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In-flight Characterisation and Calibration of Galileo FOC Reaction Control System

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This paper presents the in-flight characterisation and calibration of the Galileo Full Operational Capability (FOC) Reaction Control System (RCS), performed by the CNESOC Flight Dynamics (FD) team during six LEOPs and Drift Stop & Fine Positioning phases, where a total of 14 S/C have been operated. For each S/C, up to 12 manoeuvres are potentially required to reach the target orbit, defined by a very narrow orbital elements box: 5 m in semi-major axis and 2 mdeg in argument of latitude. In order to reach the target and possibly minimize the number of necessary manoeuvres, it is crucial for FD to be able to predict with sufficient confidence the RCS performances of the upcoming manoeuvre and apply the corresponding calibration factors to the manoeuvre computation. The post-processing of a large number of manoeuvres of different size and performed under different conditions has allowed FD to identify trends and correlations, and to prepare guidelines to follow during the calibration process, by nature semi-empirical and requiring decision-making.

Key Words: Galileo, RCS, in-flight characterisation, calibration

1. Introduction

Europe's Galileo satellite navigation system will provide high-quality positioning and timing services to users around the globe. The nominal constellation consists of 24 satellites distributed in three orbital planes. The last launch, which took place on the 17th of November 2016, was the first one performed on an Ariane-5 launcher; it injected four satellites into one of the orbital planes. All previous launches were done using a Soyuz launcher, which carried two satellites. The first four S/C launched as part of the operational constellation were In-Orbit Validation (IOV) satellites; all subsequent S/C were Full Operational Capability (FOC) satellites, being manufactured by OHB. Up to now, 18 Galileo satellites have been injected into orbit through 8 different launches. 16 of these satellites are filling nominal slots (distributed 8/4/4 in the three planes) and the other two are in a non-nominal orbit due to a launcher anomaly.[1,2]

The Launch and Early Operations Phase (LEOP) includes a set of three manoeuvres per satellite to initiate a drift towards its target orbit. Once the LEOP is finished, the Flight Control Team (FCT) hands over the satellites to the routine operators (DLR GfR). A few weeks after the handover, the Drift Stop and Fine Positioning (DSFP) phase starts. In this phase, the satellites perform a set of three drift stop manoeuvres and up to six fine positioning manoeuvres to achieve the target position.[3] The positioning requirements for this target are very strict, because the objective is to keep the satellites as long as possible without performing any manoeuvres during the routine phase. The objective is to perform a single station keeping manoeuvre during the whole 12 years life of the satellite. This is translated into an accuracy in the initial positioning of only 5 m in semi-major axis and 2 mdeg in argument of latitude. Targets are defined for the other elements too, but these two are the most strict (especially the one for the semi-major axis). This is the main reason why the process explained in this paper has been created and fine-tuned after every positioning campaign. The better the performance of the manoeuvres is, the fewer manoeuvres are required to achieve the target, thus reducing the overall cost of the orbit acquisition, and allowing to start earlier the satellite commissioning for Galileo services.

The LEOP Mission Control Team is composed by a mix of CNES and ESOC experts. The combined CNESOC team share members and tasks, and benefits from the experience and cultures of both agencies. Once the LEOP is finished and the handover to DLR GfR is done, most of the CNESOC team is no longer involved in the DSFP; however, the CNESOC Flight Dynamics team is involved in the whole DSFP phase as responsible for the generation of the manoeuvres and the achievement of the desired target.

This paper describes the approach followed by the CNESOC Flight Dynamics team to evaluate a manoeuvre to be commanded and decide on the commanded parameters. The objective is to try to minimize the manoeuvre misperformance in order to achieve the target using the minimum number of manoeuvres, while preserving the robustness of the approach.

2. Galileo FOC Reaction Control System

The Galileo FOC Reaction Control System (RCS) is composed by a hydrazine blow-down tank and two redundant branches of four thrusters, tilted by about 16 degrees around one of the S/C axes. The beginning of life (BOL) thrust of each thruster is 1.09 N and the end of life (EOL) thrust is 0.36 N.

