Laser Relativity Satellite: A Search for the Dragging of Inertial Frames (the Lense-Thirring Effect)

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The positional accuracies currently attainable with the Global Positioning System (GPS) constellation require the inclusion of corrections for Special Relativity (time dilation due to relative velocity) and General Relativity (gravitational red shift due to gravitational potential difference). Gravitational red shift is really the mismatch of coordinate time and proper time within the curved spacetime surrounding a gravitational source. GPS currently uses the corrections appropriate for a static non-rotating gravitational source (the Schwarzschild metric); a future correction, should it ever be an operational necessity, would be the inclusion of effects induced by rotation of the source (the Kerr metric). Lense and Thirring predict the existence of a gravito-magnetic effect often referred to as the dragging of inertial frames. A particle in radial free-fall toward the center of the source will experience a lateral deflection in the direction of rotation of the source; a gyroscope in free-fall will experience an anomalous precession over and above the Special Relativistic Thomas precession, and orbiting bodies will experience a non-Newtonian progression of the line of nodes. The existence of gravitational effects directly traceable to the angular momentum of the gravitating source has not been observationally established. Gravity Probe B, scheduled for launch in the near future, consists of a supremely sensitive gyroscope capable of testing for the anomalous precession. A second test based on a constellation of laser-ranged satellites is possible. The US Naval Academy Small Satellite Program proposes to supplement NASA's LAGEOS I satellite with a second laser ranged satellite to be called WeberSat-LARES. The pair of satellites would permit a second, independent test of the Lense-Thirring effect to supplement that of Gravity Probe B. In addition, WeberSat-LARES will provide supplemental data from the 6000-km regime of non-gravitational perturbations as well as enhance the geodesy mission of LAGEOS I and II.

I. INTRODUCTION

The United States Naval Academy (USNA) Small Satellite Program (SSP) was founded in 1999 to actively pursue flight opportunities for miniature satellites designed, constructed, tested, and commanded or controlled by Midshipmen. The SSP provides funds for component purchase and construction, travel in support of testing and integration, coordination with DoD or National Aeronautics and Space Administration (NASA) laboratories or with universities for collaborative projects, and guides Midshipmen through the Department of Defense (DoD) Space Experiments Review Board (SERB) flight selection process.

The satellite development process is a multi-semester effort requiring the contributions of Midshipmen from several consecutive graduating classes. First Class Midshipmen (seniors) in EA470 Spacecraft Design initiate the process in the spring semester of their First Class year with identification of the mission and determination of requirements, followed by development of the conceptual design. Students in subsequent classes take the satellite through feasibility study, final design, construction, testing and launch platform integration. Each spring, First Class Midshipmen in the design class reinitiate the process with a new satellite concept so that new projects are germinating to take the place of those that are coming to completion and awaiting launch.

The SSP has two successful launches to its credit. USNA-0, Stanford AudioPhonic PHotographic InfraRed Experiment (SAPPHIRE) was designed and constructed by students at Space Systems Development Laboratory at Stanford University, Palo Alto CA, and prepared for flight by the Project Aria team at Washington University in St. Louis,

MO. Title to the satellite transferred to SSP in order for SAPPHIRE to qualify for a DoD-sponsored launch. After deployment, SAPPHIRE served as a satellite command/control platform for training USNA astronautics students.

USNA-1, Prototype Communications Satellite (PCSat) was completely designed and constructed by Midshipmen. PCSat operated as an orbiting node of the Automatic Position Reporting System (APRS), a volunteer service maintained by amateur radio operators worldwide. [1] The satellite carried dual redundant VHF receivers operating at 145 MHz and controlled by off-the-shelf 1200 baud terminal node controllers programmed for the amateur radio service's AX.25 protocol. Amateur radio operators were able to communicate with and through PCSat with handheld transceivers of modest cost. In seventeen months of operation, PCSat provided communications support to over 2000 users on all continents, including Antarctica. PCSat's batteries expired and the satellite was declared non-operational on 10 July 2003.

USNA-2, PCSat2, is a duplicate of the PCSat package providing communications and telemetry support for a Naval Research Laboratory (NRL) experiment to be mounted externally on the International Space Station once Space Shuttle flights resume. [2] USNA-3 is a similar package providing communications support for NRL's Atmospheric Neutral Density Experiment satellite to be deployed from the Space Shuttle. USNA-4, Midsipman Space Technology Applications Research Satellite (MidSTAR-1), is being built to support two SERB-approved and STP-sponsored experiments; it is scheduled for launch in March 2006.

