FUNDAMENTAL PHYSICS WITH THE LASER ASTROMETRIC TEST OF RELATIVITY

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Abstract

The Laser Astrometric Test Of Relativity (LATOR) is a joint European-U.S. Michelson-Morley-type experiment designed to test the metric nature of gravitation – a fundamental postulate of Einstein’s theory of general relativity. By using a combination of independent time-series of highly accurate gravitational deflection of light in the immediate proximity to the Sun, along with measurements of the Shapiro time delay on interplanetary scales (to a precision respectively better than 10^-13 radians and 1 cm), LATOR will significantly improve our knowledge of relativistic gravity. The primary mission objective is to i) measure the key post-Newtonian Eddington parameter γ with accuracy of a part in 10^9, (1 − γ) is a direct measure for presence of a new interaction in gravitational theory, and, in its search, LATOR goes a factor 30,000 beyond the present best result, Cassini’s 2003 test. Other mission objectives include: ii) first measurement of gravity’s non-linear effects on light to ~0.01% accuracy; including both the traditional Eddington β parameter and also the spatial metric’s 2nd order potential contribution (never measured before); iii) direct measurement of the solar quadrupole moment $J_2$ (currently unavailable) to accuracy of a part in 200 of its expected size; iv) direct measurement of the “frame-dragging” effect on light due to the Sun’s rotational gravitomagnetic field, to 1% accuracy. LATOR’s primary measurement pushes to unprecedented accuracy the search for cosmologically relevant scalar-tensor theories of gravity by looking for a remnant scalar field in today’s solar system. The key element of LATOR is a geometric redundancy provided by the laser ranging and long-baseline optical interferometry. LATOR is envisaged as a partnership between European and US institutions and with clear areas of responsibility between the space agencies: NASA provides the deep space mission components, while optical infrastructure on the ISS is an ESA contribution. We discuss the mission and optical designs of this proposed experiment.

Key words: Fundamental physics, tests of general relativity, scalar-tensor theories, laser ranging, LATOR mission

1. Introduction

After almost ninety years since general relativity was born, Einstein’s general theory of relativity (GR) has survived every test. Such longevity, of course, does not mean that this theory is absolutely correct, but it serves to motivate more accurate tests to determine the level of accuracy at which it is violated. GR began its empirical success in 1915 by explaining the anomalous perihelion precession of Mercury’s orbit, using no adjustable theoretical parameters.
Shortly thereafter, Eddington’s 1919 observations of star lines-of-sight during a solar eclipse confirmed the doubling of the deflection angles predicted by GR, as compared to Newtonian-like and Equivalence Principle arguments. This test made general relativity an instant success.

From these beginnings, the general theory of relativity has been verified at ever higher accuracy. Thus, microwave ranging to the Viking Lander on Mars yielded a \( \sim 0.2\% \) accuracy in the tests of GR (Shapiro et al. 1976, Reasenberg et al. 1979). Spacecraft and planetary radar observations reached an accuracy of \( \sim 0.15\% \) (Anderson et al. 2002). The astrometric observations of quasars on the solar background performed with Very-Long Baseline Interferometry (VLBI) improved the accuracy of the tests of GR to \( \sim 0.045\% \) (Shapiro et al. 2004). Lunar laser ranging, a continuing legacy of the Apollo program, provided \( \sim 0.011\% \) verification of GR via precision measurements of the lunar orbit (Nordtvedt 2003, Williams et al. 2004). Finally, the recent experiments with the Cassini spacecraft improved the accuracy of the tests to \( \sim 0.0023\% \) (Bertotti et al. 2003). As a result, general relativity became the standard theory of gravity when astrometry and spacecraft navigation are concerned.

However, the tensor-scalar theories of gravity, where the usual general relativity tensor field coexists with one or several long-range scalar fields, are believed to be the most promising extension of the theoretical foundation of modern gravitational theory. The superstring, many-dimensional Kaluza-Klein, and inflationary cosmology theories have revived interest in the so-called `dilaton fields’, i.e. neutral scalar fields whose background values determine the strength of the coupling constants in the effective four-dimensional theory. The importance of such theories is that they provide a possible route to the quantization of gravity and the unification of physical laws.