The system is designed to perform two types of manoeuvres: small and large manoeuvres.

2.1. Small manoeuvres

Manoeuvres of this type have a duration comprised between 10 ms (though 50 ms is the minimum recommended by the S/C manufacturer) and 0.9 s. The duration is commanded with a resolution of 1 ms, and any number of thrusters can be used out of the available four. The thrusters are continuously on for the whole commanded duration and no attitude control is performed during the manoeuvre. The minimum achievable delta-v (assuming 1 thruster on for 50 milliseconds) is 0.059 mm/s at BOL and 0.028 mm/s at EOL.

The recommendation of the manufacturer is to always use one single thruster for manoeuvres that, if commanded using four thrusters, would have a duration shorter than 0.225 s.

When commanding a small manoeuvre, it is necessary to make an assumption on the thrust factor: this is defined as the predicted average thrust during the manoeuvre divided by the nominal thrust from the manufacturer model.

2.2. Large manoeuvres

Manoeuvres of this type have a minimum duration of one second and there is no formal limit on the maximum duration; however, the maximum delta-v is specified by the manufacturer to be 20 m/s. This is equivalent to a manoeuvre of 1.07 hours at BOL, and of 2.92 hours at EOL. The duration is commanded with a resolution of one second and all four thrusters are used. When the satellite performs a large manoeuvre, it automatically switches off a pair of thrusters for the duration of a pulse (one second) to generate some torque and correct deviations from the nominal thrusting attitude. This process is called off-modulation. As shown in section 4.3, although no earliest time is defined for the first off-modulation pulse, most of the time it is safe to assume that there will be no off-modulation during the first five seconds of a manoeuvre. The off-modulation is represented as a percentage and is defined as the total number of pulses off (of all the thrusters) divided by the total number of pulses. In a ten seconds manoeuvre with a single off-modulation pulse (two thrusters off), the off-modulation would be 5% (2 divided by 40).

As mentioned above, large manoeuvres have a resolution of one second, so it is not possible to command a manoeuvre of, for example, 1.5 s. In order to cope with this limitation, in case a manoeuvre of 1.5 s is necessary, a yaw-tilted 2 s manoeuvre needs to be commanded. The resulting cross-track delta-v component is small and has a negligible effect on the target orbit acquisition.

Due to the fact that manoeuvres are commanded by total duration, it is necessary to make an assumption on the expected off-modulation, in addition to the thruster performance, in order to command the proper manoeuvre duration and obtain the expected delta-v.

As explained in the following sections, the behaviour of large manoeuvres is very dependent on the actual duration.

3. Manoeuvre calibration approach

This chapter describes the approach followed by FD to compute the thrust and off-modulation calibration factors for an upcoming manoeuvre.

This task is generally performed at the start of a manoeuvre shift, once the performance of the previous manoeuvre is definitively assessed. The FD coordinator on shift is in charge of this task: he may seek input and advice from the attitude and manoeuvre FD subsystem experts on shift. He has limited time to come up with a decision, since he has to comply with the FD timeline, which is driven by the deadlines for products delivery to the Flight Control Team.

The calibration data of all manoeuvres performed for all Galileo FOC S/C is available and kept up to date during operations. The choice of thrust and off-modulation factors typically depends on calibration data of previous manoeuvres of the same S/C and of similar manoeuvres of other S/C. Thrust and off-modulation factors have shown to depend in a complex way on a number of factors, such as tank pressure and manoeuvre duration: hence, the simple approach of directly using the observed performance of the last manoeuvre of the same S/C is in some cases not accurate enough and may lead to large misperformances.

