SPACECRAFT RECOVERY OPERATIONS CONDUCTED TO THE GALILEO FOC-1 L3

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This paper presents the highlights of the spacecraft recovery operations conducted by Spaceopal to the Galileo FOC-1 (Full Operational Capability) spacecraft's which were injected in a severely non-nominal eccentric orbit due to a launcher anomaly the 22nd of August 2014.

1. Introduction

Galileo is Europe's program for a Global Navigation Satellite System (GNSS), providing a highly accurate, guaranteed global positioning and timing service. The complete Galileo constellation will consist of 30 satellites in three orbital planes at an angle of 56 degrees to the equator. With the satellites taking about 14 hours to orbit Earth at altitudes of 23 222 km, there will always be at least four satellites visible anywhere in the world.

At present there are ten Galileo satellites in Orbit paving the way for the Initial Service provision as planned for 2016.The next launch (Launch 6) is planned for December 2015.

Spaceopal which is a joint venture of DLR-GfR mbH and Telespazio, is the operations prime contractor for the European Galileo Satellite Navigation System, program funded by the European Union. As such Spaceopal carried out the technical and organizational coordination across the recovery participants which involved:

- DLR-GfR: flight operations preparation and execution conducted from the Galileo Control Centre in Oberpfaffenhofen.
- ESA/ESOC: mission analysis and flight dynamics support
- CNES: external ground station support

Following the successful launches for the Galileo IOV (In Orbit Validation) satellites the first two Galileo FOC (Full Operational Capability) satellites were launched from Kourou on a Soyuz ST-B equipped with a Fregat-M upper stage the 22nd of August 2014. Times for Lift-off and injection matched the nominal ones:

Lift-off [UTC]	22/08/2014 12:27:11
Injection [UTC]	22/08/2014 16:15:08

However due to a failure in the Fregat, the first two FOC satellites (GSAT0201 and GSAT0202) were deployed in a non-nominal orbit. Post launch analysis evidenced that the injection orbit was so far off from target that the nominal operational orbit could not be reached, with the fuel available on-board. The prime objective of the mission soon shifted to evaluating the in-orbit performance of the FOC-1 spacecraft´s in a manner, configuration and timescale sufficient to allow an assessment of the design implementation prior to subsequent launches.

In the recovery phase, the spacecraft's were safely handed over from the LEOP centers to the GCC-D (Galileo Control Centre in Germany) in sun pointing mode after which they underwent degraded routine contacts in a babysitting configuration. Soon after a series of orbit control manoeuvers were performed to each spacecraft in order to increase the perigee altitude to allow continuous use of nominal spacecraft AOCS configuration (Earth-pointing, Normal mode), targeting an orbit suitable for the Galileo constellation in terms of resonance and ground coverage. This was followed by limited in orbit tests sufficient to characterize the spacecraft platform and payload design implementation in line with the mission objectives.

Mission Recovery was thoroughly analyzed and prepared to ensure the spacecraft operability in an orbit far from the design specification. Ground segment operational software and procedures were duly developed, validated and installed in order for the spacecraft avionics software to be able to cope with a variable angular rate in the non-nominal elliptical orbit. This was compensated by inhibiting the Earth Sensors during the perigee crossings as the IRES (Infrared Earth Sensors) mounted on board Galileo satellites were not designed to detect the Earth at such low altitudes. During the IRES inhibitions the 3-axis gyro was used to determine the satellite's attitude for which angular rate manual corrections were performed until the perigee raising manoeuvers had increased the altitude of the perigee sufficiently in order for the Earth Sensors to operate nominally. Three different algorithms were developed and proposed, two of which were selected due to the orbital conditions:

- Spacecraft gyro biases applied on GSAT0201
- On board propagator values applied on GSAT0202

The algorithms were thoroughly simulated and validated by the Operations Teams using local simulators.

The FOC-1 Recovery Campaign results will be summarized and outlined throughout the paper in terms of target orbit achieved and in orbit spacecraft behavior and status.

2. INJECTION orbit versus nominal INJECTION

After injection and acquisition of signal, several 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.

Under these circumstances, the nominal mission was terminated.

The final consolidated OD estimating the injection parameter was performed the 23rd of August around 06:00. Ref [1].

Assessment of J2000 orbits at injection on 22nd Aug 2014 16:15:08.0					
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	-	-
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	-	-

Table 1- Assessment of J2000 orbits at injection on 22nd Aug 2014 16:15:08.0

The orbit where the satellites were injected was thousands of sigma’s away.
The Period, perigee and apogee altitude for these orbits were:

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

The plots below show the difference between the injection orbit versus nominal injection:

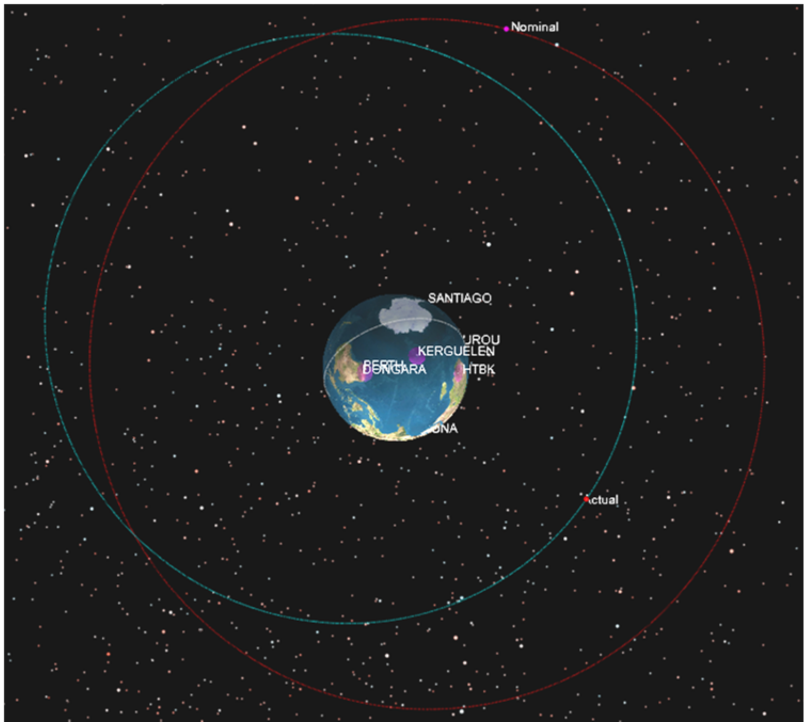

Figure 1: Bottom view from orbital plane of nominal and injected orbit

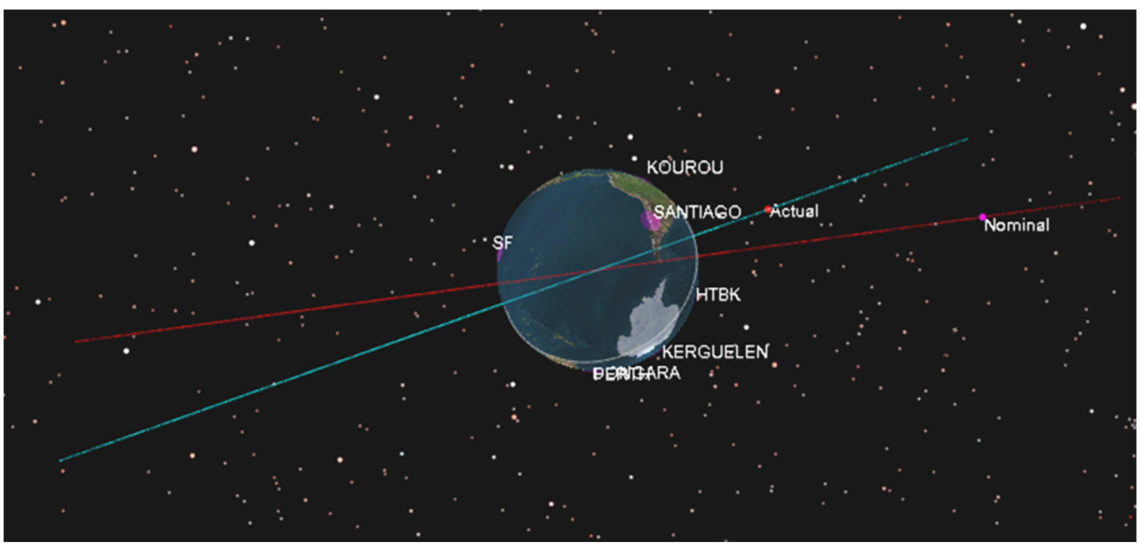

Figure 2: Side view of nominal and injected orbit

3. Babysitting-Monitoring Phase

The Spacecraft´s were successfully handed over from the LEOP centers (ESA/ESOC) to the Galileo Control Centre in Oberpfaffenhofen, Germany (DLR-GfR) the 27th August 2014 (GSAT0201) and the 28th August 2014 (GSAT0202).

