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Galileo Extended Slots Characterisation and Relation with the Nominal Constellation

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The anomalous launch of the first two Galileo FOC satellites introduced limitations to their interoperability with the rest of the constellation. A recovery campaign was conducted during winter 2014-2015 to bring both satellites to usable orbits. The selection of the reference target orbits (aka, extended slots) was done taking into account the evolution of both spacecraft relative to the nominal Galileo constellation, which would simplify their usage by the GNSS community. Furthermore, there are several benefits of using the extended slots for navigation purposes when combined with the current nominal constellation. In particular, it is shown how the extended slots contribute to enhance basic user performance parameters. Beyond the usage for navigation, these two satellites also provide interesting features for scientific application, e.g. characterisation of the gravitational red-shift.

Key Words: GNSS, Galileo, Constellation, Extended Slots

Nomenclature

GST	:	Galileo System Time
a	:	semi major axis
e	:	Eccentricity
ι	:	Inclination
Ω	:	Right ascension of ascending node
ω	:	Argument of perigee
ν	:	True anomaly
M	:	Mean anomaly
α	:	Argument of latitude ($\alpha = \omega + \nu$)
λ	:	Geocentric longitude
N_p	:	Number of planes
N_s	:	Slots per plane
Subscripts		
ANX	:	Ascending Node

1. Introduction

On August 22, 2014 the two spacecraft of the 3rd launch of the Europe's Galileo satellite navigation system (*thereafter named L3 satellites*) where injected by the upper stage into a faulty orbit out of the range that the satellites could recover for achieving the Galileo nominal Constellation. The design of a recovery mission was initiated right after taking into account the implications at satellite level of the wrong injection orbit, the operational constrains, and maximizing the programmatic return value of the spacecrafts contributing to the global constellation performance in case they could be introduced in the Galileo navigation service. A manoeuvres campaign was conducted during winter 2014 to reach a resonant orbit with a repeat cycle twice the one of the nominal constellation and positioning both spacecrafts with a relative angular phase of 180 degrees at the apsides. Thanks to further improvements in the Ground Segment processing and the expansion of the Navigation Message the introduction of these satellites into Galileo Service is under testing at the time of writing this paper. For this purpose, a reference orbit for these satellites has been provided to the European GNSS Service Centre.

2. Launch Failure and Recovery Campaign

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 August 22, 2014. Analysis of the achieved orbit indicated that Fregats second burn, nominally a circularisation manoeuvre from an elliptical transfer orbit to the final one, was performed with the correct magnitude but about 35° 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° error (13.2° in right ascension and 5.35° 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.

2.1. Selected Target Orbits

After consideration in the Galileo Project, the 37 rev / 20 days orbit was chosen as target for the recovery mission. One of the key reasons to choose this particular resonant orbit was the period being close to twice the repeatability period of the main Galileo constellation. In this way when considering the extended constellation (nominal satellites and L3 satellites) the relative positions are similar every 20 days. Additionally L3 satellites are in opposite positions in the orbit (i.e. when one is in the apogee the other is in the perigee) so every 10 days they swap positions and become resonant with the repeat-cycle of the nominal constellation.

The initial low perigee altitude introduced several constraints for the recovery campaign so the conditions for the final orbits were chosen as simple as possible and in a best-effort sense. The target orbits conditions are in summary:

- Repeat-cycle of 20 days, cycle length of 37 orbits, that translates in a mean semimajor axis close to 27 977.6 km.
- Relative apsides passage so one satellite would be at its perigee when the other is near its apogee.
- Keep the others parameters as close as possible between both spacecrafts.

The apsides passage condition improves the area coverage of both satellites together and facilitate the operations as both spacecrafts are not visible at the same time from a station. In order to fulfil this condition the argument of latitude difference between satellites must stay over 135°. The initial true anomaly difference is chosen initially to be of 180° at the GSAT0201 perigee passage and the semi-major axis accuracy has to be enough to guarantee that during at least the next six years this α condition is meet without manoeuvres. The precision was much lower than the needed for Galileo nominal orbital fine position so both spacecraft were capable of reaching it.

