FLIGHT DYNAMICS MISSION ANALYSIS AND OPERATIONS FOR GALILEO SATELLITES: ORBITAL MANEUVERS STRATEGY DESIGN AND PERFORMANCES

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Abstract: *GALILEO is going to be Europe's own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. It is going to be inter-operable with the American GPS and the Russian GLONASS. The four first operational satellites, launched in 2011 (IOV1) and 2012 (IOV2), validate the GALILEO concept. This paper presents part of the In-Orbit Validation LEOP generic mission analysis, and the operational phase after IOV1 launch, implying orbital maneuvers for correction of the injection orbit errors and phasing maneuvers to reach the final Argument of Latitude. A very accurate positioning is required, needing several days for precise orbit determination and corrections. This is needed so that the satellites remain within an Argument of Latitude deadband of ±1.5° with regard to their reference orbit, for 12 years, with only one station keeping maneuver. This paper is relevant for all IOV LEOP and addresses only flight dynamic aspects of the mission related to the orbital maneuver strategy. First the maneuver strategy itself is described. Then, the timeline of the maneuver strategy is detailed. At last, this paper presents the performances really achieved during IOV1 operations for station acquisition in terms of targeted point accuracy and total consumption.*

Keywords: *GALILEO, LEOP, Maneuver, Strategy, IOV, MEO.*

1. Introduction

The first four GALILEO operational satellites, launched two by two in 2011 (IOV1) and 2012 (IOV2) will validate the GALILEO concept with both segments: space and related ground infrastructure. Once this In-Orbit Validation (IOV) phase has been completed, additional satellites will be launched to build-up the constellation which consists of 30 satellites (27 operational and 3 spares), positioned in three circular Medium Earth Orbit (MEO) planes at an altitude of 23222 km above the Earth and at an inclination of the orbital planes of 56 degrees with reference to the equatorial plane.

This paper presents part of the IOV LEOP generic mission analysis and the operational phase after IOV1 launch. The objective of LEOP phase is to move the two injected satellites onto their operational positions. Nominally, the two satellites (let's call them SAT1 and SAT2) are directly injected on the reference orbit, only separated by opposite tangential ΔV of +/-0.722m/s (around +/-11km on semi major axis (sma)). So, only phasing maneuvers are necessary in nominal case. But, LEOP implies also orbital maneuvers due to injection orbit errors and phasing corrections to reach the final Argument of Latitude (AoL). At the end of LEOP, a very accurate positioning (mainly on semi-major axis) is required, needing several days for accurate orbit determination and corrections. This accurate positioning is needed in order that the satellites remain within an AoL deadband of ±1.5° with regard to their reference orbit, for 12 years, with only one station keeping maneuver [3]. The generic mission analysis described in this paper is relevant for all IOV LEOP and addresses only flight dynamics aspects of the mission related to the orbital maneuver strategy.

First, the maneuver strategy itself is described in this paper. Predominant sources of dispersions (injection, separation, maneuver achievement, orbit determination) are taken into account. So this strategy can be considered as generic for all possible scenarios (limited to 3σ dispersions), including all phasing angles (angle between injection point and target point on orbit, being launch date dependent). The method of rendezvous optimization in order to reach the required accuracy for all possible scenarios (limited to 3σ dispersions and including all possible phasing angles) is also explained. This maneuver strategy has been analyzed using the DRAGON software, developed at CNES, and used also for ATV maneuver strategy for analysis and operations [1, 2, 5].

Then, the timeline of the maneuver strategy is detailed. This analysis allows to determine a fixed schedule for maneuver planning, giving slots allocated to maneuver during LEOP. This paper presents the refinements performed on this nominal timeline during IOV1 operations, showing the robustness of the strategy. This schedule considers maximal number of maneuvers needed to achieve the required accuracy on final orbit. Maneuver slots were defined to cope with all known system constraints (LEOP maximal duration, In-Orbit Tests activities, performances on injection, on separation, on orbit determination and on thruster activation and accuracy, satellites capabilities and constraints, operational computation and management, double launch, ground station visibilities, etc).

At last, this paper presents the performances, in terms of targeted point accuracy and total consumption achieved, thanks to Monte-Carlo analyses performed on significant configurations of Phasing Angles (PA). Those “End-To-End” simulations campaigns (closed loops) were performed with the help of the OSCAR software [5], also developed at CNES, that can trigger several runs of DRAGON in a batch and parallelized mode, with random shots of all the dispersed parameters. Those performances are then compared to the real one obtained during operations for IOV1 station acquisition.

2. Orbital maneuver strategy design

2.1 Objectives

The aim of the maneuver strategy analysis are, first, to define the main characteristics of the strategy, as far as possible independently from injection dispersions and phasing angles. Then, it has to give elements on the effects of the main parameter dispersions (injection orbit parameters, maneuver performances, orbit determination accuracy…).

This kind of study has to take into account the following objectives as the propellant consumption minimization, but also the simplification of the operational activity scheduling taking into account the ground station visibilities and the operational timeline constraints (on total LEOP duration, on drift phase duration without maneuvers, on drift acquisition phase duration, on operational measurements, on calculations and on commands for instance). It has to take care to avoid simultaneous critical operations on both satellites or even collision risks between them.

The objective of LEOP phase is to move the injected satellites onto their operational positions. Only phasing maneuvers are necessary in nominal case. But, one of the flight dynamics objectives of maneuver strategy is also to correct the orbit plane if necessary because the launcher performances are not sufficient to reach them parameters in every dispersed cases. Then, maneuver strategy has to move both satellites to the right phasing angle, and to get the correct in-plane orbit parameters like the eccentricity vector, the accurate sma and the AoL, as well as out of plane parameters like inclination and RAAN. It shall be kept in mind that inclination and RAAN control, as well as eccentricity control, implies constraints on maneuver dates and amplitudes.

2.2. Main elements

There are basically up to four phases for each satellite LEOP called respectively the "Drift Acquisition Phase (DAP)" or phase A, the "Drift Phase (DP)" or phase B, the "Drift Stop Phase (DSP)" or phase C, and the "Fine Positioning Phase (FPP)" or phase D (see Fig. 1).

