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Using Doppler radio-tracking data to map the gravity field of planets

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Monitoring the orbital motion of space probes with radio-tracking data is the best way so far to map the gravity field of the planets (e.g. [1-4] and references therein). The method consists of precisely reconstructing the orbit of the probe around the planet from fitting its orbital motion to Doppler radio-tracking data performed from Earth-based tracking stations. This Precise Orbit Determination (POD) method needs to build a force model of the orbital motion of the probe and to model the Doppler tracking data performed at deep space tracking stations.
The Doppler tracking data are measurements of the carrier frequency variations of the radio-link established between the space probe and Earth-based deep space stations (2-way from the station to the probe then sent back to the station). The frequency of this radio-link is generally at X-band (8.4 GHz). These Doppler data must be corrected from propagation effects in the interplanetary medium and Earth's ionosphere (due to electron density fluctuations) as well as in the Earth's troposphere (in particular due to humidity content). These effects are mostly corrected through modeling, but the interplanetary plasma source of noise remains the most important in the Doppler error budget at X-band. Using X-Ka dual-frequency links, allows for reaching Doppler accuracy of 0.01 mm/s at 60 seconds count time [5].
The force model takes into account up-to-date models of the gravity field of the targeted planet as well as the gravitational attraction of the moons of the planet and of the other planets (point mass representation). The radiation from the Sun and the planet that exerts a pressure on the faces of the space probe must also be taken into account. Besides, when the probe is at the lowest altitude part of its orbit it senses atmospheric drag due to the residual air in the thermosphere of the planet. Eventually, an acceleration is generated at each attitude maneuver, which consists of desaturation of the inertial wheels of the probe attitude control system. This maneuver unfortunately generates a velocity impulse that cannot be precisely known, thus significantly hampering the quality of the gravity solution.
This force model is then fit to the Doppler tracking data in order to adjust model parameters, among them the gravity field usually developed in spherical harmonics. The performance of this fit depends on both the error on the Doppler tracking data itself and on the inaccuracy of the force model. This inaccuracy is in part compensated by tracking data given they are acquired when the force model inaccuracy is the largest (for instance at periapsis pass for the drag force, e.g. [6]). In turn, almost continuous tracking of the orbiting probe is necessary to obtain the best possible gravity field solution. Besides, high-resolution mapping requires a near-polar, near-circular orbit with as low as possible altitude given the limitation due to the atmospheric drag force.
The NASA's spacecraft around Mars have such suitable orbits and quasi-continuous tracking, thus providing a gravity field with a near-100 km spatial resolution for the gravity map of this planet. The seasonal variations of the low-degree zonal harmonics could also be determined, allowing to study the CO_2 mass deposits at the polar caps [4]. The tidal potential due to the tides raised by the Sun has also been determined (i.e. the k_2 Love number) showing that the Martian core is liquid. The k_2 Love number for Venus has also been determined from tracking data [7] but its accuracy did not allow concluding about the state of its core [9]. New missions under study at ESA (EnVision) and NASA (VERITAS) aim at improving that situation. Many other missions have also used and will continue to use this POD technics to map the gravity field of several solar system bodies (Mercury, the Moon, Ceres, Ganymede, …) and even small bodies.

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