MULTI-ARC AND BATCH-SEQUENTIAL FILTERS FOR THE ORBIT DETERMINATION OF ESA'S JUICE MISSION

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Abstract: *After Pioneer, Voyager and Galileo, ESA's JUICE mission is a further step in the exploration of the Jovian satellite system. The scheduled tour of the spacecraft (2030-2033) consists of 20 flybys of Callisto, 2 flybys of Europa and an orbital phase around Ganymede. One of the main goals of the mission is the determination of the satellites' gravity fields (up to different degrees), accessible to a precise orbit determination. The geophysical investigations are therefore closely entangled with spacecraft navigation. The smallness of the accelerations caused by tides and high degree harmonics of the gravity field requires an exceptionally accurate Doppler tracking of the spacecraft. The key instrument is a Ka-band transponder which, complemented by suitable ground instrumentation, will enable a radio link with a very high phase stability and range rate accuracy. The tracking configuration exploits Ka-band links both in the up and down legs (34-32.5 GHz), with expected range rate accuracies of 0.012 mm/s at 60 s. If the Ka/Ka link is operated simultaneously with X/X and X/Ka links (enabled by the on-board DST), a full cancellation of plasma noise is possible. The Ka-band transponder also enables precise range measurements that will improve the spacecraft orbit and the satellite ephemerides. Thanks to the use of a 24 Mcps PN code, the expected two-way accuracy is 20 cm, For the orbit determination of the spacecraft during the Ganymede phase a batch-sequential approach has been adopted. We report on the results of the simulations and provide our current best estimate of the attainable accuracies in the gravity harmonics of the satellite and the spacecraft position.*

Keywords*: JUICE, orbit determination, batch sequential, radio science*

1. Introduction

Radio science experiments with planetary spacecraft are performed using a radio-frequency link between the spacecraft and Earth stations. The required measurements are carried out by examining the change of frequency and/or phase of a microwave signal, related to the motion of the spacecraft. These observable quantities are processed by orbit determination codes to determine the spacecraft orbit together with unknown parameters of the dynamical model, such as the harmonic coefficients of gravity fields. If used together with geophysical models, the knowledge of gravity fields strongly constraints the mass properties and the interior structure of the celestial body the spacecraft is orbiting or flying by.

The geodesy experiment on-board ESA's JUICE mission will estimate crucial parameters of the Jovian moons Callisto, Europa and Ganymede, such as the spherical harmonic coefficients of their gravity fields and their degree 2 Love numbers (for Ganymede and Callisto). The updating of the Jupiter's system ephemerides represents a secondary goal of the experiment. In order to meet these scientific objectives, a very precise reconstruction of the spacecraft orbit is necessary. A good knowledge of the spacecraft orbit is also essential for the determination of Ganymede's topography.

The purpose of this paper is to provide an assessment of the accuracies attainable with the JUICE radio science experiment during the Ganymede phase, both for the gravity field determination and the spacecraft orbit reconstruction.

2. The JUICE mission

The formation of Jupiter's satellite system has always drawn the attention of the scientific community, since it represents a small-scale solar system, complete with natural satellites the size of Mercury. The most interesting bodies within the system are the icy satellites Europa, Ganymede and Callisto.

Magnetometer observations collected by the Galileo spacecraft during the three-year period 1995-1997, suggest the presence of liquid water oceans underneath the surfaces of Europa and Callisto (Khurana et al., 1998; Zimmer et al., 2000). Furthermore, a global sub-surface ocean may exist at Ganymede (Kivelson et al., 2001), which is also the only natural satellite in the solar system known to possess an intrinsic magnetosphere. Such extraordinary discoveries have made the exploration of these bodies a priority for scientists, thus stimulating proposals for a new mission to the Jovian system.

ESA responded to the needs of the scientific community by selecting the mission JUICE (JUpiter Icy moons Explorer), the first L-class mission selected in the frame of the Cosmic Vision Program. The launch is scheduled for June 2022 with an Ariane 5 ECA launcher. According to the current mission scenario, the interplanetary cruise will last 7.6 years. After a sequence of gravity assists from Venus and the Earth, the spacecraft will be inserted in a high-eccentricity orbit around Jupiter in 2030.

The main target of the mission is Ganymede, the largest satellite of the solar system. The scientific investigation at Ganymede consists of different phases; the crucial one will be carried out at low altitudes (down to 200 km) and will last more than four months. During this phase the spacecraft will be inserted in a circular, nearly polar orbit around the satellite, allowing the on-board instrumentation to gather information for the characterization of the interior structure, detection of water oceans, surface composition and intrinsic magnetic field of Ganymede.

Callisto is the outermost of the four Galilean satellites. Multiple flybys of the satellite will be used to raise the spacecraft inclination up to 29°, enabling high latitude observations of Jupiter's atmosphere and magnetosphere. The spacecraft will be in Callisto resonance and will therefore encounter Callisto at almost the same position (Dougherty et al., 2011). JUICE will also attempt to achieve some of the scientific goals of the former NASA-ESA joint mission EJSM/Laplace by means of two flybys of Europa. High radiation levels limit the number of encounters with the satellite.