The scope of projects supported by SSP is limited by the resources of the USNA Department of Aerospace Engineering. The astronautics cadre of the Department consists of five individuals: one full professor (now serving as Department Chair), one permanent military professor, two full-time visiting professors and one half-time visiting professor. These five are assisted by two staff members assigned to the USNA Satellite Ground Station (SGS): one senior engineer and one senior technician. The Midshipmen participating in SSP-sponsored projects are predominantly drawn from the First Class (senior) majors in aerospace engineering who have chosen to concentrate on astronautics. This number fluctuates from year to year; current enrollment is 20 for the class of 2004 and 17 for the class of 2005.

Financial resources are also thin. Projects are initiated with seed money from a \$50K/year grant to the USNA Foundation from The Boeing Co., or from internal USNA funds. Additional funds are occasionally available for specific projects from collaborating federal agencies or sponsors.

Cognizant of these constraints, the SSP has consciously and deliberately entered the spaceflight arena in an incremental manner. USNA-0 was obtained as a complete and tested spacecraft from an experienced university small satellite producer. USNA-1 was designed and built in-house, but with a build-it-simple-and-rugged philosophy. Onboard systems were limited: communications and electrical power only. Missions were sharply defined: the communications system itself was the primary mission, and the secondary mission (an onboard Global Positioning System receiver) needed only power and communications support that both meshed well with the PCSat design. Commercial off-the-shelf parts were chosen for ruggedness, simplicity and low cost rather than spaceflight heritage. Pre-flight testing was limited to verification of functionality after vibration and thermal/vacuum environment testing.

USNA-2 and USNA-3 are repetitions of the proven PCSat communications system design. USNA-4 is a new satellite design, larger and more complicated than PCSat, but still limited in scope and dedicated to experiments of moderate interest. The project proposed here offers a unique opportunity for SSP to participate fully in cutting-edge science, despite its limited financial and personnel resources.

II. THE LENSE-THIRRING EFFECT

The major experimental tests of general relativity — gravitational time dilation and electromagnetic frequency shift, precession of orbital pericenter and gravitational deflection of light — were all first observed or measured nearly a century ago in the decades immediately after publication of the theory, although all have been tested with increasing accuracy numerous times in the intervening years. The advent of spaceflight, the discovery of pulsars and the development of very long baseline interferometry techniques in radio astronomy added the observation of gravitational time delay to the list. The placement of laser retroreflector arrays on the Moon by the Apollo program allowed refined measurements of some of the above as well as permitting examination of the de Sitter effect. [3] Two other major tests of general relativity, the direct detection of gravitational waves and observation of a gravitodynamic field analogous to the magnetic field of a spinning electric charge (gravitomagnetism, or the Lense-Thirring effect [4]) remain to be resolved.

The origin of the Lense-Thirring effect lies in the existence of the off-diagonal term $g^{t\phi}$ in the Kerr metric [5] given in the weak-field, slow-motion limit [6] by

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 + \frac{2M}{r}\right) dr^2 + r^2\, d\theta^2 + r^2 \sin^2\theta\, d\phi^2 - \frac{4J}{r} \sin^2\theta\, d\phi dt.$$

The last term appears as a velocity-dependent non-radial addition to the classical Newtonian acceleration

$$m\frac{d^2\vec{x}}{dt^2} = m\left(\vec{G} + \frac{d\vec{x}}{dt} \times \vec{H}\right)$$

where $\vec{H}$ is the gravitomagnetic field.

The cross term integrated over the orbit of a satellite was shown by Lense and Thirring to contribute to the precession of the line of nodes in the amount of [7]

$$\dot{\Omega}^{Lense-Thirring} = \frac{2\vec{J}}{a^3(1-e^2)^{3/2}}$$

where a is the semi-major axis, e is the eccentricity and $\vec{J}$ is the angular momentum of the central body. This differs from the classical precession of the nodes caused by the mass quadrupole moment J_2 of the central body

$$\dot{\Omega}^{classical} = -\frac{3}{2}n\left(\frac{R_E}{a}\right)^2 \frac{J_2 \cos i}{(1-e^2)^2}$$

where n is the mean motion and R_E is the equatorial radius of the central body, in that the Lense-Thirring precession is independent of the inclination i while the classical precession is proportional to $\cos i$ and reverses sign for retrograde satellites ($i > \pi/2$).

