17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 203

The importance of high-fidelity simulator for Galileo Constellation - IRES Model improvement

Y. Di Crescenzio[a], A. Bauer[b]

[a] *Galileo Space Segment Maintenance Engineer, DLR Gfr mbH, Münchener Str. 20, 82234 Weßling, Germany,* ylenia.dicrescenzio@dlr-gfr.com
[b] *Galileo Spacecraft Operation Engineer for AOCS/EPS and TCS, DLR Gfr mbH, Münchener Str. 20, 82234 Weßling, Germany,* andre.bauer@dlr-gfr.com

Abstract

The Galileo Control Centre (GCC-D) in Oberpfaffenhofen is one of two control centres responsible of operating the Galileo constellation, managing a fleet of twenty-eight spacecraft flying at MEO altitudes and consisting of two different satellite families: IOV and FOC. A Constellation Simulator (CSIM) is part of the Galileo Ground Control Segment (GCS) and it is used to simulate all the satellites of the Galileo Constellation. As in a lot of other missions, the simulator is currently used for the validation of all the Flight Operations Procedures (FOPs) and for the training of the Flight Control Team. Despite not having any hardware in the loop, the Galileo CSIM is also used to support the investigation of any anomalies affecting the space segment and the development of recovery strategies. To make this possible there is a continuous effort from the Galileo Team to improve the fidelity of the simulator.

In particular, FOC and IOV spacecraft are equipped with an InfraRed Earth Sensor (IRES), which detects the edge between the Earth disc and deep space by scanning the Earth horizon with four infrared pyroelectric detectors. The Sun and the Moon may cross the IRES Field of View (FOV), inducing disturbances in the measurements, an effect designated “blinding”. Given the high inclination of the Galileo orbits, Earth’s Polar regions may also fall inside the IRES FOV: in particular, during in-orbit experience, it was also noticed that during the southern hemisphere winter season, the extremely low temperatures achieved may alter the local-emitted Earth infrared radiation, causing a IRES blinding.

A set of different use cases have been selected and real telemetry from the spacecraft have been used to improve the model of the Moon blinding in the simulator. A similar approach is expected to be used in order to characterize the capacity of the Polar season to blind the IRES detectors.

The presented paper describes the model of the Moon noise implemented in the simulator and how the telemetry (TM) coming from the spacecraft has been used to improve the fidelity with respect to the observed in-orbit behaviour. Furthermore, the paper will also describe how, the simulator was used in 2019 in the frame of the deployment of a new ASW for FOC spacecraft to validate new AOCS functionalities related to the automatic handling of the Polar season through the generation of ad-hoc breakpoint using the on-orbit propagator (OOP) data from the real spacecraft.

Keywords: Galileo, CSIM

Acronyms/Abbreviations

AOCS, Attitude and Orbit Control Subsystem
ASW, Avionic Software
CSIM, Constellation Simulator
FCT, Flight Control Team
FDF, Flight Dynamics Facility
FOC, Full Operational Capability
FOP, Flight Operation Procedure
FOV, Field of view
GCC-D, Galileo Control Centre Deutschland
GCS, Ground control segment
INMM, IRES N2 mathematical Model
IRES, Infra-Red Earth Sensor
IOV, In Orbit Validation
MCB, Multiple channel blinding
MEO, Medium Earth Orbit
PAC: Pitch axis crossing
OOP, On-board Orbit Propagator
SCCF, Spacecraft Constellation Control Facility
SLE, Space Link Extension
TM, Telemetry
TPF, Task Parameter File

1. Introduction

The Galileo Control Centre (GCC-D) in Oberpfaffenhofen is one of two control centres responsible of operating the Galileo constellation, managing a fleet of twenty-eight spacecraft flying at MEO altitudes and consisting of two different satellite families: IOV and FOC. A Constellation Simulator (CSIM) is part of the Galileo Ground Control Segment (GCS) and it is used to simulate all the satellites of the Galileo Constellation. CSIM consists of a set of tools that may be used for the validation of operational procedures, and training of operating staff. As such, it provides a high-fidelity simulation of the complete Galileo constellation of satellites and operational ground stations which can then be used to validate the procedures, train operators and investigate anomalies.