The satellites were kept in Sun Acquisition Mode and a reduced set of routine activities were performed (degraded routine contacts). This babysitting configuration had as objective the satellite health monitoring. As the satellites were not in a fully operational state only MTL uplink for the following activities was performed:

1) Contact start and contact end: Spaceraft acquisition and verification of AOS

2) TM data dump activities. Cleaning on board data stores as required

3) Time tagged command uplinks for switching the transponders in the next contacts

4) Absolute Scheduler management

5) Security operations

6) House Keeping TM Dump

7) Ranging

During the babysitting phase intensive workshops and meetings took place amongst the ESA and SPO subcontractors targeting to find a solution. Several alternatives were selected which were simulated and validated in order to start recovery phase.

The orbit at handover in this phase was as follows:

Epoch 2014-09-26 12:00:00z inertial J2000		
	GSAT0201	**GSAT0202**
Semi-major axis [km]	*26204.854*	*26187.325*
Eccentricity	*0.23259*	*0.23284*
Inclination [deg]	*49.763*	49.764
Ascending node	*85.599*	85.601
True Anomaly	345.215	22.418
Arg. Perigee [deg]	*26.320*	26.514

Table 2- Orbits at Handover

4. AOCS-IRES limitations in non-nominal orbit

Do to the degraded injection, the orbit had a very low perigee (13700 km), meaning that the Earth apparent size was too big for the Infrared Earth Sensor (IRES) to be operational. According to the Earth Sensor manufacturer, Earth sensor loses its operational margins below 18000 km and stops being operable under 15331 km. The non-nominal orbit had a perigee altitude of 13700km. meaning that more than a half of the current orbit had to be discarded for earth pointing (EAM or NOM) as the IRES is the nominal sensor for earth pointing modes (as described below). Thus making the satellite unusable for navigation purposes.

Galileo Avionica IRES Model N2 *(Reference [2], [3] and as described in the 3user manuals) was designed to manage the possible Earth detection crossing´s for high altitude orbit during the satellite transfer phase and permits to cover the entire altitude range of work from 18000 km to super-synchronous orbit up to 88000km. In order for optimizing the accuracy, manufacturer applies scale factor to the IRES output depending on the apparent size of earth disc from the designated orbit.*

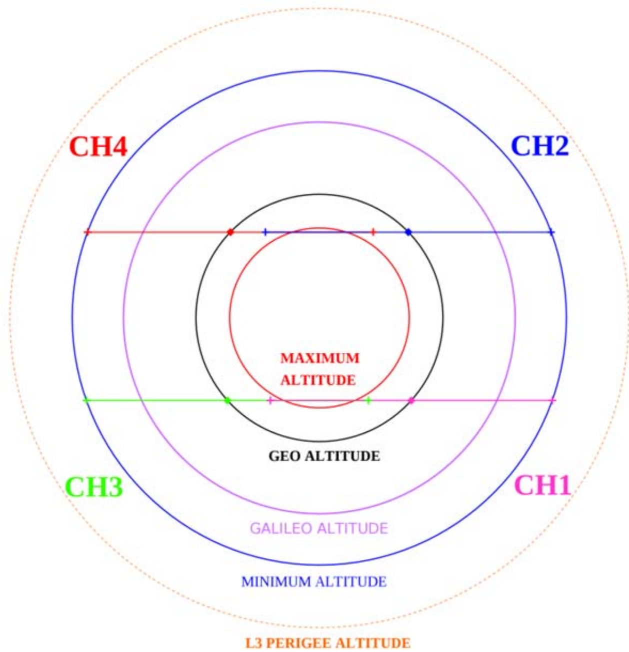

Figure 3. IRES N2: Apparent Earth size in relation to Earth Sensor field of view, for different altitudes, Ref[1]. Minimum and Maximum Altitude Determination

According to the IRES manufacturer analysis, IRES N2 sensors with default scale factor at designed circular MEO orbit (23600 km) is capable of providing pitch and roll outputs within altitude range from 18000 km to 53000km.
The minimum altitude with no Pitch and Roll offset is noted to be even lower than 18000 km. This is reported to be 15331km.

The injected orbit had even lower altitude at perigee which made the earth-space border detection by the IRES impossible with given scale factor.

Further limitations were found in the **On Orbit Propagation (OOP)** algorithm for the non-nominal orbit. The OOP algorithm works accurately for Galileo satellites in a circular orbit according to the satellite manufacturer (aka SSEG-Space Segment). This algorithm propagates errors and is valid for small eccentricities due to the conversion from Mean Anomaly to True Anomaly. For the non-nominal orbit this algorithm does not correctly calculate the orbital rates which are used by gyro which lead in the end to update the biases for gyro.

OPS Testing for Gyro usage around the perigee:

In order to test the scenario for using the gyro around the perigee, a series of simulations were conducted at the operational premises in GCC-D Oberpfaffenhofen, Germany. Similar tests were conducted by the satellite manufacturer and ESA in order to verify and validate the strategy.

Breakpoints were loaded to the simulator with an epoch=2014-08-25 14:12:01 “Nominal Mode in Early LEOP”. This breakpoint was created with respect to the elliptical orbit achieved, and verified by comparing the velocities around apogee and perigee with respect to the flight dynamics results which were in line with the expected values for such orbit. The test was performed by replacing the IRES with Gyro usage around the perigee for ~4hours. Meaning that the 3-axis gyro on-board was activated shortly after the IRES was deactivated. Flight dynamics entry conditions were at 16000 km (altitude was 16009 km at 16:57z), exit conditions where at 16000km (19:36z). Altitudes were chosen due to the limitations imposed by the IRES documentation, claiming 15331 km as minimum altitude for usage, as explained above.

Conclusions were that shortly after the perigee crossing, when the IRES was activated a safe mode triggered due to the large attitude deviations. The reason for those large attitude deviations soon became clear after a satellite manufacturer analysis, which explained that the wrong orbit rates calculated by the OOP were used by the Gyro which led to the wrong attitude propagation by the Gyro at perigee exit. In fact the error started as soon as the Gyro was used for attitude determination and was propagated until perigee exit. This motivated the gyro bias method explained in the Recovery Operations section.

5. Recovery Operations

Mission Recovery Drivers:

- Reduce the operational burden on the AOCS-IRES, which translates in increasing the perigee, in order to enable earth pointing (EAM/NOM), thus the possibility to carry out payload operations (Navigation). This would reduce Doppler and increase the receiver visibility.
- Reduce the eccentricity and therefore reduce the power dynamic range.
- Reduce exposure to the Van Allen belts radiation, which translates into increasing the perigee altitude as soon as possible.

- Improve contribution to the global constellation performance should the satellites be introduced in the Galileo navigation service by searching an orbit configuration that complement the current defined nominal slots.

Mission Recovery Objectives:

- Perform orbit-correction maneuvers to allow continuous use of nominal spacecraft AOCS configuration (Earth-pointing, Normal mode) and hence continuous payload operations;
- Perform a limited in orbit test campaign sufficient to characterize the spacecraft design implementation in line with the objectives.
- To evaluate the in-orbit performance of the FOC-1 spacecraft´s in a manner, configuration and timescale sufficient to allow an assessment of the design implementation of those spacecraft´s prior to subsequent launches.

As Mission recovery risk mitigation measure each spacecraft would be recovered and tested (IOT) at a time, therefore mitigating possible propagation of errors and benefitting from the recovery campaign lessons learned. Recovery operations start with GSAT0201 followed by GSAT0202.

The delta-V, mass consumption and target orbit analysis could be found in Ref [1].