3.1. Manoeuvre types

Based on the operational experience gained with the manoeuvre calibration process, the FD team has classified the manoeuvres into the following types:

- **High pressure (20-22 bar)**: for manoeuvres taking place in this tank pressure range, it is likely to have a large decrease of the off-modulation as the pressure decreases. If the previous manoeuvre is in this pressure range and shows this trend, it is possible to take the off-modulation at the end of the previous manoeuvre (e.g. last 200 s) as baseline value for the next manoeuvre, and add a predicted decrease with the pressure if the manoeuvre is large. The thrust factor also generally decreases by a comparable amount as a function of the pressure: this has the implication that, for this manoeuvre type, using both thrust and off-modulation factors observed in the previous manoeuvre is practically a valid alternative approach, as the two effects compensate each other.
- **Manoeuvre duration 50-150 s:** in this duration range, it is advisable to look at the off-modulation of the first *N* seconds of the previous manoeuvre of the same S/C (where *N* is the commanded duration of the upcoming manoeuvre). It is best to look at the off-modulation plot rather than at a single computed value, as the off-modulation will vary in a certain range, and an accurate value is hard to predict. This information has to be merged with the effect of a lower pressure.
- **Manoeuvre duration 6-50 s**: in this case, the off-modulation factor should be computed based on predicted number of off-modulation pulses. The information about when the off-modulation pulses have occurred for previous manoeuvres of the same

S/C is available: in particular, manoeuvres in a similar pressure range should be taken as reference.

- **Manoeuvre duration 1-5 s**: in this case, no off-modulation is expected. For the thrust factor, if it is the first manoeuvre of this type, it is advisable to either use 1 (the default value), or to look at the performance of similar manoeuvres of other S/C. This is because the thrusters are not operating in pulsed mode, and generally show a different (higher) performance compared with manoeuvres executed in pulsed mode.
- **Manoeuvre duration < 1 s**: this is a proper small manoeuvre. If it is the first small manoeuvre, it is advisable to either use the default thrust factor or a value based on the small manoeuvres performance observed on other S/C. More details are provided in section 4.6.

3.2. Mitigation of manoeuvre misperformance

The choice of thrust and off-modulation factors is in some cases relatively straightforward and leads to reliable values. In some other cases, different thrust and off-modulation behaviors are equally possible for the upcoming manoeuvre, and a seemingly arbitrary decision needs to be taken. Some examples of these situations are cases in which it is unclear whether the manoeuvre is long enough to reach a stable off-modulation value, or whether a certain number of pulses or a different one will occur for a manoeuvre of a few seconds, or whether a certain predicted decrease of the thrust factor will actually take place.

In such cases, a wrong decision (or simply unlucky, considering the unpredictability of the involved factors), can lead to a large misperformance and introduce the need for additional manoeuvres to reach the target. As an example, an error in the prediction of one single off-modulation pulse in a 10 s manoeuvre corresponds to a 5% misperformance.

One available resource to mitigate the effect of a possible manoeuvre misperformance is to interact with the FD manoeuvre subsystem at the time of choosing the calibration factors. More specifically, an analysis should be performed concerning the impact of under- and over-performance of different extent on the target acquisition strategy.

Once this input is available, the FD coordinator can proceed as follows:

- Choose thrust and off-modulation factors based on his estimation of their most likely behaviour.
- Consider the possible alternative behaviours, and assign a likelihood to each of them.
- Using the input from the FD manoeuvre subsystem, determine the impact of each alternative behaviour on the target acquisition strategy.
- Finally, bias the initial choice of thrust and off-modulation factors (in fact, only biasing one of them is sufficient) to guarantee the highest probability of success considering all cases, rather than trying to achieve a perfect manoeuvre performance in a single possible case.

4. Manoeuvre data analysis

During six Galileo FOC launches, the CNESOC FD team has performed 128 manoeuvres with delta-v ranging from 20 m/s to a few tenths of mm/s. Data regarding these manoeuvres has been logged in order to perform analyses aiming at the improvement of the manoeuvre commanding. This section describes the main results of these analyses.

4.1. Off-modulation trends

The thruster off-modulation has shown a number of different trends on the S/C operated so far. While the off-modulation decrease with the decrease of pressure is generally common to all S/C, the extent of this decrease varies depending on the S/C. Useful information about the off-modulation behaviour can be obtained by analyzing its trend as a function of the manoeuvre duration, using data from the latest manoeuvre.