The functional scope of the CSIM includes the following major functionalities

- Initial validation and commissioning of the Spacecraft Constellation Control Facility (SCCF)
- Training of the Flight Control Team
- Validating flight control procedures for both LEOP and routine operations
- Validating flight control procedures for use in anomaly situations
- Validating on-board software patch procedures prior to upload to the spacecraft

2. CSIM Architecture

CSIM is designed to emulate the behaviour and end-to-end command and control of the Galileo spacecraft by interfacing directly with other elements of the Galileo Ground Control Segment. To this end, it is comprised of three principal functional components:

- Simulator Environment: a tailored version of the ESA/ESOC SIMSAT simulation runtime environment which provides the human-machine-interface and controls the other components.
- Ground Station Simulator: providing the modelling and simulation of the ground station telemetry and telecommanding equipment as well as a Space Link Extension (SLE) interface to the Galileo SCCF.
- Satellite Simulator: a complete simulation environment of the Galileo Satellites that receives and responds to all telecommands and generates housekeeping telemetry. All spacecraft subsystems are modelled (Satellite Models) as well as the spacecraft environment, orbit, dynamics, and thermal and electrical behaviour (Behavioural Models).

The Satellite Simulator component executes an image of the real spacecraft on-board software (ASW) in an emulated environment of the satellite Processor Module (PM) without any changes. CSIM provides all the necessary interfaces that the ASW expects, including the appropriate dynamic behaviour and models of all the satellite subsystems which react to and respond to the ASW in the same way as the real satellite subsystems.

2.1 CSIM AOCS Sensor Models

CSIM Satellite Simulator component contains an AOCS model which implements mathematical models for each of the AOCS sensors based on the positions and dynamics of the satellite, Moon, Sun, and Earth (where required) as calculated by the Behavioural Models. In this way, relevant sensor data is provided to the ASW in the same way as the real spacecraft, allowing the on-board AOCS software to run with realistic inputs. The AOCS sensor models include telecommand interfaces to respond to requests by the AOCS software or operator inputs (for example to switch the unit on/off or to modify the unit configuration).

2.2 Breakpoint Generation

To support the wide-ranging functional scope of CSIM, the full simulation state can be saved at any time as a state vector or 'Breakpoint'. In addition, several scripts are implemented to allow the generation of breakpoints for user defined conditions (for example particular orbital conditions). In this way, a simulation can be created/saved/started with both the simulated spacecraft and the simulated environment in the desired state. Breakpoints are generated from scratch sequentially by specifying the environmental conditions, running the ASW through its boot sequence, updating the relevant on-board variables and setting the desired spacecraft modes and configuration (in a similar manner to normal operations).

For many operational scenarios, it is necessary to simulate the spacecraft in specific orbital conditions. This can be achieved on CSIM by generating a breakpoint using the same data required by the spacecraft On-Orbit-Propagator (OOP). The breakpoint is generated using the Keplerian orbital elements of the satellite, Sun, Moon, and Earth for both the CSIM Behaviour Models as well as the States module of the AOCS software running on the simulated spacecraft. The Galileo Ground Control Segment includes a Flight Dynamics Facility (FDF) which, amongst many other functions, is responsible for the generation of Task Parameter Files (TPFs) containing the orbital elements for upload to the spacecraft during real operations. These same TPFs can be used by CSIM to generate a breakpoint at any given epoch with matching orbital conditions, allowing the simulation of any scenario defined by the Flight Control or Flight Dynamics teams.

3. Usage of CSIM for the Functional Validation of New AOCS Functionalities

Despite there not being any hardware in the loop, the Galileo CSIM is also used to support the investigation of anomalies affecting the space segment, develop recovery strategies and to perform functional validation of new ASW functionalities**.** In particular, in 2019 an updated version of the avionics software (ASW v2.1) was developed by the manufacturers for FOC spacecraft [1].

3.1 Introduction of the AOCS Subsystem and the Galileo InfraRed Earth Sensor (IRES)

Galileo's main purpose is the dissemination of navigation signals to the ground; this is achieved with an Earth pointing attitude that keeps the navigation antenna continuously pointing towards Nadir.