3. The JUICE geodesy experiment

In order to fully characterize the interior structure and investigate the formation of the three satellites, gravity measurements during the science phases of the mission are essential. The main objective of the gravity experiment of the JUICE mission is the determination of the gravity fields (both static and variable) of Ganymede, Callisto and Europa to different degrees:

- Spherical harmonics expansion up to degree and order 10 (at least), and Love number k_2 for Ganymede;
- Spherical harmonics expansion up to degree and order 3, and Love number k_2 for Callisto;
- Spherical harmonics expansion up to degree and order 2 for Europa.

If the bodies are found in hydrostatic equilibrium, the radial density distribution may be constrained from their moment of inertia factor and low-degree gravity field coefficients (Asmar et al., 2009). Besides, the long-lasting phase at Ganymede, will allow the detection of possible gravity anomalies of the satellite through the estimation of its high degree harmonics. The Love number k_2 provides the magnitude of the satellite's response to the tidal forces exerted by Jupiter. Since the tidal deformation of a satellite would be much larger in case of presence of a liquid layer within the body, the determination of this parameter represents the evidence for sub-surface oceans on Ganymede and Callisto.

The Ka-band transponder is the key instrument to conduct the gravity experiment. The transponder, together with appropriate ground segment facilities and instrumentation, is capable of maintaining a highly phase-stable link between the spacecraft and the Earth station. The use of the Ka-band in deep space tracking systems has improved the accuracy of range-rate measurements to 0.003 mm/s or less. Furthermore, high accuracy (20 cm) range measurements will contribute to improve the ephemerides of the Jupiter's system. All the radiometric measurements will be carried out in a coherent way, using a very stable frequency standard for the generation and conversion of the carrier.

The main configuration of the Radio Science Instrument (RSI) for the gravity measurements consists of a link in Ka-band both in up-link (34.3 GHz) and in down-link (32.5 GHz). If necessary, the RSI is also capable of operating in a multi-frequency configuration, together with the on-board Deep Space Transponder (DST), which transmits and receives in X-band. In the last option, two up-link carriers and thee down-link carriers are used at the same time, namely:

- (Ka/Ka) downlink in Ka-band (32.5 GHz) coherent with an uplink in Ka-band (34 GHz);
- (X/X) down-link in X-band (8.4 GHz) coherent with an up-link in X-band (7.2 GHz);
- (X/Ka) down-link in Ka-band (32.5 GHz) coherent with an up-link in X-band (7.2 GHz);

This configuration, successfully used for the Cassini mission, is needed for a complete cancellation of the plasma noise, both in range and range rate measurements.

4. Orbit determination

For an artificial satellite, the orbit determination problem consists of the determination of its trajectory within a certain period of time, given an adequate number of observations from Earth stations. In radio science, the observables are radiometric measurements such as the spacecraft range *ρ* (the radial distance from the tracking station), and range-rate *dρ/dt* (the radial velocity of the probe). Tracking data are then processed by means of an orbit determination code, which produces an estimation of the state vector *X*, a *n*-dimensional vector of the solved-for parameters. This vector contains at least the components of the spacecraft position and velocity vector at a given time, but also significant parameters relative to the dynamical model (e.g. spherical harmonic coefficients of a celestial body), that have to be estimated.

5. Multi-arc method and batch-sequential filter

A planetary geodesy experiment may last several months. Therefore it is convenient to divide the whole time period into many non-overlapping single arcs of short duration (e.g. 1 day). The components of the spacecraft position and velocity vector at the beginning of each time lapse are characteristic of the specific arc, and therefore are called local parameters. The other free parameters such as the gravity field coefficients or the central body's state vector at a given reference epoch, represent the global parameters, shared by all arcs.

A single-arc estimation of the state vector consists of an independent solution for both the local and global parameters within the single arc. Interactions between adjacent arcs for the purpose of an optimal estimate are not considered whatsoever.

In case of a long-duration experiment, the number of local (and therefore total) parameters to be estimated raises. In addition, effects that are not properly considered in the dynamical model (e.g. mis-modeling of non-gravitational forces) tend to produce errors that accumulate with time. For these reasons, a single-arc estimation of the solution vector may be inadequate.

These effects can be absorbed using a multi-arc filter that provides sufficient over-parameterization of the problem. This method includes an independent estimation of the local parameter vector l_i relative to each single arc (i) and a combined estimation of the global parameter vector g, shared by all arcs. The tracking phase is divided into n arcs: the duration of the single arc must be neither too long, in order to avoid accumulation of dynamical errors, nor too short, for in this case the solution could be driven to instability.