Mission Recovery Plan:

	GSAT0201		*GSAT0202*
10/27/2014	*EAM/NOM Transition*	*1/15/2015*	*Mission Readiness Meeting*
10/28/2014	*NOM Monitoring (Characterisation)*	*1/16/2015*	
10/29/2014	*Test Manoeuvre*	*1/17/2015*	*EAM/NOM Transition*
10/30/2014	*Calibration (including S/C TM analysis)*	*1/18/2015*	*NOM (Characterisation)*
10/31/2014	*Mano Slot 1*	*1/19/2015*	*Test-1 Small Manoeuvre*
11/1/2014	*Mano Slot 2*	*1/20/2015*	*Test-2 Large Manoeuvre*
11/2/2014	*Mano Slot 3*	*1/21/2015*	
11/3/2014	*Mano Slot 4*	*1/22/2015*	*Mano Slot 1*
11/4/2014	*Mano Slot 5*	*1/23/2015*	*Mano Slot 2*
11/5/2014	*Key Point*	*1/24/2015*	
11/6/2014	*Mano Slot 6*	*1/25/2015*	
11/7/2014	*Mano Slot 7*	*1/26/2015*	
11/8/2014	*Mano Slot 8*	*1/27/2015*	*Mano Slot 3*
11/9/2014	*ES Monitoring at Perigee*	*1/28/2015*	*Mano Slot 4*
11/10/2014	*Mano Slot 9*	*1/29/2015*	*Mano Slot 5*
11/11/2014	*Mano Slot 10*	*1/30/2015*	*Mano Slot 6*

	GSAT0201		GSAT0202
11/12/2014	Fine Pos slot 1	1/31/2015	
11/13/2014	Calibration	2/1/2015	
11/14/2014	Fine Pos slot 2	2/2/2015	Mano Slot 7
11/15/2014	Final OD	2/3/2015	Key Point
11/16/2014	FD H/O	2/4/2015	Mano Slot 8
11/17/2014	PF Commissioning	2/5/2015	
11/18/2014		2/6/2015	Mano Slot 9
11/19/2014		2/7/2015	
11/20/2014		2/8/2015	
11/21/2014		2/9/2015	Mano Slot 10
11/22/2014		2/10/2015	
11/23/2014		2/11/2015	Fine Pos slot 1
11/24/2014		2/12/2015	
11/25/2014		2/13/2015	Fine Pos slot 2
11/26/2014	End PF commissioning	2/14/2015	
11/27/2014	261 PL-B Activation	2/15/2015	
11/28/2014	261 Early S-IOT and monitoring	2/16/2015	
11/29/2014	261 NAV Payload IOT (PL-B with CSU-B)	2/17/2015	
11/30/2014		2/18/2015	
12/1/2014		2/19/2015	
12/2/2014		2/20/2015	
12/3/2014		2/21/2015	
12/4/2014		2/22/2015	
12/5/2014		2/23/2015	PF Commissioning
12/6/2014		2/24/2015	
12/7/2014		2/25/2015	
12/8/2014		2/26/2015	
12/9/2014		2/27/2015	
12/10/2014	261 SAR Payload IOT	2/28/2015	
12/11/2014		3/1/2015	
12/12/2014		3/2/2015	
12/13/2014		3/3/2015	End PF commissioning
12/14/2014	261 S-IOT C-Band/L-Band (PL-B CSU-B)	3/4/2015	2612 PL-B Activation
12/15/2014		3/5/2015	261 Early S-IOT and monitoring
12/16/2014		3/6/2015	261 NAV Payload IOT (PL-B with CSU-B)
12/17/2014	End IOT	3/7/2015	
12/18/2014		3/8/2015	
12/19/2014		3/9/2015	

Table 7- FOC-1 S/C Recovery Plan

Mission Recovery Conduction:

The Recovery Operations were dealt as a separate special operation decoupled from the Galileo Routine Operations but nevertheless benefiting from the existing expertise and resources of the Galileo Operational teams across organizations: Spaceopal, DLR-GfR, ESA, CNES and OHB.

Daily Technical checkpoints were led by Spaceopal which coordinated across organizations. The Galileo conventional processes for special operations were recycled in terms of configuration control, anomaly review, operations planning and conduction. The Key roles during the recovery operations are listed below which reported to the ESA Mission Director.

- Spaceopal – Operations Service Manager. Overall Technical and Organizational Lead
- DLR-GfR – Spacecraft Operations Manager.
- ESA-ESOC – Flight Dynamics Support.
- CNES – External Ground Station Support.
- Satellite Manufacturer (OHB). Space Segment Support.

A. Recovery Strategy A – Gyro Bias Compensation

Two recovery methods were developed:

Method-1:

- Single transition from SAM to EAM/NOM.
- Stay in NOM onwards.
- During the perigee crossings (17k km entry 17k km exit) the IRES channels would be inhibited and the gyro activated. Compensation of the Gyro would be required during the perigee crossing.
- At a given time, transition to OCM would be commanded just before apogee in order to perform the maneuver
- Perform the maneuver and go back to NOM
- This would be repeated until the perigee was raised to an altitude where IRES does not need to be inhibited. The satellite manufacturer considered the 17000 km altitude the operational threshold. Before the IRES full inhibition the Gyro would have to be compensated. New operational products and Ground Software upgrades were developed and validated for this matter.

Method-2:

Perform the sequence above before the preceding perigee of each manoeuver and after the manoeuver execution perform the transition back from OCM to NOM and finally to SAM again (leaving the wheels running)

Method-2 would have required more operations per maneuver, but would have saved performing IRES inhibitions and gyro compensation each perigee, thus saving the need to develop additional operational products.

Finally after thorough analysis and simulations by Ops and the satellite manufacturer, Method-1 was selected for the GSAT0201 recovery, as Method-1 proved to be more reliable. The associated Flight Operation Procedures were developed.

“Low Altitude Perigee Crossing” Flight Operations Procedure developed by Operations

The objective of the FOP (Flight Operations Procedure) was to detail the activities to be carried out in order to stay in AOCS NOM at altitudes below 17000km, out of the operational range of the IRES.

All four IRES channels were inhibited and the Gyro was used to maintain earth pointing.
The activities were conducted around the perigee of the non-nominal orbit. The duration of the IRES Inhibition and Gyro usage was up to 4 hours depending on the perigee altitude. The FOP was applied for every perigee pass until the maneuver phase lifted the perigee above the critical altitude.

Gyro Bias and Time to apply Bias is provided by FD via TPF files GY_BIAS0 and GY_BIAS1. TPF (Task Parameter Files) are products which are usually generated by Flight Dynamics. These files have variable parameters which at the end populate command parameters to be uplinked to the satellite. Particularly the aforementioned files contain three parameters (which are bias values per gyro axes) and are used to set the gyro bias to be used during perigee crossing (GY_BIAS1) and reset the bias to 0 after perigee crossing is complete, above the critical altitude (GY_BIAS0). IRES Inhibition is performed relative to the time of Gyro Bias settings at 17000km altitude. The time of full IRES inhibition is configured to 5 minutes after setting the bias. The time of reactivation of IRES is set to 5 minutes before the reset of Gyro Bias to 0 respectively.

The gyro compensation TPFs are generated by FDF. This was possible after having patched the Ground Software -FDF (Flight Dynamics Facility). This implementation and the resulting TPF files contain 3 TC parameters for supporting gyro propagation error compensation due to the circular orbit assumptions which had originally been taken in to account by OHB in the ASW for the computation of the orbital rate. In order for being able to use the TPFs, FCT needed to create command sequences aligned with these new TPFs in the operational database.

From an operational perspective, the FCT (flight control team) had a strict constraint regarding the gyro bias commanding. Since the operation required up-linking time tagged so-called “Long TC” which modifies AOCS module configurations, a great care was required to not uplink any manual long TC to the satellite through the perigee crossing.

In order not to have disturbances on attitude at IRES re-activation, FCT and FD (flight Dynamics) teams also double checked whether any blinding is forecasted at the time of IRES re-activation.

The satellite altitude information was not in the database. Since it was essential to closely monitor satellite altitude, and Cartesian position information are implemented in the on board software, a synthetic parameter has been created on-ground.

The FOP was used multiple times until the perigee altitude went above the predefined threshold which had been defined as 17000 km allowing the earth sensors function properly. The FOP contained the following steps:

- Schedule the activity minimum 1.5 hours before perigee crossing starts (start is defined as the satellite altitude goes below 17000 km.
- Confirm FD inputs for bias setting. GY_BIAS0 and GY_BIAS1 with relevant epoch had to be received and confirmed.
- Redundant IRES and Gyro are activated in order to collect data for comparison. This is done by switching the units in troubleshooting mode which means the units perform the measurements but not involved in the control loops. The measurements of IRES B with the ones from IRES A are not identical but close to each other. The comparison is done to check whether there is an issue with the redundant IRES. As a recommendation, the raw measurements of the IRES are checked to not deviate more than 80 units in raw. The procedure handles packet configuration to let the OPS team receive necessary packets for monitoring and later analysis purpose.
- Gyro bias values are sent via tpf files coming from FD. Gyro has been kept on during the whole recovery period including the maneuvers. As mentioned earlier, at this point, the command stack which contains long TCs for later setting up AOCS configuration on-board, operations engineer, operations manager, mission director and SSEG experts check the commands carefully and give confirmation for uplink.
- All IRES channels are inhibited, from this point onwards; attitude information is gathered by 3-axis gyro. During the perigee pass (from 17000 km to 17000 km altitude) satellite attitude, rates and raw measurements from IRES are closely monitored by flight control team and SSEG experts.
- As described in GS-SAT-OHB-TN-0313, there is an angle of up to 12° in the worst case between the SA normal and the Sun position coming from the guidance module. So the procedure instructs to monitor list of power related telemetry besides AOCS parameters.
- Emergency Step for forcing SAM transition. Trigger transition to SAM in case of unexpected behavior. This step has been added for manual transition to sun acquisition mode as a contingency case. However, never been used during the recovery operations as all went smooth.
- Reactivate IRES by enabling all four channels and setting up configuration parameters for IRES. The same care has been given before up-linking the commands. OPS relaxes the FDIR limits for attitude deviation to 25° from its default value of 3° for avoiding safe mode triggering.