In order to accomplish this mission requirement, the AOCS subsystem is equipped with two InfraRed Earth Sensors (IRES) N2 used to calculate roll and pitch. The Earth sensor measurements are based on the cold-hot transition detection on 4 pyro-detectors sensitive to the infrared radiation emitted by Earth. These units are traditionally used in geostationary spacecraft.

Due to the Galileo MEO orbit, the Sun or the Moon may enter the sensor's field of view and the infrared radiation from these bodies may blur the Earth disk border resulting in disturbed data output from the IRES. This effect is known as "channel blinding", indicating the fact that the concerned channel cannot provide reliable measurements if affected by a "blinding body". In order to avoid a channel blinding, the channel itself needs to be "inhibited": when a channel is inhibited, its raw data output is not taken into consideration by the IRES logic to compute Roll and Pitch measurements. The Earth sensor provides its best accuracy when all the four channels are not inhibited (or "active") but can also satisfy the pointing requirements of the mission using only three active (not inhibited) channels.

Channel inhibition might happen autonomously via the AOCS SW, if the On-Orbit-Propagator predicts that a blinding body is crossing the so-called "blinding region" of the channels. This is a subset of the Earth Sensor channel FOV, and it is different in size for each of the possible blinding bodies (see Fig.1).

Experience shows that, under certain conditions, the Earth Arctic and Antarctica regions have a significant impact too. During their coldest season, if the Polar Regions enter the IRES field of view, the distinction between the Earth IR radiation and deep space is not so sharp. This again results in disturbed data output and imprecise measurements.

These problems can also be compounded. In fact, it is possible that two disturbances enter the IRES field of view concurrently e.g. Antarctica and the Moon, known as a Multiple Channel Blinding (MCB). It can also happen that the Antarctic region may inject noise in two detectors of the IRES whilst crossing the IRES pitch axis, known as a Pitch Axis Crossing (PAC). The IRES is not designed to determine the Earth position with fewer than three detectors out of four.

The new ASW deployed for the FOC constellation has been improved in order to handle automatically multiple channel disturbances in the earth sensor by disregarding completely the information that comes from the IRES. During PAC and MCB the three-axis Gyro is used to calculate roll and pitch

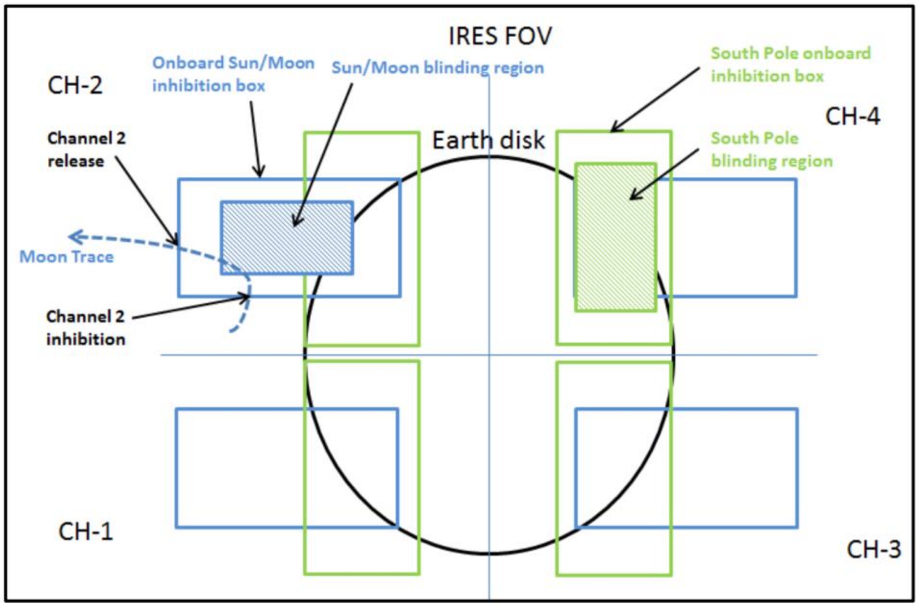

Fig. 1: IRES FoV, blinding region, inhibition box and trace [2]

3.2 Functional Validation of the new ASW Functionalities using CSIM

In the new ASW, in case the AOCS SW detects that more than one channel is blinded by one of the previously mentioned celestial bodies, it will switch the gyro ON, and modify the control law used on-board to “Gyro_Only” so that the IRES measurements will be completely out of the control loop and the spacecraft will fly relying on the gyro propagation for the estimation of roll and pitch until only one channel is blinded. Additionally, to increase the robustness of the ASW with respect to the MCB issue a hysteresis has been implemented. That means that the channel will be blinded when the body enters in the inhibition box, but it will be released only when the body leaves the inhibition box plus the hysteresis (usually 1 degree).