The overall solution vector is:

$$x = [g; l] \qquad (1)$$

where:

$$l = [l_1; l_2; ...; l_n] \qquad (2)$$

Each arc is characterized by its own vector of the observables, associated by the same index i:

$$y_i \qquad i = 1,..,n \qquad (3)$$

While the overall vector of the observables is:

$$y = [y_1; y_2; ...; y_n] \qquad (4)$$

In this case, the matrix of the partial derivatives (5) is composed of two different parts:

- Partial derivatives of the observables with respect to each vector of the local parameters $H_{l_i}{}^j = \partial y_j / \partial l_i$ (=0 for i≠j) (left part);

- partial derivatives of the observables with respect to the vector of the global parameters $H_g{}^j = \partial y_j / \partial g$ (right part);

$$H = \begin{bmatrix} \partial y_1 / \partial l_1 & 0 & \dots & 0 & \partial y_1 / \partial g \\ 0 & \partial y_2 / \partial l_2 & \dots & 0 & \partial y_2 / \partial g \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \partial y_n / \partial l_n & \partial y_n / \partial g \end{bmatrix}; \qquad (5)$$

Each arc contributes to build the normal matrix C (Milani and Gronchi, 2010):

$$C = \begin{bmatrix} \left(C_{gg} + \Gamma^{-1}{}_g\right) & C_{gl_1} & \dots & C_{gl_{n-1}} & C_{gl_n} \\ C_{l_1 g} & \left(C_{l_1 l_1} + \Gamma^{-1}{}_{l_1}\right) & 0 & \dots & 0 \\ \dots & 0 & \dots & \dots & \dots \\ C_{l_{n-1} g} & \dots & \dots & \left(C_{l_{n-1} l_{n-1}} + \Gamma^{-1}{}_{l_{n-1}}\right) & 0 \\ C_{l_n g} & 0 & \dots & 0 & \left(C_{l_n l_n} + \Gamma^{-1}{}_{l_n}\right) \end{bmatrix} \qquad (6)$$

Where $C_{l_i l_j} = \left(H^j{}_{l_i}\right)^T H^j{}_{l_j}$ (=0 for i≠j), $C_{gl_i} = \left(H^i{}_g\right)^T W_{l_i} H^i{}_{l_i} = C_{l_i g}{}^T$ and $C_{gg} = \sum_{i=1}^{n} \left(H^i{}_g\right)^T W_{l_i} H^i{}_g = C_{gg}{}^T$.

W_{li} is the weighting matrix of the i^th arc, Γ_g and Γ_l are the *a priori* covariance matrices respectively for global and local parameters. The part of the right hand of the normal equation concerning the observables, becomes:

$$D = \left[D_g; D_l\right] = \left[D_g; D_{l_1}; \dots; D_{l_n}\right] \qquad (7)$$

Where $D_g = -\sum_{i=1}^{n} \left(H^i{}_g\right)^T y_i$ and $D_{l_i} = -\left(H^i{}_{l_i}\right)^T y_i$.

Once these matrices have been built, the normal equation becomes a system of linear vector equations (Milani and Gronchi, 2010) that can be easily solved for vectors Δg and Δl:

$$\begin{cases} C_{gg}\Delta g + C_{gl}\Delta l = D_g \\ C_{lg}\Delta g + C_{ll}\Delta l = D_l \end{cases} \qquad (8)$$

Although the use of the multi-arc method represents a step further in the estimation of the global parameters, the presence of errors in the dynamical model that stretch over the whole duration of the experiment leads to an ineffective reconstruction of the spacecraft orbit.

The batch-sequential method has been developed for the MORE radio science experiment of the BepiColombo mission (Genova et al., 2010), and can be successfully adopted for the numerical simulations of the JUICE gravity experiment. This method can be divided into three different logical steps.

In Step 1, the total number of arcs (n) is divided into a number of batches (b), each of which contains a certain number of adjacent arcs (a). This way axb=n. Each batch is then processed following three sub-steps (**Fig. 1**):

- Single arc estimation of *a* arcs;
- Multi-arc estimation of the batch. The initial conditions and the *a priori* uncertainties for the global parameters are equal to the last single arc solution and to the *a priori* uncertainties of the single arc estimation respectively;
- The batch multi-arc solution for the global parameters is propagated to the next batch.

