Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI
SIS – Pubblicazioni

LNF–08/ 03 (P)
February 4, 2008

A NEW APPROACH TO LAGEOS SPIN ORIENTATION AND ITS ROLE IN GENERAL RELATIVITY MEASUREMENTS

Douglas Currie
Depart. of Physics, University of Maryland, College Park, MD, 20742, USA

Simone Dell'Agnello, Giovanni Delle Monache, Marco Garattini, Roberto Tauraso
INFN–LNF, via E. Fermi, 40, Frascati (Rome), ITALY

Abstract

The two LAGEOS Satellites have addressed a variety of issues in Geophysics (GP) and General Relativity (GR). The extreme accuracy of laser ranging (currently approaching millimeter accuracy) now means that very small error sources act upon LAGEOS and have become important, affecting the study of GP (e.g., the tides) and GR (e.g., Lense-Thirring Effect). Initial measurements and analysis of the spin orientation were first performed at the in the early 1990s at the University of Maryland. However, the spin rate of LAGEOS has slowed to the point that this method is no longer effective. A new observing approach (the "Pocket Modulation Effect") to determine the spin axis has been proposed by the first author. Data that addresses this method has been collected at various sites and is being analyzed at INFN-LNF. We will report on the physics involved in the PME and describe the laboratory data and simulations performed to validate the proposed approach, the LAGEOS data obtained at sites, the new analysis procedures and then address the impact of this new information.

Submitted to the 10th ICATPP Conference on Astroparticle, Particle,
Space Physics, Detectors and Medical Physics Applications,
8-12 October 2007, Villa Olmo (Como), Italy

1. SCIENCE MOTIVATION

1.1. Mach's Principle and General Relativity (GR)

Mach's Principle addresses the fact while we cannot distinguish the physics in frames in relative linear motion, we can clearly distinguish a rotating frame. Earnest Mach addressed this problem in 1893, and hypothesized that a "non-rotating" frame was established by the distant matter in the universe, that is, the distant matter of the universe affects the physics in a local frame. Within the framework GR, such an effect may exist, related to the measurement of the so-called Lense-Thirring effect.

1.2. Lense-Thirring Effect – (L-TE)

Many parameters of GR have been experimentally addressed. However, almost all of these experiments address static effects, that is, the effects on experiments of a static configuration of masses. The dynamical effects, that is, the effects caused by moving masses has only recently been addressed. The L-TE is the effect of the mass current of the rotating earth, i.e., as it twists space-time and alters the orientation of a gyroscope. Using the LAGEOS satellite, Ciufolini has evaluated the L-TE at the 10% level. GPB is another experiment expected to address the measurement of the L-TE.

1.3. Gravito-Electro-Magnetics

The L-TE can be understood by noting the close relationship between these aspects of L-TE and the theory of Electrodynamics. Just as an electric current in a closed loop generates a dipole magnetic field that causes a compass needle to twist, the mass current generated by the rotation of a finite size spinning body such as the earth and its rotation generates effects in L-TE that causes a twist in a local frame outside the earth. This is the L-TE for a satellite such as LAGEOS. Another effect that can be addressed with respect to the Gravito-Electro-Dynamics approach as the interaction of two parallel currents. In electrodynamics this is referred to as Ampere's Law. The "mass currents" generated by the motion of the earth and moon about the sun also cause an effect on the moon's orbit. This should be measurable with the new accuracy expected with the APOLLO Lunar Ranging Station and the even higher accuracy of the proposed new arrays for the moon proposed by the University of Maryland.

1.4. Chern-Simons Gravity

Within the structure of String Theory, Chern & Simons have proposed a modification of the GR equations. It has recently been shown by Smith et. al. that using the measurements of the L-TE with the LAGEOSs they can place interesting limits on the magnitude of the coupling coefficients. This addresses such recently discovered phenomena as Dark Energy.

2. TECHNOLOGY ASPECTS

We now address some technology aspects of the measurements using LAGEOS and future similar satellites. We will review the methods of measurements and then the possible error sources and finally the methods to correct these forces. However, most of the material will be review very briefly and we shall concentrate on the effects of photon thrust. That is, the emission of photons from the heated surface of the satellite and the reaction that moves the satellite into an new orbit.