As mentioned above “Pitch Axis Crossings” (PACs) refer to the South Pole or North Pole crossing the zero-roll coordinate (e.g., the “pitch” axis) in any negative-to-positive or positive-to-negative direction. As can be seen in Fig.1 the inhibition boxes of the South Pole of two different channel are really close on the zero-roll axis. Due to this, during the time the South Pole take traversing that small gap, it might still “blind” the adjacent channel. In order to handle this situation a new function has been implemented on the AOCS SW in ASW 2.1. This function manages this channel swap by forcing the blinding status of the old channel to false, then only the new channel will be blinded and the AOCS SW will swap the inhibition to the new channel. The SW decides which channel has to be released using a counter system. During the handling of the PAC events the SW will rely on the gyro propagation for the estimation of roll and pitch as for the MCB.

To validate these new functionalities, it was necessary to generate ad-hoc breakpoints in CSIM based on the on-board orbit propagator (OOP) of the real spacecraft. The OOP contains the information of the Keplerian elements and the position of the Sun, satellite and Moon in Earth-Centred Inertial reference frame.

Flight Dynamics Engineers were requested by the Spacecraft Operation Engineers to provide a list of scenarios worth testing with the corresponding OOP to be used for a simulation campaign. Ten different scenarios were identified, and they covered all the possible combinations of PAC and MCB, including the possible overlap of these two cases. Additionally, two specific test cases applicable for the L3 spacecraft have been tested in order to see the behaviour of the SW also on those spacecraft that have an elliptical orbit due to a failure of the Soyuz launcher [3] [4].

In particular, the following breakpoints were generated in CSIM starting using the OOP of the real spacecraft:

- Nominal PAC

- Nominal MCB

- Fake PAC – South Pole visible in the IRES FoV right before it crosses the pitch axis.

- Fake PAC – South Pole visible in the IRES FoV right after it crosses the pitch axis

- Critical PAC – no visibility at PAC start - the South Pole is only visible right before crossing the Pitch axes

- Critical PAC – Overlap PAC - MCB (e.g. PAC start before a MCB caused by the Moon and the South Poles)

- Critical PAC – Overlap MCB – PAC

- Critical PAC – Overlap PAC – MCB with the Moon on the third channels.

- Critical PAC - PAC immediately after FSS AOS (two test cases). The objective of this case was to test a PAC which starts immediately after the end of the collinearity. In particular, the fine sun sensor is used for the calculation of the yaw angle. When the spacecraft is in collinearity the Sun is not in the FSS field of view and the gyro is also used for the propagation of the yaw angle. If the difference between both events is smaller than 20 seconds the gyro will be switched off after the Sun enters again in the FSS field of view, and the gyro won’t be able to be switched back on until later than nominal for the handling of the PAC. This delay is due to the overlap of the gyro switch-off switch-on sequence and the fact that the first one needs to be over before the second one can start. If the difference between both events is smaller than 1 second both gyro commands (off and on again) might collide on the same AOCS cycle.