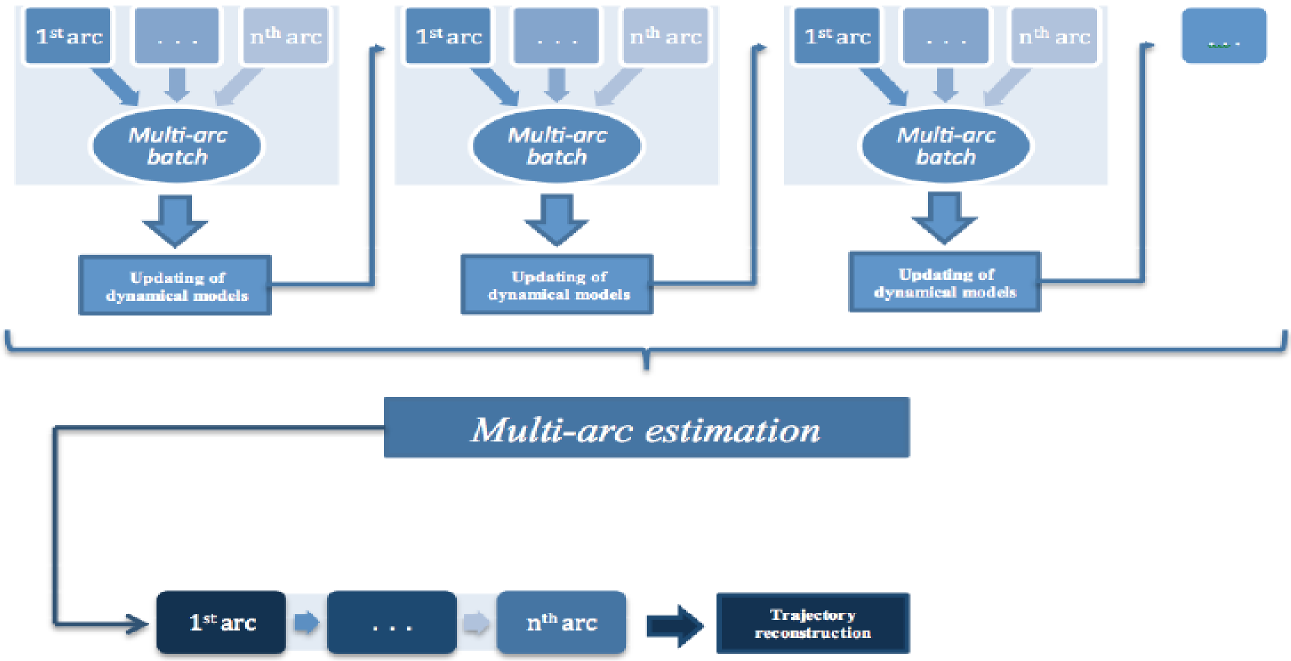

Figure 1 *Batch-sequential estimation (Genova et al.2010).*

With this procedure the dynamical model is continuously updated, improving the estimation of the spacecraft state vector in the following batches. Furthermore, thanks to this sequential updating, the solution for the global parameters converges after a certain number of batches.

The objective of these first three sub-steps is to initialize the global parameters for the overall multi-arc (Step 2) using the improved dynamical model. The initial conditions relative to the vector *g* are now equal to the values obtained from the last batch-multiarc solution. The solution for the global parameters $\hat{b}$ obtained from the overall multi-arc is used to build a "definitive" dynamical model, which represents the best estimate of the forces acting on the spacecraft.

Using the improved knowledge of the dynamical environment, it is possible to proceed to the reconstruction of the spacecraft orbit. The definitive solution $\hat{b}$ for the global parameters and its formal uncertainties are used as initial values and *a priori* uncertainties, respectively, for a last single arc estimation (Step 3), which provides a better estimation of the of the local parameters, generally a large set. The accuracies achieved by this last step in the determination of the spacecraft position with respect to the satellite-centered reference frame (see Sect. 7.), fully meet the mission requirements on orbit reconstruction.

6. Simulation setup for the science phase at Ganymede

In order to anticipate the accuracies achievable in the determination of Ganymede's gravity field and in the reconstruction of the spacecraft orbit, numerical simulations of the mission's gravity experiment have been carried out. A realistic simulation requires a careful definition of the dynamical model, which must closely represent all forces acting on the probe, both gravitational and non-gravitational.

Among the gravitational forces, in addition to the gravitational pull, relativistic effects must be taken into account for bodies characterized by a large mass such as the Sun, Jupiter and Saturn. For Ganymede, the gravitational potential has been expanded in spherical harmonics up to degree and order 10. The reference gravity field has been produced using Kaula's rule:

$$C_l^2 = A_k \frac{10^{-10}}{l^4} \tag{9}$$

where l represents the degree of the Kaula's coefficients C_l. A_k is a constant term that has been tentatively assumed equal to 2 for Ganymede (a very weak field).

The tidal model of Ganymede assumes a (real) Love number k_2 equal to 0.3. The variations of the degree 2 spherical harmonic coefficients depend linearly on this parameter.

Being solar powered, the spacecraft will be characterized by a large area-to-mass ratio, therefore requiring an accurate modeling of the non-gravitational forces. In addition to solar radiation pressure, the drag from the thin and variable atmosphere of Ganymede has to be taken into account in the simulations. Effects due to the moon's albedo and infrared emission have to be considered as well.

For the observational model, a tracking period of approximately 8 hours a day has been assumed during the Ganymede science phase. Data relative to time periods within which the spacecraft is characterized by an elevation angle from the Earth station less than 20° have been discarded. Furthermore, loss of data due to occultations of the radio link by Jupiter and its satellites has been considered.

The simulation of the geodesy experiments has been performed assuming a Gaussian white noise with a standard deviation of 0.12 μm/s at 60 s integration time. This noise level is easily attainable if plasma noise is completely cancelled thanks to a multi-link configuration and tropospheric noise is reduced by means of water vapor radiometers. It can be attained also from the Ka/Ka radio link when the beam is not too close to the sun. The tracking coverage has been assumed to be provided by a single station (DSS 25 in Goldstone and occasionally from a station in Spain).

7. Results

The low-altitude phase at Ganymede will last 132 days. The first 102 days will be spent at 500 km above Ganymede's surface, while during the remaining 30 days of the mission the orbital altitude of the spacecraft will be lowered to 200 km.

As Ganymede's dynamical environment is not well known, a batch-sequential approach has been adopted. For the purpose of numerical simulations, the whole duration of the science investigation has been divided into 12 batches of 11 arcs each, which turns out to be a nearly optimal configuration for the experiment. Being every single arc of a 1-day duration, the total length of the batches is larger than the orbital period of Ganymede around Jupiter (7.155 days). This corresponds to the highest frequency at which the dynamical model can be updated, in fact shorter batches would not allow an adequate estimation of periodic dynamical effects such as the tides of Ganymede.