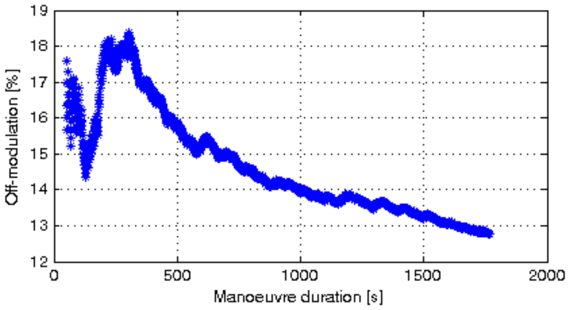

Fig. 1. Off-modulation as a function of manoeuvre duration for the A1 manoeuvre on S/C 26B: manoeuvre duration 1767 s, initial pressure 22.1 bar.

As represented in Fig. 1, the off-modulation can show large variations for manoeuvres executed with high tank pressure. In this case, the off-modulation reached a maximum of about 18% after 300 s from manoeuvre start; afterwards, it steadily decreased until reaching its final value of 12.76%. The plot represents the off-modulation of the whole manoeuvre as a function of the manoeuvre duration. The "current" off-modulation at a given time during the manoeuvre can be estimated by using a moving time window of duration 200 s: this is represented in Fig. 2, for the same manoeuvre as in Fig. 1. The off-modulation shows an initial value of 18-20%, decreases to about 12% after 800 s, and decreases further to about 10% at manoeuvre end.

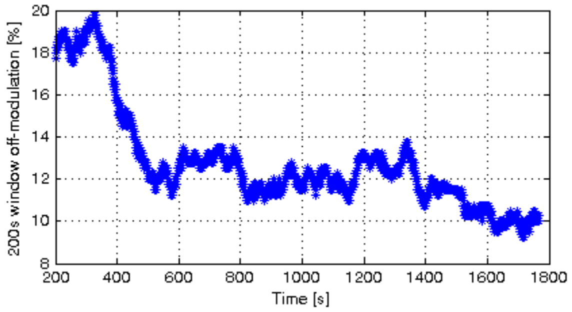

Fig. 2. Off-modulation computed with a 200 s moving time window for the A1 manoeuvre on S/C 26B.

The following manoeuvre on the same S/C, of comparable duration, ended up with a total off-modulation of 10.47%: its trend, considerably more stable, is represented in Fig. 3. This value is similar to the one obtained at the end of the previous manoeuvre with the 200 s moving time window (see Fig. 2).

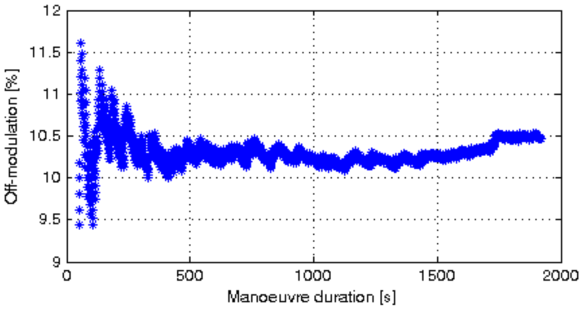

Fig. 3. Off-modulation as a function of manoeuvre duration for the A2 manoeuvre on S/C 26B: manoeuvre duration 1919 s, initial pressure 20.0 bar.

The next large manoeuvres on the same S/C, performed with an initial pressure in the 17-18 bar range, showed an off-modulation of 10.33% and 10.73%, confirming that a stable trend had been reached.

4.2. Manoeuvres larger than 50 seconds

Figures 4 and 5 show the off-modulation and the thrust factor versus the average pressure during the boost of manoeuvres with a duration longer than 50 s.