- L3 specific test cases - MCB due to the Moon and Sun in different channel to test how the software deals with big yaw corrections as the one at the end of the modified yaw flip events. The Sun is not expected to enter in the Sun FoV in the nominal Galileo orbit and this can only happen on L3 spacecraft, due to their elliptical orbit, in the so-called Modified yaw flip seasons. The yaw steering law is a function of the AOCS Software and it fulfils the requirement to keep the solar panel axis perpendicular to the Sun to ensure the best illumination possible and to keep the clock panel always pointing towards deep space. The yaw steering law has a discontinuity (180° jump) when the sun is in the satellite orbit plane (sun elevation is zero) and the satellite is at the plane of the ecliptic. A modified yaw steering law is applied when the angle between the satellite orbit and the sun vector (beta angle) is within +/- 4.1° and the angle between satellite and sun-earth-satellite collinearity direction is smaller than 10°. In this way the satellite can follow, with its actuators, a realistic guidance law without discontinuity. The modified yaw steering law it is used twice per orbit during the low Beta angle season and the software switches autonomously between the two functions. Anyway, as when this condition is verified the spacecraft is also in collinearity, and therefore, the sun is not in the fine sun sensor field of view an error may be visible in the controller at the end of the event once the sun is back on the fine sun sensors field of view. Due to this error in the controller the Sun can enter in the blinding area of the IRES and causes a MCB.

- L3 specific test cases – fast PAC due to the yaw correction at the end of the modified yaw flip events

Thanks to this extensive simulation campaign it was possible to see how the ASW would have behaved in the real spacecraft even in very peculiar orbital/geometrical conditions. The overall validation of the new functionalities was considered successful.

As an outcome of the validation campaign, it was also possible to identify that in some specific cases few seconds of delays may be experienced in the switch-on of the gyro. In this time frame the perturbations visible in the IRES may enters in the AOCS SW, but the extensive validation confirmed that there are no risks on inhibiting two channels at the same time and that there are no risks in having an AOCS reconfiguration triggered by the on-board FDIR mechanism.

4. IRES Model Improvement Using In-Flight Telemetry

In the frame of the extensive simulation, it was identified that in CSIM it was not always possible to see the perturbation induced by the celestial body (such as the Moon) in the roll and pitch measurement when the channel is not inhibited. In particular, when the Moon is inside the blinding boxes and the corresponding channel is not inhibited, as for example may happen during the handling of the MCB, it is expected to see the following signature (ref. fig.2) in the roll and pitch measurements.

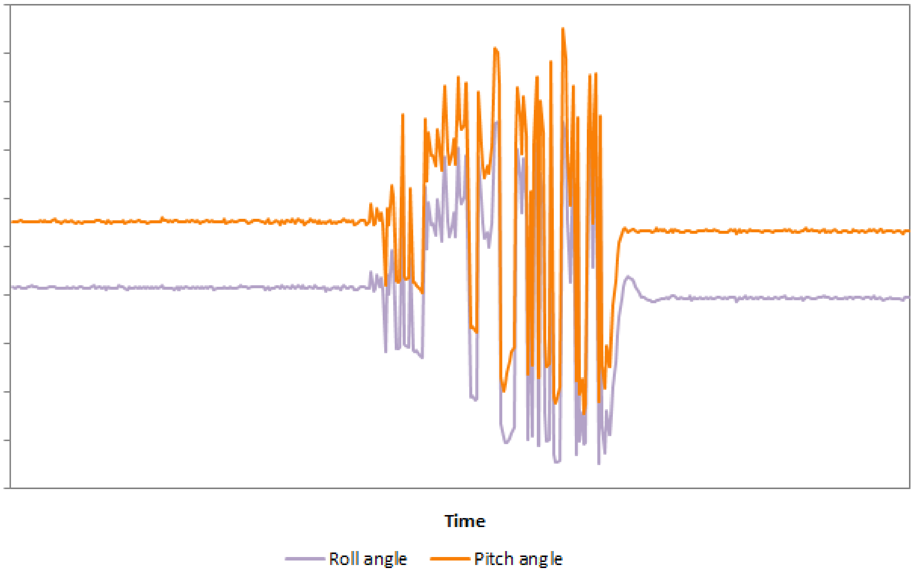

Fig. 2: Effect of a blinding body on the IRES measurements [2]

If the IRES is used by the AOCS SW for the determination of the roll and pitch, then the same signature is expected to be visible in the controller deviations. During the handling of the MCB and PAC, as the AOCS SW relies only on the gyro propagation, then there is no perturbation visible in the controller.

4.1 IRES Model in CSIM

The IRES N2 mathematical Model (INMM) implemented in CSIM considers a set of input and output parameters.