- Reset the gyro bias to zero.
- Switch off the redundant IRES and Gyro as the required data for comparison are gathered.
- Set the FDIR limits for attitude deviation to its default value of 3°.

During the whole recovery period, some additional packet handling rules were followed. As the redundant IRES and Gyro were switched on during perigee crossing, and additional TM parameters were required to be monitored and analyzed, necessary packets were stored in a dedicated packet store on-board. This store was dumped after each perigee for further analysis. This was executed via conventional operational processes like configuration change requests and recommendations.

Also clear information and instructions on the foreseen deviations in TM were transferred (which causes false out of limit alarms) to the satellite shift team operators who were performing monitoring/babysitting contacts outside of the special operations period.

Strategy A accounted for the perigee crossing part of the recovery strategy. After the perigee crossing and until apogee crossing minus margin time, the operation teams prepared for the perigee raising maneuvers. In the flow chart below the overall strategy could be depicted involving manoeuvers and perigee crossings.

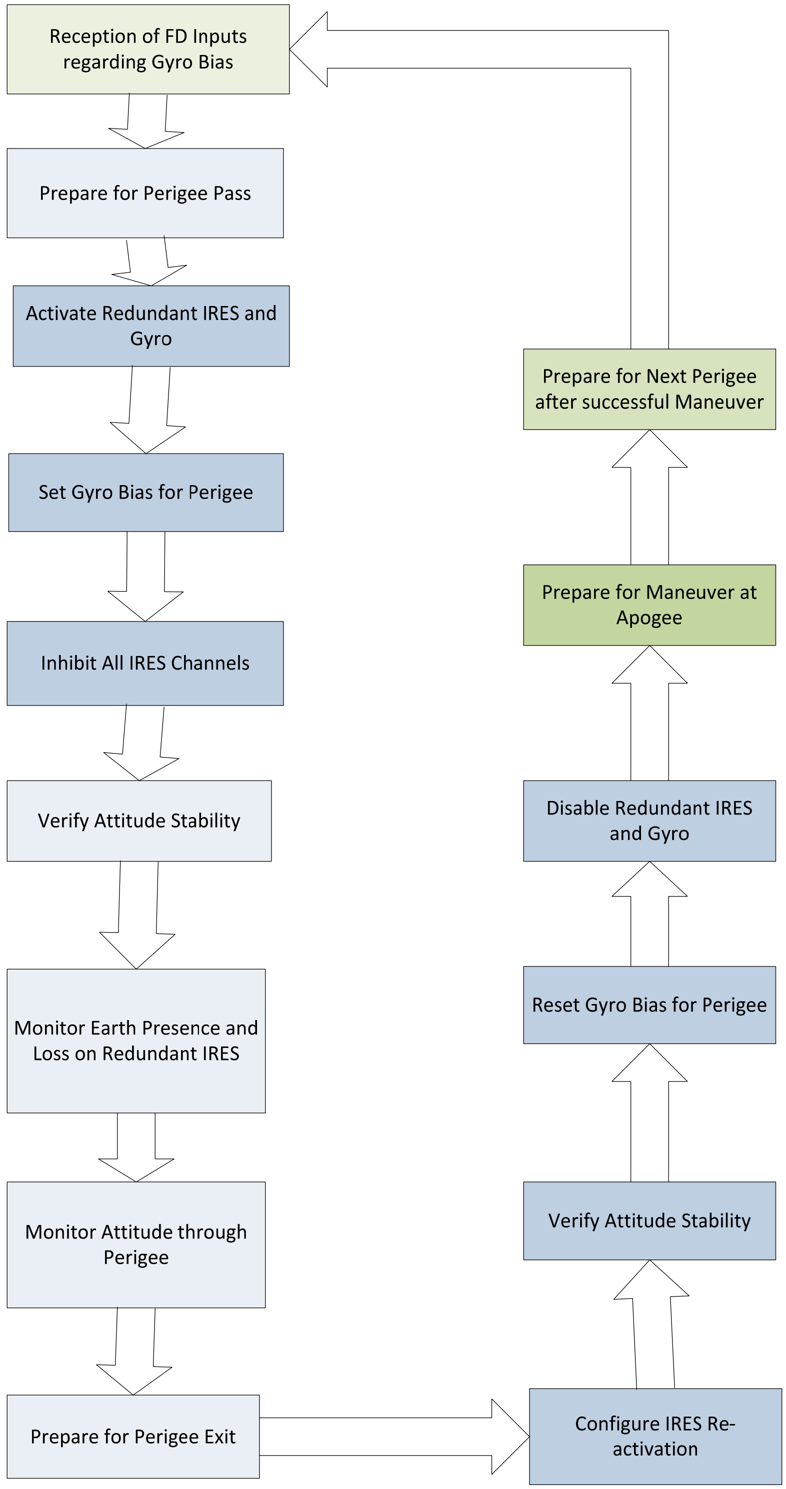

Figure 4. Overall Gyro Bias Compensation- Manoeuver Strategy

On the 17th of November 2014 the perigee reached a height of 17239.82226 km. This marked the First Perigee crossing carried out with the IRES fully in control (without any channel inhibition) as can be found in the figure-4.

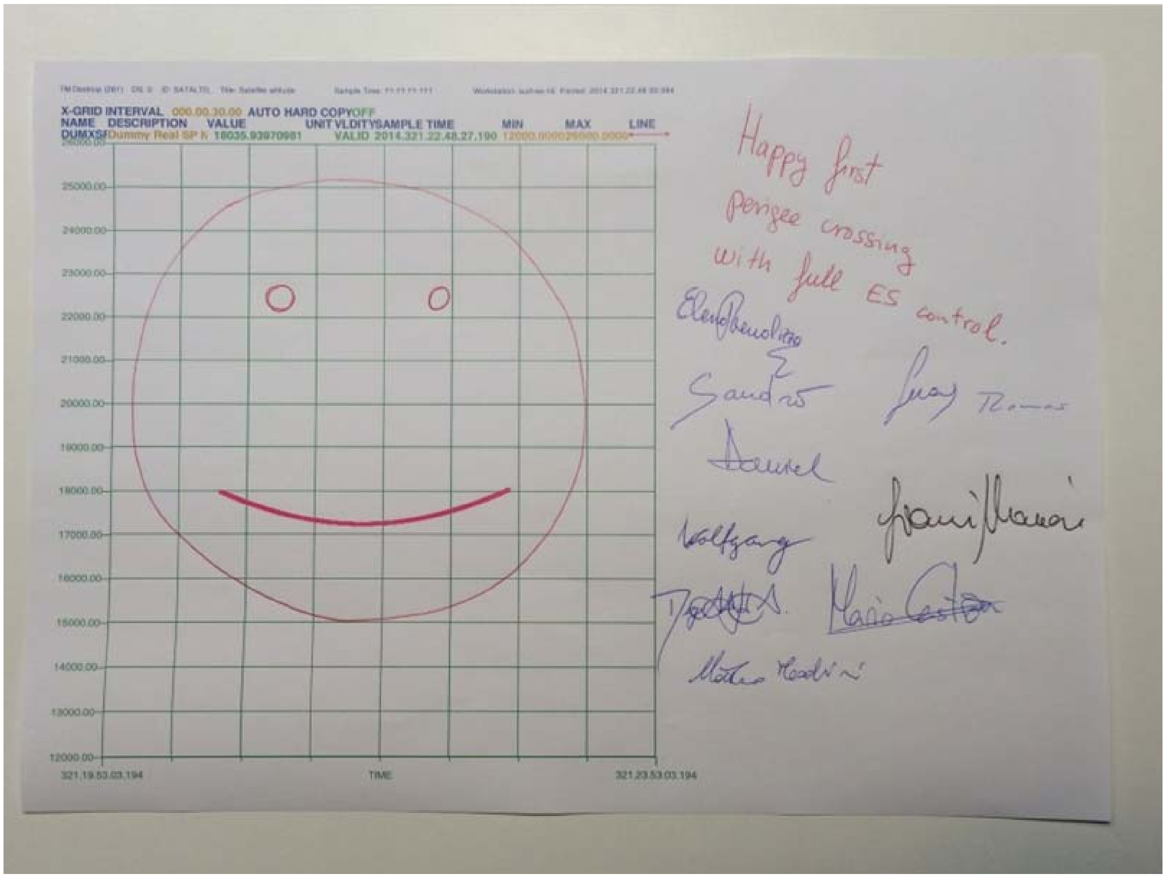

Figure 4. Perigee Crossing 17239.82226 km achieved congratulations

The 19th of November 2014 after nine perigee raising manoeuvers and the final fine position manoeuver a major milestone was achieved in the Galileo project as the orbit-correction maneuvers had been successfully completed for spacecraft GSAT0201 in order to allow continuous use of the nominal spacecraft AOCS configuration (Earth-pointing, Normal mode), hence continuous payload operations

Platform commissioning and Payload IOT (redundant side) were subsequently achieved the 19th of December 2014. Since then GSAT0201 has been broadcasting worldwide the nominal Navigation dummy message.