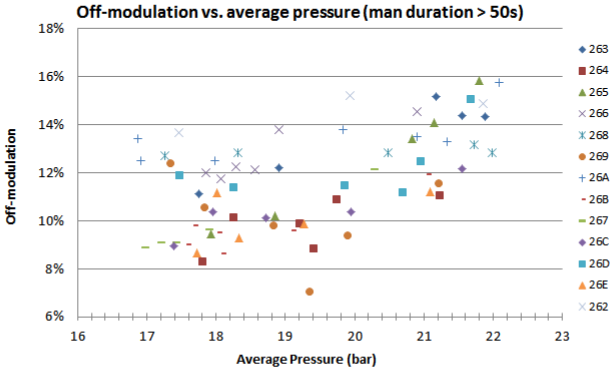

Fig. 4. Off-modulation versus average boost pressure for manoeuvre durations larger than 50 s.

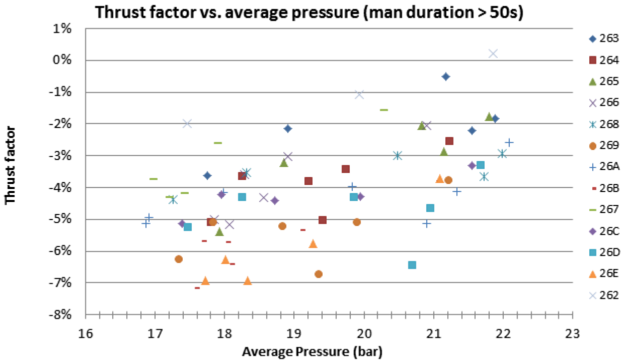

Fig. 5. Thrust factor versus average boost pressure for manoeuvre durations larger than 50 s.

Both the thrust factor and the off-modulation decrease with the pressure. However, we cannot establish an accurate correlation between these parameters and the pressure, which would allow to predict the next value based on previous manoeuvres. In contrast, we can observe that both parameters decrease with the pressure in a similar way; thus, using the calibration factor, defined as:

$$cal = (1 - off)(1 + thr), \qquad (1.)$$

one can reduce the dependency on the pressure. Figure 6 shows that, indeed, the calibration factor is mostly constant and independent of the pressure; therefore, the use of the previous manoeuvre calibration factor to command the next one is a good solution for large manoeuvres.

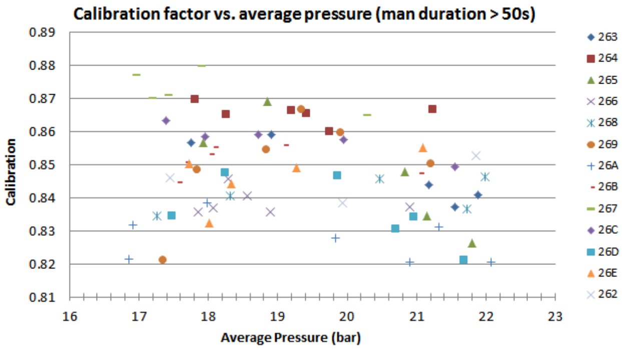

Fig. 6. Calibration factor versus average boost pressure for manoeuvre durations larger than 50 s.

In order to determine the minimum boost duration below which the use of the calibration factor is no longer valid, one can plot it against the boost duration (in logarithmic scale). In Fig. 7, we can see that for durations shorter than 50 s the calibration factor is not constant anymore, presumably because the boost is not long enough to reach a stable off-modulation. Consequently, the use of calibration factor for durations shorter than 50 s is not valid.

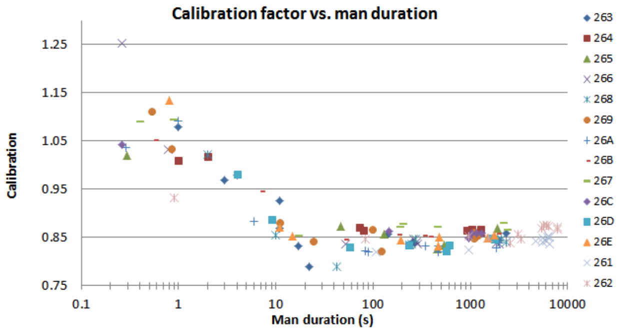

Fig. 7. Calibration factor versus boost duration.