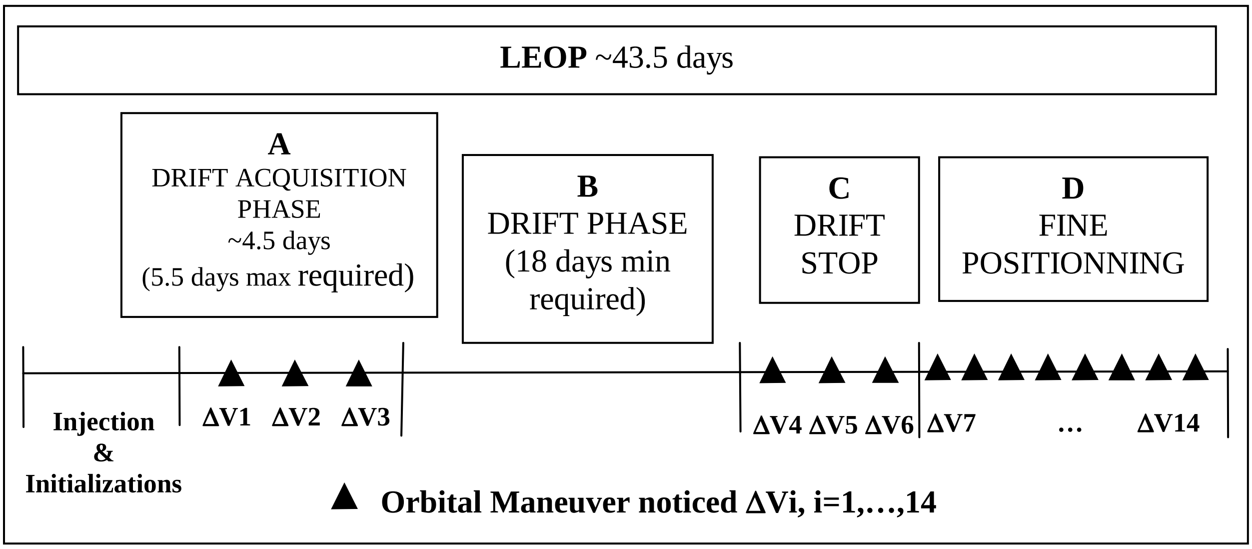

Figure 1. Maneuver scenario with phasing constraints

The "Drift Acquisition Phase" covers the injection and separation activities, the satellite initialization, the Sun acquisition, the Earth acquisition and the entry in normal mode. Then, follow the orbit determination and maneuver plan calculations to initialize the satellite drift. Up to 3 maneuvers could be needed depending on phasing strategy (because the angle between injection point and target point on orbit is launch date dependent). As a requirement, the transfer of maneuver parameters has to be performed not later than 5 days after separation and the drift start phase has to be completed, nominally, earlier than 5.5 days after separation.
The "Drift Phase" consists in several days without maneuvers for S/C monitoring, IOT (In-Orbit Tests) activities, orbit calculation for the needs of payload IOT and for the next maneuver preparation. This drift phase duration shall last, at least, 18 days to facilitate IOT planning.
"Drift Stop Phase" is supposed to stop the satellite drift and to achieve the coarse positioning. The sma reached is typically less than 50 km compared to the targeted one, and the AoL reached less than 2 deg compared to its target, depending on dispersions and the phasing angle to reach. The eccentricity and the out-of-plane parameters achieved are nominally in the final range. Up to 3 maneuvers could be needed depending on phasing strategy.
The "Fine Positioning Phase" puts the sma in a window of +/-5m compared to the targeted one, and the AoL in a window of +/-0.002 deg compared to the target, taking into account

orbit determination accuracies. Up to 8 decreasing small maneuvers could be needed depending on phasing strategy and dispersed cases.

2.2. Detailed strategy

Drift duration

The minimum propellant cost is obtained with a maximum drift duration. This means that the drift acquisition phase (A) shall be finished as early as possible, and the drift stop phase (C) shall start as late as possible. For both satellites, the targeted phasing angle can be relatively far from the injection point (up to 180° because the drift direction is supposed free). For fuel-cost saving reasons, all the allowed durations shall then be used with a minimal absolute drift rate in phase B. Once the drift has been initiated, the drift stop date is determined and cannot be postponed (without over consumption).

Drift Direction

The phasing angle is known because the targeted AoL is imposed. So it can take any value depending on the day of launch and the injection point. The drift direction (or drift sign) is roughly defined by the "shortest way" (i.e. the "cheapest way") to reach the target, i.e. positive drift for a phasing angle between 0° and 180°, negative drift for a phasing angle between -180° and 0°. Actually, this is not exactly the case because injection sma dispersions at $+3\sigma$ (+100 km on sma) give a negative drift of about 3°/day and because of constraint of the satellite order on final positions. Indeed, the second satellite SAT2 shall be 40° ahead of the first one SAT1 at the end of LEOP. The injection increment is positive for the SAT1 along-track and negative for the SAT2. This gives a positive relative drift of SAT2 wrt SAT1. So, depending on the day of launch, the choice of the drift direction is either pre-defined or undefined before launch. In the latter case, both strategies have to be prepared before launch, and the choice is done after post-insertion orbit determination, accounting for the actual launcher dispersion.

Out-of-plane corrections

An out-of-plane correction could be performed as early as possible to correct injection errors. Therefore, the problem can become a two dimension problem only that can be solved by in-plane corrections.

But, an out-of-plane correction could also be necessary after the free drift period (phase B) due to the influence of the second zonal harmonic J2 term of the terrestrial potential on the relative RAAN drift resulting from the differential of altitude between the two satellites during phase B.