Keeping the other parameters as close as possible in both satellites minimises their divergences due to the orbital perturbations during the whole satellite life, although it is not a main objective of the campaign.

The criteria to consider the target fulfilled was not in terms of tolerances as for the nominal constellation but as long term stability of both satellites so no orbital corrections would be necessary during the whole duration of the mission.

2.2. Reached orbits

The recovery campaign for GSAT0201 was successful after 11 manoeuvres between November 5, 2014 and November 19, 2014,[1)] the table 1 shows reached state vector together with the injection conditions.

Table 1. GSAT0201 State Vectors.

GSAT0201		Injection	End of Recovery
Epoch	UTC	2014.08.22	2014.11.22
		16:15:08	05:13:10
a	km	26197.6	27979.0
e		0.232	0.156
ι	deg	49.77	49.78
Ω	deg	87.47	82.69
α	deg	249.77	28.93
ω	deg	24.73	28.93

The perigee raising campaign for GSAT0202 was also nominal initiated two months later introducing improvements from the lessons learnt with the GSAT0201 campaign. Additionaly it was interrupted during 15 days to clarify an anomaly in the Earth sensor and the consequent resynchronisation of GSAT0202 apsides with respect to GSAT0201.[1)] The reached state vector together with the initial condition is in table 2.

During the three months between manoeuvre campaigns GSAT0202 had a semi major axis 300 km lower than GSAT0201, so the perturbations of the Earth gravitational field introduces a deviation between both orbits.

Figure 1 shows the evolution of the semimajor axis with each manoeuvre for the full campaign, where is clearly visible the perigee raising performed. Figure 2 shows ascending node and

Table 2. GSAT0202 State Vectors.

GSAT0202		Injection	End of Recovery
Epoch	UTC	2014.08.22	2015.03.05
		16:15:08	10:36:18
a	km	26181.3	27978.6
e		0.233	0.156
ι	deg	49.77	49.87
Ω	deg	87.48	77.52
α	deg	249.76	34.35
ω	deg	24.88	34.35

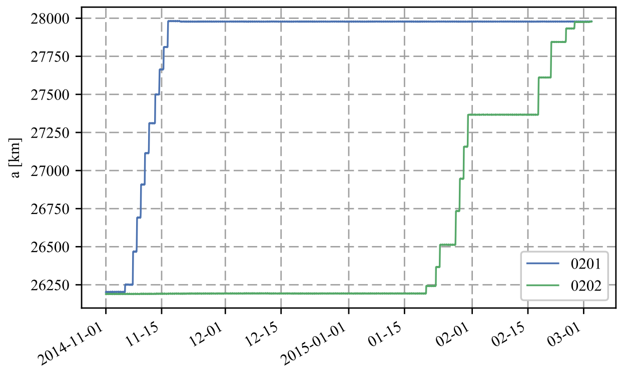

Fig. 1. Evolution of a during the period between the start of the first perigee raising in GSAT0201 and the last manoeuvre of GSAT0202.

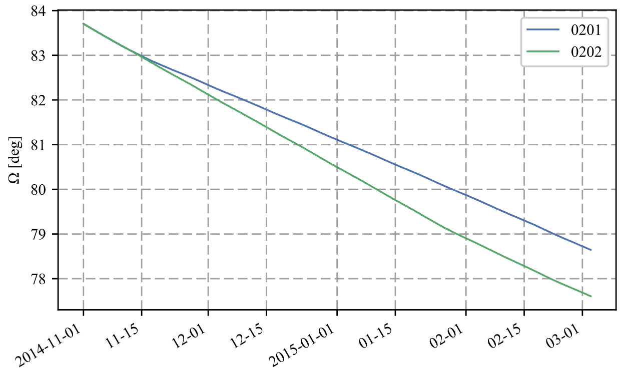

Fig. 2. Evolution of Ω during the period between the start of the first perigee raising in GSAT0201 and the last manoeuvre of GSAT0202.

and Fig. 3 the argument of perigee, both parameters shows a different slope for each satellite during the manoeuvre hiatus that results in a fixed offset between satellites at the end of the campaign.