The vector of the solved-for parameters is composed of:

- 6 local parameters for each arc: 3 components of the position vector + 3 components of the velocity vector;
- 118 global parameters: 117 spherical harmonic coefficients (Σ 2l+1=117 for l=1,..,10) + Love number k_2;

To show how convenient the use of a batch-sequential filter is for the determination of the spacecraft position during the long Ganymede orbital phase, 2 different configurations have been considered:

- No batch division, equal to a classic multi-arc solution;
- 12 batches of 11 arcs each.

Fig. 2 and **Fig. 3** show the true errors (estimated values minus simulated values) in the estimation of the spacecraft position against time (expressed in terms of mission duration), relative to the two different cases described earlier. The red lines represent the norm of the position error vector, while the blue lines represent the correspondent formal uncertainties.

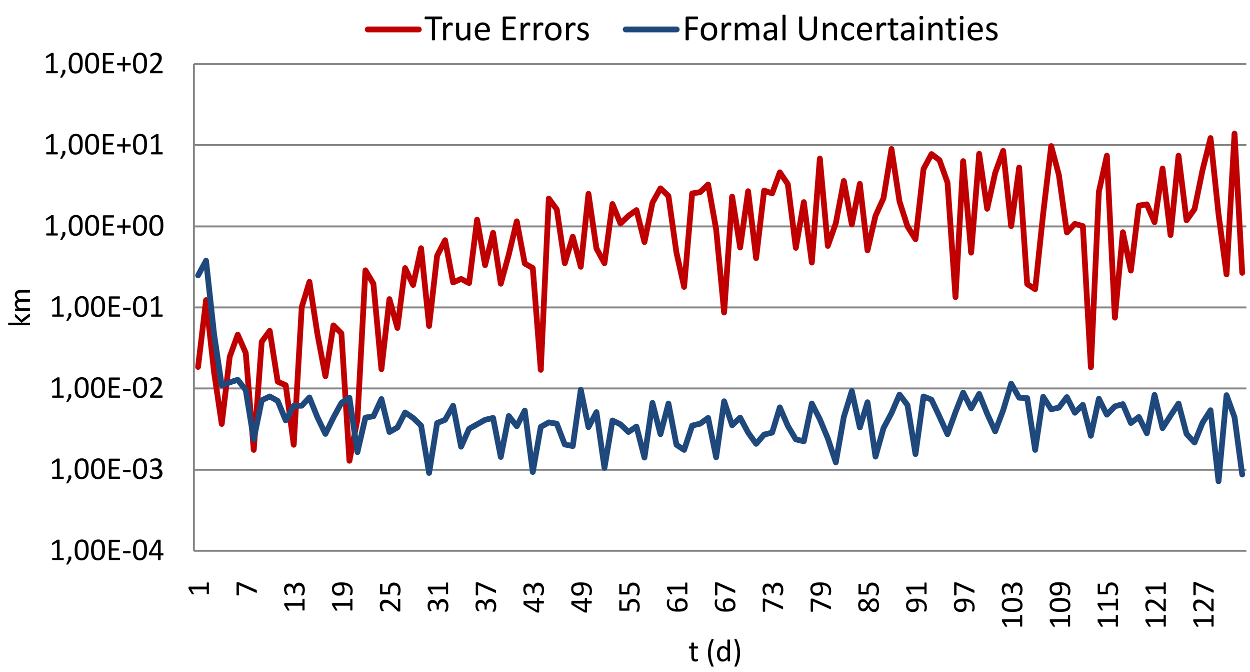

Figure 2 *Classic single-arc estimation with no dynamical model propagation: true errors and formal uncertainties in the estimation of the position vector of the spacecraft.*

