IAF SPACE COMMUNICATIONS AND NAVIGATION SYMPOSIUM (B2)
Space-Based Navigation Systems and Services (6)

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SPACECRAFT NAVIGATION USING PHASE TRACKING OF X-RAY PULSAR SIGNALS

Abstract

X-ray pulsars are potential spacecraft navigational aids due to signal periodicity, uniqueness, and stability. A subset called millisecond pulsars (MSPs) has the best timing characteristics with long term stabilities similar to atomic clocks. Phase tracking exploits the pulsar's periodic signal to determine spacecraft position. A method of phase tracking X-ray pulsar signals that is applicable to MSPs, which are constrained by low flux, is proposed and simulated. The detected photons are separated into time blocks with observed pulsar signal frequency derivative assumed constant. A maximum likelihood estimator (MLE) for initial phase and a third-order digital phase-locked loop (DPLL) are used over each block to track the phase history. The MLE uses a second-order Taylor polynomial phase model with frequency and frequency derivative fed back from the DPLL. This allows for long blocks where the observed pulsar signal frequency varies to accommodate low flux.

Empirical MLE tests are performed to find ranges for the product of detector area and block time when compared to the Cramer-Rao Bound. There is an area-time product lower bound due to low flux and Poisson statistics and an upper bound due to the dynamic stress from the mismatch of orbit dynamics with constant acceleration. For a 1 m^2 detector, the threshold time ranged from one second for the Crab pulsar to 4000 seconds for the lowest flux MSPs.

Simulations are performed modeling ten hours of pulsar signal outputs. Two heliocentric trajectories, cruise stage segments of the Cassini and MSL missions, and three Earth orbits: the ISS, a GPS satellite, and a DirecTV satellite were simulated. The Crab pulsar and four MSPs: B1821-24, B1937+21, J0218+4232, and J0437-4715 were considered. Tracking performance depends on detector area due to the trade-off between accumulating photons and reducing dynamic stress. All scenarios were tested with a 1 m^2 detector. The phase tracking output locked on the heliocentric trajectories for all pulsars with errors under 10 km, and the tracking maintained lock for the Earth orbits with the Crab pulsar and B1821-24 with errors around 1 to 10 km. Different areas were tested to bound performance. The Crab pulsar signal tracked with error under 1 km with a smaller 100 cm^2 detector. The remaining MSPs required detectors around 5 - 10 m^2 to track the Earth orbits with error under 20 km. An extended Kalman filter is simulated to combine multiple pulsar observations resulting in position error under 10 km.