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 system. After launch in June 2022 and an interplanetary cruise lasting 7.6 years (entailing gravity assists from Venus and the Earth), the spacecraft will be captured by Jupiter in 2030. The Jovian tour consists of flybys of Callisto and Europa, observations of Jupiter polar regions and an orbiting phase around Ganymede.

The main target of the exploration is Ganymede, the largest satellite of the solar system. A probe will orbit the moon for more than four months at low altitudes (up to 200 km), during which it will gather information for the characterization of the interior structure, surface composition and intrinsic magnetic field.

Callisto is the outermost of the four Galilean satellites. Multiple flybys of the satellite will be used to raise the spacecraft inclination, enabling high latitude observations of Jupiter's atmosphere and magnetosphere. 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 Europa flybys.

One of the main goals of the mission is the detection of tidal effects on the three Galileian moons. Magnetometer observations collected by the Galileo spacecraft suggest the presence of liquid water oceans underneath the surfaces of Europa, Callisto (Khurana et al., 1998; Zimmer et al., 2000). A global ocean may exist also at Ganymede. If present, these oceans would give rise to tidal deformations that are accessible to a precise orbit determination. The geophysical investigations of the mission 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 adopted configuration of the radio system exploits Ka-band links both in the up and down legs (34-32.5 GHz), with expected range rate accuracies below 0.003 mm/s at 1000 s integration times (0.012 mm/s at 60 s). If the Ka-band links are operated simultaneously with X/X and X/Ka links (enabled by the onboard DST), a full cancellation of plasma noise is possible. The tracking system enables also range measurements with 20 cm accuracy by means of a 24 Mcps PN code. Range observables will improve the spacecraft orbit reconstruction and the knowledge of satellite ephemerides.

Numerical simulations of the geodesy experiments were carried out for the crucial science phases of the mission, 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 cancelled thanks to a

multi-link configuration and tropospheric noise is reduced by means of water vapor radiometers.

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

For Europa and Callisto, simulated data are processed in a square-root batch filter. Effects that are not considered in the dynamical model (e.g. mis-modeling of non-gravitational forces) are absorbed using a multi-arc approach that provides sufficient over-parameterization of the problem. With the current mission profile, the accuracy in the estimation of Callisto's Love number k_2 is at most 0.14 under realistic conditions. Better results are obtained if the distribution of flybys along the orbit is more favorable.

For the Ganymede phase (nine months) a batch-sequential approach is adopted. The orbit is separated into 282 arcs, each of 24 h duration, and adjacent arcs are then grouped into batches. The estimation of the global parameters from each batch is then propagated to the next batch. At the end of this process, the entire data sequence is reprocessed in a nearly unconstrained, global multi-arc fit. Inspection of the resulting covariance matrix shows that Ganymede's gravity harmonics can be estimated at least to degree 10 (more if the field follows a stronger Kaula's rule). The Love number k_2 can be estimated to better than 10^{-3}, thus allowing an unambiguous detection of a subsurface ocean. In the Ganymede phase, the spacecraft orbit can be reconstructed to a level more than adequate for an excellent determination of the satellite topography by means of the onboard laser altimeter.

References:

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