As such, the classical precession of the nodes will be equal and opposite, and therefore cancel out, for two satellites in orbits of supplementary inclination (i and $\pi - i$) with identical semi-major axis and eccentricity. The line of intersection of the two orbital planes will be stationary with respect to an inertial reference frame. The Lense-Thirring precession will be the same for the two satellites, however, and will introduce a precession of that line of intersection with respect to the inertial frame in the direction of rotation of the central body. Long-term observation of the satellite pair allows the calculation of the anomalous precession and the demonstration of the existence of the gravitomagnetic field.

Ciufolini et. al. [8] [9] [10] have proposed a search for the Lense-Thirring effect based on such a two-satellite constellation. The satellites are mounted with optical retroreflectors permitting precise determination of location via laser ranging. Precise measurement of the round-trip travel time can determine the distance from ground station to satellite to an accuracy of a few millimeters.

III. THE LASER RELATIVITY SATELLITE (LARES)

Ciufolini's proposal takes maximum advantage of existing infrastructure by pairing a new satellite with the first LAser GEOdynamics Satellite (LAGEOS I) launched in 1976 to measure crustal motion, plate tectonics movements, polar wandering and Earth rotation variations via laser ranging. LAGEOS I consists of 424 retroreflectors 48 mm in diameter mounted on a hollow aluminum shell 0.3 m in radius. A brass cylinder .28 m long, .32 m in diameter will be mounted at the center of the aluminum sphere to provide a high ballistic coefficient and minimize susceptibility to aerodynamic drag. Total mass is 407 kg. LAGEOS I is in a circular orbit of semi-major axis $a = 12270$ km (5900 km altitude), eccentricity 0.004 and inclination 109.94 degrees.

WeberSat-LARES will be placed in an identical orbit save that the inclination will be supplementary: 70.06 degrees. The satellite could either be a duplicate of LAGEOS I, or a smaller 100 kg sphere of 15 cm radius. Prevous proposals for LAGEOS III called for an orbit of essentially zero eccentricity; LARES requires an eccentricity of 0.04 ± 0.01. This permits a measurement of the precession of the perigee that will substantially enlarge the range of general relativistic effects which can be investigated.

The ground segment for this experiment will be the International Laser Ranging Network (ILRN) which currently tracks both LAGEOS I and LAGEOS II (identical to LAGEOS I but in an orbit unsuitable for this experiment). The network is capable of adding WeberSat-LARES to its tracking set at no additional cost. The ranging data, plus corrected elevation and azimuth data for the satellites, will be processed by NASA Goddard Space Flight Center and archived in a public domain data base accessible to the data analysis team.

IV. THE WEBERSAT-LARES PROGRAM

The SSP has initiated a program to launch LARES as USNA-5 under the name WeberSat-LARES in memory of Joseph Weber, a USNA graduate of the class of 1940.

SSP management feels that this is a suitable project for SSP as the engineering challenges associated with producing the spacecraft are limited and well-defined by the conceptual simplicity of the satellite. The lack of active onboard systems removes the necessity for power, communications, telemetry/control and command/data handling. Tracking is accomplished by the ground segment. The symmetrical design removes the necessity for attitude determination and control. Precise knowledge of spin dynamics is required for data reduction and analysis, but this will also be acquired by the ground segment of the mission.

With current plans, the satellite will be funded and constructed by international partners and delivered to USNA SSP for flight testing, flight certification, and launch platform integration. Midshipmen majoring in engineering disciplines at USNA will perform vibration, acoustic, and thermal/vacuum testing on the spacecraft under the guidance of USNA faculty, professional staff, and consultant engineers supported by the SSP. Midshipmen will participate in the exchange of test data with the integrating contractor, in the process acquiring first-hand experience with DoD launch acquisition procedures and large-systems acquisition management practices.

SSP submitted a proposal for WeberSat-LARES to the Navy SERB in August of 2002. After receiving the endorsement of the Navy SERB, the experiment was presented to the DoD SERB in November of 2002. WeberSat-LARES was accepted by DoD SERB and assigned to the 2002 DoD SERB Approved List with a priority of 40 out of 45. Its presence on the 2002 DoD SERB Approved List makes WeberSat-LARES eligible for launch by the DoD Space Test Program (STP) administered by the US Air Force (USAF) Space and Missile Systems Center (SMC). STP chooses experiments for flight based on sometimes conflicting parameters of SERB priority, available launch resources and readiness for flight. STP typically pays all of the costs of the launch including procurement of the launch vehicle, modification as required for the specific experiment and integration of the spacecraft onto the launch platform.