Once GSAT0202 reached the target semimajor axis all the parameter's evolutions return to be similar, although it accumulates an offset around 1.0374° for the right ascension and 1.2468° in argument of perigee.

It should be also mention the change of 0.06° in inclination during GSAT0201 campaign noticeable in Fig. 4. The unpredicted off-modulation of a thruster introduced a small out-of plane components in the manoeuvres that produced the inclination change, as all the manoeuvres were performed close to the descending node. The better knowledge of the thruster behaviour during the GSAT0202 campaign reduced greatly the impact of the off-modulation. It was decided not to take actions to correct this deviations as the only tight constraint were in the semi-major axis and didn't affect the objectives of the recovery.

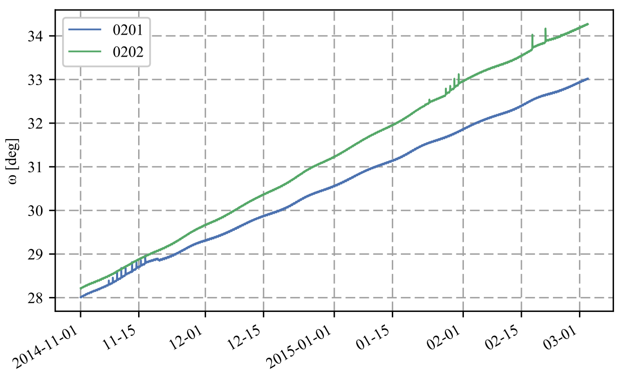

Fig. 3. Evolution of ω during the period between the start of the first perigee raising in GSAT0201 and the last manoeuvre of GSAT0202.

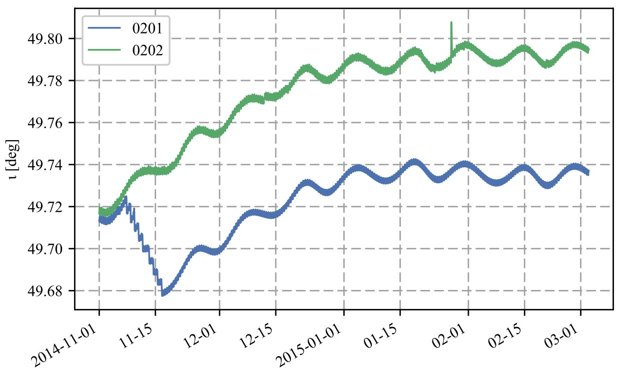

Fig. 4. Evolution of ι during the period between the start of the first perigee raising in GSAT0201 and the last manoeuvre of GSAT0202.

3. Galileo reference orbit

The reference orbit provides the centre of the slot used for station keeping of each satellite so it fulfils the relative position constraints within the tolerance. It is important to notice that it does not represent a real orbit. The objective is to extend the nominal Galileo reference orbit representation to include the L3 satellites with no impact for applications that only uses the nominal constellation.

The reference uses CIRS as inertial reference frame, a geocentric coordinate system based on the current position of the Celestial Intermediate Pole. In this system, the right ascension is calculated along the Celestial Intermediate Equator from the Celestial Intermediate Origin, a point close to the vernal equinox.[2)] The exact definition can be found in the Nomenclature for Fundamental Astronomy Glossary edited by the International Astronomical Union.

The semi-major axis, eccentricity and inclination are consider constant as either their variations are only noticeable in a long term time scale or are slow and periodic with an amplitude that will not result in any satellite being out of the slot box.

