Testing Gravitational Time Delay Predictions of General Relativity

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There is yet no theory that successfully combines general relativity (GR) with quantum theory, so testing GR more fully is an important scientific goal for new observation programs. Deviations from GR of a large class of alternative gravity theories is characterized by the difference $\gamma - 1$, where γ is a spatial curvature parameter. Improved information about γ would provide important insight into the evolution of the universe and directly limit the range of applicability of alternative theories. The outstanding stability and accuracy of optical clocks would best be utilized by placing such clocks in space, outside of noisy laboratory environments. The unique logarithmic time signature of time delay of electromagnetic signals passing near the sun is uncorrelated with most systematic error sources and could allow accurate clocks placed in strategically located positions to improve measurements of $\gamma - 1$ by three orders of magnitude. Currently the uncertainty in $\gamma - 1$ is about 2×10^{-5}.

Consider a spacecraft (S1) containing a highly stable optical clock, placed in an orbit around the Lagrange L1 point. A second spacecraft (S2) could be placed in a 2 year period orbit in the ecliptic plane, with an eccentricity of 0.37. S2 would pass through superior solar conjunction at aphelion, as seen from L1, about one year after launch and 2 and 4 years thereafter. Both spacecraft would have carefully designed drag-free systems to nearly eliminate the effects of spurious non-gravitational forces on them. Statistical analysis of measurement errors for such a mission is available and shows that a measurement of $\gamma - 1$ to a level of 10^{-8} could be carried out by observing the time delay of laser signals exchanged between the spacecraft when the line of sight passes near the sun's limb. Also, at aphelion the spacecraft temperature will not change much during an 8 day observing period. By adjusting the phase of the S2 orbit with respect to the earth, the aphelion of the S2 orbit can be made to occur during the measurements; the range rate then becomes very close to zero, and the orbit determination problem is much reduced. The theoretical expression for the time delay has been worked out to second order. Other effects, such as time delay due to the sun's quadrupole moment, can be estimated with sufficient accuracy that they will not contribute to the error budget of such a mission.

The major requirement is to fly an optical clock on S1 that has very high stability over a period of at least 8 days around superior conjunction. The nominal design goal for such a mission is to achieve a fractional frequency noise power spectral density amplitude of $3 \times 10^{-15} / \sqrt{Hz}$ from 1 Hz down to at least 10^{-6} Hz. One leading candidate for the optical clock is a Yb positive ion clock based on a single cooled ion in a trap; only low laser power is required for such a clock, giving Yb^+ an advantage. A second leading candidate is a neutral ^{87}Sr optical clock based on optical lattice confinement of the atoms.

Additional effects such as those arising from non-linear terms in the 00-component of the metric tensor, parameterized by β, as well as other time delay effects originating in the sun's rotation, could also be measured. Continued development of advanced, space-qualified optical clocks is a prerequisite for such relativity missions.