ESA's JUICE End-to-End Orbit Determination Simulation to Calibrate On-Board Accelerometer

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The purpose of this work is to determine an in-flight calibration procedure for JUICE's on-board accelerometer. Its measurements will be combined with the range and range-rate observables by 3GM gravity experiment to estimate the Callisto's gravity field, during its eleven flybys. The 3GM experiment needs a precise orbit determination to fulfill its scientific goals, but propellant sloshing would affect this precision. In order to improve the physical model implemented in the OD software, it is necessary to measure these disturbances using an accelerometer. The accelerometer's measurement error model is composed of a random noise, a bias, a bias rate and a scale factor. This investigation shows that the scale factor does not affect the estimation of Callisto's spherical harmonic coefficients in a significant way. On the other hand, the estimation of bias and bias rate parameters is a difficult process because of their strong correlation. This work demonstrates that the 3GM scientific goals can be achieved, but high caution on JUICE's accelerometer design is necessary. In order to overcome these difficulties, an in-flight calibration strategy is proposed.

I. Nomenclature

$3GM$	=	Gravity and Geophysics of Jupiter and the Galilean Moon
$AWGN$	=	Additive White Gaussian Noise
COM	=	Center Of Mass
ISA	=	Italian Spring Accelerometer
OD	=	Orbit Determination

II. Introduction

JUICE- JUpiter ICy moons Explorer - is an ESA L-class mission devoted to study the Jovian system. Following a launch with the Ariane 5, JUICE will use an Earth-Venus-Earth-Earth gravity assist strategy to reach Jupiter. The nominal launch date is in September 2022, with an arrival at Jupiter in July 2030 [1].

After insertion into the Jupiter system, JUICE will use multiple gravity assists of the Galilean satellites to shape a comprehensive orbital tour over 3.5 years. After reducing the orbit period with Ganymede flybys, this tour will implement two close Europa flybys, then a series of Callisto flybys to reach an inclination of 22° with respect to the equatorial plane of Jupiter. A dedicated series of Callisto and then Ganymede gravity assists will make it possible to approach Ganymede at a low velocity. During the tour, Jupiter's magnetosphere and atmosphere will be continuously monitored. The mission will culminate in a dedicated, eight-month tour around Ganymede, the first time any moon beyond our own will be orbited by a spacecraft.

The present work is realized in the context of the JUICE's 3GM gravity experiment. 3GM (Gravity and Geophysics of Jupiter and the Galilean Moons) addresses JUICE scientific objectives pertaining to gravity, geophysics and atmospheric science through radio occultations. 3GM on JUICE will improve our understanding of the origin, evolution and structure of the Galilean icy satellites through highly precise spacecraft tracking. By itself and in combination with altimetry and other measurements, radio tracking will provide information on the static gravity fields of Ganymede, Callisto and

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Europa, on the rotational state and tidal deformation of Ganymede and Callisto, on the presence of density variations within the ice shell of Ganymede, and on dissipation within the Jovian interior. Specifically, 3GM will:

- Determine the gravity field of Ganymede to degree and order 15 or higher, enabling the identification of density anomalies within the body. This will be the first time that the high degree gravity field of a large, mostly solid icy body will be characterized.
- Determine the nature and extent of the likely internal ocean within Ganymede and the thickness of the overlying ice shell through time-dependence of gravity at degree 2 arising from the eccentricity tide.
- Determine the degree 2 and 3 gravity field of Callisto with a precision sufficient to assess the extent of differentiation within that body and extent of hydrostatic equilibrium, thus removing the current ambiguity in the interpretation of Galileo results.
- Determine the presence or absence of an internal ocean within Callisto by measuring the time dependence of gravity at degree 2 arising from the eccentricity tide.
- Independently determine the J_2 and C_{22} of Europa, further constraining the moment of inertia and extent of hydrostaticity for that body.
- Contribute to the improvement of the ephemerides of the Solar system and the Jovian satellites and carry out tests of laws of gravity.

All these goals require a precise orbit determination that justifies the presence of the on-board accelerometer, to compensate for non-gravitational accelerations. In fact, attitude maneuvers to point towards Callisto's surface during its flybys will excite sloshing vibrations, that deteriorate the radio-tracking measurements by roughly a factor of 100 (see Fig. 3), rendering the radio observables useless. Gravity measurements will rely mainly on the Ka/Ka link enabled by the KaT (Ka band Translator/Transponder) [2]. This radio link is highly immune to interplanetary plasma noise over a broad range of solar elongation angles. The TT&C, X/X and X/Ka radio links may be used together with the Ka/Ka link to reduce or even cancel plasma noise and to separate neutral and charged particle effects.

In Sec. III, we discuss the Orbit Determination (OD) process with particular attention to the accelerometer implementation; in Sec. IV, we explain how the propellants sloshing has been modeled; in Sec. V, we present the simulation setup and results; Sec. VI contains the conclusion and the future developments.

III. Orbit Determination

When studying the evolution of a dynamical system, its description in terms of mathematical model is needed. This model is affected by a certain degree of uncertainty on the parameters it contains. By comparison between the mathematical model results and the physical world observations the model parameters can be estimated, and so their knowledge is improved.