The representation considers the argument of perigee drift and the mean anomaly. The parameters that evolve with time due to Earth geopotential and the 3$^{\text{rd}}$ body effects (Sun and

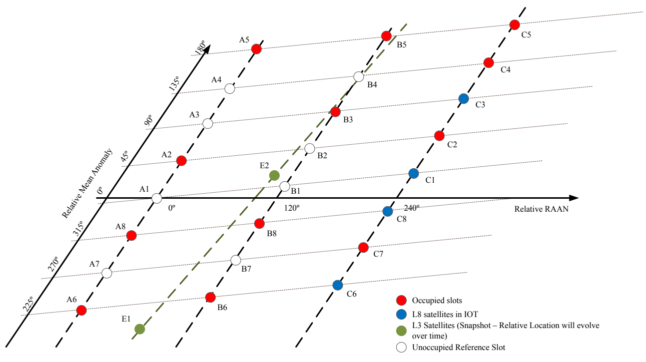

Fig. 5. Galileo constellation schema (April 2017)

Moon) are given by the expressions:

$$\Omega(T) = \Omega_0 + 360\frac{p-1}{N_p} + \dot{\Omega}\cdot(T - T_0) \tag{1}$$

$$\omega(T) = \omega_0 + \dot{\omega}\cdot(T - T_0) \tag{2}$$

$$M(T) = M_0 + 360\frac{s - 1 + \frac{p-1}{N_p}}{N_s} + \dot{M}\cdot(T - T_0) \tag{3}$$

The reference time T is given in UTC although the quantity $T - T_0$ in Eq. (1), Eq. (2) and Eq. (3) must be evaluated in a continuous time scale with SI seconds like GST.

After each launch of new satellites a snapshot of the reference orbit is provided.[3)] The values for the nominal constellation and extended slots in November 21, 2016 are given in table 3 and an schematic of the current used slots in Fig. 5.

Table 3. Galileo constellation at 2016/11/21 00:00:00 UTC.[3)]

Parameter		Nominal	Extended
T	UTC	2016/11/21 00:00:00	
N_p		3	1
N_s		8	2
a_0	km	29599.8	27977.6
e_0		0.0	0.162
ι_0	deg	56.0	49.85
Ω_0	deg	77.632	52.521
ω_0	deg	0.0	0.162
M_0	deg	15.153	316.069
$\dot{\Omega}$	deg/day	-0.02764398	-0.03986760
$\dot{\omega}$	deg/day	0.0	0.03383184
$\dot{M}$	deg/day	613.72253566	667.86467481

The satellites in the main constellation are actively controlled to stay in the slot within a box defined by:

$$\iota = \iota_{ref} \pm 2^\circ \tag{4}$$

$$\alpha = \alpha_{ref} \pm 2^\circ \tag{5}$$

$$\Omega = \Omega_{ref} \pm 1^\circ \tag{6}$$

For the the extended slots no tolerances are defined and the active control of the slot is not foreseen except for unexpected events. Therefore the values of the reference were chosen to assure that during at least six years after the last manoeuvre the orbital parameters stays in the vicinity of the reference in a similar way.

Figures 6, 7, 8, 9 10 and 11 shows the evolution of the orbital parameters for both spacecrafts with respect to their reference slot calculated using the parameters and equations of this

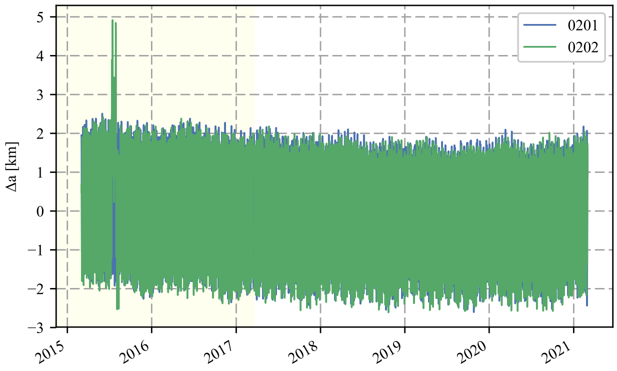

Fig. 6. Evolution of GSAT0201 and GSAT0202 a with respect to the reference during the six years after the last manoeuvre.