In theory, this out-of-plane correction could be anticipated and included in the out-of-plane correction applied before the free drift phase B. Nevertheless, a correction has generally to be performed after this free drift phase B due to the propagation model mismodelling over such a long period (18 days) where IOT and phase A inaccuracy maneuver effects are not predictable, and also because out-of-plane unwished effects of the in-plane corrections can be encountered, especially in case of contingency on pointing attitude of the first non calibrated maneuver or other important ones during phases A and C.

So, at least two out-of-plane corrections are needed. Other out-of-plane corrections could be performed on other boosts depending on the performances achieved. This solution gives also more opportunities on the AoL needed to perform out-of-plane corrections as it is shared out among several boosts.

In-plane corrections

In-plane correction means only a tangential correction, so without radial component, not feasible because of a linear range of the Earth sensor that limits pitch angle to +/- 2deg.

First, during the drift acquisition phase A, the eccentricity correction is not mandatory. It could be fully corrected in the drift stop phase C. Then, in-plane correction time could be set (as early as possible to minimize the phasing cost) taking into account the ground station visibilities and two in-plane corrections may be enough for phase A. It will be tried to equalize as much as possible those first two tangential corrections, in order: to limit dispersion errors, to predict with more accuracy the performance of the second tangential correction according to the observation of the first one and to remain in the duration range of each maneuver. A third in-plane correction is considered, with a limited value in order to: tune the drift (as out-of-plane corrections generate in-plane components for instance), avoid over-cost due to a possible over performance of the second boost and limit the unwished drift due to maneuver dispersions during the phase B.

Then, for phase C, the in-plane correction dates are highly constrained by the phasing objective and by the eccentricity correction needs (if any). As far as possible, in-plane corrections of phase A are computed to avoid simultaneous maneuvers of both satellites in phase C. For this phase C, two in-plane corrections may be enough. As in phase A, it will be tried to equalize as much as possible those two in-plane corrections. A third in-plane maneuver is also considered, with a limited value, in order to: refine the rendezvous (out-of-plane corrections generate in-plane components for instance), avoid over-cost due to a possible over performance of the previous boost, limit dispersions on the sma and the AoL in order to be able to reach the required target during the fine positioning phase D within the estimated maximal number of maneuvers.

At last, for phase D, the in-plane corrections are mainly constrained by the tangential amplitude to reach the accuracy required on the sma. Indeed, this tangential component has to be smaller and smaller until reaching an expected 3σ maximal error less than 5m. The effect of these corrections on eccentricity and on AoL is far under the targeted ranges because of their small amplitudes. So maneuver dates are not very constrained by that. The schedule is mainly determined by the minimum number of orbits needed before and after maneuvers to reach the best orbit determination accuracy on the sma. It is also conditioned by the ground station visibility constraints, the avoidance of simultaneous maneuvers for both satellites and the LEOP maximal duration. For this phase D, a maximum of 8 in-plane corrections is foreseen to reach the targeted sma range for any targeted phasing angle and any dispersion case related to the injection: the boost achievements and the orbit determination (in the range of the 3σ specified). Furthermore, due to the impossibility to introduce a pitch angle and because of the necessity to decrease little by little boost tangential components, the eccentricity rendezvous is only completely solved up to $\Delta V7$ computation (3D rendezvous solved with 4 tangential boosts). Then, for $\Delta V8$ computation, only one of the eccentricity vector component is completely solved (ex or ey depending on dispersions, solved with the help of 3 tangential boosts). From $\Delta V9$ to $\Delta V14$ computations, the eccentricity rendezvous is no more required as maneuvers are small enough to stay in the eccentricity window even with maximal dispersions (1.84m/s error induces an eccentricity increment of 0.0005 in a worst case, corresponding to the targeted eccentricity window).

Combined in-plane and out-of-plane corrections (IOM)

Maneuver strategy combines the opportunity to calculate all maneuvers with in-plane and out-of-plane components. The main advantages are the correction of the out-of-plane side-effects of in-plane corrections, the correction of the unwished in-plane side-effects of out-of-plane corrections, and a larger range of opportunities on the AoL for each maneuvered.

Overall positioning of the maneuvers

The maneuver strategy analysis consists in building a "standard" scenario for the LEOP, trying to define a relative fixed maneuver schedule.
For phases A and C, the choice of the time slots for maneuvers can be driven by the propellant cost optimization. Indeed, the satellite with the highest phasing angle starts the drift sooner than the other one. For this satellite, maneuvers are performed, in phase A, just before the other satellite ones and in phase B, just after (as far as possible). But this also depends on the injection errors and on the negative or positive phasing strategy that can be applied. Then, the attribution of maneuver time slots for each satellites is chosen only during operations (it is the reason why this is not applied for the Monte Carlo analysis for which it was chosen to move always SAT1 before SAT2 as a worst case of consumption).
Moreover, due to constraints on simultaneity between both satellites, the order chosen to maneuver the two satellites inside a phase (phase A on one side, and then phases C/D on the other side) cannot be switched due to operational mission profile constraints defined in the next paragraph.

3. Generic mission profile

The generic mission profile covers a 43.5-day LEOP duration, corresponding to about 75 orbit revolutions. It defines generic maneuver time slots (to be tuned in real time), covering all the phasing strategies and all the dispersed cases in terms of injection. Those generic time slots are determined by:

- the maximal 5.5-day duration of the drift acquisition phase A
- the minimal 18-day duration of the drift phase B
- the maximal 43.5-day duration of the whole LEOP
- the fact that maneuvers, including their critical periods (two hours before the beginning of the boost and one hour after the end of the boost), have to be performed in visibility of ground stations. The best effort shall be made to have a double station visibility (on only two stations) for each maneuvers of phase A, within a margin of 15 minutes before and after the first boost. A simple station visibility (on only one station) is required for all the other maneuvers, within a margin of 3 hours before and 2 hours after each boosts. In real time, if generic time slots reserved for maneuvers are not compliant with these visibility constraints, a part of the time or during the whole slot, only a longer LEOP duration (more than 43.5 days) and/or a shorter free drift phase B (less than 18 days) could be envisaged (only some hours are concerned).
- the non simultaneity constraint of maneuvers achievement between both satellites launched together, implying a minimal duration of one hour between critical periods of both vehicles;
- the minimum orbit number between maneuvers for orbit measurements, which is related to the required accuracy of the orbit determination.
- the minimum orbit number between maneuvers for maneuver calculations (date, module, attitude…), updated pointing data calculations for ground stations and other operational tasks before uploading this maneuver to the satellite (including briefings,

telecommand calculations and uploading, and so on…). For this point, it is assumed a maximal of 0.25 orbit (3.5 hours) to achieve these last calculations before uploading the next maneuver. As this delay is quite short, preliminary calculations could have been done before (about again 3.5 hours) with less measurements available.