Recent theoretical findings suggest that the present agreement between GR and experiment might be naturally compatible with the existence of a scalar contribution to gravity. In particular, Damour & Nordtvedt (1993) (see also Damour & Polyakov 1994) for non-metric versions of this mechanism together with Damour et al. (2002) for the recent summary of a dilaton-runaway scenario have found that a scalar-tensor theory of gravity may contain a `built-in’ cosmological attractor mechanism towards GR. These scenarios assume that the scalar coupling parameter \( \frac{1}{2}(1-\gamma) \) was of order one in the early universe (say, before inflation), and show that it then evolves to be close to, but not exactly equal to, zero at the present time. Under some assumptions (see e.g. Damour & Nordtvedt 1993, Damour et al. 2002) one can even estimate what is the likely order of magnitude of the left-over coupling strength at present time, with results in the range from \( 10^{-6} \) to \( 5 \times 10^{-8} \) for \( (1-\gamma) \), i.e. for observable post-Newtonian deviations from general relativity predictions. This would require measurement of the effects of the next post-Newtonian order \( (\propto G^2) \) of light deflection resulting from gravity’s intrinsic non-linearity. An ability to measure the first order light deflection term at the accuracy comparable with the effects of the second order is of the utmost importance for gravitational theory and a major challenge for the 21st century fundamental physics.

Another attractive theoretical possibility to extend GR involves a putative breaking of Lorentz invariance through a nonvanishing vacuum expectation value of a vector field (Kostelecký 2004). This is a quite realistic scenario, for instance, in the context of string field theory. Solutions and potential observational implications have recently been examined (Bertolami & Páramos 2006).

When the light deflection in solar gravity is concerned, the magnitude of the first order light deflection effect, as predicted by GR, for the light ray just grazing the limb of the Sun is \( \sim 1.75 \) arcsecond. (Note that 1 arcsecond \( \approx 5 \) \( \mu \)rad; when convenient, below we will use the units of radians and arcseconds interchangeably.) The effect varies inversely with the impact parameter. The second order term is almost six orders of magnitude smaller resulting in \( \sim 11 \) microarcseconds \( (\mu\text{as}) \) light deflection effect, and which falls off inversely as the square of the light ray’s impact parameter (Epstein & Shapiro 1980, Richter & Matzner 1982, Nordtvedt 1987, Turyshev et al. 2004a).

This paper discusses the Laser Astrometric Test of Relativity (LATOR) mission that is designed to directly address the challenges outlined above with an unprecedented accuracy (Turyshev et al. 2004a). LATOR will test the cosmologically motivated theories that explain the small acceleration rate of the Universe (so-called `dark energy’) via modification of gravity at very large, horizon or super-horizon distances. This solar system scale experiment would search for a cosmologically-evolved scalar field that is predicted by modern theories of quantum gravity and cosmology, and also by superstring and brane-world models (Dvali et al. 2000). The physics of a scalar field in the solar system have also been invoked (Bertolami & Páramos 2004) as a possible solution to the Pioneer anomaly (Dittus et al. 2005). The value of the Eddington parameter \( \gamma \) may hold the key to the solution of the most fundamental questions concerning the evolution of the universe. In the low energy approximation suitable for the solar system, modern theories discussed above predict measurable contributions to the parameter \( \gamma \) at the level of \( (1-\gamma) \sim 10^{-6} - 10^{-8} \), detecting this deviation is LATOR’s primary objective. With the accuracy of \( 1 \times 10^{-9} \), this mission could discover a violation or extension of general relativity, and/or reveal the presence of any additional long range interaction.