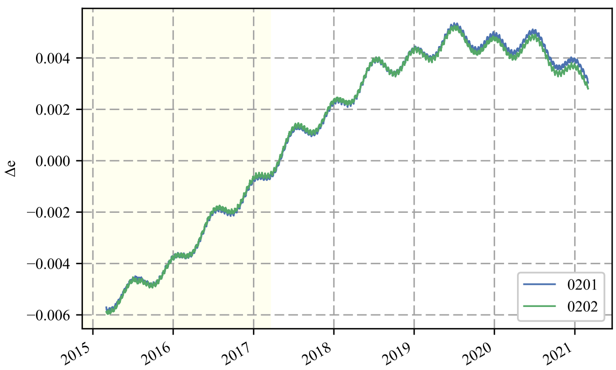

Fig. 7. Evolution of GSAT0201 and GSAT0202 e with respect to the reference during the six years after the last manoeuvre.

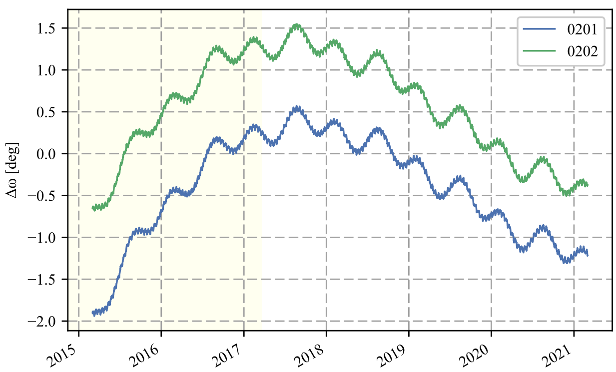

Fig. 8. Evolution of GSAT0201 and GSAT0202 ω with respect to the reference during the six years after the last manoeuvre.

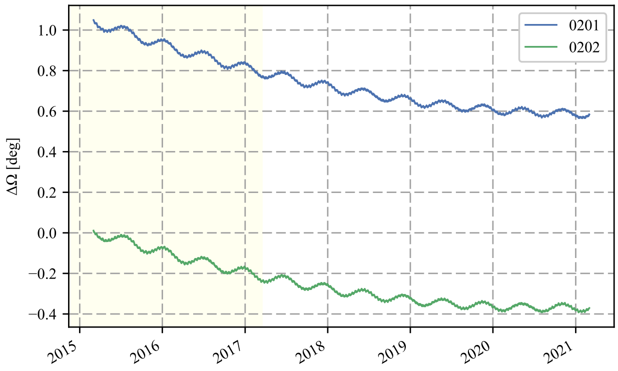

Fig. 9. Evolution of GSAT0201 and GSAT0202 Ω with respect to the reference during the six years after the last manoeuvre.

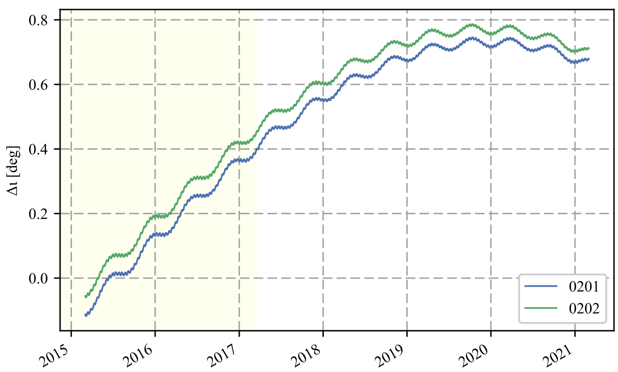

Fig. 10. Evolution of GSAT0201 and GSAT0202 ι with respect to the reference during the six years after the last manoeuvre.

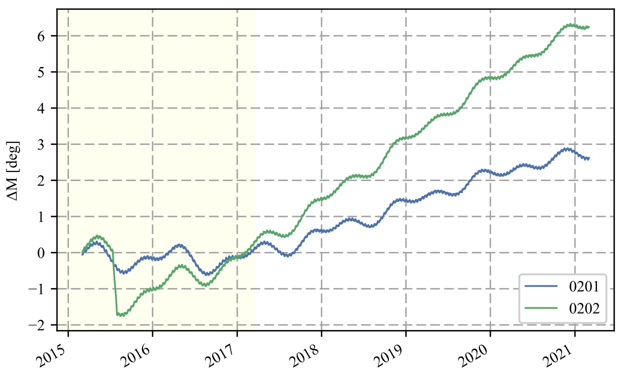

Fig. 11. Evolution of GSAT0201 and GSAT0202 M with respect to the reference during the six years after the last manoeuvre.

section. During June 2016 the spacecraft GSAT0202 had unexpected thrusting, due to entering safe mode, that translated in a jump of semimajor axis of around 2 km and that was recovered shortly after with a manoeuvre. This is visible in Fig. 6 in the evolution of the semimajor axis as a jump and in argument of perigee and mean anomaly as an additional change in the slope. The recovery manoeuvre was planned following the same philosophy as in the recovery campaign.