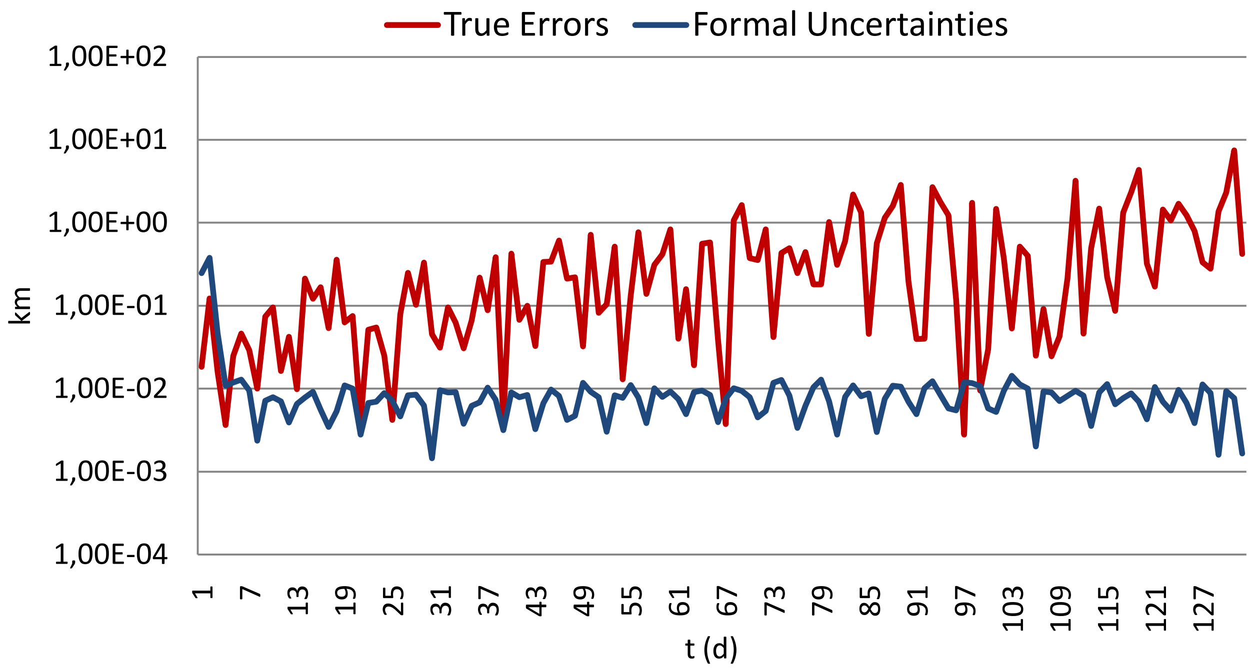

Figure 3 *Batch-sequential estimation. 12 batches of 11 arcs each: true errors and formal uncertainties in the single arc estimation of the position vector of the spacecraft.*

In both cases, the estimation errors exceed the formal uncertainties after few days of the mission, a confirmation of the inadequacy of single-arc estimation for local and global parameters. Nevertheless **Fig. 2** shows that the solution obtained with a single-arc estimation leads to larger errors than the one obtained with a batch-sequential filter (**Fig. 3**, single arc estimation where the dynamical model is propagated from batch to batch). In the first case the error exceeds 1 km just after 35 days, while the formal uncertainties are of order 10 m, whereas in the batch-sequential estimation the error exceeds 1 km after 70 days and never goes beyond 10 km.

The real edge of the batch-sequential approach over the classic multi-arc estimation is evident after the final estimate of the global parameters by means of the overall multi-arc (Step 2). **Fig. 4** and **Fig. 5** compare the solutions obtained for the spherical harmonic coefficients of Ganymede in the two different cases:

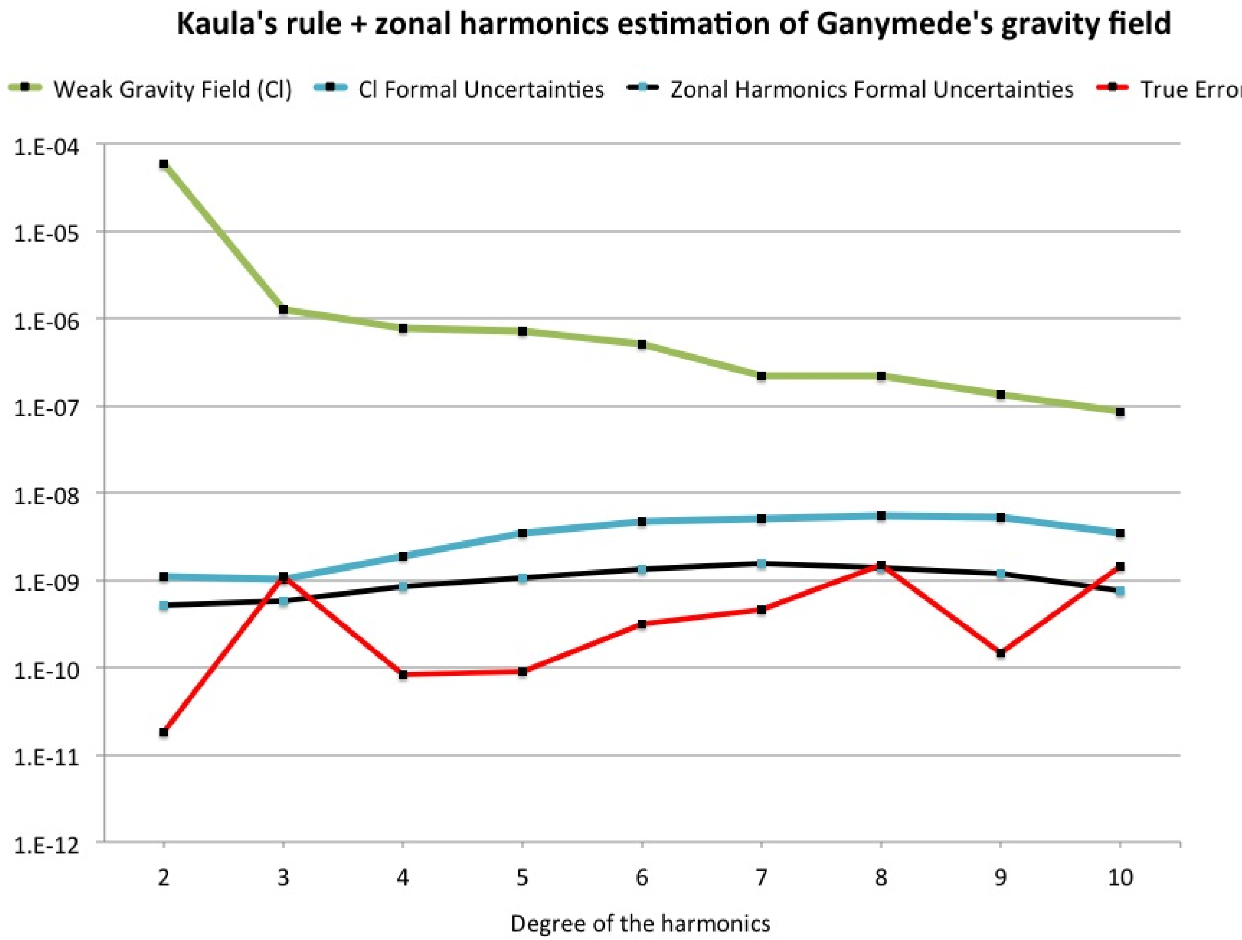

Figure 4 *Zonal harmonic coefficients estimated with the classic multi-arc filter. The red line represents the estimation errors of the zonal harmonics.*

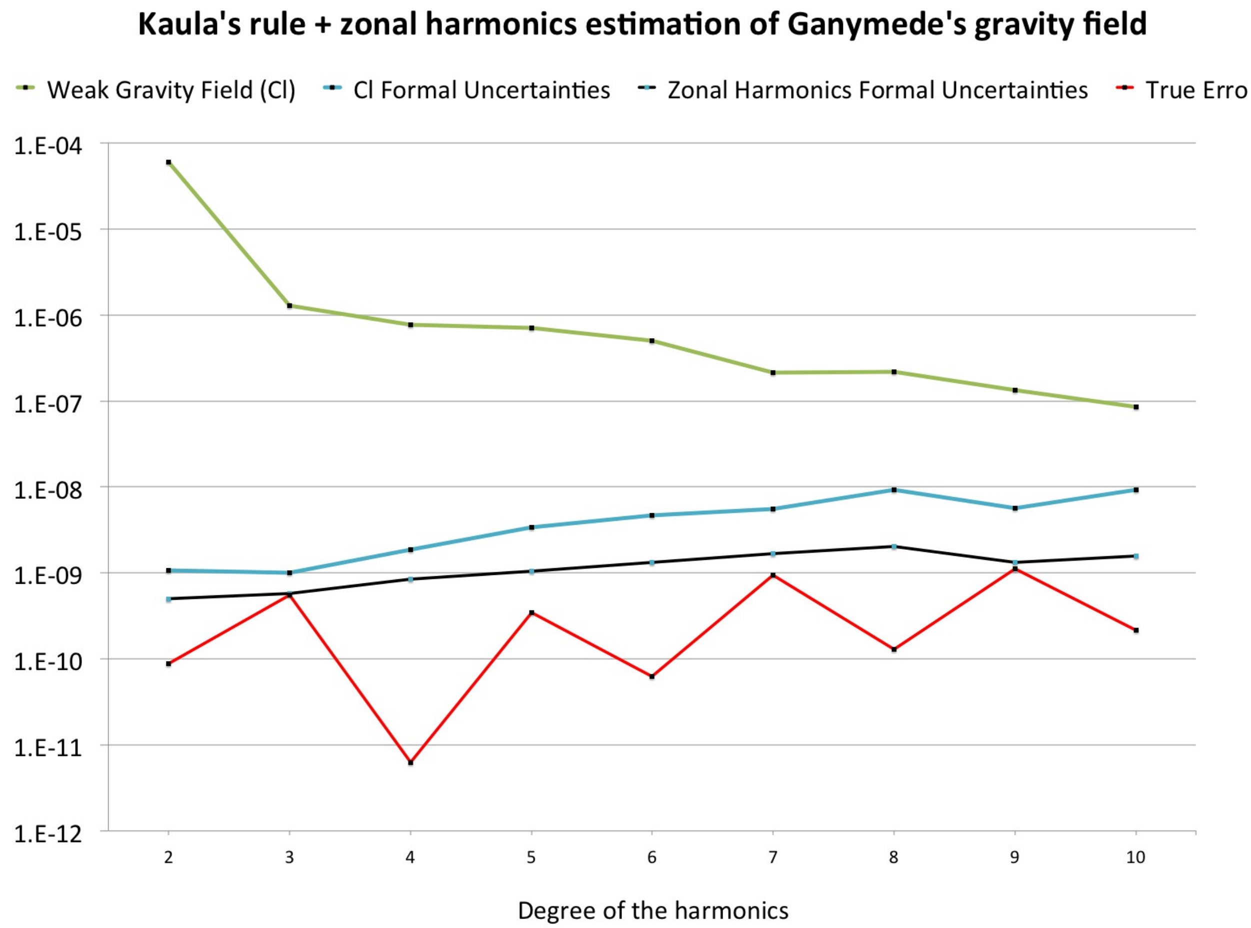

Figure 5 *Zonal harmonic coefficients estimated with the final multi-arc of the batch-sequential filter. The red line represents the estimation errors of the zonal harmonics.*

The plots show that the estimation of the zonal harmonic coefficients is more accurate using the batch-sequential approach, where the requirements for the determination of Ganymede's gravity field are fully met. In this case the error line (red line) always lies under the zonal harmonic uncertainties line (black line). This means the solution has converged to the simulated values of Ganymede's gravity field coefficients.