If WeberSat-LARES is not manifested in the current fiscal year (FY) (defined as assigned to a scheduled launch) it must be reviewed by the following fiscal year's Navy and DoD SERBs. It will continue to be eligible for flight only if it is once again approved and assigned a new priority. This process must be repeated each year until WeberSat-LARES is manifested, withdrawn by SSP, or rejected by the SERB. Once manifested, the experiment need no longer undergo SERB review.

The SERB evaluates experiments on the basis of military relevance (60%), quality (20%) and flight readiness (20%). SERB ranking is independent of funding status, but STP does not consider any experiment for flight unless it has adequate funding to support fabrication, delivery and data reduction.

The military relevance of WeberSat-LARES is primarily founded on the role of USNA SSP as the overall program manager of the experiment. As program manager and DoD sponsor, SSP is able to include USNA students (Midshipmen) in the Aerospace Engineering major in the program management process. This gives the students the unique opportunity to learn space systems program management and engineering development by direct participation and contributes immensely to their training as Naval officers and future leaders of Navy space activities. Additional military relevance flows from the contribution that this experiment will make to the fundamental understanding of astrodynamics, space navigation and geodesy.

The quality of the WeberSat-LARES experiment, defined as its intrinsic scientific interest, maturity of engineering design and low risk of failure, is undeniably high.

The flight readiness of WeberSat-LARES in non-existent as there is no spacecraft in being and no pledge of financial support for the construction of the spacecraft. Nevertheless, the 2002 SERB was sufficiently impressed by this experiment to give its approval. Viewed in retrospect, a firm committment to fund construction of the satellite would have secured it a higher position on the SERB list. SSP management is optimistic that any future review of WeberSat-LARES, bolstered by a firm pledge of support for fabrication will yield a significantly higher priority number and elevated level of interest within STP.

By far, the greatest obstacle to the flight of WeberSat-LARES is acquisition of a launch vehicle. The dedication of a launch vehicle to this specific mission alone is difficult to justify. And needless to say, the SSP does not have the funds needed to purchase a launch outright. Two credible possibilities exist: as with all previous SSP-sponsored spacecraft, access to space might come in the form of a secondary-payload slot on another project's launch; or more colorfully, WeberSat-LARES might ride into space as a low-risk, low-value payload on a demonstration or test launch. This last possibility requires a fortuitous configuration of test requirements consistent with the WeberSat-LARES orbit.

Thus constrained, the SSP strategy is to anticipate and wait. The first step is to acquire the satellite — either with the resources and cooperation of the international partners, or domestically with SSP-acquired and managed resources — and immediately complete the test and flight certification process. The satellite is then put in long-term storage and the second step begins — a broad community announcement that the completed, immediately flight-ready satellite exists and is available for manifest on risk-reduction, test and certification or demonstration launches. SSP explicitly acknowledges in advance that the chance of losing the spacecraft, or of ending up in an unsuitable orbit, is accepted without question and without regret.

V. POSSIBLE LAUNCH SCENARIO

The Rocket Systems Launch Program (RSLP) Office of Detachment 12/SMC, Kirtland AFB NM has recently awarded Orbital Sciences Corp. (OSC) of McLean VA a contract for the development and launch of space launch vehicles derived from decommissioned Peacekeeper Intercontinental Ballistic Missiles, to be known as the PKSLV. Launch and range support for the PKSLV will be available at Cape Canaveral Air Force Station (CCAFS), Vandenberg Air Force Base (VAFB), NASA's Wallops Island (VA) Flight Facility (WFF), and the Alaska Aerospace Development Agency's Kodiak Island Lauch Complex (KLC).

Preliminary performance estimates have been released for all four sites [11]. Range safety considerations dictate that only KLC is capable of direct injection into a 70 deg inclination orbit. Each of the other sites would require a plane-change maneuver with a concomitant sacrifice of performance in order to complete the mission.

The PKSLV is capable of putting 1500 kg into a 200 km altitude, 70 deg circular orbit when launched from KLC. The total Δv necessary to proceed from there to the WeberSat-LARES orbit (6000 km altitude, at the same inclination) is 2.1 km/sec. Assuming a moderate specific impulse of 350 sec, the mass ratio required is 1.8. Of the 1500 kg total placed into low-earth parking orbit, 810 kg total is available for payload (407 kg) and airframe (403 kg). For the low mass variant of WeberSat-LARES (100 Kg), 710 kg would be available for the airframe. Any mass not needed for the airframe could be allocated to secondary payloads for maximum return on investment.

