expected achieved orbit was needed to find out the optimum semi-major axis which minimise the long-term departure of the ground-track from the required resonant orbit. It should be noted that the target orbit was always optimised and given at perigee as the most constringent point.

As first guess a semi-major axis value based on the secular evolution was considered for the first time. The eccentricity used was an approximation from the spare delta-v. Then an iterative process based in long term propagation to find out the optimum semi-major axis was launched obtaining a preliminary target orbit which was passed to ESOC. With this orbit a fully optimised manoeuvre strategy plan was elaborated by CNESOC Flight Dynamics to raise the orbit to the required semi-major axis and minimising the eccentricity with apogee (and perigee) manoeuvres.

CNESOC provided back the orbit at perigee time achieved with the manoeuvre plan. As eccentricity and argument of perigee are modified a new iterative semi-major axis process is needed. The new outcome was handled by ESOC providing a new manoeuvre plan and analysed back at ESTEC. This was repeated until the semi-major axis modification from one iteration to the next one was less than one meter, usually after one or two iterations.

During actual manoeuvres the orbital elements changed (slighted) from the expected ones due to miss-performances. Therefore, after the Orbit Determination, the real achieved orbit at perigee was provided again and a new iterative process initiated, i.e. the target semi-major axis needed to be further refined based on the rest of parameters of the achieved orbit (mainly due to a change in the argument of perigee). In particular, during the execution of the plan the target changed a bit between manoeuvres, it was a moving target. This change was in the order of several meters, so the rest of the manoeuvres were able to easily cope with this change of target and only the Fine positioning manoeuvres were affected.

8.2 Mission Recovery Manoeuvres

At first a strategy to raise both satellites' orbits in parallel was devised. However, the priority to start the in-orbit tests activities before the end of 2014 provoked a change to a sequential satellites raise plan.

The first manoeuvres are always done in the apogee in order to increase the perigee to an altitude where the Earth sensor is able to work. Only in this way manoeuvring in the perigee would be possible since the current satellite SW version qualification status does not allow for manoeuvres performed with gyro-only attitude controlled.

Since achievement of the target orbit relied on the correctness of thrusters modelling, only once the first manoeuvres were performed and calibrated the target orbit could be confirmed. A Key Point was conceived as the latest possible decision point in the manoeuvre sequence: up to the Key Point, the manoeuvre sequence was valid for three of the target orbit candidates (37/20, 19/10, or simply achieving the maximum perigee possible) in case of an achievable alternative was needed. At the Key Point, the final target orbit was confirmed taking into account manoeuvre and platform performance.

The recovery of GSAT0201 was very nominal. Only a minor discrepancy in the propellant consumption was detected. This could have compromised reaching the target resonant orbit of 37 rev / 20 days, but it was quickly resolved as a Data Base problem.

Table 8 shows the manoeuvres performed. The test manoeuvre number 1 was intended to assess the capabilities if the satellite to perform manoeuvres and to characterise the propulsion system. The Fine positioning manoeuvre at the end of the sequence was intended to reduce the error in the semi-major axis coming from the manoeuvre delta-V dispersion, in order to achieve the Station Keeping tolerances.

Table 8: GSAT0201 Mission Recovery Manoeuvres as performed

Man Id	Burn start (UTC)	Actual Delta-v (m/s)	Approx. Perigee altitude (km)
Initial state	-	-	13703
TEST-1	2014-11-05 19:29	4.49	13824
MANO-1	2014-11-07 18:01	20.06	14259
MANO-2	2014-11-08 17:42	20.19	14694
MANO-3	2014-11-09 17:43	19.20	15122
MANO-4	2014-11-10 18:06	17.82	15528
MANO-5	2014-11-11 18:46	16.65	15917
MANO-6	2014-11-13 08:11	15.73	16289
MANO-7	2014-11-14 09:28	13.39	16613
MANO-8	2014-11-15 10:58	11.86	16905
MANO-9	2014-11-16 12:27	13.50	17240
FP-1	2014-11-19 12:30	0.22	17238

The recovery of GSAT0202 was as well nominal. Table 9 shows the manoeuvre performed. The first test manoeuvre was used to characterise the thermal and Power subsystem models for specific orientation with respect Sun. Test manoeuvre 2 had the same intention as the first test manoeuvre in GSAT0201, to assess the manoeuvre capabilities of the satellite.

