J. THE ROLE OF SLR AND LLR IN RELATIVITY

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While General Relativity has been adopted as the standard theory of relativity, there are alternative theories, with important implications for gravitational physics, which can only be discounted with tests of sufficient accuracy. Table 1 indicates the status of some of these tests. In addition to its contributions to lunar and solar system dynamics, Lunar Laser Ranging (LLR), in combination with other solar system data, continues to refine some important limits [Dickey et al., 1994]. SLR tracking to geodetic satellites can provide similar tests, but the accuracy is usually limited by the variety of gravitational and nongravitational perturbations [Vincent, 1986].

One important exception is the proposed Lageos-III mission, which would provide a measurement of the Lense-Thirring precession. The Lense-Thirring precession is the gravitomagnetic, or "frame-dragging", effect on a satellite orbit, in which the orbit plane is "dragged" in the direction of the Earth's rotation. The analogous effect on a gyroscope, called the Schiff precession, is expected to be measured by the Gravity Probe B mission to better than one percent. Using a pair of high-density, high-altitude satellites in orbits with supplementary inclinations, the existence of the gravito-magnetic effect could be confirmed, providing experimental support for the general relativistic formulation of the Mach Principle [Ciufolini, 1986]. The supplementary inclinations provides for a precise cancellation of the most important gravitational perturbations, while the orbital height and small area-to-mass ratio reduces the surface forces to a level which can be effectively modeled.

It is estimated that a three-year Lageos-III mission could verify the Lense-Thirring precession at the few percent level, with further improvement possible if extended over a longer period [Tapley and Ciufolini, 1989; Ries et al., 1993]. While there are a number of forces acting on the satellite which affect the orbit plane to some degree, none of them appears to affect the secular drift of the orbit plane sufficiently to interfere with the experiment. Preliminary analysis indicates that the Lageos-III satellite could be launched supplementary to Lageos-1 or Lageos-2 with about the same results. With the dual satellite configuration in place, there also may be other relativistic and geophysical experiments possible that have not yet been imagined.

SLR tracking to Lageos has also provided the most accurate determination of the Earth's gravitational coefficient (GM) and demonstrated the importance of considering the relativistic consequences of the definition of time in the various reference frames (Ries et al., 1992). The accurate determination of GM is critical in the definition of the absolute scale of the geocentric reference frame, affecting intercomparisons of SLRdetermined station coordinates with VLBI and the determination of absolute ocean height from altimetric satellites. In addition, the Lageos SLR analysis has demonstrated the need for considering additional relativistic geopotential effects in the solar system barycentric model or near-Earth applications [Ries et al., 1988]. The precise determination of absolute distance is a primary reason for the sensitivity of SLR to relativistic effects, and the continued improvement in the SLR system will increase the accuracy in the determination of the scale of the geocentric frame.

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Table 1. Solar System Relativity Tests

Light deflection by the Sun (Viking Lander data)	verified $\gamma = 1 \pm .002$
Excess perihelion precession of Mercury	verified $\beta = 1 \pm .003$
Gravitational redshift (Gravity Probe-A)	verified effect of gravity on time
Weak equivalence principle	verified to few parts in 10^{11} in laboratory
Strong equivalence principle	LLR limit on Nordtvedt effect $\Rightarrow \beta = 1 \pm .0006$
PPN constants due to preferred frame effects or violation of conservation of total momentum	deviations from GR less than 10^{-3}
Geodetic (de Sitter) precession	verified to <1% via LLR and VLBI
Gravitomagnetic, or 'frame-dragging' effect not yet directly observed	'Lense-Thirring' precession of orbit 'Schiff' precession of gyroscopes
$\dot{G} / G$	limit from LLR + solar system data $< 10^{11}$/yr

(β and γ are Parameterized Post-Newtonian parameters which are identically 1 in General Relativity)