In Table-8 can be found information on the **GSAT0201 Achieved vs Target Orbit** after the manoeuver campaign. As can be seen the orbital requirements set were all accomplished, which set a major breakthrough in the campaign. Table-9 shows an as run summary of the campaign.

GSAT0201	Achieved	Target	Difference	Requirement	Accomplished
Epoch (UTC)	2014/11/22-05:13:10	2014/11/22-05:13:10		Epoch at Perigee	YES
Semi-major Axis (km)	27979.043	27978.985	0.058	diff < 95 km	YES
Perigee height (km)	17232.983	17232.91	N/A	> 17000 km	YES
Eccentricity	0.156	0.156	N/A	minimum	YES
Inclination (deg)	49.776	49.776	N/A	N/A	N/A
Ascending Node (deg)	82.692	82.692	N/A	N/A	N/A
Argum. Perigee (deg)	28.927	28.927	N/A	N/A	N/A
True Anomaly (deg)	0	0	0	N/A	N/A

Table 8- GSAT0201 Achieved vs Target Orbit

Maneuver Number	Date	Perigee Crossing Number	Gyro Bias Uplinked	Perigee Altitude Before (km)	Perigee Altitude After (km)
0	5/11/2014	5	X component: 13.6331035 microrad/s Y component: -6.6003003 microrad/s Z component: 0.0092676 microrad/s	13729.0623	13835.05993
		6	X component: 13.5389202 microrad/s Y component: -6.6112385 microrad/s Z component: 0.0091291 microrad/s		
		7	X component: 13.5082442 microrad/s Y component: -6.5701277 microrad/s Z component: 0.0091142 microrad/s		
		8	X component: 13.4773860 microrad/s Y component: -6.5288379 microrad/s Z component: 0.0090453 microrad/s		
		9	X component: 13.4471940 microrad/s Y component: -6.4883763 microrad/s Z component: 0.0090830 microrad/s		
1	7/11/2014	10	X component: 12.3932713 microrad/s Y component: -6.4119350 microrad/s Z component: 0.0097844 microrad/s	13823.46	14250.48406
		11	X component: 12.3597550 microrad/s Y component: -6.3847816 microrad/s Z component: 0.0098667 microrad/s		
2	8/11/2014	12	X component: 11.7285428 microrad/s Y component: -6.7981892 microrad/s Z component: 0.0098960 microrad/s	14252.72827	14688.4088

Maneuver Number	Date	Perigee Crossing Number	Gyro Bias Uplinked	Perigee Altitude Before (km)	Perigee Altitude After (km)
		13	X component: 11.7034312 microrad/s Y component: -6.7742080 microrad/s Z component: 0.0100237 microrad/s		
3	9/11/2014	14	X component: 11.3507599 microrad/s Y component: -7.0125994 microrad/s Z component: 0.0100973 microrad/s	14693.70808	15123.64792
		15	X component: 11.3290268 microrad/s > Y component: -6.9902793 microrad/s > Z component: 0.0101707 microrad/s		
4		16	X component: 10.9800263 microrad/s > Y component: -7.2493699 microrad/s > Z component: 0.0104207 microrad/s	15122.21759	15525.78673
		17	X component: 10.9580016 microrad/s Y component: -7.2289504 microrad/s Z component: 0.0104688 microrad/s		
5	11/11/2014	18		15528.14221	15911.82109
		19			
		20	X component: 10.5863249 microrad/s Y component: -7.5299507 microrad/s Z component: 0.0108724 microrad/s		
		21	X component: 10.5674417 microrad/s Y component: -7.5156123 microrad/s Z component: 0.0109134 microrad/s		
		22	X component: 10.5480914 microrad/sY component: -7.4995789 microrad/sZ component: 0.0109037 microrad/s		
6	13/11/2014	23	X component: 10.1160946 microrad/s Y component: -7.8634617 microrad/s Z component: 0.0115413 microrad/s	15915.40304	16285.95047
		24	X component: 10.0993318 microrad/s Y component: -7.8559482 microrad/s Z component: 0.0114627 microrad/s		
7	14/11/2014	25	X component: 9.5960698 microrad/s Y component: -8.2514783 microrad/s Z component: 0.0122354 microrad/s	16288.43319	16611.82319
		26	X component: 9.5750344 microrad/s Y component: -8.2508523 microrad/s Z component: 0.0121343 microrad/s		
8	15/11/2014	27	X component: 8.8328377 microrad/s Y component: -8.7052186 microrad/s Z component: 0.0133245 microrad/s	16612.19208	16902.43466

Maneuver Number	Date	Perigee Crossing Number	Gyro Bias Uplinked	Perigee Altitude Before (km)	Perigee Altitude After (km)
		28	X component: 8.8070266 microrad/s Y component: -8.7200809 microrad/s Z component: 0.0131675 microrad/s		
9	16/11/2014	29	X component: 9.5268260 microrad/s Y component: -6.0517328 microrad/s Z component: 0.0084111 microrad/s	16903.65	17239.82226
		30	X component: 9.5154885 microrad/s Y component: -6.0188482 microrad/s Z component: 0.0082676 microrad/s		
FP	19/11/2014			17237.13361	17234.15237

Table 9- GSAT0201 Recovery Overview

First Moon Eclipse after Recovery: Special mention should be made regarding the eclipse impact on operations due to the non-nominal orbit. The generic FOP regarding the eclipse preparation and eclipse monitoring for the FOC satellites was modified and adjusted for the FOC-1 spacecraft´s. The most important modification was to change the "cssMaxUmbra" parameter from its default 4000 in current FOP which considers 60 minutes eclipse with some margin to 5000.

The validation was executed using the on-site simulators. Validation was completed before the forecasted eclipse on 22nd of November. Additional measures were taken for increasing the safety by having a full team deployed at GCC-D during the moon shadow; as risk mitigation for in order to minimize preparation and execution time in case of a USM triggering.

The first successful FOC Time Tagged Moon eclipse monitoring took place the 22nd of November 2014 in which a smooth transition through the moon eclipse was observed. Temporary widening of pointing thresholds for moon eclipse exit was executed as per satellite manufacturer recommendation, and tracked via usual CCR process.

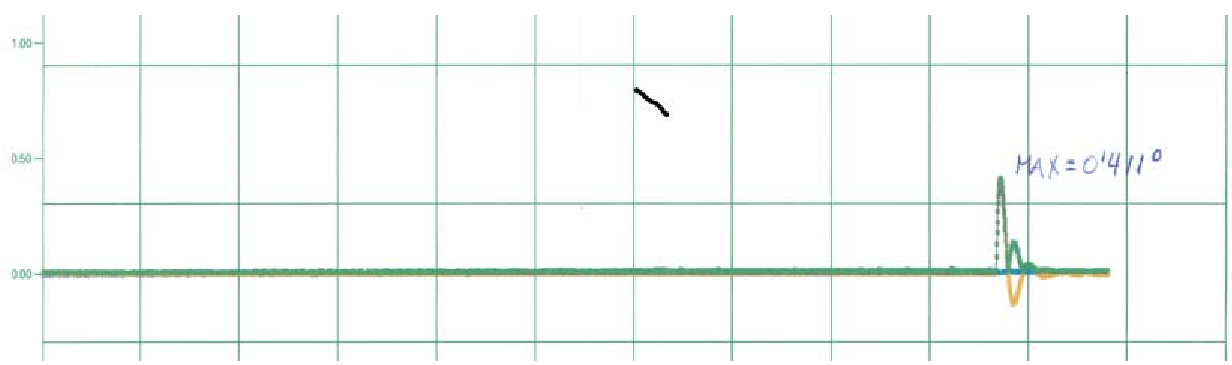

Figure 5. Moon intrusion attitude perturbation

B. Recovery Strategy B – On Orbit Propagator Updates around Perigee

After successful recovery of satellite GSAT0201, preparation, studies and discussions started for the recovery of GSAT0202 .

The simple solution would have been to have applied Strategy A as for satellite GSAT0201 because it was proven to be reliable and the operational products had already been developed and validated on Ground and in Orbit. However the method used for GSAT0201could not be recycled for the recovery of GSAT0202.