In the Orbit Determination problem, the dynamical system is the set of differential equations needed to describe the spacecraft motion; the parameters under estimation are collectively referred as the state. Usually, the Navigation Team provides the position and velocity of the spacecraft at certain epochs with a certain accuracy; this information is used to initialize the dynamical model and propagate it. When comparing the propagated spacecraft states with observations, a discrepancy occurs which is a symptom of errors in the model parameters. The model parameters (GMs, gravity coefficients, reference frame parameters, optical coefficients of the spacecraft materials. . .) can be included in the estimation to minimize these differences.

The 3GM radio science experiment uses the radio observables (e.g. 2-way Doppler and range) as measurements to process in the orbit determination. The observables collected at the ground stations (observed observables) are compared with the predictions (computed observables) derived from the model propagation. The discrepancies (residuals) between the observed and computed observables, due to model inaccuracy, are minimized by correcting the initial spacecraft state and other model parameters in a least squares fit. All this process is used to reach a better knowledge of the Solar system parameters.

The well-known weighted least squares correction with a priori information [3] is given by :

$$\delta\hat{\mathbf{x}} = (H^T W H + \bar{W})^{-1}(H^T W \delta\hat{\mathbf{y}} + \bar{W}\delta\bar{\mathbf{x}}) \tag{1}$$

where $\mathbf{x}$ is the unknown n-dimensional vector of solved-for parameters (differential corrections). The matrix H, called mapping matrix, contains the partial derivatives of the observable quantities with respect to the solve-for parameters, W is a weight matrix and $\delta\bar{\mathbf{x}}$ and $\bar{W}$ represent respectively the a priori estimate and covariance matrix of $\mathbf{x}$. The final estimate is obtained through an iterative procedure based on Eq. (1). The inverse of the information matrix constitutes the covariance matrix of the vector $\mathbf{x}$.

During the eleven Callisto flybys, 3GM will use Doppler (range-rate) and range measurements to determine the spacecraft's trajectory. Since the mission has yet to be launched, observed observables have been simulated. These measurements are expected to have an Allan Deviation (ADEV, frequency stability) of 10^{-14} at a $1000s$ integration time. This level of noise, assumed to be white, means that the velocity of the spacecraft will be measured with an accuracy of $3\mu m/s$ and the position with $20cm$ at $300s$ along the line-of-sight. The Allan deviation and the range-rate are linked by the following equation:

$$ADEV = \frac{\Delta f}{f} = \frac{\dot{\rho}}{c} = 10^{-14} @ 1000s \tag{2}$$

Where Δf represents the variation of the received frequency, f is the downlink frequency and $\dot{\rho}$ range rate.

From now on, we will use the term simulation to refer to the process of generating observed observables and the term estimation to refer to the OD process.

A. OD with accelerometer

JUICE will be the second interplanetary mission, after BepiColombo, using accelerometer's readings in the OD process.

The OD process is typically performed by integrating the trajectory of the spacecraft Center Of Mass (COM). As a consequence of the large propellant sloshing on JUICE, the COM moves randomly around the structure. This unpredictable movement makes it impossible to relate the Doppler measurements, depending on the antenna phase center position, to the COM with the required precision. In fact, it would cause a Doppler noise of about 100 times the 3GM sensitivity. It can be demonstrated that the usage of an accelerometer, whose vertex is fixed with respect to the structure, avoids the necessity of COM position knowledge. The equation of motion of the COM, using the accelerometer measurements is given by:

$$\ddot{\mathbf{r}} = \nabla U(\mathbf{r}) + \mathbf{a}_{ACC} - \ddot{\mathbf{r}}_{ACC}^{SC} - \mathbf{a}_{ROT} + \mathbf{a}_{GG} \tag{3}$$

Where $\ddot{\mathbf{r}}$ is the acceleration of the COM, the gravitational forces are expressed as the gradient of a potential $U(r)$, $\mathbf{a}_{ACC}$ constitutes the accelerometer's readings, $\mathbf{a}_{ROT}$ is a term that contains the acceleration due to the rotation of the accelerometer reference point around the spacecraft COM, and $\mathbf{a}_{GG}$ is the acceleration due to gravity gradient. This formulation still requires the knowledge of the COM position with respect to the antenna phase center. As stated before, this position is not well known and changes randomly.

The main advantage of our approach is to be independent from the knowledge of the COM. Writing the equation of motion of the accelerometer as:

$$\ddot{\mathbf{r}}_{ACC} = \nabla U(\mathbf{r}_{ACC}) + \mathbf{a}_{ACC} \tag{4}$$

waives the need for the knowledge of the COM. The use of an accelerometer allows the integration of the accelerometer vertex trajectory, instead of the COM trajectory. The vector from the vertex to the antenna phase center is known since both are fixed in the structure.

B. Filters

The present study considers eleven Callisto flybys. The entire trajectory has been divided into eleven 48-hours arcs centered around the closest approach to simulate the real mission tracking setup [2]. When processing time-discontinuous arcs, two different algorithms are viable: batch sequential algorithm (Fig. 1a) and multi-arc algorithm (Fig. 1b).

The main difference between the two algorithms is the way they deal with the arcs. In the first case the OD process is performed over each arc. Once the process has reached convergence, the Callisto's gravity field covariance matrix is passed as a priori covariance matrix to the following arc.

In the multi-arc strategy all arcs are processed in parallel and then the filter is executed and iterated on the entire batch of data simultaneously. This allows to parallelize the trajectory integration, thus drastically reducing the computation time.

