Quantification of interplanetary laser ranging system requirements through bottom-up link simulations

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Interplanetary laser ranging (ILR) is an emerging technology for very high accuracy distance determination between Earth-based stations and spacecraft or landers at, for example, Martian or Jovian distances and possibly beyond. Current estimates of the attainable range measurement accuracy using this technology are at the mm- to cm-level. By comparison, radiometric range measurements are at the m-level. ILR has evolved from laser ranging to Earth-orbiting satellites, modified with active laser transmitter/detector systems at both ends of the link instead of the passive space-based retroreflectors, in order to overcome the inverse-quartic relation of signal strength with target distance. High-accuracy range measurements over interplanetary distance have applications in planetary sciences, for instance the measurement of tidal deformation of extra-terrestrial bodies, the improvement of planetary ephemerides, tests of general relativity and precision deep space navigation.

By placing a detector on the space segment, one-way range measurements can be acquired over interplanetary distances by transmitting laser pulses from Earth-based stations. This measurement technique is used for improving the orbit determination of the LRO spacecraft. However, the processing of such measurements suffers from the fact that they are made by different, not ideally synchronized, clocks. By placing an active transmitter and detector system on the space segment, dual one-way ranges (space-to-ground and ground-to-space) can be used to solve for clock offset and range simultaneously. Such a system will perform two-way ranging asynchronously, i.e. the ground- and space-segment will fire laser pulses independently of one another. This done to prevent laser signal transmissions in response to noise receptions and to ensure constant frequency laser system firing. Space-based clock stability will still be a crucial technological element of such a system, but the space-based clock stability can be substantially reduced compared to the ground-based clock, by emulation of a two-way range in the data processing.

In addition to clock stability, there are several aspects that can limit the performance of an ILR system. For instance, stray light from the Sun will strongly increase the detected noise level at small solar separation angles, causing link outages at certain values of this angle. Estimates of the limiting angle range from 2 to 10 degrees and are strongly dependent on hardware characteristics. For missions to the outer solar system or gravitational physics experiments, this could have a detrimental effect on the performance. Additionally, pointing of the spacecraft will have much more stringent requirements that is the case for current radiometric tracking.

Work is being performed in the ESPaCE project to evaluate in greater detail the potential and limitations of interplanetary laser ranging, taking into account the various technological and physical aspects. This will be done by means of concurrent, bottom-up laser link and dynamical simulations. The detection time tags of laser pulse transmissions and receptions, as well as noise signals, will be simulated directly from hardware and environmental models. Subsequently, the simulated data will be used for orbit determination and parameter estimation, allowing for a transparent link between system characteristics and the attainable precision of science observables. The virtue of this approach is that the mapping of hardware and mission geometry characteristics to link performance is obtained directly from system models, allowing for a bottom-up characterization of this performance. It also allows for easy modifications of the fidelity of hardware system models in the simulations. The software will provide the framework for a reliable definition of ground- and space-based hardware requirements, as well as mission requirements of ILR mission architectures from top-level requirements.

By performing the link simulations and subsequent orbit determination determination using the simulated measurements, several research questions will be addressed. Firstly, bottlenecks in hardware, environmental and mission geometry characteristics in the performance of the system will be assessed and the feasibility of the near-term implementation of ILR for a given set of mission types will be determined. For example, stray light characteristics of the detection system will be used in the simulation to determine, in a bottom-up manner, the minimal solar separation angle that can be achieved with it.

Secondly, the added value of having a two-way laser link instead of a one-way laser link, as well as having a laser link in addition to radiometric tracking data, will be quantitatively assessed for a variety of mission configurations. The combination of radio Doppler, VLBI and laser range measurements will be simulated and the impact of inclusion of the laser observables assessed. Thereby, the choice of the inclusion of a laser tracking system on a given mission, either by dedicated instrumentation of by making use of an existing laser altimetry or communications system, can be based firmly on science and mission requirements.

The main software validation steps that will be performed are: 1) Comparing simulated laser ranging measurements to LRO to the measured full-rate data (in the statistical sense). 2) Comparing the results of orbit determination of the LAGEOS satellites to existing orbit estimates. 3) Comparing simulated noise levels of sources important in ILR to those measured by a ground station.

The analysis framework that will be set up will aid for the future implementation of ILR, as it will assist in the quantification of the benefits of laser tracking for a given mission during the preliminary design stage.