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Interplanetary laser ranging - an emerging technology for planetary science missions

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Abstract

Interplanetary laser ranging (ILR) is an emerging technology for very high accuracy distance determination between Earth-based stations and spacecraft or landers at interplanetary distances. It has evolved from laser ranging to Earth-orbiting satellites, modified with active laser transceiver systems at both ends of the link instead of the passive space-based retroreflectors. It has been estimated that this technology can be used for mm- to cm-level accuracy range determination at interplanetary distances [2, 7]. Work is being performed in the ESPaCE project [6] to evaluate in detail the potential and limitations of this technology by means of bottom-up laser link simulation, allowing for a reliable performance estimate from mission architecture and hardware characteristics.

1. Introduction

Laser ranging to retroreflector-equipped Earth-orbiting satellites (SLR), as well as reflectors on the Moon (LLR), has been performed for the last 40 years, with attainable lunar distance accuracies currently at the cm level. These measurements have been invaluable to both Earth and lunar sciences, [3]. The retroreflector technology is limited by an inverse-quartic relation between distance and signal power, however, making it infeasible for direct extension to ILR. Over such distances, an active two-way system is required, in which Earth-based and space-based transponder systems simultaneously and independently fire laser pulses towards one another, which are then detected by the opposite terminal, a method termed asynchronous laser ranging [2]. Time tagging of pulse transmission and reception times can be used to solve for the orbital characteristics of the two ends of the links, as well as geophysical and fundamental physics parameters. It has not yet been applied in the operations of a planetary spacecraft, but asynchronous ranging experiments using the laser altimeter onboard the MESSENGER spacecraft were successfully carried out [5]. Additionally, a one-way ranging variant of it is being employed for orbit determination of LRO [8].

2. ILR overview

Previous analyses of attainable ILR accuracy estimate it at the mm- to cm-level [2, 7], similar or better than those to retroreflectors [3]. This would be a several orders of magnitude increase this accuracy compared to current radiometric techniques. Advantages of laser over radiometric methods include the absence of ionospheric and solar coronal influence on a laser pulse, the use of relatively small, stable detection and transmission systems and a decrease in free-space loss. However, as laser ranging yields only a line-of-sight range measurement, the combination with VLBI and Doppler systems for interplanetary precise orbit determination should be analyzed.

Due to the absence of reflectors in a tw-way interplanetary configuration, the uncertainty associated with these systems is absent in ILR. To achieve the range determination from time tags at the two ends of the link, detected and transmitted pulses must be matched, so that the time-of-flight of the laser pulses can be determined. To achieve this, the laser pulse transmission time jitter inherent in transmitters is employed, by matching the jitter pattern as recorded at both ends of the link. High noise levels are expected at small solar incidence angles, due to stray light in the optical detection system. Retaining a reliable laser link through a minimal solar incidence angle depends on both stray light minimization and rejection in the hardware, for instance through the use of baffles, at the receivers, as well as advances in data analysis. In addition, clock stability and detection system precision at both ends of the link limits the attainable measurement precision. However, the stability of the spacecraft clock need not be of the same order as that of the ground station [1]. By pairing up- and down-link range measurements, only the time between successive receptions and transmissions at the spacecraft needs to be accurately measured, whereas the ground-based clock needs to be stable over the sum of the paired up- and down-link times.

3. Link simulation

Research into the quantitative influence of, among others, the aforementioned parameters on ranging performance and attainable accuracy of science observables is being performed in the context of the FP7 ESPaCE project by means of concurrent simulation of the laser pulse propagation, laser transceiver system performance and the dynamics of both ends of the laser link. Software is to be developed, capable of simulating laser ranging measurements and noise levels, as well as the subsequent orbit determination and parameter estimation. As part of the validation process of the simulations, laser ranging data to Earth-orbiting and lunar reflectors is to be simulated and compared to measurement data. In addition, modeled noise levels are to be compared to those measured by satellite laser ranging stations. Statistical similarity of the simulated and measured data under a variety conditions would indicate the sufficient accuracy of the model in representing the physical parameters of the link, including the associated uncertainties. Extension of the models to interplanetary distances will allow for an improved, bottom-up, understanding of the limiting parameters and a reliable definition of laser system and mission requirements from science requirements, aiding the development of mission concepts involving this technology.

4. Mission architectures

Interplanetary laser ranging can be applied in a variety of mission architectures and its data analysis can be used for gaining an improved estimation of science observables in both planetary science and gravitational physics. The possibility for orders of magnitude improvement in attained accuracy would allow for better determination of planetary gravity fields, rotational behaviour, atmospheric characteristics, etc.

A typical laser ranging architecture is described in [7] for the Phobos Laser Ranging mission proposal. It calls for the placement of a laser transceiver on the surface of Phobos, which performs asynchronous ranging to Earth-based stations. An example of a more complex mission architecture is the GETEMME mission proposal [4], in which laser retroreflectors are to be placed on both Phobos and Deimos, which are to be ranged to by a Mars orbiter. In addition, the Mars orbiter is to perform interplanetary laser ranging to Earth. Both these mission concepts aim at determining characteristics of Mars and its moons, such as their internal structure, as well as gravitation physics parameters.

5. Summary and Conclusions

Interplanetary laser ranging has the potential to allow much improved estimation of planetary science observables through a possible a orders of magnitude improvement in range determination. The work performed in the ESPaCE project will focus on determining the system, mission and operational requirements from science requirements through bottom-up simulation of interplanetary laser link,

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