Since the results of this investigation are of vital importance for the 3GM success, both techniques have been used to validate the results. These two approaches are different realizations of a minimum variance estimator, therefore, we expect to reach the same conclusions.

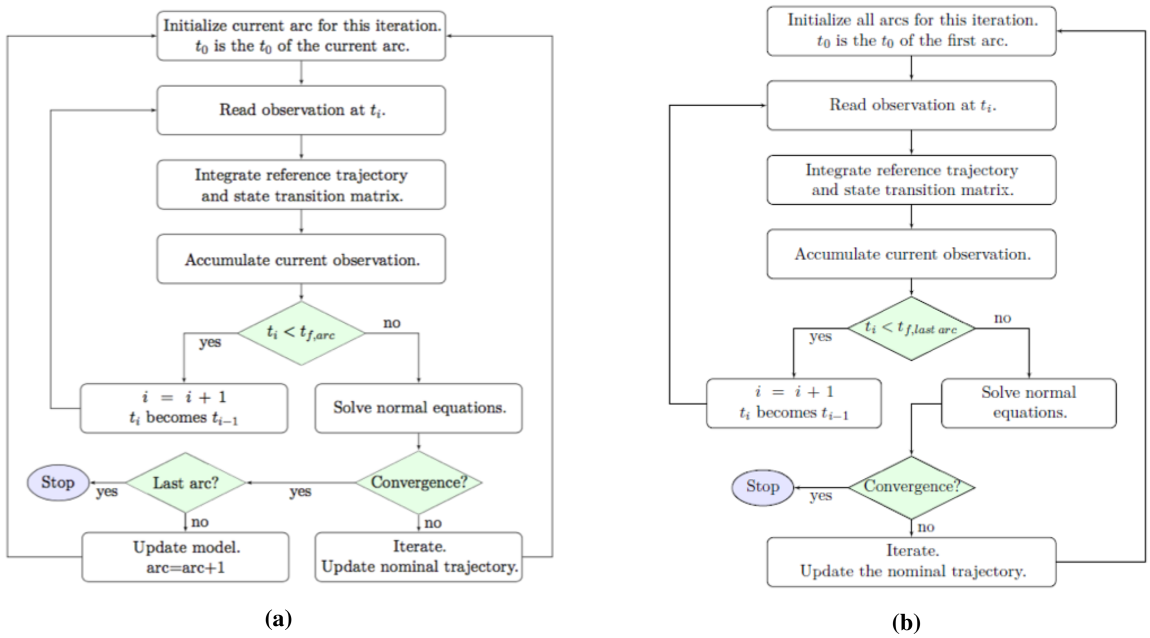


Figure 1 Algorithm flowcharts: (a) Batch-Sequential filter and (b) Multi-Arc filter

IV. Sloshing

Propellant sloshing displacements from the initial equilibrium position of the two membrane tanks MMH and MON3 have been simulated with a realistic Computational Fluid Dynamics (CFD) model. The simulation was performed with the average amount of propellant that the tanks will store during the Jovian satellites flybys. It has a total mass of 1 ton: 380kg in the MMH and 620kg in the MON3. The data provided by the simulation are shown in the following Figs. 2a, 2b, 2c and 2d.

The simulation covers a time span of approximately 15000s that corresponds to the time the spacecraft will spend in the Callisto's sphere of influence. The data have been centered at the closest approach where the highest disturbances occur. The range of frequencies over which the sloshing acts ($10^{-4} - 10^{-1} Hz$) is the same as for the gravitational spherical harmonics' induced accelerations, making it impossible to isolate sloshing disturbances by direct filtering. The accelerometer solves this problem by providing these values to the physical model, though introducing an error that must be considered to evaluate its impact on the estimation. Fig. 3 compares the 3GM requirements with propellant sloshing and Italian Spring Accelerometer (ISA) requirements *. It clarifies the usefulness of the ISA readings: the propellants sloshing (cyan line) is a disturbance much higher than the 3GM Medium Gain Antenna (MGA) and High Gain Antenna (HGA) requirements, while the accelerometer noise (red line) is below the requirement level. The purpose of ISA, thus, is to remove the sloshing disturbances without introducing a significant source of error. In the following Sec. V, we investigate this aspect and prove it through simulations of Callisto flybys.

V. Numerical Simulations

The dynamical model takes into account the gravity fields of all the planets of the Solar system and the Jovian moons. Gravitational parameters values as well as orbits are taken from the JPL ephemerides DE430 [4] while ground station locations, reference systems definitions and the JUICE CReMA v3.2 trajectory are taken from the ESA COSMOS kernel repository [5]. The physical model comprehends relativity effects, solar radiation pressure induced-accelerations and polynomial interpolated accelerations to model the sloshing. The tracking data have been simulated considering three Ka-band capable ESTRACK stations: New Norcia, Cebreros and Malargue (DSA 1, DSA 2, DSA 3 respectively).

The spacecraft structure has been modeled as a parallelepiped of dimension 4.0x2.2x3.9m with a bus dry mass equal to 2000kg. The two solar panels have been modeled as two identical panels with an overall area of $100m^2$ and mass equal to 180kg. The most recent data for Callisto's gravity field found in the literature [6] are shown in Table 1.