The paper is organized as follows: Section 2 provides the overview for the LATOR experiment, including the preliminary mission design. In Section 3 we discuss the current optical design for the LATOR flight system. We also present the expected performance for the LATOR instrument. Section 4 discusses the next steps that will be taken in the development of the LATOR mission.
2. THE LATOR MISSION

The LATOR mission architecture uses an evolving light triangle formed by laser ranging between two spacecraft (placed in ∼1 AU heliocentric orbits) and a laser transceiver terminal on the International Space Station (ISS), via European collaboration. The objective is to measure the gravitational deflection of laser light as it passes in extreme proximity to the Sun (see Figure 1). To that extent, the long-baseline (∼100 m) fiber-coupled optical interferometer on the ISS will perform differential astrometric measurements of the laser light sources on the two spacecraft as their lines-of-sight pass behind the Sun. As seen from the Earth, the two spacecraft will be separated by about 1°, which will be accomplished by a small maneuver immediately after their launch (Turyshev et al. 2004a; Turyshev et al. 2005b). This separation would permit differential astrometric observations to an accuracy of ∼10⁻¹³ radians needed to significantly improve measurements of gravitational deflection of light by the solar gravity.

Figure 1. The overall geometry of the LATOR experiment.

To enable the primary objective, LATOR will place two spacecraft into a heliocentric orbit, so that observations may be made when the spacecraft are behind the Sun as viewed from the ISS (see Figures 2 and 3). To avoid having to make absolute measurements, the spacecraft will be placed in a 3:2 Earth resonant orbit that provides three observing sessions during the initial 21 months after the launch, with the first session starting in 15 months (Turyshev et al. 2004a). Such an orbit provides significant variation of the impact parameter (i.e. distance between the beam and the center of the Sun): the parameter will vary from 10 to 1 solar radii over a period of ∼20 days. The three arms of the triangle will be monitored with laser ranging, based on the time-of-flight measurements accurate to ∼1 cm. From three measurements one calculates the Euclidean value for any angle in this triangle.

As is evident from Figure 1, the key element of the LATOR experiment is a redundant geometry optical truss to measure departure from Euclidean geometry (∼8 × 10⁻⁶) caused by the solar gravity field. This departure is shown as a difference between the calculated Euclidean value for an angle in the triangle and its value directly measured by the interferometer. This discrepancy, which results from the curvature of the space-time around the Sun and can be computed for every alternative theory of gravity, constitutes LATOR’s signal of interest. The built-in redundancy eliminates the need for drag-free spacecraft for high-accuracy navigation (Turyshev et al. 2004a). The uniqueness of this mission comes with its built-in geometrically redundant architecture that enables LATOR to measure the departure from Euclidean geometry to a very high accuracy. The precise measurement of this departure constitutes the primary mission objective.

2.1. SCIENCE WITH LATOR

LATOR is a Michelson-Morley-type experiment designed to test the pure tensor metric nature of gravitation - a fundamental postulate of Einstein’s theory of general relativity (Turyshev et al. 2004a). With its focus on gravity’s action on light propagation it complements other tests which rely on the gravitational dynamics of bodies. By using a
combination of independent time-series of highly accurate gravitational deflection of light in the immediate proximity to the Sun along with measurements of the Shapiro time delay on the interplanetary scales (to a precision respectively better than $10^{-13}$ rad and 1 cm), LATOR will significantly improve tests of relativistic gravity.

The primary mission objective is to measure the key post-Newtonian Eddington parameter $\gamma$ with an accuracy of a part in $10^9$. This parameter, whose value in GR is unity, is perhaps the most fundamental PPN parameter, in that $(1 - \gamma)$ is a direct measure of the presence of a new interaction in gravitational theory (Damour & Nordtvedt 1993, Damour & Esposito-Farese 1996, Turyshchev et al. 2004a). Within perturbation theory for such theories, all other PPN parameters to all relativistic orders collapse to their GR values in proportion to $(1 - \gamma)$. This is why the measurement of the first order light deflection effect at a level of accuracy comparable with the second-order contribution would provide the crucial information separating alternative scalar-tensor theories of gravity from the general theory of relativity (Nordtvedt 1987) and also to probe possible scenarios for the quantization of gravity, as well as testing modern theories of cosmological evolution (Damour & Polyakov 1993, Dvali et al. 2000, Damour et al. 2002) discussed in the previous section. LATOR is designed to directly address this issue with an unprecedented accuracy.
Table 1. LATOR Mission Summary: Science Objectives