The fact that the L3 satellites follow the reference with this accuracy facilitates to improve the tools designed for the nominal constellation (i.e. service volume simulators) to include the extended satellites with an equivalent approximation.

3.1. Repeat-Cycle

The repeat-cycle pattern of 37 revs / 20 days is one of the most useful features of the chosen orbits and even when there is no active control of the orbit trace the results shows that repeat pattern is followed with enough accuracy during the six years.

Figure 12 shows the evolution of the longitude of the ascending node for each satellite respect to the value August 3, 2016. This variation is around $\pm 1.5°$ in both cases, equivalent to a ground track of ± 167 km, although for the GSAT0202 values prior to entering safe mode the deviation is slightly bigger.

In the Fig. 13 the relative longitude after a semi-resonant period measured as longitude of GSAT0202 ascending node with

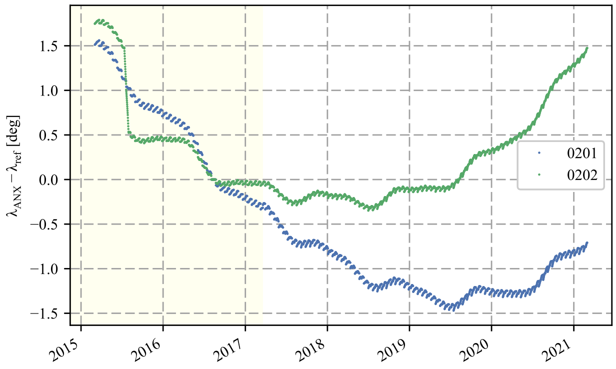

Fig. 12. Repeat-cycle match in longitude at ascending node for six years after last manoeuvre.

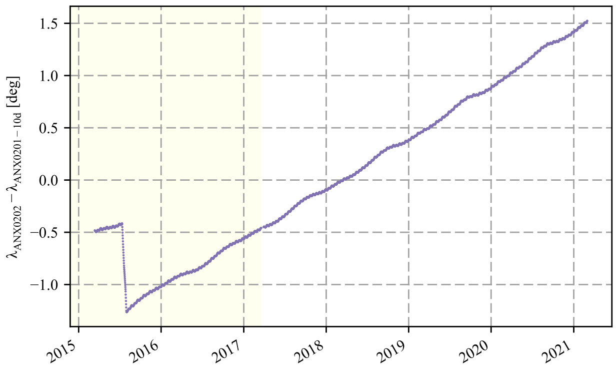

Fig. 13. GSAT0202 vs GSAT0201 semi-cycle match in ascending node longitude for six years after last manoeuvre.

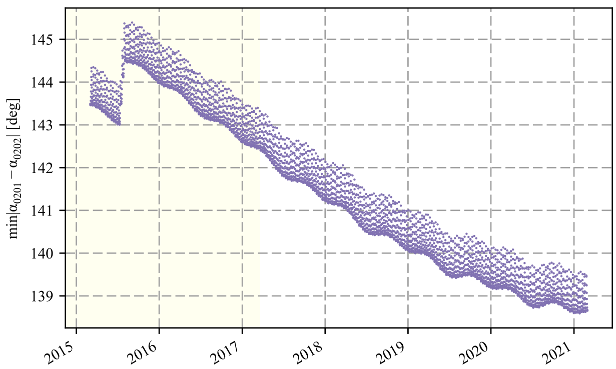

Fig. 14. GSAT0202 vs GSAT0201 minimum argument of latitude difference for six years after last manoeuvre.