* Technical note: 3GM Team, *3GM requirements for an onboard accelerometer*, JUI-3GM-TN-ACC-001, 2016

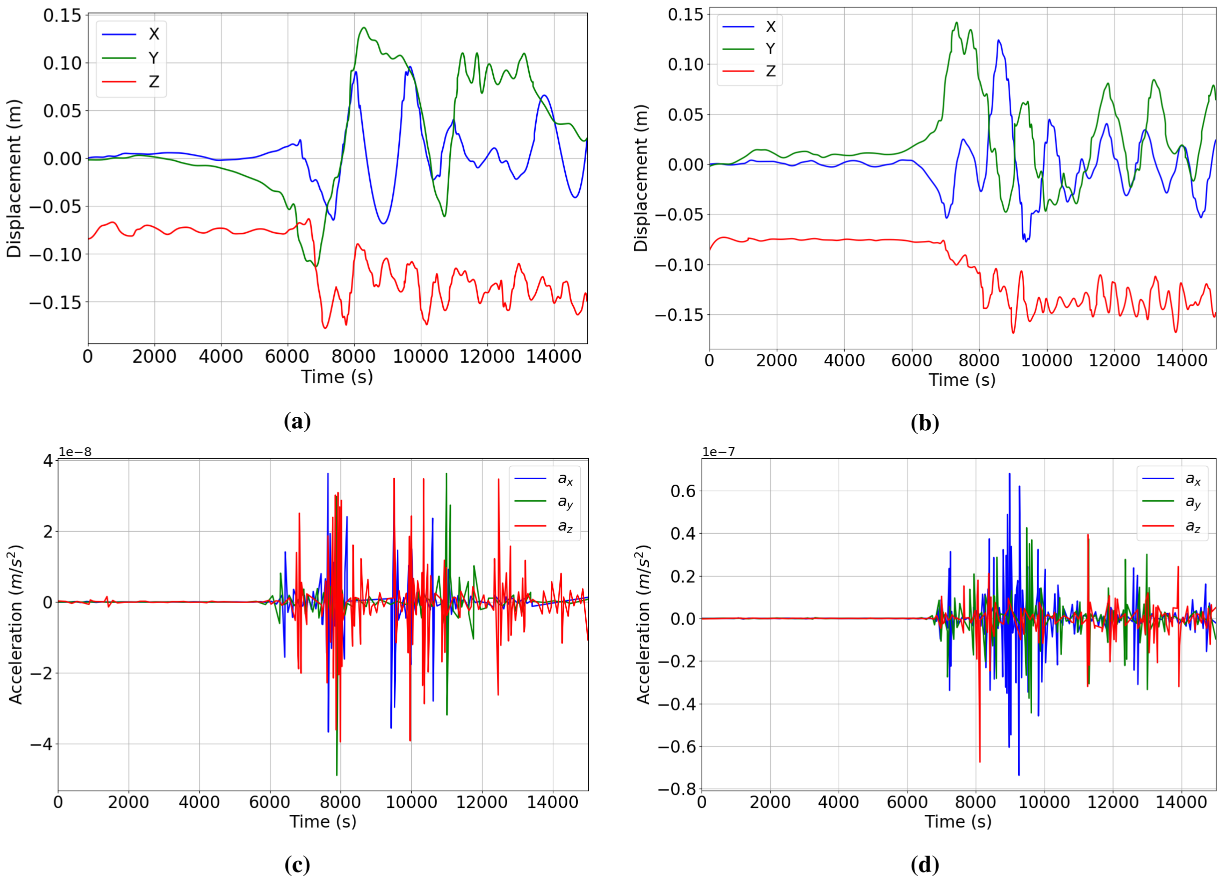


Figure 2 Sloshing simulation results: (a) Propellant COM displacement in the MON3 tank, (b) Propellant COM displacement in the MMH tank, (c) Propellant COM induced acceleration in the MON3 tank and (d) Propellant COM induced acceleration in the MMH tank.

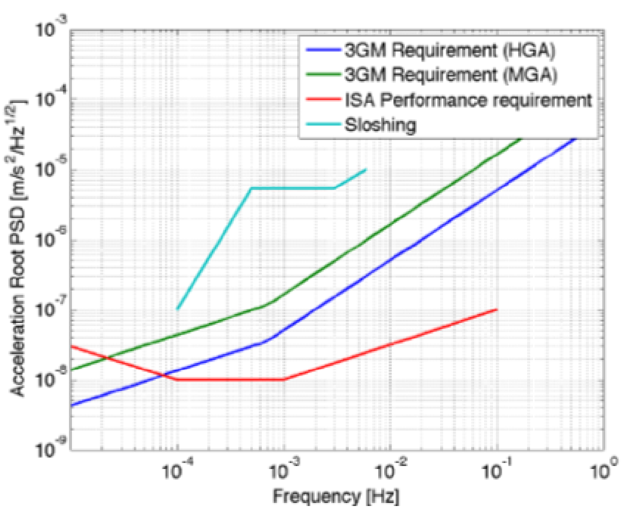


Figure 3 ISA noise requirements compared to 3GM requirements on the High Gain Antenna (HGA) and Medium Gain Antenna (MGA). The cyan line shows the Amplitude Spectral Density of the sloshing-induced accelerations.