That is the reason why, for the first maneuver on the first satellite, it is considered 0.5 orbit for calculations instead of 0.25 because it is the first matching of the nominal strategy in function of injection and separation dispersions.

For ΔV2 to ΔV6 with only one orbit measurements before and after the maneuver, the orbit determination accuracy is far under maneuver achievement errors, so the preliminary calculation is slightly degraded compared to the final and accurate one.

For ΔV of fine positioning phase D, as the orbit determination accuracy is in the same order of magnitude than maneuver achievement errors, it is also not negligible compared to the required target range concerning the sma. But, for those maneuvers, we have more and more measurement orbits (from 3 to 7). So, a preliminary diagnostic of orbit determination without ¼ of orbit measurements is also slightly degraded compared to the final and accurate one.

- At last, only 90 deg of orbit arc time slots were taken into account for each effective boost (without the critical periods before and after boosts). This is the maximal possible value with respect to all the previous constraints. The only consequence is an increase of the consumption that remains acceptable (see further results) and that could be considered as a sizing case with margins. In real time, it is possible to extend those slots according to the previous operations achieved. This possibility could also be used to improve the optimization and especially to compensate the impossibility to perform maneuvers with pitch components if needed.

Figure 2 illustrates a generic sequence for a given boost on both satellites. Considering previous constraints, and orbit determination performances related to the required targeted sma and AoL ranges, the generic mission profile is designed with the following maximal and needed orbit numbers N for orbit measurements, presented in Table 1.

Table 1. Number of orbit measurements N before each ΔVi and before handover.

	ΔV1	**ΔV2,3,4,6,8,10,12**	**ΔV5**	**ΔV7,9,11,13**	**ΔV14**	**Handover**
N	1.25 orbit (SAT1) 2 orbits (SAT2) Non simultaneity	1 orbit	1.5 orbits	2 orbits	4 orbits	2.5 orbits (SAT1) 2 orbits (SAT 2)

At least 2-orbit measurements is needed between last maneuver and handover to ensure an orbit determination accuracy of the sma less than 2m. Because the 2 satellites are not performing maneuvers at the same time, it is needed to have 2.5-orbit measurements for SAT1.