| Qualitative Objectives:                                                                                                           |
|-----------------------------------------------------------------------------------------------------------------------------------|
| • To test the metric nature of the Einstein’s general theory of relativity in the most intense gravitational environment available in the solar system – the extreme proximity to the Sun |
| • To test alternative theories of gravity and cosmology, notably scalar-tensor theories, by searching for cosmological remnants of scalar field in the solar system |
| • To verify the models of light propagation and motion of the gravitationally-bounded systems at the second post-Newtonian order (i.e. including effects $\propto G^2$) |

| Quantitative Objectives:                                                                                                           |
|-----------------------------------------------------------------------------------------------------------------------------------|
| • To measure the key Eddington PPN parameter $\gamma$ with accuracy of 1 part in $10^9$ – a factor of 30,000 improvement in the tests of gravitational deflection of light |
| • To provide direct and independent measurement of the Eddington PPN parameter $\beta$ via gravity effect on light to $\sim 0.01\%$ accuracy |
| • To measure the 2-nd order gravitational deflection of light with accuracy of $\sim 1 \times 10^{-9}$, including first ever measurement of the post-PPN parameter $\delta$ |
| • To measure solar quadrupole moment $J_2$ (using the theoretical value of $J_2 \simeq 10^{-7}$) to 1 part in 200, currently unavailable |
| • To directly measure the frame dragging effect on light (first such observation and also first direct measurement of solar spin) with $\sim 1 \times 10^{-3}$ accuracy.|

and in its search, LATOR goes a factor 30,000 beyond the present best result, Cassini’s 2003 test (Bertotti et al. 2003). It will also reach ability to measure the next, i.e. post-post-Newtonian, order ($\propto G^2$) of light deflection with accuracy to 1 part in $10^3$. (Note that it has been shown that there are no new higher-order PPN parameters entering the $O(G^2)$ order of light deflection.) Other mission objectives are presented in Table 1. LATOR’s primary measurement pushes to unprecedented accuracy the search for cosmologically relevant scalar-tensor theories of gravity by looking for a remnant scalar field in today’s solar system.

The goal of measuring deflection of light in solar gravity with accuracy of one part in $10^6$ requires serious consideration of systematic errors. This work requires a significant effort to properly identify the entire set of factors that may influence the accuracy at this level. Fortunately, we initiated this process aided by previous experience in the development of a number of instruments that require similar technology and a comparable level of accuracy (Turyshev et al. 2004a). This experience comes with understanding various constituents of the error budget, expertise in developing appropriate instrument models; it is also supported by the extensive verification of the expected performance with instrumental test-beds and existing flight hardware. Details of the LATOR error budget are being developed and will be published elsewhere, when fully analyzed. Recent covariance studies confirmed the expected mission performance and emphasized the significant potential of the mission (Nordtvedt 2005; Plowman & Hellings 2005).

We shall now consider the LATOR optical design.

3. Optical Design

A single aperture of the interferometer on the ISS consists of three 20 cm diameter telescopes (see Figure 3 for a conceptual design). One of the telescopes with a very narrow bandwidth laser line filter in front and with an InGaAs camera at its focal plane, sensitive to the 1064 nm laser light, serves as the acquisition telescope to locate the spacecraft near the Sun.

The second telescope emits the directing beacon to the spacecraft. Both spacecraft are served out of one telescope by a pair of piezo controlled mirrors placed on the focal plane. The properly collimated laser light ($\sim 10\text{W}$) is injected into the telescope focal plane and deflected in the right direction by the piezo-actuated mirrors.