Table 1 Callisto's unnormalized gravity coefficients, from [6]

Coefficient	J_2	C_{21}	S_{21}	C_{22}	S_{22}
Value	$3.27 \cdot 10^{-5}$	0.0	0.0	$1.02 \cdot 10^{-5}$	$-1.1 \cdot 10^{-6}$
Uncertainty	$8 \cdot 10^{-7}$	$7 \cdot 10^{-7}$	$1.6 \cdot 10^{-6}$	$3 \cdot 10^{-7}$	$3 \cdot 10^{-7}$

The gravity field up to the fifth degree has been taken into account in the simulations. Normalized coefficients, higher than degree 2, have been derived from the Kaula's rule [7].

A. Accelerometer Measurement Error Model

The accelerometer's measurement error model used in this work is expressed by:

$$\mathbf{a}_{ISA} = \lambda \mathbf{a}_{ACC} + \mathbf{b}_0 + \mathbf{b}_r(t - t_0) + \boldsymbol{\epsilon}_{rand} \tag{5}$$

Where $\mathbf{a}_{ISA}$ is the total ISA reading, λ is a diagonal matrix containing the scale factors, $\mathbf{b}_0$ is the bias, $\mathbf{b}_r$ is the bias rate and $\boldsymbol{\epsilon}_{rand}$ is the random noise. The bias can be considered as a systematic error on the value of the accelerometer's readings. The bias rate introduces a constant time-shift of the bias. The scale factor induces an error on the amplitude of the accelerometer's readouts, therefore on the propellant sloshing induced accelerations.

The scale factor has been simulated as 1.2 with an a priori uncertainty of 1.0. Such a high deviation from the nominal value has been selected in order to test the convergence of the OD filters. The bias has been considered having an unconstrained value of $4.2 \cdot 10^{-11} km/s^2$. Concerning the bias rate, a null value has been considered with an a priori uncertainty of $1.0 \cdot 10^{-13} km/s^3$. The random noise ASD shows to be well below the non-gravitational accelerations magnitude, as can be seen by comparing Fig. 3 and Fig. 4.

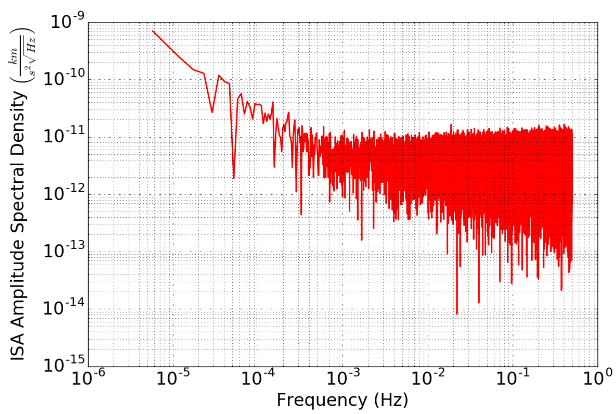


Figure 4 ISA accelerometer - $\boldsymbol{\epsilon}_{rand}$ Amplitude Spectral Density

The numerical simulations of JUICE's Callisto flybys have been run in different configurations in order to understand which is the best OD strategy to calibrate the accelerometer's parameters. Both the batch sequential and multi arc filters have been used leading to the same conclusions, thus proving the reliability of the results.

B. Setup 1: Evaluation of the sloshing effect

The first simulation has been run to evaluate the sloshing effect and the possibility to compensate it without an accelerometer. To do that, the non-gravitational perturbations have been included in the simulation of observed observables, while not taking them into account in the generation of the computed observables. When the OD process reaches convergence the only noise visible on the residuals must be the AWGN (Additive White Gaussian Noise) imposed on the observations (see Sec. III). The presence of a signature is a clear sign of a mismodelling of the physical phenomenons for which the filter cannot compensate (i.e. a least squares fit cannot be obtained).

In Fig. 5a we can clearly see a strong signature in the Doppler residuals, meaning that the experiment would fail. In fact, performing a formal uncertainty analysis of the Callisto gravity field parameters, it is clear that 3GM could not obtain the scientific results requested.

The estimation error of a solve-for parameter is the difference between the estimated and simulated value. We would expect it to be within the range of three times the formal uncertainty (σ) since the same physical model is used both in simulation and estimation. This is not the case. As an example, S_{54} has an estimation error 780 times greater than its formal uncertainty, meaning that the OD filter adjusts the gravity parameters (incorrectly) in order to fit the data. Those parameters should not be affected by an estimation error greater than 3σ because the same gravity field coefficients have been used to generate observed and computed observables. In order to attain part of the 3GM gravity scientific goals, an accelerometer is needed. In the next Sec. V.C the results of a simulation considering an accelerometer mounted on-board is presented.