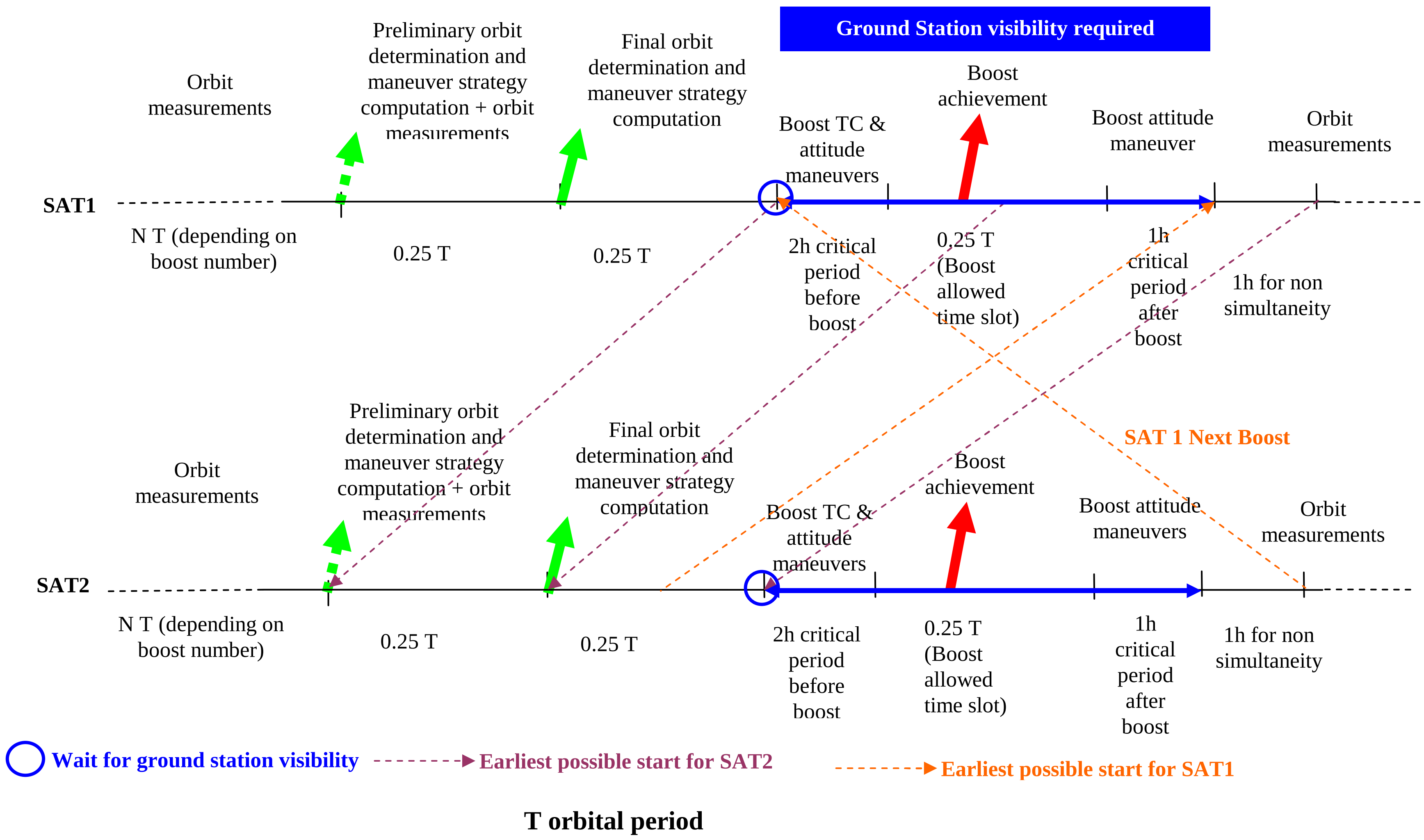

Figure 2. DV generic sequence strategy

4. Orbital maneuver strategy performances

For this generic maneuver strategy analysis, a complete "End-to-End" simulation (in closed loop) for two significant cases of phasing angles ("+" is for a positive drift and "-" is for a negative one) were performed:

- a "large one" corresponding to +130 deg for SAT1 and +170 deg for SAT2 (case of a launch on 10/21/2011);
- a "small one" corresponding to +23 deg for SAT1 and +63 deg for SAT2 (case of a launch on 10/22/2011).

A Monte Carlo analysis was conducted for all the phasing cases studied and both satellites. 1000 random shots were simulated for each studied case. The errors taken into account are the dispersions on injection, on separation, on orbit determination, on boost achievement and on orbit propagation model (mainly on the Sun radiation pressure coefficient which is the most active perturbation for GALILEO orbits). Dispersions are considered as Gaussian ones.
All simulations were conducted with the OSCAR & DRAGON tools, developed at CNES (see above). With those tools, for each shot, the complete closed loop is simulated with orbit determination, ΔVi computation and achievement for each of the 14 maneuvers. Those tools compute the optimal strategy in terms of consumption allowing to join the target in the defined window, and for given time slots and chosen solving strategy as discussed before (3D complete solving, only ex or ey solving, only sma and AoL solving, only sma solving, with or without bias on normal direction…). Same tools are also used for GALILEO LEOP operations.
The targeted box of the orbital parameters are then presented in Table 2.

Table 2. Targeted box of the orbital parameters.

	Δa	ΔAoL	Δi	ΔRAAN	Δe
Targeted windows	+/-5m	+/-0.002deg (~ +/-1000m ΔX)	+/-0.01deg	+/-0.01deg	+/-0.0005

4.1. Launch on 10/21/2011: Phasing angle of +130 deg for SAT1 and +170 deg for SAT2

Figure 3 presents the statistics obtained on the orbital elements at the handover compared to the targeted ones. The window is definitively achieved for all random shots, even with some margins. It can be pointed out that those margins are very comfortable for out-of-plane components (inclination and RAAN).

Figure 4 shows the statistics on total consumption. For this case of phasing angles, which depends mainly on injection dispersions, the consumption lays within the range 19-43m/s, including out-of-plane corrections.