2.1. Laser Ranging Accuracy

The orbits of the satellites are determined by laser ranging, using a very narrow laser pulse is sent from a ground station, reflected directly back to the ground stations by special mirrors, the Cube Corner Retro-reflectors, (CCRs). Photo-detectors then receive the reflected pulse and determine the time since the transmission. From such repeated measurements, one determines the orbit of the satellite. Currently, for most of the interesting measurements, the limiting accuracy is not the precision to which this time can be measured, but other more systematic effects to be addressed in the next sub-sections.

2.2 Gravitational Forces

Of course the dominate “force” on the satellites is the gravitational force of the earth, the “force” that assures the satellite moves on a geodesic from the view of GR. The higher moments in the gravitational field must be known very accurately in order to form a basic reference orbit. Recent satellite measurements have reduced the gravitational field uncertainties to a level that is acceptable.

2.3. Non-Gravitational Forces

In addition to the gravitational forces, there are a number of non-gravitational forces that must be addressed. These consist of solar pressure, atmospheric drag due to both neutral particles and charged particles. Again, these are manageable. However, the photon thrust or thermal thrust is a force that must be addressed in order to make the accurate measurements of the perturbations that are of interest.

2.4. Satellite Motions

We now briefly review the rotational effects on LAGEOS. It is essentially a metal ball rotating in the magnetic field of the earth so electrical currents are generated within the satellite. The energy of these currents, which comes from the rotational energy, is converted to heat, so the rotation rate of the satellite slows. Further, the earth’s magnetic field acting on these currents twists the orientation of the spin axis.

2.5. Photon Thrust

Photon Thrust is the effect caused by the combination of the solar heating of the satellite and the rotation of the satellite. Thus as the sun heats the satellite on one side, an excess of infra-red photons are emitted. However, this warm side is rotated away from the sun and the direction of the reaction force now depends upon the rotation of the satellite. A more detailed analysis shows that for a rapidly rotation satellite, the force is along the axis of rotating. Thus is critical to determine the orientation of the spin axis in order to make these corrections.

3. DETERMINATION OF THE DIRECTION OF THE PHOTON THRUST

3.1. Background – Solar Glint Approach (SGA)

There is a cluster of theoretical estimates of the spin rate, the orientation of the spin axis. However, the first determinations of the orientation based upon observations were conducted in the 1990s at the University of Maryland. The orientation of the spin axis has been determined by the observation of the sun glints reflecting from the front surface of the CCRs. These photometric records can be used to determine the orientation of the spin axis. Andres was the first incorporate the measurements into an orbital determination program LOSSAM. In recent years, other stations have been performing the photometry to contribute to the improved orbit evaluated by Andres.

3.2. Current Challenges

After launch, the rapid rotation of LAGEOS I permitted the SGA to be used very effectively. However, it now has a period of thousands of seconds and the SGA is no longer a feasible approach. The reason for the difficulty with slow rotation is that the reflected image of the sun is a narrow beam as it sweeps across the earth. Unless the apparent axis of rotation (primarily changing due to the geometry of the pass) remains within one degree for a quarter of a rotation period, the SGA cannot effectively be used. Thus the combination of the narrow beam of the solar reflection and the slow rational period causes the problem. For this reason, a new method is required.