After Flight Dynamics analysis it was found that the Gyro compensation algorithm used successfully during the GSAT201 recovery was not valid for the orbital conditions in which the GSAT202 recovery was planned to take place during the months January and February 2015. As the beta angles was very low and applying only the gyro bias before the perigee would not have helped on correcting the errors (according to the simulations to simulation conducted by Operations). Furthermore strategy A was applicable for small yaw variations.

During the study phase three algorithms had been proposed, the first of which was applied during the GSAT0201 recovery. Algorithm #2 was selected to be used during the GSAT0202 recovery operations, as it was and is valid for any yaw angle variation. It makes use of the temporary update of the OOP to a "fake" circular orbit during the perigee passage. The main operational drawback of Algorithm #2 is that it required once more the development and validation of a new FOP (Flight Operations Procedure) by Operations.

Since the orbital conditions had considerable effects on the strategy, simulations were performed by using exactly the same orbital conditions. Simulator status and environment were set in accordance with mid-January where the planned recovery operations took place with the maximum orbital impact conditions the 17th of January 2015 due to the lowest beta angle.

Another change to the previous strategy is that this time the perigee entry and exit conditions are differently defined. Perigee entry is defined at 17000 km before reaching the perigee as per the strategy A, whereas exit is defined at 18000 km after perigee point.

Modifications to the FOP procedure “Low Altitude Perigee Crossing” developed by Operations

In principal, gyro bias setting and TPF reset files were no longer needed as the bias values were no longer supposed to modified. However the command sequences bound to GY_BIAS1 and GY_BIAS0 TPF files contain not only gyro bias commands, but also IRES inhibition, FDIR parameter value modifications and IRES re-activation commands as well. All commands are time-tagged with respect to the reference time given in the GY_BIAS1 and GY_BIAS0 files at TPF (and command sequence) loading to the monitoring and control system (SCCF). Since the objective was to get rid of the gyro bias, gyro bias setting commands are removed from command sequences. This required on-board database changes.

As previously stated, instead of 2 TPFs (former gyro bias TPFs) , 4 TPF files are needed for each perigee. Two of them are the gyro bias TPF files which are GY_BIAS1 (for IRES inhibition and relaxing the FDIR limits only), and GY_BIAS0 (for re-activating IRES and resetting FDIR limits). The other two are the OOP files. The FOP required to send a fake OOP before the perigee, and then resend the real OOP after the perigee.

As there is an existing OOP update procedure, the change in the FOP only required the calling the OOP update procedure within the FOP.

Strategy B Validation at GCC-D

Validation is performed with close coordination with Flight Dynamics due to the criticality in reproducing the real orbit environment. The breakpoint was saved as:

"GSAT0201_GSAT0202_NmR_Customisation_2015_01_15_GYRO_TEST_NOM.ssv.gz in folder "/CSIM/SatelliteSimulatorFoc/breakpoints/GYRO_TEST_20150115/" for further tests/simulations.

The least favorable date in terms of orbital conditions was chosen for the simulation. Hence the testing took place the 17th of January due to the lowest β-angle as explained above (worst test case scenario).

The following command stacks necessary for the test were prepared and times for TT commands were modified in accordance with the delta between SCCF (Satellite Command and Control Facility) and CSIM (Simulator) which was 2 days 0 hours 29 minutes and 58 seconds:

- GY_BIAS1_OOP-Fake (consisting of FDD_parameter_data-20150108182048-S262-GCC-1-FDF-00000123 (OOP valid starting from 17:07:19 before the perigee 2015/01/15-19:09:11.000) and FDD_parameter_data-20150108171816-S262-GCC-1-FDF-00000115 (GY_BIAS1 which is used for time reference, ES and FDIR commands)

- GY_BIAS0_OOP-Correct (consisting of FDD_parameter_data-20150108171817-S262-GCC-1-FDF-00000116 (GY_BIAS0 which is used for time reference, ES and FDIR commands) and FDD_parameter_data-20150108182102-S262-GCC-1-FDF-00000126 (OOP valid after 21:11:34 after the perigee 2015/01/15-19:09:11.000)

Simulation results indicated that the maximum attitude deviation occurred DOY 13 at 16:36:41z (equivalent to DOY15 at 21:06:41 in SIM EPOCH time) with a value of 2.48 deg. Which happened after re-enabling all IRES channels on IRES-A DOY 013 at 16:36:36z. During the entire 10 hour simulation no AOCS event (no warning nor alarm) was generated on board.

Flow of Strategy B: The satellite altitude monitoring was an essential part of the recovery operations as it was done for satellite GSAT0201. However for GSAT0202 it was not as simple as for GSAT0201 due to the fact that the OOP values which were used by the on board propagator during the whole perigee are not the correct ones and hence provided wrong altitude information. Even though the synthetic parameters for altitude were kept in the database, they were declared unreliable for the recovery operations. As an alternative to that flight dynamics prepared a table and graph for each perigee crossing providing the satellite altitude versus time. This was prepared and closely coordinated throughout the operations teams. Defined in the maneuver report file and distributed to flight control team through the recovery operations.

Same as Strategy A the Operations Shift Team received clear instructions on how to proceed against out of limits due to the execution of time tagged commands which updated the OOP with “fake” content, via the conventional operational processes (recommendation and pass on info sheets) where information was provided regarding the Satellite semi-major axis, FDIR limits on the pointing deviation from Nadir, etc. This helped the correct monitoring/babysitting contacts outside of the special operations period.

The FOP was used multiple times until the perigee altitude went above the predefined threshold which had been defined as 17000 km allowing the earth sensors function properly. The FOP contains the following steps:

- Confirm that the following inputs are provided by Flight Dynamics for the upcoming perigee.

  - OOP TPF file valid for perigee phase, its req. id, its epoch

  - OOP TPF file valid for the rest of the orbit, its req. id, its epoch

    - GY_BIAS1 TPF file, its req. id, its epoch

    - GY_BIAS0 TPF file, its req. id, its epoch

    - A report for Satellite Altitude vs. Time

- Redundant IRES is activated in order to collect data for comparison. This is done by switching the units in troubleshooting mode which means the units perform the measurements but not involved in the control loops. The measurements of IRES B with the ones from IRES A are not identical but close to each other. The comparison is done to check whether there is an issue with the redundant IRES. As a recommendation, the raw measurements of the IRES are checked to not deviate more than 80 units in raw.
- Packet configuration. The procedure handles packet configuration to let the OPS team receive necessary packets for monitoring and later analysis purpose.
- All IRES channels are inhibited, from this point onwards; attitude information is gathered by 3-axis gyro. During the perigee pass (from 17000 km to 18000 km altitude) satellite attitude, rates and raw measurements from IRES are closely monitored by flight control team and SSEG experts.

- Load OOP valid for perigee phase. Use the TPF with request id regarding the “Apply OOP” from FD input. Normally it is the first TPF in the table for that perigee.
- Monitoring the satellite in perigee crossing phase. During this period, emergency stack for forcing SAM transition is loaded in order to trigger transition to SAM in case of unexpected behavior. However, never been used during the recovery operations as all went smooth.
- Load OOP TPF file (valid for the rest of the orbit)
- Reactivate IRES by enabling all four channels and setting up configuration parameters for IRES. The same care has been given before up-linking the commands. OPS relaxes the FDIR limits for attitude deviation to 25° from its default value of 3° for avoiding safe mode triggering.
-
- Switch off the redundant IRES as the required data for comparison are gathered. Set the FDIR limits for attitude deviation to its default value of 3°.
- Print the manual stack; circulate for checks and signatures before the commands relevant to all these steps are uplinked.

Strategy B accounted for the perigee crossing part of the recovery strategy. After the perigee crossing and until apogee crossing minus margin time, the operation teams prepared for the perigee raising maneuvers. In the flow chart below the overall strategy could be depicted involving manoeuvers and perigee crossings.