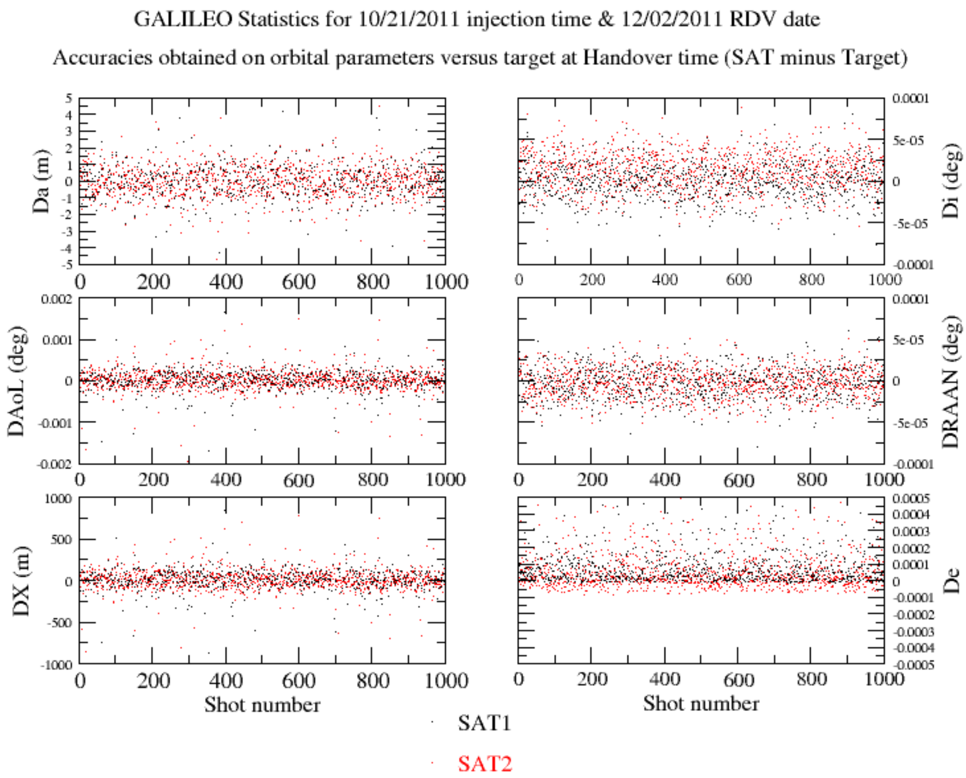

Figure 3. Target statistics

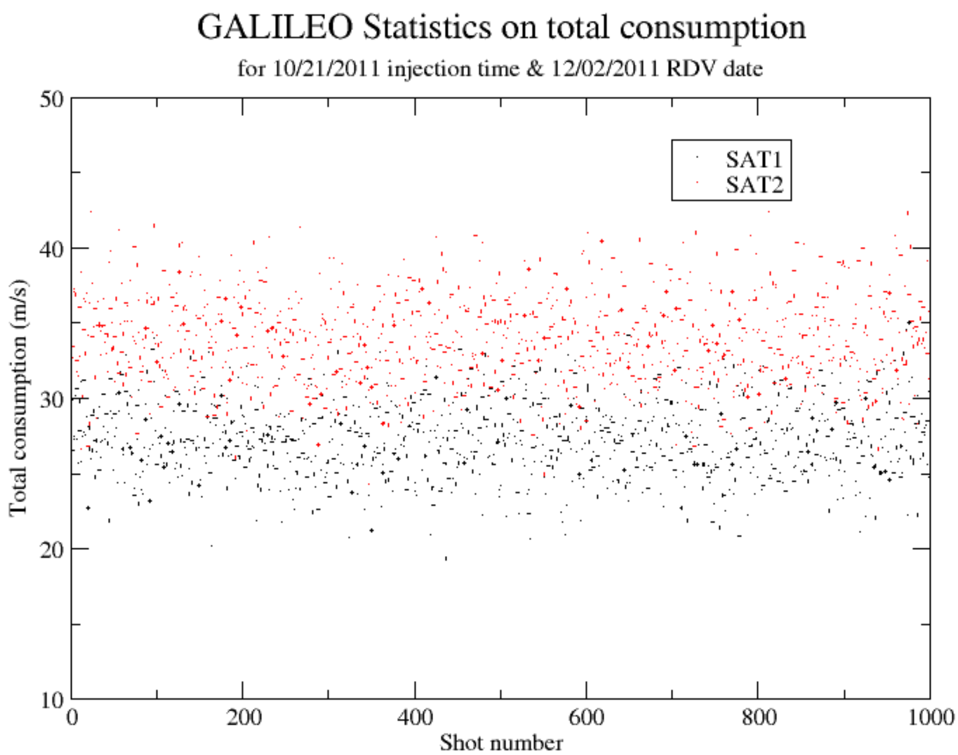

Figure 4. Consumption statistics

4.2. Launch on 10/22/2011: Phasing angle of +23 deg for SAT1 and +63 deg for SAT2

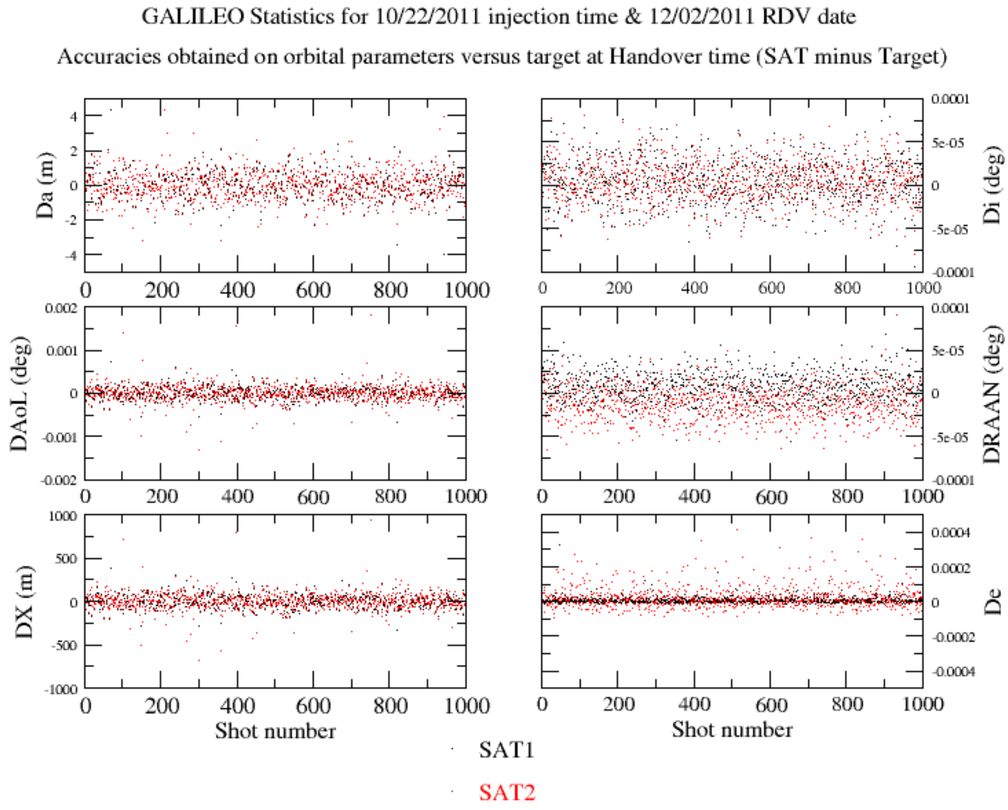

Figure 5. Target statistics

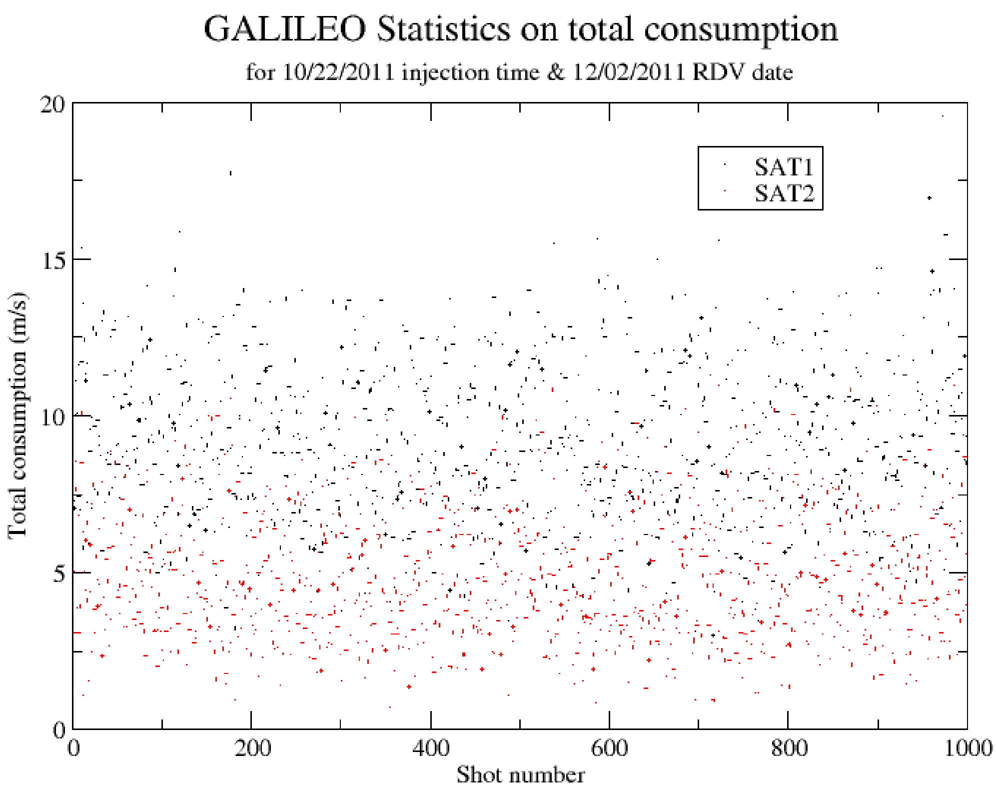

Figure 6. Consumption statistics

Figure 5 plots the statistics obtained on the orbital elements at the handover compared to the targeted ones. The window is also definitively achieved for all random shots, even with some margins. Those margins are again very comfortable for out-of-plane elements (inclination and RAAN).
Figure 6 shows the statistics on total consumption. For this kind of phasing angles, mainly depending on injection dispersions, the consumption is always below 20m/s, including out-of-plane corrections.

4.3. Remarks

Depending on dispersions and on phasing angles, the targeted window can be reached earlier with less than 14 maneuvers. Statistics show that it could happen after ΔV9. The probability to reduce LEOP duration is better for the smallest phasing angles, maneuvers being smaller too. So, GALILEO LEOP can be reduced to 35 days and 11 maneuvers for instance for nearly 30% of cases as initially required.

5. LEOP Preparation and Realization of the two first Galileo Satellites IOV1 [4]

5.1. Particularities of the IOV1 Specific Mission Analysis

Some particularities compared to the IOV generic mission analysis were asked for IOV1. First, the minimum free drift phase B duration was extended to 24 days (instead of 18 days) . Furthermore the maximum LEOP duration was extended to 46 days instead of 43.5 days. Some new operational constraints were added too as a minimum of 28 hours after separation before the first boost beginning, and also a minimum of 5h30mn between two maneuvers. French work law had also to be taken into account in case of a double team shift during all LEOP. Therefore, orbit measurements implementation between maneuver slots were managed differently from the generic mission analysis in order to be compliant with those new constraints (see Table 3).

Table 3. IOV1 Min. number orbits of measurements before each orbit determinations.

	ΔV1	ΔV2,3,4,6,8,11,13	ΔV5,7,9,10,12,14	Handover
N	1.25 orbit (SAT1) 2 orbits (SAT2)	1 orbit	2 orbits	4.5 orbits (SAT1) 4 orbits (SAT 2)

Backup strategy were also studied with the help of reduced Monte Carlo analysis.