The input parameters of the INMM are:

- Sensor telecommands and commands (e.g. sensor channel inhibition status, sensor scanning Mode, On/off status)
- The Earth positions (in term of orbit altitude pitch and roll angular positions) with respect to the satellite/sensor position
- The Moon position (in term of pitch and roll angular positions) with respect to the satellite/sensor position
- The Sun position (in term of pitch and roll angular positions) with respect to the satellite/sensor position
- Environmental temperature of the sensor/satellite

The output parameters of the INMM are:

- Pitch and roll data (value of the pitch and roll measured by the IRES considering the geometrical aspects of the Earth model)
- Earth presence flag
- On/off data
- Thermistors´ resistance
- Angular noise (e.g. the noise effect is calculated as noise equivalent angle that affect the measurement considering the sensor temperature and the mean value of a gaussian distribution)
- Sensor power consumption

- Sensor housekeeping data

In the Earth Model, the dimension of the Earth is calculated as reported in the following equation (1):

$$R_e = \frac{180}{\pi} * arcsin\left(\frac{Mean\ Earth\ Radius\ in\ 14{-}16\ \mu m}{Mean\ Earth\ Radius + Satellite\ quite}\right) \qquad (1)$$

4.2 Moon Input inside the IRES Model in CSIM

The possible effect due to Moon or Sun presence in the FoV of the sensor are taken into account on the chord calculation (e.g. distance between the IRES detector and the Earth body) of each channel and on the angular noise budget.

The dimension of the Moon in the IRES FoV has been assumed to be equal to 0.25° considering a spacecraft orbit of 23222 km. The contribution of the Moon on the chord calculation (e.g. chord error) is modelled considering the distance *d* between the body and the detector and the altitude *h* with respect to the 0° line as can be seen in the following qualitative figure (fig.3).

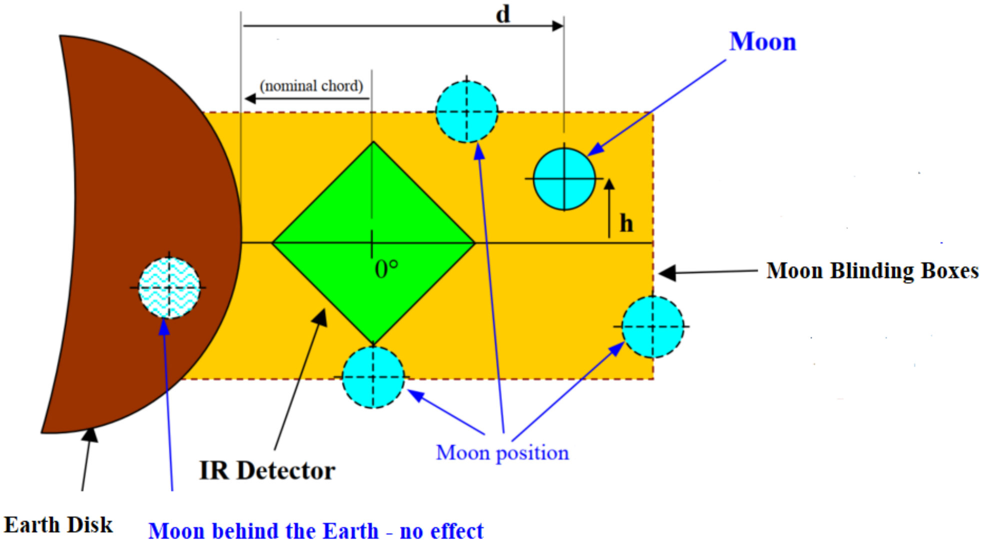

Fig. 3: Qualitative representation of the Moon inside the Moon Blinding area of the IRES

In particular, the Moon Presence parameters is a flag that indicate the presence or absence of the Moon in the FoV of the sensor. If the Moon Presence word is 0 the position of the Moon is not relevant for the IRES model either because it is not present or because it is behind the Earth disk. If the Moon presence flags is 1 then the anugular position of the body becomes relevant and the possible effect of the Moon on the chord is evaluated considering the relative position of the Moon with each detector scanning path.