The cost of the mission is dependent upon timing. The RSLP/OCS contract calls for the first flight of the PKSLV to be procured on a cost-plus-incentive-fee basis with an additional mission success payment. The fly-away cost for a typical mission is estimated at $26-29 million. Subsequent missions are to be procured on a firm-fixed-price-plus-incentive- fee basis plus a mission success payment. Fly-away costs here are estimated at $17.5-19.5 million. These prices include all mission documentation, engineering support, payload integration/processing, launch and range costs as well as the cost of the launch vehicle itself.

For WeberSat-LARES, additional funds would be needed to procure and integrate the transfer stage necessary for transfer to the 6000-km orbit.

The first mission is expected to require a 24 month development schedule; subsequent launches are expected to require an 18 month development schedule.

VI. SCIENTIFIC INTEREST

The nature of dark energy may be found through string theory and thereby signal a violation of general relativity. Interest in the investigation of the dynamical aspects of general relativity is increasing within the cosmological and theoretical physics community. Gravity Probe B, scheduled for launch in the near future, will test for the existence of Lense-Thirring frame dragging in the form of anomalous gyroscopic precession. The WeberSat-LARES experiment will permit a second, independent test of the Lense-Thirring effect with a relative accuracy of 1%. In addition, the experiment will

- improve precision bounds on the existence of weak, long-range gravitational forces; deviations from the inverse-square law for weak gravitational fields; and improve on tests of the equivalence principle for ranges of a few thousand kilometers;
- test the existence of preferred frames of reference in some alternative metric theories of gravity;
- provide a precision measurement of the general relativistic precession of the perigee of WeberSat-Lares to test general relativity against other metric theories of gravity; and,
- provide significant improvements in satellite laser ranging contributions to geodesy and geodynamics in the areas of plate tectonics, crustal deformation, and variability of Earth rotation and geocenter location.

This experiment is a rare conjunction of high scientific potential with straightforward technological implementation, and an unprecedented challenge for USNA's undergraduate aerospace engineering majors and military officer candidates.

[1] B. Bruninga, B. Smith and D. Boden, PCSat Success! and follow-on payloads, *16th Annual AIAA/USU Conference on Small Satellites*, Logan UT, 12-15 August 2002.

[2] B. Bruninga, C. Otero, H. Evans, T. Kolwicz, M. Silver, E. Henry and D. Jones, PCSat2: Synergy in the Amateur Satellite Service, *17th Annual AIAA/USU Small Satllite Conference*, Logan UT, 11-14 August 2003.

[3] I. Ciufolini and J. A. Wheeler, *Gravitation and Inertia* (Princeton University Press, Princton, 1995) p. 89. Secondary reference; see this item for primary references.

[4] J. Lense and H. Thirring, Über den Einfluss der Eigenrotation der Zentralkörpfer auf die Bewegung der Planeten und Monde nach der Einsteinen Gravitationstheorie, *Phys. Z.* 19:156-63 (1918). Available in English translation by B. Mashhoon, F. W. Hehl and D. S. Theiss in *Gen. Rel. Grav.* 16:711-750 (1984).

[5] R. P. Kerr, Gravitational field of a spinning mass as an example of algebraically special metrics, *Phys. Rev. Lett.* 11:237-8 (1963).

[6] I. Ciufolini and J. A. Wheeler, *Gravitation and Inertia* (Princeton University Press, Princton, 1995) p. 42. Secondary reference; see this item for primary references.

[7] I. Ciufolini, Measurement of Lense-Thirring drag on high-altitude laser ranged artificial satellies, *Phys. Rev. Lett.* 56:278-81 (1986).

[8] I. Ciufolini, et. al., *LARES Phase A Study for ASI* (1998).

[9] I. Ciufolini and A. Paolozzi, LARES: A new laser-ranged satellite for fundamental physics and general relativity, *Actual Problems of Aviation and Aerospace Systems: Processes, Models, Experiments*, No.1 (7), 61-73, (1999).

[10] I. Ciufolini, D. Currie and A. Paolozzi, The LARES mission for studying the dynamics of general relativity, IEEEAC paper #1456, 3 January 2003.

[11] K. Sebek, H. Knorreck, M. Elson and S. Buckley, Low-cost, reliable spacelift for small satellites using a Peacekeeper ICBM derived space launch vehicle and multi-payload adapters, *17th Annnual AIAA/USU Small Satellite Conference*, Logan UT, 11-14 August 2003.