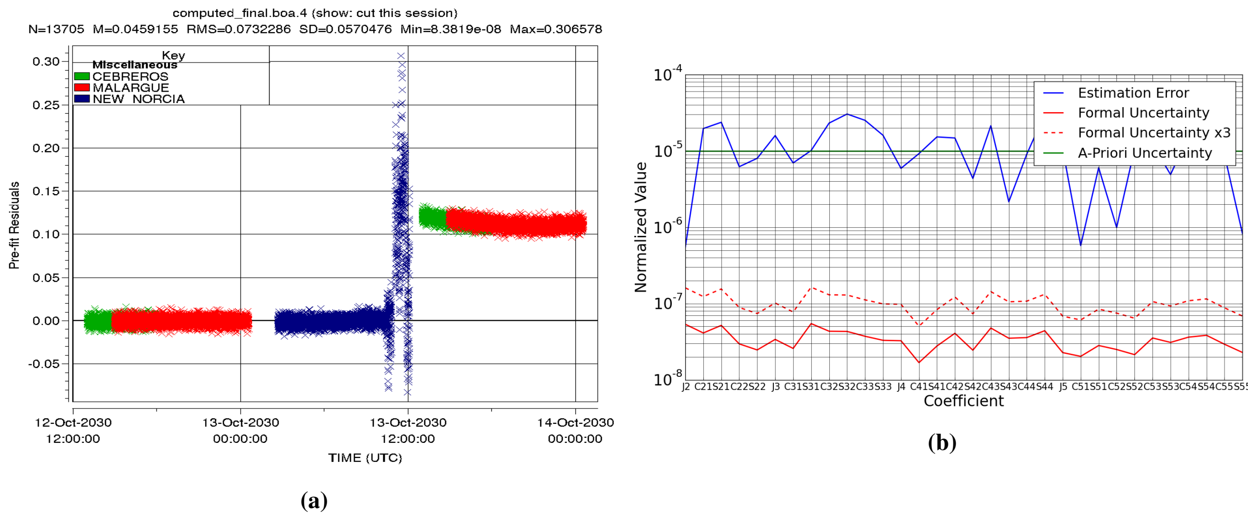


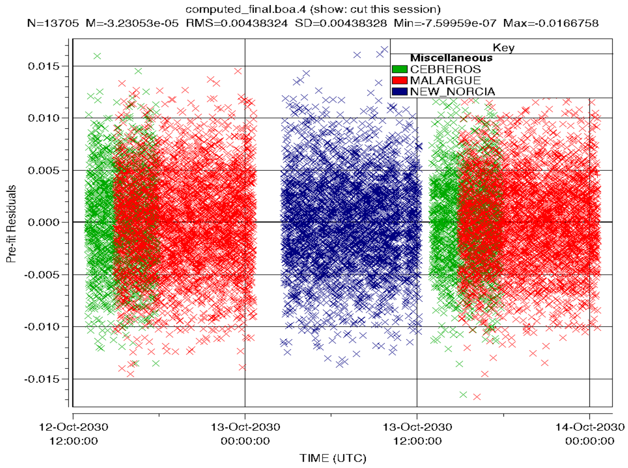
Figure 5 Results of setup 1: (a) The Doppler residuals show a strong signature caused by the propellant sloshing, after four OD filter iterations, (b) Estimation performances on the Callisto spherical harmonics coefficients

C. Setup 2: Estimation Considering Full Accelerometer Error Model

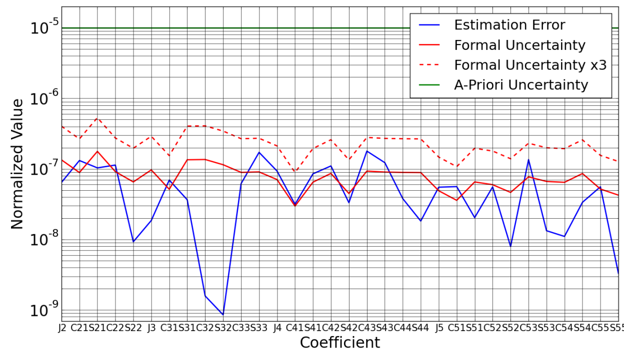
An ideal accelerometer would completely solve the problem of non-gravitational accelerations. However, a real accelerometer introduces measurement errors, (as seen in Sec. V.A). The ISA's reading error model includes a bias, a bias rate and a scale factor. These parameters are not known and they change every time the accelerometer is switched on, making their prediction impossible. This makes it necessary to insert the accelerometer calibration coefficients in the list of the solve-for parameters. This setup considers the full set of accelerometer error model parameters to understand if their simultaneous estimation is possible. To simulate the accelerometer's readings, the accelerations obtained in Sec IV have been inserted both in the simulation and estimation.

Fig. 6a shows that with this setup the OD process has reached convergence, because the residuals show only the AWGN contribution superimposed on the observed observables. Fig. 6b shows the estimation of Callisto gravity field coefficients. Here, the estimation errors are inside the desired bound of 3σ, meaning that the accelerometer solves the problem of propellant sloshing induced accelerations.

Since the OD filters have reached convergence we can now analyze the accelerometer's calibration parameters results. Figs. 7a, 7b and 7c show the estimation of the bias, bias rate and scale factor in the three dimension of the spacecraft frame, respectively. In Fig. 7a we can see that the bias formal uncertainty does not show a great improvement with respect to the a priori knowledge; the uncertainty on its knowledge is almost ten times higher than its central value. This might be symptom of a correlation between the parameters. Fig. 7d, in fact, shows a great correlation between bias and bias rate. This behavior makes a good flyby OD solution impossible because of a poor knowledge of their true values. The bias rate coefficient could be estimated during a pre-flyby phase. In fact, during this period sloshing accelerations do not occur. The accelerometer would read only a biased random noise with a non-zero time derivative depending on the bias rate, which could be estimated precisely. Therefore, its value could be included in the physical model to fit the flyby data accurately. Therefore, in the next section the performances of a λ and $\mathbf{b}_0$ setup are investigated.