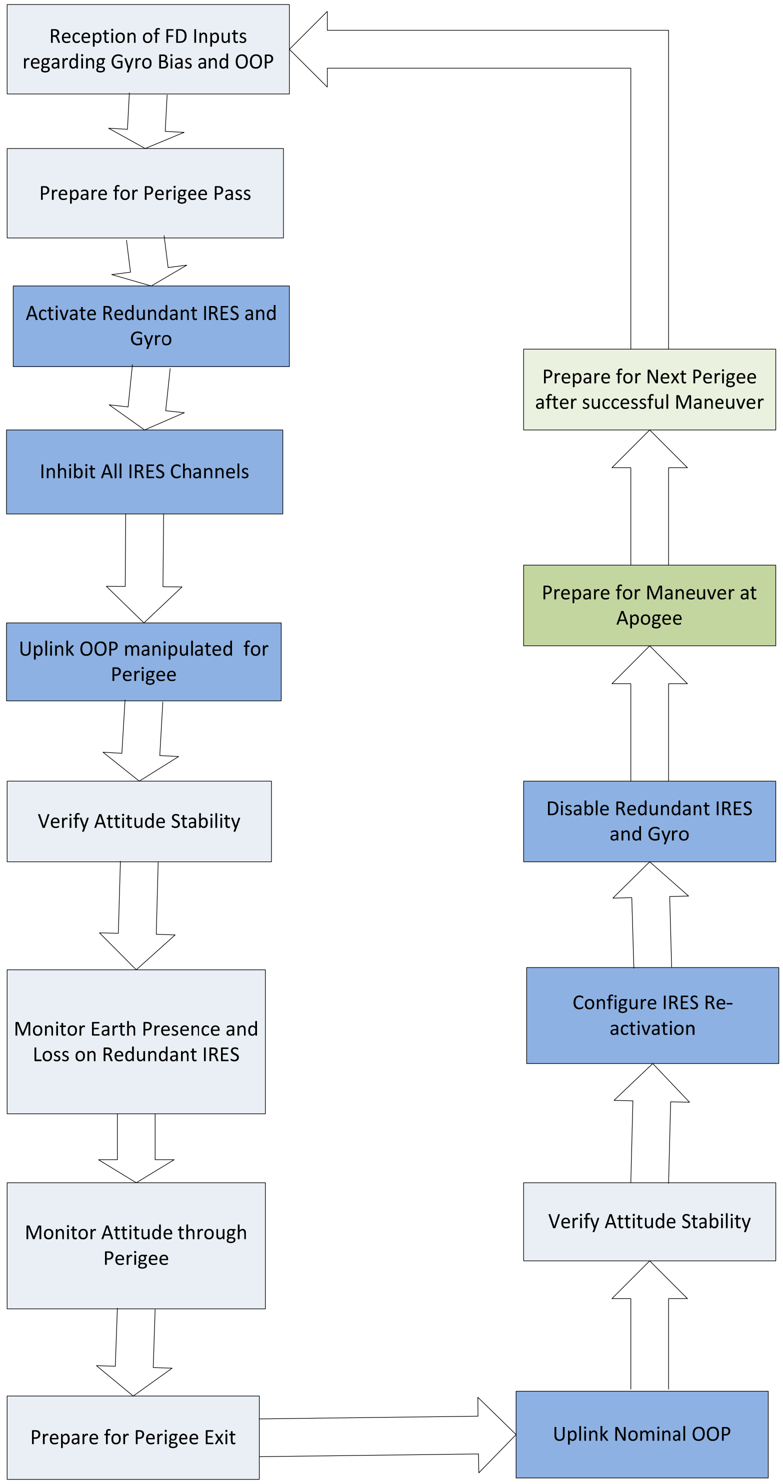

Figure 4. Overall Fake OOP - Manoeuver Strategy

Issue encountered close to the end of GSAT0202 Recovery Period:

On 2nd and 3rd of February, unexpected attitude jumps were encountered shortly after the correct OOP was uplinked to the satellite.

IRES A Pitch word at 33/20:09=1142

IRES A Pitch word at 34/08:39=1131

Both values were larger than experienced during the simulations which were a 1/10th factor of simulated results.

An Emergency Anomaly Review Board took place in which this high angular deviation on yaw at perigee exits were discussed with the satellite manufactures and system experts. The Immediate decision was to increase yaw deviation FDIR value from its default 21 degrees to 90 degrees as temporary workaround to avoid probable safe mode triggering.

Further analysis from the satellite manufacturer evidenced that the time between IRES inhibition and OOP updates were far too long (5 minutes). OOP parameters were rapidly updated in the following way:

- After IRES inhibition before perigee entry. Fake OOP upload **+3s** after inhibition

- Before IRES re-activation after perigee exit. Real OOP upload **-3s** with respect to ES enabling

OPS validated the suggested against the local simulators (CSIM) and confirmed that the values achieved in same orbit changed to:

- **IRES_A PITCH WORD** observed as soon as the ES channels were enabled again **= -115.7 raw (-0.290°)**
- **IRES_A ROLL WORD** observed as soon as the ES channels were enabled again = **12 raw (0.030°)**

After this confirmation, a change was performed to the FOP sequence as explained below:

- ...
- …
- IRES Channel inhibition at 17000km
- Fake OOP upload **+3s** after inhibition
- …
- …
- IRES channel enabling at 18000km
- Real OOP upload **-3s** with respect to ES enabling
- …
- …

On the 26th of February 2015 the perigee reached a height of 17143.63586 km. This marked the First Perigee crossing carried out by GSAT0202 with the IRES fully in control (without any channel inhibition) as can be found in the figure-4.

The 2nd of March 2015 after ten perigee raising manoeuvers and the final fine position manoeuver a major milestone was achieved in the Galileo project as the orbit-correction maneuvers had been successfully completed for both spacecraft´s, GSAT0201 and GSAT0202 in order to allow continuous use of the nominal spacecraft AOCS configuration (Earth-pointing, Normal mode), hence continuous payload operations

Platform commissioning and reduced Payload IOT (redundant side) were subsequently achieved the 25th of March 2015. Since then GSAT0202 has been broadcasting worldwide the nominal Navigation dummy message.

In Table-8 can be found information on the **GSAT0202 Achieved vs Target Orbit** after the manoeuver campaign. As can be seen the orbital requirements set were all accomplished, which set a major breakthrough in the campaign.

Table-9 shows an as run summary of the campaign.

GSAT0202	*Achieved*	*Target (SMA)*	*Difference*	*Requirement*	*Accomplished*
Epoch (UTC)	*2015/03/05-10:36:11.679*	*2015/03/05-10:36:17.766*	*6 s (= 65 mdeg)*	*< 2 deg*	*YES*
Semi-major Axis (km)	*27978.585*	*27978.583*	*2.66 m*	*diff < 45 m*	*YES*
Perigee height (km)	*17232.2*	*17232.186*	*N/A*	*> 17000 km*	*YES*
Eccentricity	*0.156*	*0.156*	*N/A*	*minimum*	*YES*
Inclination (deg)	*49.875*	*49.875*	*N/A*	*N/A*	*N/A*
Ascending Node (deg)	*77.52*	*77.52*	*N/A*	*N/A*	*N/A*
Argum. Perigee (deg)	*34.35*	*34.347*	*N/A*	*N/A*	*N/A*
True Anomaly (deg)	*0*	*0*	*0*	*N/A*	*N/A*

Table 10- GSAT0202 Achieved vs Target Orbit

Maneuver Number	*Date*	*Perigee Altitude Before*	*Perigee Altitude After*
1	*22/01/2015*	*13801.49359*	*14050.81037*

Maneuver Number	*Date*	*Perigee Altitude Before*	*Perigee Altitude After*
2	*23/01/2015*	*14050.27099*	*14339.11462*
3	*27/01/2015*	*14341.25287*	*14509.8681*
4	*28/01/2015*	*14779.24745*	*15194.87591*
5	*29/01/2015*	*15198.04461*	*15611.70064*
6	*30/01/2015*	*15613.07794*	*16028.37525*
7	*3/2/2015*	*16027.58731*	*16501.42623*
8	*20/2/2015*	*16509.96158*	*16965.71358*
9	*24/2/2015*	*16966.37091*	*17143.63586*
10	*26/2/2015*	*17141.68025*	*17227.31866*
11	*2/3/2015*	*17227.16592*	*17231.77423*

Table 11- GSAT0202 Recovery Overview

6. Conclusion

The 19th of November 2014 after nine perigee raising manoeuvers and the final fine position manoeuver a major milestone was achieved in the Galileo project as the orbit-correction maneuvers had been successfully completed using Strategy A – Gyro Bias Compensation for spacecraft GSAT0201 in order to allow continuous use of the nominal spacecraft AOCS configuration (Earth-pointing, Normal mode), hence continuous payload operations

Platform commissioning and Payload IOT (redundant side) were subsequently achieved the 19th of December 2014. Since then GSAT0201 has been broadcasting worldwide the nominal Navigation dummy message.

In Table-12 can be found information on the **GSAT0201 Achieved vs Target Orbit** after the manoeuver campaign. As can be seen the orbital requirements set were all accomplished, which set a major breakthrough in the campaign.