respect to the longitude of GSAT0201 ascending node a semi cycle before. This difference is also in the range of $\pm 1.5°$ confirming that is possible to consider that the L3 satellites geometry repeats every 10 days, although with the other spacecraft of the couple. Therefore this 10 days semi cycle allows the comparison with respect to the Galileo Nominal Constellation, approximation that is valid for many applications. Finally Fig. 14 shows the evolution of the minimum argument of latitude distance between both satellites, confirming that is always greater than 135°. This guarantees that both L3 satellites are not visible at the same time from a ground station and thus facilitate the planing of the operations and data collection.

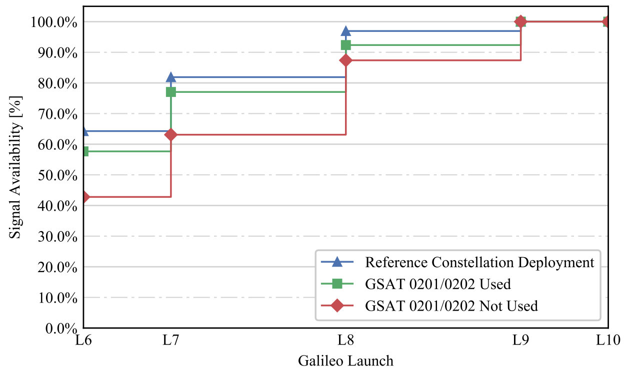

Fig. 15. Availability of 4 or more Signals in Space available at User Level.

4. Contribution of the L3 satellites to End User Navigation Performance

The successful recovery of the L3 satellite orbits, and the completion of the adaptations of the Galileo system infrastructure enable the use of these satellites for navigation purposes.

Both satellites are currently under intense testing regarding the achievable accuracy of the orbit and clock estimation and prediction. Another objective of the testing is to confirm that the introduction of both satellites does not have detrimental effects on the performance of the operational satellites in the nominal orbits and to confirm the expected added value of both for the end user of the Galileo GNSS.

Figure 15 illustrates the contribution in terms of receivable signals at user level throughout the deployment of the Galileo Satellites. It can be seen that the two additional signals significantly improve the availability of four Signals in space (four visible Galileo Satellites). The reception of four satellites under good geometry is a pre-condition for determining the position, velocity and time at user level.

Another important parameter is the prediction error (Ranging Error) of the evolution of the orbit and clock information provided in the navigation message. Following the upgrades of the Galileo core infrastructure, the two L3 satellites achieve equivalent performance levels as those obtained by the satellites in the nominal orbits for operationally exploited prediction intervals up to approximately two hours (see Fig. 16). The degradation of this parameter beyond the two hours is due to the nature of the eccentric orbits which results in higher errors of the broadcast navigation messages due to the higher dynamics.

The L3 recovery activities are in their final phase at the time of writing this paper, during which the overall navigation performances of the GSAT0201/0202 are tested. The testing activities is confirming the good quality achieved by those satellites without impacting the nominal satellites. In addition to the system oriented testing the campaign will also confirm whether these satellites are usable for end-users. Figure 17 shows the achieved ranging performance as part of this final system testing phase. It can be seen from table 4 that the obtained performance is in line with the ranging performance provided by the nominal satellites.

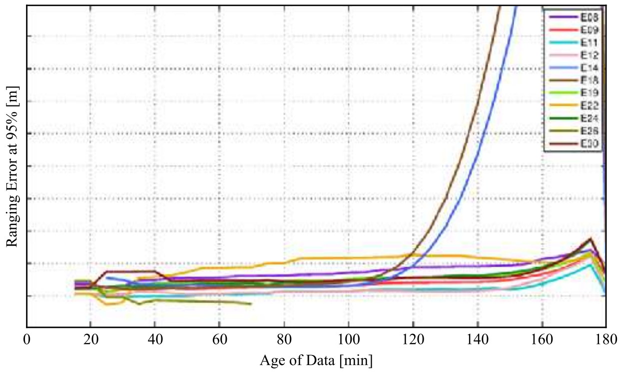

Fig. 16. Ranging error evolution with the age of the navigation message. Worst user location in global service volume - with 5° minimum elevation above horizon

Table 4. Achieved Ranging Accuracy in meters for Galileo Satellites.