The Orbit raising manoeuvre were interrupted between 30 January and 17 February to analyse an anomaly on the Earth Sensor inhibition at the perigee passage. The problem was identified as procedural, and quickly resolved. The pause time was needed to allow the resynchronisation of GSAT0202 with respect to GSAT0201. In the meantime, a test manoeuvre was performed to test a manoeuvre mode for very small manoeuvers, which would be needed in nominal operations. The fine positioning manoeuvre at the end of the sequence, as for GSAT0201, was intended to reduce the error in the semi-major axis coming from the manoeuvre delta-V dispersion, in order to achieve the Station Keeping tolerances. Manoeuvres 8 to 10 have a decreasing magnitude in order to approach the target slowly and avoid overshooting in case of a delay of one of them. Figure 11 shows the true anomaly difference evolution between the actual orbit and the target orbit.

Table 9: GSAT0202 Mission Recovery Manoeuvres as performed

Man Id	Burn start (UTC)	Actual Delta-v (m/s)	Approx. Perigee altitude (km)
Initial state	-	-	13703
TEST-1	2015-01-19 09:35	0.0030	13702
TEST-2	2015-01-20 10:20	4.6603	13804
MANO-1	2015-01-22 20:52	11.6005	14056
MANO-2	2015-01-23 20:27	13.4207	14343
MANO-3	2015-01-27 19:38	19.9421	14781
MANO-4	2015-01-28 19:46	18.6607	15200
MANO-5	2015-01-29 20:10	18.1172	15615
MANO-6	2015-01-30 20:51	17.7041	16031
TEST-3	2015-02-03 14:23	0.0006	16031
MANO-7	2015-02-17 14:10	20.1024	16512
MANO-8	2015-02-20 18:16	18.7756	16969
MANO-9	2015-02-24 12:51	7.1203	17143
MANO-10	2015-02-26 16:41	3.3863	17230
FP-1	2015-03-02 11:26	01828	17235

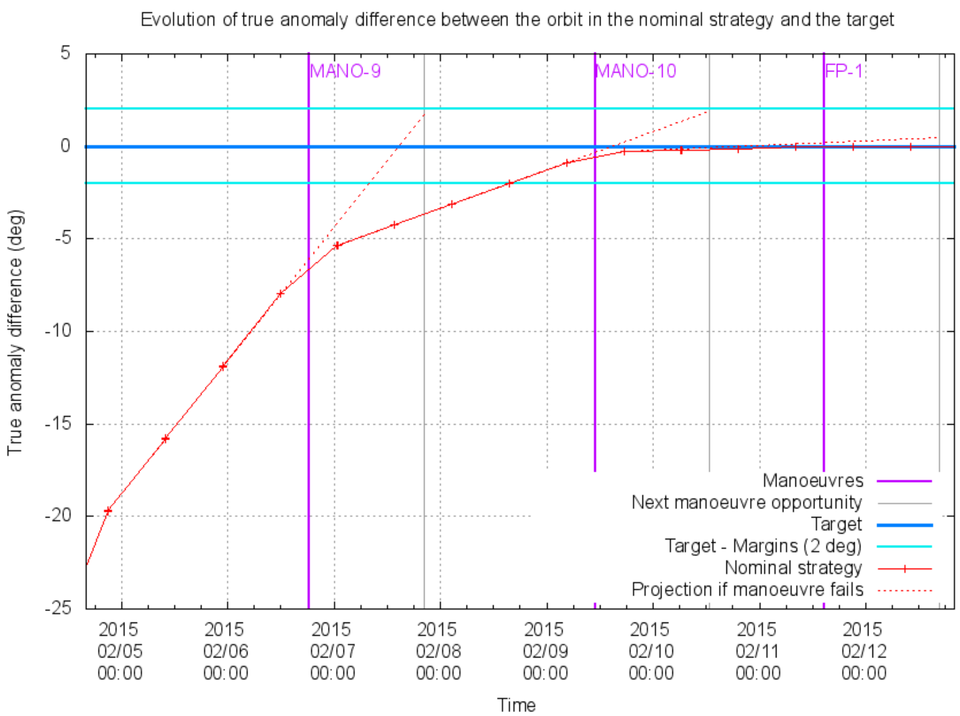

Figure 11. Evolution of the true anomaly difference between the satellite orbit and the target.

9. Conclusions

The failure of Fregat left the first FOC satellites in a non-nominal orbit, completely out of the range of orbits that the satellites could recover using their own propulsion system. The injection orbit was not usable for Navigation mission due to operational burdens at several levels.

After careful analysis, a recovery mission was planned using the available propellant, in such a way that the perigee was raised to an altitude for safe operation of the Earth Sensor, reaching a resonant orbit too, synchronising both satellites to optimise the coverage over the Earth and improving considerably the contribution to the global constellation performance in case these satellites could be introduced in the Galileo navigation service.

The recovery mission was very successful and provided the opportunity to explore the capability of the FOC satellites outside their design envelope.

10. References

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