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Space-based PNT (Position, Navigation, Timing) Architectures, Applications, and Services (1)

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STUDY OF LUNAR NON-GRAVITATIONAL PERTURBATION MODELS FOR ADVANCED ORBIT DETERMINATION SERVICES IN ELLIPTICAL LUNAR FROZEN ORBITS

Abstract

Commercial and institutional lunar missions are poised to explore the Moon from the second half of this decade, highlighting the growing need for a satellite constellation to deliver communication and navigation services to future users in this environment. Position, Navigation, and Timing (PNT) services are indispensable, facilitating human and robotic activities across the lunar surface and its orbital vicinity. Ground-based Orbit Determination (OD) is fundamental to precisely localize the lunar satellite constellation, ensuring that their positions are known with a high degree of accuracy. Orbit Determination relies on the processing of radio-metric observables and on a good knowledge of the accelerations, both gravitational and non-gravitational, acting on the satellites. This paper investigates the impact of accurately modelling non-gravitational accelerations on position and velocity errors, as well as on uncertainties in both inertial and local lunar frames, and on ephemeris aging. The precision of each spacecraft dynamic model is paramount in mitigating ephemerides aging, underlining the critical importance of this research for ensuring the reliability and effectiveness of the information that lunar navigation and communication systems provide to the final users to compute PVT. The reference lunar constellation is a GNSS-like system composed of four satellites distributed over different planes of Elliptical Lunar Frozen Orbit (ELFO), designed to provide PNT services specifically for users in the lunar South Pole region. Three ground stations are simulated to track the satellites by receiving and processing coherent two-way range and Doppler measurements. Four primary non-gravitational perturbations —Solar Radiation Pressure, Thermal Recoil Pressure, lunar Albedo, and lunar InfraRed radiations— are modelled, implemented and validated in the GODOT software, the European Space Agency (ESA) astrodynamics library for mission analysis and operations. Through extensive simulations of realistic OD scenarios, the consequences of excluding each non-gravitational acceleration on the ephemerides reconstruction and their aging are explored. The outcomes of this paper not only deepen the understanding of the complexities inherent in lunar orbit determination, but also demonstrate to what extent a more accurate dynamical model enables better orbital reconstruction and a slower aging of the OD solution, without exceeding the positioning and velocity requirements. As a result, practical insights for optimizing the performance of future lunar navigation and communication systems are proposed.