Satellite	User Location	
	Worst	Average
Values in meters	95^{th} percentile over time	Average over time
GSAT0101	0.51	0.2
GSAT0102	0.56	0.24
GSAT0103	0.58	0.21
GSAT0201	0.58	0.21
GSAT0202	0.55	0.17
GSAT0203	0.46	0.17
GSAT0204	0.46	0.15
GSAT0205	0.42	0.15
GSAT0206	0.48	0.17
GSAT0208	0.48	0.18
GSAT0209	0.45	0.16
GSAT0210	0.61	0.32
GSAT0211	0.64	0.25

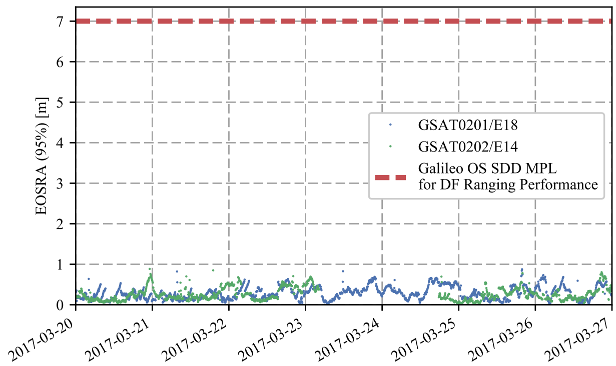

Fig. 17. GSAT0201/0202 F/NAV as Observed Ranging Error. Worst User Location Impact

5. Scientific Opportunities with L3 satellites

The L3 satellites, provide a range of features which make them perfect candidates to conduct scientific experimentation on relativistic effects. The atomic clocks on-board both satellites offer a highly stable reference signals for the data collection. Both satellites are continuously monitored by a ground network of reference stations and the long satellite life-time allows to integrate the collected measurements over long time intervals further boosting the accuracy of the result.

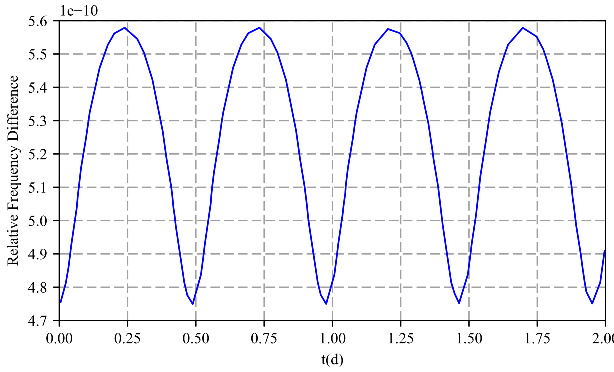

Fig. 18. Periodic change of clock rate due to the gravitational potential variation in the eccentric orbit.

Without interfering with the nominal usage of the satellites for navigation purposes, the elliptic orbits of both satellites produce a regular modulation of the gravitational redshift observable in the clock monitoring data.[4] The periodic change in the gravitational potential due to the orbital motions leads to a periodic change of the clock rate as shown in Fig. 18.

The achievable accuracy of the gravitational redshift measurements would allow to push the current state of the art by at least a factor of 5. Todays best measurements of the gravitational potential are based on the Gravity Probe-A experiment performed with an accuracy of 1.4×10^{-4}, in 1976 by NASA.

6. Conclusion

The recovery campaign was a success for both GSAT0201 and GSAT0202 bringing them to an orbit that follows a 37 revs / 20 days repeat-cycle with a relative phase between them of 180° which provides several benefits. The extended slots for the L3 satellites included in the Galileo Constellation represents these orbits with an accuracy similar to the nominal satellites until at least March 2021. The use of the L3 satellites improves the ranging accuracy and availability of the constellation and is an opportunity for the scientific community for advanced studies.

Operational use of these satellites is under consideration at the time of writing this paper.

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