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Antenna pattern and sensitivity analysis for an interplanetary laser trilateration mission

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Objectives

The objective of our research was to assess the fidelity and accuracy of gravitational monitoring of motions of bodies in the solar system, which could be achieved via deployment of an interplanetary laser trilateration network.

Most current information on motions of planets is obtained by use of radio-frequency range and range-rate measurements on single baselines. Deploying laser transponders in orbit about Earth, Mars, and Venus would allow simultaneous measurements on all 3 legs of that triangle. That provides much more information, including both lengths of the triangle legs, and the included angles.

In order to justify deployment of such a system, we proposed to simulate the system performance, and thereby obtain initial estimates of the measurement accuracy attainable.

Background

An array of laser transponders, moving along orbits centered on Venus, Earth, and Mars, could provide significant new information about the distribution of mass in the solar system and beyond. In this report we begin an analysis of the sensitivity and effective antenna pattern for such a device. While the main source of changes in the lengths of the three legs of the Venus-Earth-Mars triangle is motion along the nearly circular heliocentric orbits of those bodies, measurable perturbations can be caused by other masses, either inside or outside the triangle.

Our main focus here is on sources which are close to the ecliptic plane, and farther from the Sun than Jupiter. We present results on simulations of the ability of the transponder array to measure accelerations, and use that to describe the ability of the array to characterize sources of perturbing mass. Measurements of time-of-flight for short laser pulses between pairs of detectors directly constrains distance between them.

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Approach and Results

Fitting a quadratic model to a daily collection of range measurements yields an estimate of the average daily difference in accelerations at those points, projected onto the baseline between them. Range measurements along a single baseline, with 1 cm accuracy, and a 1 Hz sampling cadence, will yield acceleration sensitivity of 10^{-15} m/s^2, for each daily acceleration normal point.

We consider two different types of sources: one is an isolated point mass, and the other is a sinusoidal variation in mass density along a circular arc. In both cases, we are able to characterize the performance of the transponder array. Simultaneous projections of acceleration differences onto the 3 baselines, at a single epoch, provide unique values for the mass and position of a single point source. Characterization of distributed sources requires a range of baseline orientations.

Our focus is on analysis of the measurement accuracy attainable in this configuration.

As a first step, we estimate how well the baseline-projected difference in accelerations at the end points of the baseline can be determined, from ~1 cm accuracy range-measurements, with a ~1 Hz sampling cadence, to produce daily normal points.

A second step is to compare the accelerations due to a variety of sources, with the expected measurement accuracy. Of course, the laser trilateration network does not directly sense accelerations of the detectors. However, we can easily compute an acceleration-related quantity which is observable. It is the difference between accelerations at the ends of a baseline connecting two receivers, projected onto the direction of that baseline.

A third step moves from source-defined accelerations to perturbations of the orbits of the planets hosting the transponders. These changes in orbit geometry are directly observable in the range data.

We have examined the simulated performance of an interplanetary laser trilateration system, with sensors moving along the orbits of Venus, Earth, and Mars. Our primary focus is on the system’s ability to sense and characterize mass sources in the outer solar system. Assuming that each interplanetary range measurement has an accuracy of 1 cm, and that such measurements are made at a 1 Hz sampling cadence, the daily normal point acceleration accuracy would be of order *2 ×10-15 m/s2*.

As a possible signal, consider a 1 Earth mass source at 100 AU distance from the Sun. It yields an acceleration of 1.8 10^{-12} m/s^2. The difference in accelerations, from that source, at the opposite ends of a 2 AU baseline, oriented parallel to the source direction, is considerably smaller, only 7 10^{-14} m/s^2, but still above the measurement threshold for a one day observing session. The hypothetical planet 9 (Batygin et al. 2019) has been suggested to be at a 4-8 times larger distance, with a mass 5-10 times larger. It is thus conceivably detectable via a gravitational signature, within a single day.

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Significance

We have shown that an interplanetary laser trilateration network, using measurement accuracies already demonstrated on relevant baseline lengths, would provide orders of magnitude improvement in recovered accuracy of the lengths and angles in the Earth-Mars-Venus triangle. The accuracy would be sufficient to allow this network to determine masses of many solar system bodies.

Characterizing distributed sources requires a time series of projected acceleration differences, but also appears promising. The higher harmonics of the interior potential from a ring of mass, located beyond Jupiter, yield smaller signal amplitudes than the lower harmonics. The ultimate achievable spatial resolution will depend upon the signal amplitude spectrum.

There are still many aspects of the design and implementation of such a network, which require further attention. Our focus here has been upon characterizing distant mass sources. The system proposed by Smith et al. (2018) is mainly focused on examining solar mass loss, and consequent changes in the inner solar system.

Characterizing distributed sources requires a time series of projected acceleration differences, but also appears promising.

References

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