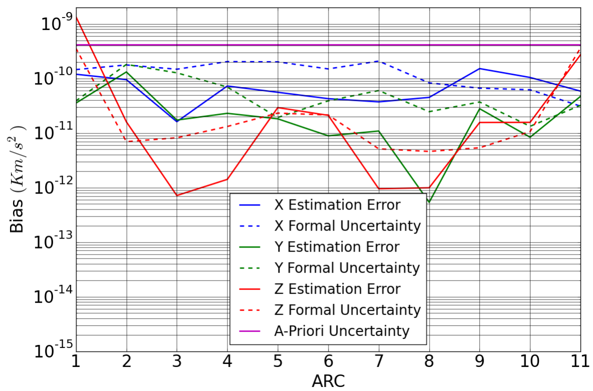


(a)



(b)

Figure 6 Results of setup 2: (a) Residuals of the first arc after four OD filter iterations show only measurement AWGN, (b) Estimation performances on the Callisto spherical harmonics coefficients



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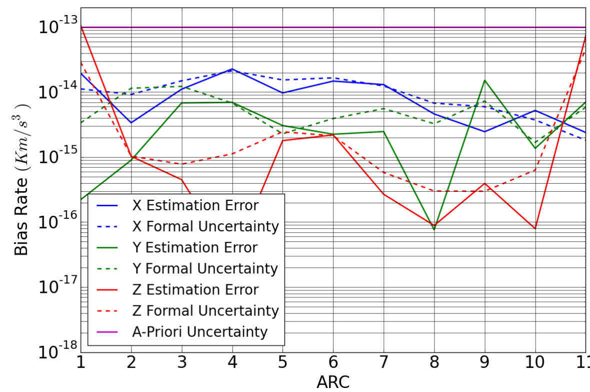

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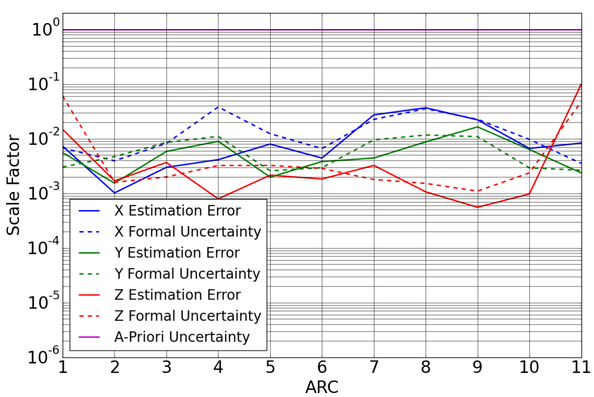
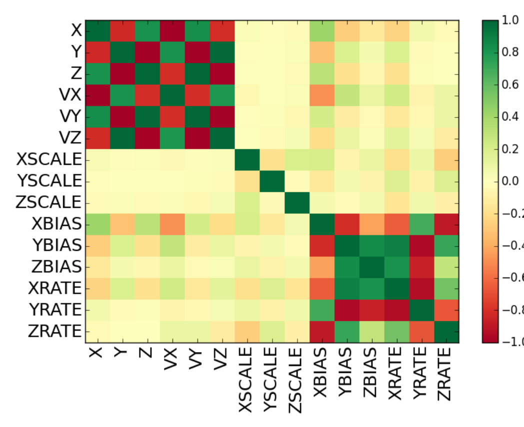


(c)



(d)

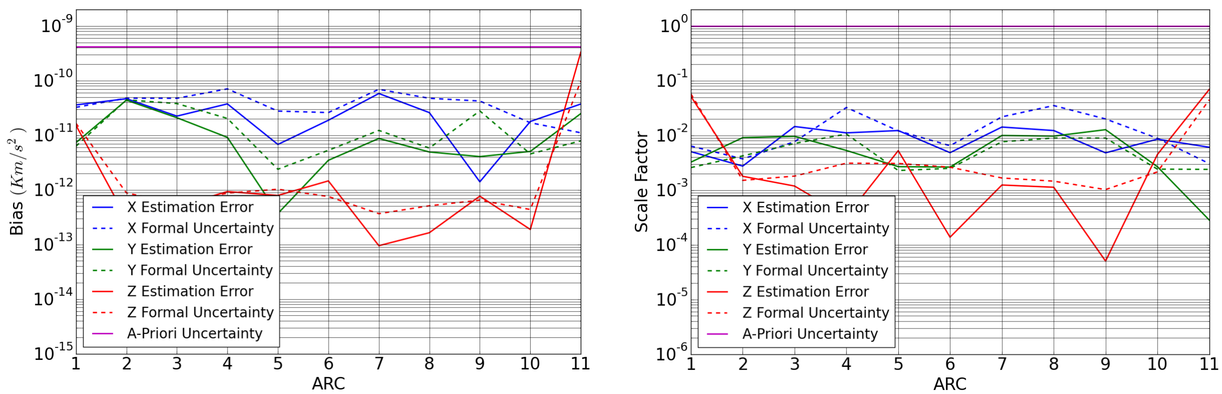
Figure 7 Results of setup 2: (a) Biases estimation performances, (b) Bias rates estimation performances, (c) Scale factors estimation performances and (d) Correlation matrix shows the strong correlation between biases and bias rates.