The third telescope is the laser light tracking interferometer input aperture which can track both spacecraft at the same time. To eliminate beam walk on the critical elements of this telescope, two piezo-electric X-Y-Z stages are used to move two single-mode fiber tips on a spherical surface while maintaining focus and beam position on the fibers and other optics. Dithering at a few Hz is used to make the alignment to the fibers and the subsequent tracking of the two spacecraft completely automatic. The interferometric tracking telescopes are coupled together by a network of single-mode fibers whose relative length changes are measured internally by a heterodyne metrology system to an accuracy of less than 10 pm.

The spacecraft are identical in construction and contain a relatively high powered (1 W), stable (2 MHz per hour) laser at 1064 nm. Three quarters of the power of this laser is pointed to the Earth through a 10 cm aperture telescope and its phase is tracked by the interferometer. With the available power and the beam divergence, there are enough photons to track the slowly drifting phase of the laser light. The remaining part of the laser power is diverted to another telescope, which points towards the other spacecraft. In addition to the two transmitting telescopes, each spacecraft has two receiving telescopes. The receiving telescope, which points towards the area near the Sun, has laser line filters and a simple knife-edge coronagraph to suppress the Sun light to 1 part in $10^4$ of the light level of the light received from the space station. The receiving telescope that points to the other spacecraft is free of the Sun light filter and the coronagraph.

In addition to the four telescopes they carry, the spacecraft also carry a tiny (2.5 cm) telescope with a CCD
Figure 4. Basic elements of optical design for the LATOR interferometer: The laser light (together with the solar background) is going through a full aperture (∼20 cm) narrow band-pass filter with ∼10^{-4} suppression properties. The remaining light illuminates the baseline metrology corner cube and falls onto a steering flat mirror where it is reflected to an off-axis telescope with no central obscuration (needed for metrology). It is then enters the solar coronograph compressor by first going through a 1/2 plane focal plane occulter and then coming to a Lyot stop. At the Lyot stop, the background solar light is reduced by a factor of 10^6. The combination of a narrow band-pass filter and coronograph enables the solar luminosity reduction from $V=-26$ to $V=4$ (as measured at the ISS), thus, enabling the LATOR precision observations.

In the next Section we present elements for the LATOR optical receiver system. While we focus on the optics for the two spacecraft, the interferometer’s architecture includes essentially similar optical components.

3.1. The LATOR Optical Receiver System

The LATOR 100 mm receiver optical system is a part of a proposed experiment. This system is located at each of two separate spacecraft placed on heliocentric orbits, as shown in Figure 4. The receiver optical system captures optical communication signals from a transmitter on the ISS, which orbits the Earth. To support the primary mission objective, this system must be able to receive the optical communication signal from the uplink system at the ISS that passes through the solar corona at the immediate proximity of the solar limb (at a distance of no more than 5 Airy disks). Our recent analysis of the LATOR 100 mm receiver optical system successfully satisfied all the configuration and performance requirements (Turyshev et al. 2004b; Plowman & Hellings 2005). We have also performed a conceptual design (see Figure 5), which was validated with a ray-trace analysis. The ray-trace performance of the designed instrument is diffraction limited in both the APD and CCD channels over the specified field of view at 1064 nm. The design incorporated the required field stop and Layot stop. A preliminary baffle design has been developed for controlling the stray light.