If a boost is not or only partially achieved (out of the 3σ range), the idea is to define two more maneuver slots: one at the end of Drift Acquisition phase A and the other one at the end of the fine positioning phase D; and then to shift all following maneuvers on the next slots to let us the possibility to perform again the boost for the satellite on which the problem occurred. This solution permits us to not disturb the nominal LEOP for the satellite which has no problem and to keep the time schedule as nominally defined.
Then, if there is an injection problem, some cases need to perform first a transfer phase towards the nominal injection orbit before beginning the phasing phase as it was planned.
At last, if there is a maneuver date failure, the maneuver can be postponed if this delay remains compliant with all other constraints, and it is re-optimized. In a worst case, all maneuvers are shifted as in the case of a boost failure.
Analysis shows that in most of the cases, a nominal scenario, with additional backup slots or with additional transfer phase, seems to be sufficient to recover the mission. For failed cases,

some constraints or a backup strategy could be necessary, with no guaranty to recover the mission as those cases are out of 3σ cases. For those cases, the best effort will be made during LEOP operations as for all kind of contingencies.

5.2. Particularities of the IOV1 real LEOP operations

At the day of launch on October 20th in 2011, the strategy was identical to the IOV1 specific mission analysis (see Table 4). SAT1 was called PFM and SAT2 called FM2.

Table 4. IOV1 nominal strategy at launch epoch.

MANOEUVRES PLAN FOR PFM

Date Hour	22/10/2011 02:01:54:000	23/10/2011 02:10:42:000	24/10/2011 03:37:04:000	20/11/2011 00:57:24:000	21/11/2011 14:31:57:000	22/11/2011 15:53:00:000
DVq (m/s)	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
DVs (m/s)	3.8224596	3.8860380	0.4500000	-4.2066934	-4.2610314	-0.4500000
DVw (m/s)	-0.7472436	0.0991663	0.0000000	0.0000000	0.0000000	0.0000000
Durat. (s)	936	934	258	996	1006	258

MANOEUVRES PLAN FOR FM2

Date Hour	22/10/2011 16:01:12:000	23/10/2011 15:30:22:000	24/10/2011 15:28:20:000	19/11/2011 10:53:48:000	21/11/2011 00:25:04:000	22/11/2011 02:44:38:000
DVq (m/s)	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
DVs (m/s)	3.4584713	3.3836020	0.3500000	-2.2999554	-3.8567373	-0.3500000
DVw (m/s)	-0.5253238	-0.0255014	0.0000000	0.0000000	0.0000000	0.0000000
Durat. (s)	859	838	227	631	928	227

The final countdown was stopped on the 20th due to a launcher problem and another attempt was done the day after. So the strategy was then updated (see Table 5), keeping the previously mentioned constraints unchanged (drift start duration, free drift duration, etc…).

Table 5. IOV1 nominal strategy after launch delay.