4. POCKET EFFECT APPROACH

4.1. Theoretical Pocket Effect Approach (PEA)

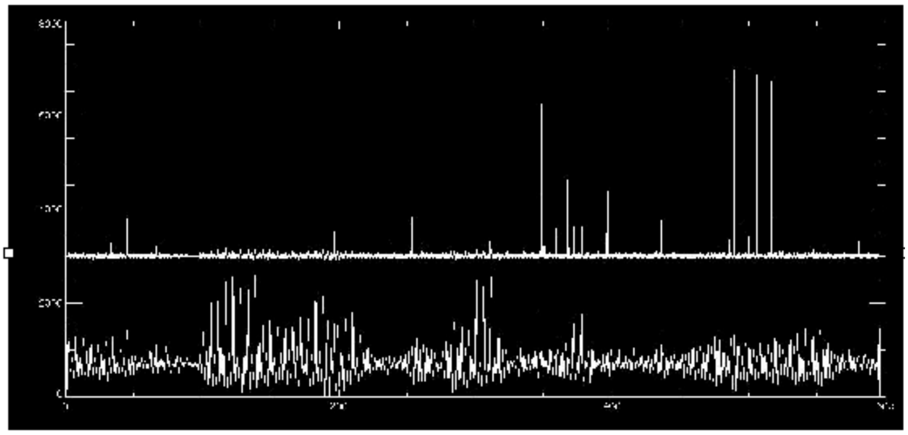
In order to understand the PEA, consider the LAGEOS satellites as a shiny ball with no CCRs. Viewed in the sunlight, we see a small (a few millimeters) image of the sun on the surface. As the ball rotates, the brightness of the image remains the same, yielding a constant photometric signature. Now consider a shiny ball that his many holes or pockets so much of the surface is covered with pockets. Now as the shiny ball with pockets rotates, when the image of the sun is on the remaining shiny surface, we again see the constant photometric signature. However, as a hole rotates into the image of the sun, the intensity of the reflection will go to zero. During the rotation, we expect to see no intensity for about 8 degrees of rotation and the bright surface signature during abut 2 degrees of rotation. Thus due to the larger angles of rotation covered by the PEA, one has several hundred times better coverage for the rotation information. In fact, since more than half of the surface is covered with pockets so we always get signatures, unlike the SGA. Now consider a CCR in each of the pockets. If the image of the sun passes very precisely over the center of the pocket, we will get a Fresnel reflection and a very bright signal. However, this will happen only occasionally for LAGEOS II and never twice for the same band for LAGEOS I due to the latter's slow rotation.

4.2. Experimental Laboratory Test

To confirm these theoretical expectations of the satellite behavior, we have obtained a GSFC engineering model that was built with LAGEOS I. It is a sector of the LAGEOS satellite that has been loaned to INFN for these tests. A video taken as the sector rotates confirms the above expectations.

4.3. LAGEOS II observations

In 2004, LAGEOS II was observed on the 3.6 meter telescope at the Starfire Optical Range in New Mexico, USA, using the RULLI camera built by LANL. This camera records the time of arrival of individual photoelectrons w/extreme precision. The figure shows a 600 second recording of the solar reflection of LAGEOS II.



RULLI Observations of LAGEOS II

The upper plot displays the solar glints recorded by the RULLI Camera These solar glints have been used at the University of Maryland to determined the orientation of the spin axis. The lower curve illustrates the variation in the diffuse reflection. It is the latter we are now using to test the new method to determine the orientation.

4.4. Data Reduction

The development of the analysis algorithms is in progress. This data will initially be treated in the same manner as the SGA data. However the results are obviously less accurate in the angle than the SGA. The PEA will predict and/or identify when a SGA glint will occur. Thus with a single SGA glint, we can identify its source and use it to the upgrade the accuracy to the SGA level.

5. CONCLUSIONS

The use of artificial and natural satellites has already yielded most of the most accurate tests of GR. In the future, they should lead to a better understand of the dynamical effects in GR, especially w.r.t. the L-TE, String theory in the Chern-Simons approach and torsion effects. A critical aspect is to retain the ability to measure the orientation of the spin axis of the LAGOES-type satellites during the time that they are slowing. The PEA is providing such an observational and analytic approach. An expanded version of this paper with figures, videos and references may be found at
http://www.physics.umd.edu/rgroups/astrometro.html
http://www.lnf.infn.it/acceleratori/lares/LAGEOS%20article%20list.htm

6. ACKNOWLEDGEMENTS

The authors thanks David Thompson of LANL, Mark Davis of NRL and Ron Dantowitz of the Clay Center Observatory for LAGEOS observations. The first author thanks INFN for travel support to coordinate the analysis of this data.