In order to check this result, the manoeuvre performance of all manoeuvres with duration larger than 50 s has been recomputed assuming that the manoeuvres had been commanded using the calibration of the previous manoeuvre of the same spacecraft. Figure 8 shows that the misperformance would have been better than +/- 2% in 94% of the cases, with a maximum of -3.34%.

The mean value of the calibration factor of the first manoeuvre performed on each satellite is 0.844, about 1% lower than the value recommended by the satellite manufacturer (0.855). The mean value of the calibration factor of all the manoeuvres larger than 50 s is 0.849.

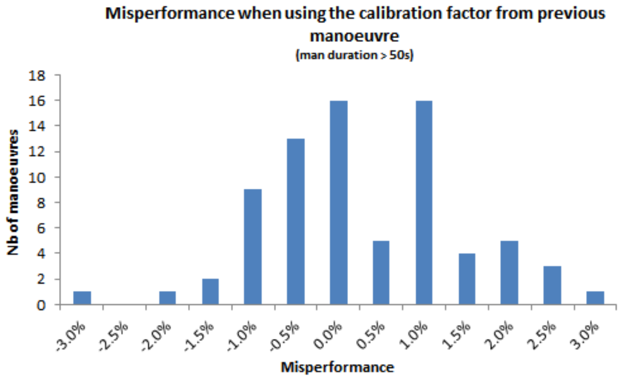

Fig. 8. Manoeuvre misperformance histogram, assuming that the manoeuvres had been commanded using the calibration factor of the previous manoeuvre of the same spacecraft.

4.3. First off-modulation pulse

As shown in Fig. 9, for all the manoeuvres except one, the first off-modulation pulse occurred after the fifth second of the boost. Thus, for manoeuvres shorter than 6 s, we can assume that no off-modulation occurs.

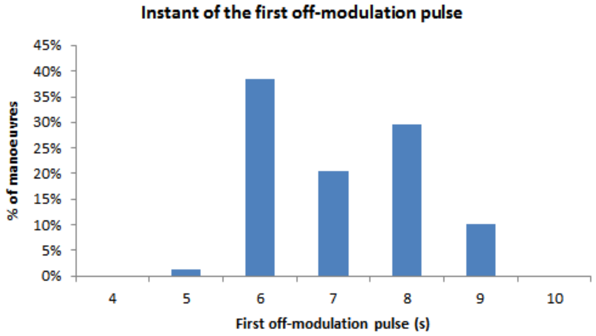

Fig. 9. Histogram of the first off-modulation pulse.

An analysis of the repeatability of the first off-modulation pulses has been attempted, but yielded no useful result. The recommended approach remains to look at the first off-modulation pulses of previous manoeuvres of the same S/C and make a solid assumption, also considering the possible effects on the target acquisition, as described in section 3.2.

4.4. Manoeuvre duration 6-50 seconds

As discussed in section 4.2, for manoeuvre durations below 50 s the boost is too short to reach a stable off-modulation and the use of the calibration factor is no longer valid. Consequently, in order to command the next manoeuvre, the off-modulation factor and the thrust factor have to be assessed separately.

For manoeuvres between 6 and 50 s, it is recommended to deduce the off-modulation from the first seconds of previous manoeuvres with a similar value of pressure.

Regarding the thrust factor, the number of manoeuvres performed in the 6-50 seconds region is quite limited and it is difficult to perform reliable statistical analyses. However, from Fig. 10 we can observe that thrust factor decreases with respect to large manoeuvres when the duration decreases up to 20 s. This decrease of the thrust factor is probably not due to the manoeuvre duration itself, but to the pressure drop with respect to the previous manoeuvre. Thus, if the previous manoeuvre was performed with a similar value of pressure, it is recommended to use the previous thrust factor. If not, a decrease of 1 to 2% is a good assumption.

