Precise Doppler measurements for navigation and planetary geodesy using low gain antennas: test result from Cassini

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ABSTRACT

Articulating elements such as scan platforms and steerable high gain antennas (HGA) introduce significant complications to the spacecraft design and surely result in increased cost. Spacecraft designers tend therefore to avoid their use, even if this choice invariably lead to constraints in spacecraft operations and reduction of science return. For example, most planetary missions lack expensive scan platforms for remote sensing instruments and rather rely on attitude changes for pointing to targets. This approach to spacecraft design, while significantly simplifying the overall system, makes communications to ground by means of high gain antennas (i.e. Earth pointing) incompatible with simultaneous pointing of other instruments for remote sensing observations. This limitation is especially detrimental to celestial mechanics, geodesy and radio science investigations, which rely on the radio link to generate observable quantities (range, range rate and delta-DOR).

The lack of a scan platform severely affected the Cassini mission in its exploration of the Saturnian system. Because the science investigations rely on a limited number of flybys of the moons to attain their goals, the impossibility to operate simultaneously several instruments on the same target forced the project to assign each flyby a single, prime instrument. The pointing to the desired target was obtained by turning the entire spacecraft, a rather slow maneuver for a large platform. Gravity measurements were even more affected. Indeed, the determination of a gravity field relies crucially on a global coverage, while the Cassini radio science investigations could count only on a handful of flybys and suboptimal geometries.

Cassini has a 4m, fixed HGA and a radio system operating at X and Ka-bands. The narrow half-power beamwidth (HPBW), about 0.6° at X-band, 0.16° at Ka-band, provides excellent SNR during flybys devoted to gravity science, but unfortunately makes gravity measurements impossible during flybys assigned to other instruments. This limitation could in principle be mitigated if the radio link were enabled through one of the two onboard low gain antennas (LGA). LGA1 is located on the tripode of the HGA, therefore pointing in the same direction as the HGA (the –z axis in the body frame). LGA2 is mounted on a short boom close to the engines, pointing in the +z direction. Their HPBW is about 30°. The lower gain caused by the broad antenna pattern results in reduced power of the uplink signal received from the Earth such that 2-

way transponder lock can be achieved only for pointing up to 55° off the z-axis. This sub-optimal configuration has two drawbacks, namely the much smaller SNR of the signal received by the ground antenna and the need to compensate the effects of spacecraft rotations on range rate measurements when the entire spacecraft body articulates. In order to assess the feasibility of gravity measurements using the LGA a dedicated test was carried out on 15 August 2010, when Cassini was tracked in coherent 2-way mode from DSS-63. The main goals were (1) a quantitative assessment of the degradation of link stability, measured by Allan deviation, under low SNR conditions and spacecraft rotation and (2) verification of our ability to control systematic errors when correcting the Doppler data for the moving phase center of the LGA . To this end, the spacecraft was turned repeatedly about its x- and y-axes in order to assess capability to maintain lock at large off-boresight angles and determine the compensation of the attitude motion by means of the quaternions and angular rates generated by the ACS. For comparison, range rate data were acquired also before and after the period when the spacecraft turns took place.

The analysis was based on sky frequencies generated by a digital PLL operating on electric field samples acquired by the open loop Radio Science Receivers (RSR). The use of an offline analysis allowed us to tune the detection algorithm and better recover the carrier under low SNR conditions. The reconstructed sky frequencies were then processed through JPL Orbit Determination Program (ODP) to separate the effects of orbital motion and attitude dynamics on Doppler data. Starting from the orbital solution provided by the Cassini Navigation (NAV) team, obtained using HGA data, the LGA range rate observables were fitted to generate residuals which included the spacecraft rotations. These residuals contain only the Doppler shift induced by the motion of the LGA about the spacecraft center of mass (CoM), while the orbital motion has been effectively removed. This Doppler shift can be computed if the velocity of the LGA phase center (PC) in the inertial frame is known. While the ACS provides accurate attitude quaternions and angular rates, the PC position in the spacecraft frame is not accurately known and therefore was estimated.

The residuals from the open loop sky frequencies were then analyzed and compared to those obtained under normal condition (HGA and no attitude motion). We found that the quality of HGA and LGA residuals acquired during the test is comparable. This indicates that attitude motions have been removed to a level below the noise. This encouraging result was partially due to the large plasma noise experienced during the test, which hid the thermal noise increase in LGA data. As a byproduct, we obtained also an excellent determination of the position of the center of mass of the spacecraft relative to the PC of the LGA. The test showed that LGA data can provide valuable range rate data for gravity science experiments when the radio link cannot be established through the HGA. The good knowledge of the vector connecting the spacecraft CoM and the PC allows us to process Doppler data without the need to fit for additional parameters: attitude quaternions and angular rates are sufficient to remove the effect of spacecraft rotations in any future flyby if the propellant consumption is known. These results may be relevant also to future planetary missions hosting geodesy experiments.