GSAT0201	*Achieved*	*Target*	*Difference*	*Requirement*	*Accomplished*
Epoch (UTC)	*2014/11/22-05:13:10*	*2014/11/22-05:13:10*		*Epoch at Perigee*	*YES*
Semi-major Axis (km)	*27979.043*	*27978.985*	*0.058*	*diff < 95 km*	*YES*
Perigee height (km)	*17232.983*	*17232.91*	*N/A*	*> 17000 km*	*YES*
Eccentricity	*0.156*	*0.156*	*N/A*	*minimum*	*YES*
Inclination (deg)	*49.776*	*49.776*	*N/A*	*N/A*	*N/A*

GSAT0201	Achieved	Target	Difference	Requirement	Accomplished
Ascending Node (deg)	82.692	82.692	N/A	N/A	N/A
Argum. Perigee (deg)	28.927	28.927	N/A	N/A	N/A
True Anomaly (deg)	0	0	0	N/A	N/A

Table 12- GSAT0201 Achieved vs Target Orbit

The 2nd of March 2015 after ten perigee raising manoeuvers and the final fine position manoeuver a major milestone was achieved in the Galileo project as the orbit-correction maneuvers had been successfully completed for GSAT0202 using Strategy B – On Orbit Propagator Updates around Perigee in order to allow continuous use of the nominal spacecraft AOCS configuration (Earth-pointing, Normal mode), hence continuous payload operations

Platform commissioning and reduced Payload IOT (redundant side) were subsequently achieved the 25th of March 2015. Since then GSAT0202 has been broadcasting worldwide the nominal Navigation dummy message.

In Table-13 can be found information on the **GSAT0202 Achieved vs Target Orbit** after the manoeuver campaign. As can be seen the orbital requirements set were all accomplished, which set a major breakthrough in the campaign.

GSAT0202	Achieved	Target (SMA)	Difference	Requirement	Accomplished
Epoch (UTC)	2015/03/05-10:36:11.679	2015/03/05-10:36:17.766	6 s (= 65 mdeg)	< 2 deg	YES
Semi-major Axis (km)	27978.585	27978.583	2.66 m	diff < 45 m	YES
Perigee height (km)	17232.2	17232.186	N/A	> 17000 km	YES
Eccentricity	0.156	0.156	N/A	minimum	YES
Inclination (deg)	49.875	49.875	N/A	N/A	N/A
Ascending Node (deg)	77.52	77.52	N/A	N/A	N/A
Argum. Perigee (deg)	34.35	34.347	N/A	N/A	N/A
True Anomaly (deg)	0	0	0	N/A	N/A

Table 13- GSAT0202 Achieved vs Target Orbit

Both spacecraft´s are being operated safely by Spaceopal from the Galileo Control Centre Germany. The figures below represent a graphical summary of the corrected orbit with respect to the non-nominal at launch, and the foreseen nominal one. In which:

- The blue orbit represents the target orbit at launch.
- The red orbit represents the non-nominal orbit due to the Soyuz-Fregat injection failure.
- The green orbit represents the achieved orbit achieved after the successful manoeuver campaign.

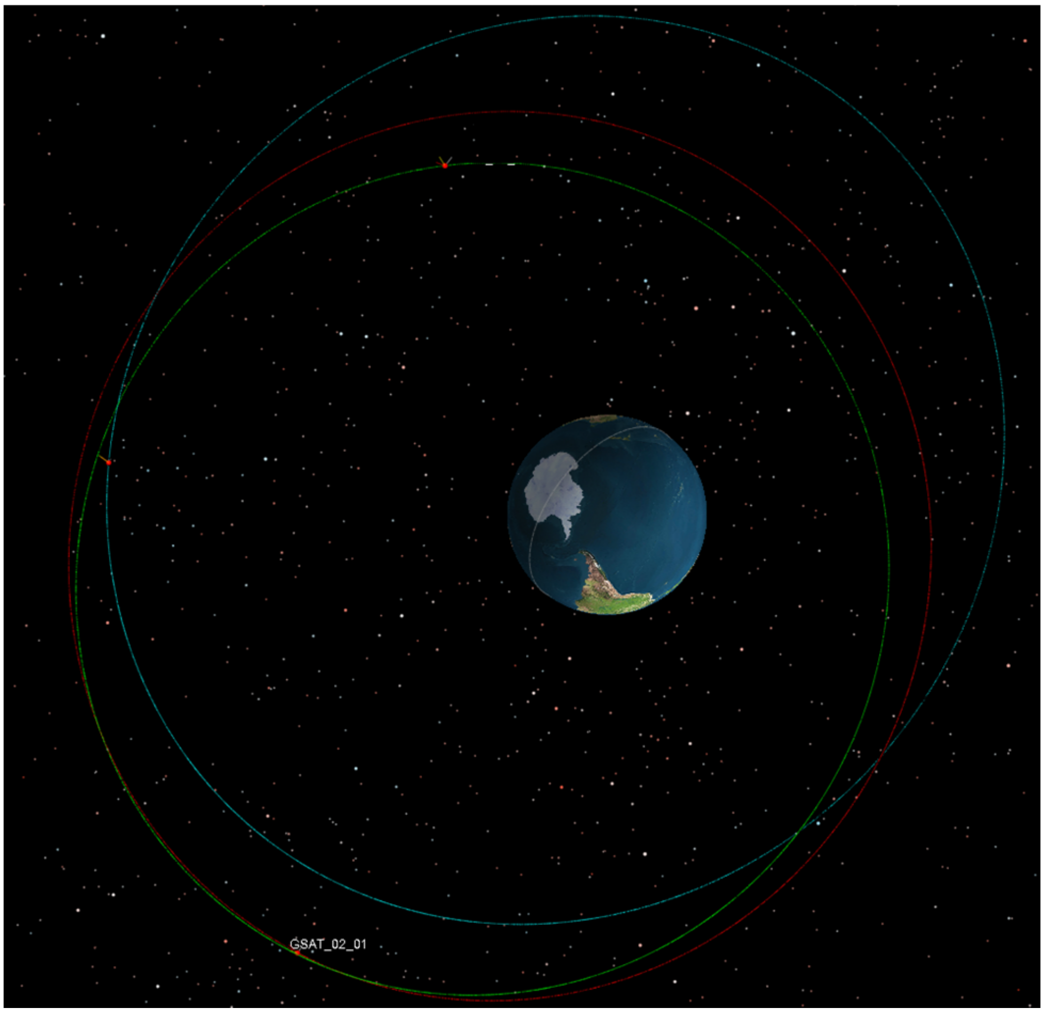

Figure 5. Corrected orbit w.r.t the non-nominal and nominal one

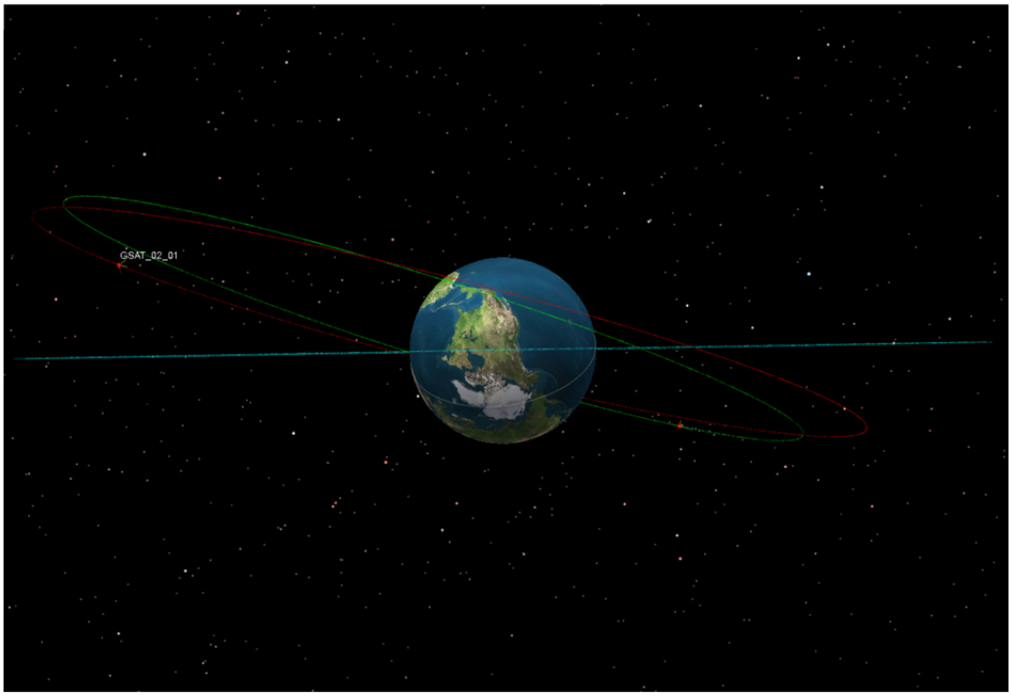

Figure 6. Corrected orbit w.r.t the non-nominal and nominal one

7. References:

[1] Navarro-Reyes, D. et al. *"Galileo First FOC Launch: Recovery Mission Design"*. Munich, Germany, 2015.

[2] Galileo Avionica IRES N2 DDJF

[3] Amendment to Satellite Design Data and Models Document