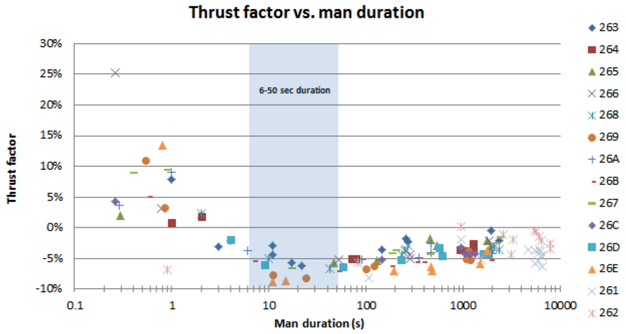

Fig. 10. Thrust factor versus boost duration. The blue region corresponds to the 6 to 50 s boost duration.

For manoeuvre durations below 20 s, the thrust factor slightly increases when the manoeuvre duration decreases.

Consequently, for a 6 to 20 s boost it is recommended to use a thrust factor between the one of the previous manoeuvre and a value 1 to 2% higher, depending on the boost duration.

4.5. Manoeuvre duration 1-5 seconds

As shown in section 4.3, for boost durations below 6 s no off-modulation is foreseen and the thrusters operate in a continuous mode without on-off cycles. Figure 10 shows that between 1 and 5 s the thrust factor increases when the manoeuvre duration decreases, becoming positive for 1 s manoeuvres. Based on this, it is recommended to command these manoeuvres with a thrust factor higher than for the previous off-modulated boosts, with slightly positive values possible if the duration is between 1 and 2 s.

4.6. Manoeuvre duration less than 1 second (small manoeuvres)

The CNESOC FD team performed 16 small manoeuvres, four of them with only one thruster. The thrust factor of the small manoeuvres performed with four thrusters varies from -7% to +25%. It should be noted that the manoeuvre with a thrust factor of -7% was performed with a very high pressure (22.5 bar). All the other manoeuvres, performed with moderate values of pressure (around 17 bar), showed a positive thrust factor, varying from 2% to 25%. Our recommendation is to command these manoeuvres with a thrust factor of around 5%. Nevertheless, the behaviour of this kind of manoeuvres is difficult to predict and one can expect misperformances in the order of 10% or higher.

Three out of four small manoeuvres performed with one thruster showed a high thrust factor, up to 44%. However, the size of these manoeuvres is a few tenths of mm/s and the determined DV accuracy is close to the DV itself, so the determined thrust factor is not fully reliable. The recommendation is to command these manoeuvres with a thrust factor of around 10%, expecting misperformances of the same order of magnitude.

5. Conclusion

During the six LEOPs and DSFPs performed so far, the CNESOC FD team has acquired a thorough understanding of the Galileo FOC RCS behaviour. This has allowed to develop a manoeuvre calibration approach and to progressively expand it with new ideas as soon as new trends were highlighted by the performed manoeuvres.

This calibration approach classifies the manoeuvres in different types, depending on their initial pressure and their duration. It aims at minimizing the manoeuvre misperformance and its impact on the target acquisition strategy considering all possible off-modulation and thrust factor behaviours for the upcoming manoeuvre, and their respective likelihood.

With data available from 128 manoeuvres of different size and performed under different conditions, it was also possible to approach the problem in a more statistical manner. For manoeuvres of duration longer than 50 s, it has been observed that, although the thrust and off-modulation dependency on the pressure is rather complex to model, the calibration factor is largely independent of the pressure, and should be directly used to command the next manoeuvre of this type.

For smaller manoeuvres, where the off-modulation has to be estimated separately based on predicted number of pulses, the dependency of the thrust factor on the manoeuvre duration has been characterized.

With at least eight more S/C to launch, these findings can be applied during operations, providing the FD team with additional means to perform precise manoeuvres. Furthermore, the analyses presented in this paper can be expanded with new data from the upcoming LEOPs, and the ideas developed in this context can possibly be applied to other S/C with similar RCS systems.

Acknowledgments

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Considerations

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