D. Setup 3: Estimation considering bias and scale factor

Concerning the estimation of Callisto's gravity coefficients, this setup provided almost the same results of Sec. V.C. The filter reaches convergence and the formal uncertainties of Callisto's spherical harmonics coefficients are all of the order of 10^{-8}, thus providing a reliable estimation of its gravity field.

Comparing Figs. 7a and 8a, we can clearly see a great reduction, by at least an order of magnitude, of the bias formal uncertainty meaning that it can be estimated with an average uncertainty of about 10% of the value. While comparing Figs. 7c and 8b, we can note that the scale factor estimation is almost the same as in Sec. V.C, confirming that it is uncorrelated with other solve-for parameters.

Fig. 9 shows the gravity anomaly (i.e. all gravity field coefficients but J_2 and C_{22}) uncertainties mapped onto Callisto's surface. The blue zone represents the area in which the gravity field is known with the best accuracy which are strictly linked to the ground track of JUICE. We can see a dark blue signature in the middle of the map projection; this is the zone with the best coverage. The western hemisphere gravity field is better sampled than that of the eastern hemisphere because of two equatorial passes at low altitude. This is the setup that provided the best results in terms of solve-for parameter estimation, reflecting the best strategy of data processing.



(a) Bias estimation

(b) Scale factor estimation

Figure 8 Results of setup 3: (a) Biases estimation performances and (b) Scale factors estimation performances

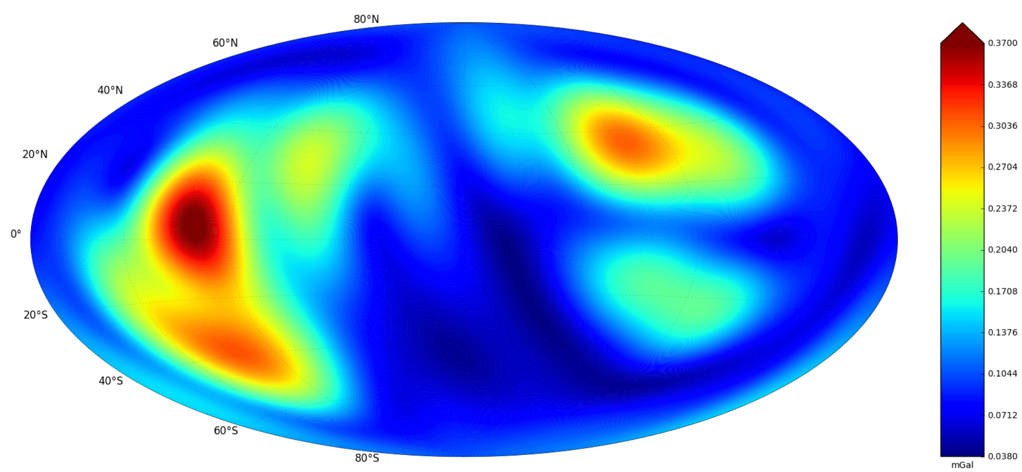


Figure 9 Gravity field anomaly uncertainties up to the 5^{th} degree mapped onto the Callisto's surface (Hammer-Aitoff projection), expressed in $mGal(10^{-5}m/s^2)$

VI. Conclusion

This work demonstrated how the presence of an on-board accelerometer could solve the problem of propellant sloshing for the 3GM experiment. In order to verify that, simulations have been performed to evaluate the effects of accelerometer noise and systematic error on Callisto's gravity field parameters.

The first simulation demonstrated that the absence of an on-board accelerometer would lead the 3GM experiment to fail because of propellant sloshing. Then, simulations were executed to demonstrate how in-flight calibration parameters would affect 3GM performances. The simulations' strategy considered two different approaches (a batch-sequential filter and a multi-arc filter) to validate the results.

It has been demonstrated that by using an accelerometer with the same properties as BepiColombo's, the Italian Spring Accelerometer (ISA), 3GM measurements are still possible. In addition, the results can be used to derive constraints on the measurement errors of accelerometer. The main result of this study is the proof that some parameters of the accelerometer (bias and bias rate) are correlated, implying that the simultaneous estimation would be impossible. This leads to the definition of two possible solutions. The first regards a modification of the data acquisition strategy, requiring to estimate the bias rate before and after the flyby because this trajectory is weakly dependent on the Callisto's gravity field and the propellant sloshing is absent. This phase can be exploited to estimate the bias rate. The permanence of JUICE in Callisto's sphere of influence will last less than 5 hours, therefore, the bias rate value should remain approximately constant. This way the computed value can be implemented in the physical model to estimate other solve-for parameters during the flyby (see Sec. V.C).

The second strategy affects the accelerometer design, requiring an improved measurement accuracy. The second approach is clearly safer but more expensive, because it would involve a change to the hardware rather than the software.

On the other hand, it has been demonstrated that scale factor is well determined also in the presence of bias and bias rate. In Sec. V.C, it has been shown that this parameter is almost uncorrelated with other accelerometer's parameters, as we can see from Fig. 7d.

To summarize, it has been demonstrated that accelerometer could solve the problem of propellant sloshing disturbances in Callisto's 3GM gravity experiment. Nevertheless, it is important to pay strong attention to the accelerometers systematic error that can be mainly induced by thermal variations, technological process and electronics degradation. This work has proven that the OD software can estimate only bias and scale factor as accelerometer's measurement errors. Hence setup 3, Sec. V.D, should be considered as a reference for future investigations.

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