MANOEUVRES PLAN FOR PFM

Date Hour	23/10/2011 16:07:02:000	24/10/2011 15:06:46:000	25/10/2011 15:10:23:000	20/11/2011 02:40:15:000	21/11/2011 16:25:28:000	22/11/2011 18:23:08:000
DVq (m/s)	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
DVs (m/s)	-6.2203280	-5.1940047	-0.6000000	2.2625579	6.3756676	0.2000000
DVw (m/s)	-2.4251784	-0.9801145	0.0000000	0.0000000	0.0000000	0.0000000
Durat. (s)	1477	1205	298	624	1417	172

MANOEUVRES PLAN FOR FM2

Date Hour	23/10/2011 02:00:12:000	24/10/2011 03:06:59:000	25/10/2011 02:59:47:000	20/11/2011 12:53:53:000	22/11/2011 05:10:17:000	23/11/2011 04:23:49:000
DVq (m/s)	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
DVs (m/s)	-6.4131609	-6.0380993	-0.7000000	5.4719490	5.6539959	0.1500000
DVw (m/s)	0.0484968	-0.5288225	0.0000000	0.0000000	0.0000000	0.0000000
Durat. (s)	1425	1356	323	1241	1276	147

After the injection of the satellites, the first days of operations lasted longer than expected. As the first two IOV satellites were the first ones in orbit, some additional investigations and activities were conducted. This had a direct impact on the maneuver strategy as the first maneuver was not feasible anymore at the expected date. Then, the first maneuver occurred only on the 30/10/2012 on PFM. To get a limited impact of this delay on the LEOP, some options were considered. The summary is presented in the Table 6.

Table 6. IOV1 constraints modification after first maneuver delay.

Constraints	Reasons for change
New target orbits for PFM and FM2	The objective was to choose target slots closer to the current position of the satellites to : - reduce the drift rate, - reduce the maneuver magnitude. This was possible thanks to the fact that IOV1 satellites were the first ones of the constellation.
Drift phase start (phase A) and stop (phase C) with 2 maneuvers instead of 3	This was proposed to reduce the phases duration. This was possible as the 3rd manoeuvre of each phase was a trim one to compensate the preceding dispersions. The DV magnitude being lower (because of the new target orbit), this was possible with no risk.
Free drift duration reduced and drift stop beginning on the 15/11/2012	The idea here is to limit the impact of the initial delay on the final hand-over date. The free drift phase was dedicated to IOT activities which were then reported after the final hand-over.

So, for the drift start phase A, the maneuver plan was re-computed with these new constraints (see Table 7). From the 30th, the operations occurred nominally and the end of the drift start phase A happened the 1st and 2nd of November for respectively PFM and FM2.

Table 7. IOV1 drift start maneuvers.

	PFM		FM2	
	DV (m/s)	Date	DV (m/s)	Date
30/10/2011	1.69	13 :01 :50	2.02	23 :41 :07
31/10/2011	1.49	14 :09 :33	1.67	23 :51 :22

For the Drift Stop phase, the operations started as expected and the strategy was done without big difficulties. The strategy was nevertheless slightly adapted in real time due to some operational constraints (listed below):

Table 8. Drift stop maneuvers

	PFM		FM2		Strategy adaptation
	DV (m/s)	Date	DV (m/s)	Date	
15/11/2012	1.95	20:46:37	0.55	09:41:24	-
16/11/2012	-	-	0.61	23:40:38	-
17/11/2012	1.04	11:41:00	0.16	21:01:48	-
18/11/2012	0.016	11:15:55			-
20/11/2012	0.0358 0.0174	00:15:33 23:54:59	0.38	13:20:51	Request from GCC for having a break on 21st and 22nd for their teams.
23/11/2012	-	-	0.15	19:50:34	Request for having the next maneuver on PFM at “comfortable” working hours
24/11/2012	0.00025	04:40:51	0.0238	16:27:05	-
25/11/2012	-	-	0.0014	19:58:52	-
26-29/11/2012					Final orbit determination to prepare the final hand-over
30/11/2012	Final handover		Final handover		

The level of deltaV reached at the end of the LEOP (some mm/s for PFM) can be pointed out. This was the condition to enter the box in semi major axis in any cases of dispersions.

The final hand-over took place on November the 30th. The final orbit was communicated by FDS to GCC and the flight dynamics responsibility transfer was formally agreed.

The actual maneuver plan was far from the expected one at the launch epoch and not in the mission analysis documents. Nevertheless, the FDS showed its capability to adapt the strategy in real time and guarantee its feasibility. The concept of fixed maneuver slots was still applicable: after the constraints modifications presented above, a new maneuver slot schema was given to the teams. This scheme was respected up to the final hand-over in our strategy updates.

6. Conclusions

The main points to be reminded for the GALILEO maneuver strategy are:

- The maneuver strategy consists in building a “standard” scenario for LEOP, trying to define a relative fixed maneuver schedule.
- Errors on the targeted point are less than 5m for the sma, less than 1000m along-track (less than 0.002deg on AoL), and less than 0.0005 on eccentricity. Margins are larger concerning out-of-plane parameters (inclination and RAAN).
- 14 maneuvers (6 for phasing phases A and C, and 8 for fine positioning phase D) are needed most of the time. So, taking into account all the constraints (maximum LEOP phase durations, ground station visibilities, non simultaneity operations on both satellites when they are maneuvering, operational constraints and localisation measurement constraints implied by the required accuracy on the target, …), the generic timeline has no margin. Nevertheless, if thruster performances prove to be better than expected, LEOP duration will probably be shorter.
- Collision risks between the two currently launched satellites during LEOP are avoided in a nominal case, but have to be managed during LEOP due to dispersions at separation.
- The maximal consumption is less than 50 m/s with hypothesis taken for analysis (without margin) for the correction of maximum out-of-plane dispersions and 180 degrees of station acquisition thanks to a 18-day long drift.
- This strategy showed during IOV1 operations its capability to be adapted in real time and to guarantee its feasibility and robustness.

8. References

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