3.2. Preliminary Baffle Design

Figure 6 shows the LATOR preliminary baffle design. The out-of-field solar radiation falls onto the narrow band pass filter and primary mirror; the scattering from these optical surfaces puts some solar radiation into the FOV of the two focal planes. This imposes some requirements on the instrument design. Thus, the narrow band pass filter and primary mirror optical surfaces must be optically smooth to minimize narrow angle scattering. This may be difficult for the relatively steep parabolic aspheric primary mirror surface. However, the field stop will eliminate direct out-of-field solar radiation at the two focal planes, but it will not eliminate narrow angle scattering for the filter and camera. This telescope is used to initially point the spacecraft directly towards the Sun so that their signal may be seen at the space station. One more of these small telescopes may also be installed at right angles to the first one to determine the spacecraft attitude using known bright stars. The receiving telescope looking towards the other spacecraft may be used for this purpose part of the time, reducing hardware complexity. Star trackers with this construction have been demonstrated many years ago and they are readily available. A small RF transponder with an omni-directional antenna is also included in the instrument package to track the craft while they are on their way to assume the orbital position needed for the experiment.

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primary mirror. Finally, the Lyot stop will eliminate out-of-field diffracted solar radiation at the two focal planes. Additional baffle vanes may be needed at several places in the optical system. This design will be further investigated in series of trade-off studies by also focusing on the issue of stray light analysis. Figure 7 shows the design of the focal plane capping. The straight edge of the ‘D’-shaped CCD field stop is tangent to the limb of the Sun and it is also tangent to the edge of APD field stop. There is a 2.68 arcsecond offset between the straight edge and the concentric point for the circular edge of the CCD field stop. The results of the analysis of APD and CCD channels point spread functions can be found in (Turyshev et al. 2004b).

4. Conclusions

The LATOR experiment benefits from a number of advantages over techniques that use radio waves to study the light propagation in the solar vicinity. The use of monochromatic light enables the observation of the spacecraft almost at the limb of the Sun, as seen from the ISS. The use of narrowband filters, coronagraph optics, and heterodyne detection will suppress background light to a level where the solar background is no longer the dominant noise source. The short wavelength allows much more efficient links with smaller apertures, thereby eliminating the need for a deployable antenna. Advances in optical communications technology allow low bandwidth telecommunications with the LATOR spacecraft without having to deploy high gain radio antennae needed to communicate through the solar corona. Finally, the use of the ISS not only makes the test affordable, but also allows conducting
the experiment above the Earth’s atmosphere, the major source of astrometric noise for any ground based interferometer. This fact justifies the placement of LATOR’s interferometer node in space.

The concept is technologically sound; the required technologies have been demonstrated as part of the international laser ranging activities and optical interferometry programs at JPL. LATOR does not need a drag-free system, but uses a geometric redundant optical truss to achieve a very precise determination of the interplanetary distances between the two micro-spacecraft and a beacon station on the ISS. The experiment takes advantage of the existing space-qualified optical technologies, leading to an outstanding performance in a reasonable mission development time. In addition, the issues of the extended structure vibrations on the ISS, interferometric fringe ambiguity, and signal acquisition on the solar backgrounds have all been analyzed, and do not compromise mission goals. The ISS is the default location for the interferometer, however, ground- and free-flying versions have also been studied. While offering programmatic benefits, these options differ in cost, reliability and performance. The availability of the ISS (via European collaboration) makes this mission concept realizable in the very near future. A recent JPL Team X study confirmed the feasibility of LATOR as a NASA Medium Explorer (MIDEX) class mission.

LATOR is envisaged as a partnership between NASA and ESA wherein both partners are essentially equal contributors, while focusing on different mission elements: NASA provides the deep space mission components and interferometer design, while building and servicing infrastructure on the ISS is an ESA contribution. The NASA focus is on mission management, system engineering, software management, integration (both of the payload and the mission), the launch vehicle for the deep space component, and operations. The European focus is on interferometer components, the initial payload integration, optical assemblies and testing of the optics in a realistic ISS environment. The proposed arrangement would provide clean interfaces between familiar mission elements.

This mission may become a 21st century version of the Michelson-Morley experiment in the search for a cosmologically evolved scalar field in the solar system. As such, LATOR will lead to very robust advances in the tests of fundamental physics: it could discover a violation or extension of general relativity, and/or reveal the presence of an additional long range interaction in the physical law. There are no analogs to the LATOR experiment; it is unique and is a natural culmination of solar system gravity experiments.

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