The third step of the filter is devoted to the reconstruction of the spacecraft orbit. The *a priori* values for the global parameters and the relative *a priori* uncertainties used in this final step are the ones obtained form the overall multi-arc solution. This improved knowledge of the dynamical model provides better accuracies in the determination of the spacecraft motion in the orbital frame (Ganymede-centered) as shown in **Fig. 6**.

1.

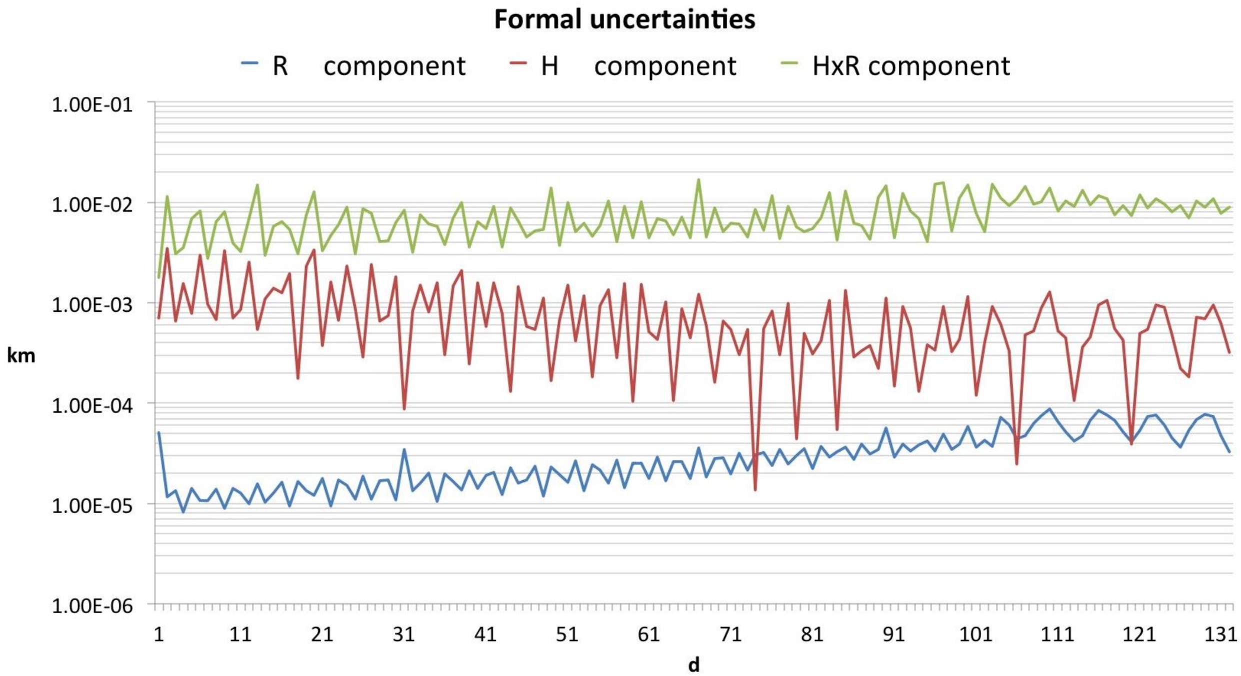

Figure 6 *Spacecraft position error in the orbital frame (radial, across-track and along-track).*

Fig. 6 shows that:

- The accuracies achievable in the determination of the radial (*R*) component of the spacecraft position are of order 1-10 cm (blue line);
- The accuracies achievable in the determination of the across-track (*H*) component of the spacecraft position are of order 1 m (red line);
- The accuracies achievable in the determination of the along-track (*HxR*) component of the spacecraft position are of order 10 m;

The precise determination of the spacecraft orbit has important implications for the satellite's topography reconstruction by the on-board laser altimeter and for precise georeferencing of optical images. The accuracies attained in the determination of the *H* component (across-track) also enable a good detection of Ganymede's librations.

8. Conclusions

From the results shown in **Sect. 7**, emerge that for long-duration gravity experiments, such as the science phase at Ganymede, the batch-sequential method provides a good estimate of the model parameters and the spacecraft position.

In particular **Fig. 5** shows that is possible to perform an uncorrelated estimate of the 2-degree coefficients J_2 and C_{22} with a relative accuracy of about 0.001% on both parameters. The plot also shows that even considering a very weak gravity field for Ganymede, the experiment configuration allows the determination of the spherical harmonic coefficients at least up to degree and order 10.

Furthermore, the mission requirements on the spacecraft orbit reconstruction (to better than 1 m in the nadir direction) will be fully satisfied if the accuracies achievable in the determination of the spacecraft position are those shown in **Fig. 6**. As the across-track component can be determined with accuracies of order 1 m, it is plausible to assume that Ganymede's librations in longitude can be determined with an accuracy of 1 arcsec or better (Cicalò, 2012; for applications to the Galilean moons see also Baland and Van Hoolst, 2010).

These results represent a starting point for the preliminary design of the gravity experiment on-board the JUICE mission, though the implementation of the simulations still has some limitations. To begin with, a more realistic model of the atmospheric drag expected at Ganymede is needed and the model for Ganymede's librations has yet to be implemented.

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