4.3 Improvement of the Moon Noise Model using in-flight TM

Every year, from June to October, during the so-called Antarctica seasons [2] the redundant IRES on some Spacecraft is selected in troubleshooting (this means that the unit is ON but not used by the AOCS SW to control the attitude and therefore there is no channel inhibition). A limited number of occurrences, in which the IRES is only blinded by the Moon, can be selected in this particular time frame in order to see the impact of the Moon on the raw data of the Earth sensors.

In order to identify a set of relevant use cases, a screening of the available TM during one Antarctica season was performed.

Four Moon blinding events that could be used as a starting point of the characterization of the model of the noise generated by the Moon when it is inside the IRES FoV were identified. In particular the four test cases were selected with a different signature of the noise in the raw data telemetries in order to allow a better characterization of the noise.

- Test case 1: Decreasing noise visible in the IRES raw data during the Moon blinding due to the path of the Moon inside the IRES FoV

- Test case 2: Costant noise visible in the IRES raw data for more than 20 minutes

- Test case 3: No noise visible on the IRES raw data

- Test case 4: Long Moon blinding with different evolution visible in the TM

The proposed approach had some intrensic limitation, for which some work-arounds had to be developed:

- The position of the Moon in the ECI frame could not be taken from the telemetry as these data are not dumped as part of the Routine contact. As a work-around, the Flight Dynamics Engineers were requested to plot the Moon position during the relavent epoch times.
- Only the IRES-B raw data were available as the unit in troubleshooting is not considered by the AOCS SW. As work-around a script that converted the raw data into pitch and roll information was created.
- The result will only be fully representative of the error visible when no channel is inhibited; In particular, experience shows that when 1 channel is inhibited the error injected in Pitch and roll is higher with respect to what happens when all channels are used and this is expected due to the way the chord measurement is used to calculate the roll and pitch output.

The OOP had to be generated with an epoch time at least 2 hours before the Moon blinding events in order to create ad-hoc breakpoints in CSIM using the same orbital/geometrical conditions of the real spacecraft. Additionally, for each event, the Flight Dynamics Engineer were requested to plot the path of the Moon inside the IRES. The data from the real spacecraft were used in order to compare the magnitude of the error visible in the CSIM with the one experienced by the real IRES and fine-tune the noise model implemented in the simulator.

The in-orbit data has been used in order to improve the model of the Moon blinding and a script to simulate this effect has been inserted into the new version of the GCS infrastructure.

The validation of the improved model has been done in two phases. In particular, at the beginning the four test cases used for the fine-tuning of the blinding mode were used to see if the function was behaving as expected and then, a second validation was executed by using a different set of use cases taken from the real TM in order to reproduce real scenario experienced by the spacecraft.

4.4 Possibility to Develop a Model for the Antarctica Perturbation Using In-Flight TM

The noise injected from the Polar bodies in the roll and pitch measurement of the IRES is not considered in the actual version of the INMM. This is because the impact of the Antarctica and Artic regions on the IRES was only discovered during the preliminary phases of Galileo Operations [5]. The idea to use the in-flight TM available in GCC-D in order to build up a blinding model of the Polar region that could be implemented in the new version of the simulator is currently under investigation.

Similarly, to what was done for the improvement of the Moon blinding Model, a set of test cases when the IRES is blinded only by the Polar region and the unit is selected for troubleshooting can be identified in order to start with a model for the noise injected in the chord measurements. The main difference between the Moon blinding effect and the Antarctica/Artic effect it is that the last one is a high seasonal influence.

5. Conclusion

The Galileo CSIM is widely used not only for FOP validation but also for functional validation of the ASW and for anomaly investigation and it has always demonstrated a high level of reliability, especially in reproducing spacecraft software issues. Thanks to the possibility to inject failure scenarios inside CSIM, it is also used to reproduce in-flight anomalous behaviour and develop recovery strategies or workarounds.

For this reason, the Galileo Flight Control Team is always working to identify room for improvement on the fidelity of the simulator.

Acknowledgements

A special thanks to all the colleagues from DLR GfR, Spaceopal, EUSPA for the continuous support provided in the management of the Galileo Constellation.

In 2016 EUSPA awarded the GSOp contract to Spaceopal. DLR GfR mbH is the German company that has been contracted by Spaceopal to operate Galileo constellation in the frame of the GSOp contract

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