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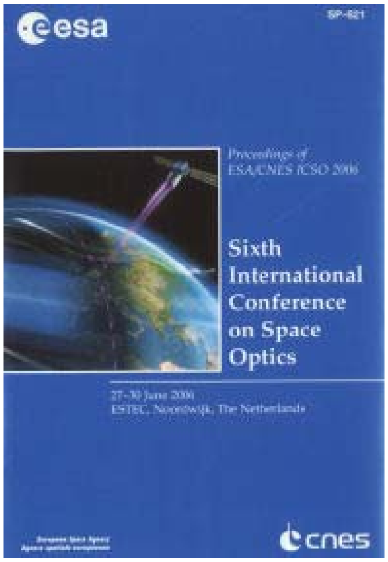

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# *Science, technology and mission design for LATOR experiment*

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# SCIENCE, TECHNOLOGY AND MISSION DESIGN FOR LATOR EXPERIMENT

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## ABSTRACT

The Laser Astrometric Test of Relativity (LATOR) is a Michelson-Morley-type experiment designed to test the Einstein's general theory of relativity in the most intense gravitational environment available in the solar system – the close proximity to the Sun. By using independent time-series of highly accurate measurements of the Shapiro time-delay (laser ranging accurate to 1 cm) and interferometric astrometry (accurate to 0.1 picoradian), LATOR will measure gravitational deflection of light by the solar gravity with accuracy of 1 part in a billion, a factor ∼30,000 better than currently available. LATOR will perform series of highly-accurate tests of gravitation and cosmology in its search for cosmological remnants of scalar field in the solar system. We present science, technology and mission design for the LATOR mission.

Key words: gravitation, interferometry, laser ranging.

## 1. SCIENTIFIC MOTIVATION

The continued inability to merge gravity with quantum mechanics, and recent cosmological observations indicate that the pure tensor gravity of general relativity needs modification. 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. Although the scalar fields naturally appear in the theory, their inclusion predicts corrections to Newtonian motion that may be observed in properly designed experiments. As a result, this progress has provided strong motivation for high precision relativistic gravity tests.

In this paper we will consider new scientific motivations for high-accuracy gravitational tests with LATOR; we will also present the proposed technological solution and mission design (for more details please consult (Turyshev et al., 2005; Turyshev, Shao, and Nordtvedt, 2006)).

### 1.1. The PPN Formalism

Generalizing on a phenomenological parameterization of the gravitational metric tensor field which Eddington originally developed for a special case, a method called the parameterized post-Newtonian (PPN) metric has been developed Will (1993) (see also discussion in (Turyshev, Shao, and Nordtvedt, 2006) and references therein). This method represents the gravity tensor's potentials for slowly moving bodies and weak interbody gravity, and it is valid for a broad class of metric theories including general relativity as a unique case. The several parameters in the PPN metric expansion vary from theory to theory, and they are individually associated with various symmetries and invariance properties of underlying theory. Gravity experiments can be analyzed in terms of the PPN metric, and an ensemble of experiments will determine the unique value for these parameters, and hence the metric field, itself.

In locally Lorentz-invariant theories the expansion of the metric field for a single, slowly-rotating gravitational source in PPN coordinates is given by:

$$\begin{aligned} g_{00} &= 1 - 2\frac{M}{r}Q(r,\theta) + 2\beta\frac{M^2}{r^2} + \mathcal{O}(c^{-6}), \\ g_{0i} &= 2(\gamma+1)\frac{[\vec{J}\times\vec{r}]_i}{r^3} + \mathcal{O}(c^{-5}), \\ g_{ij} &= -\,\delta_{ij}\Big[1 + 2\gamma\frac{M}{r}Q(r,\theta) + \frac{3}{2}\delta\frac{M^2}{r^2}\Big] + \mathcal{O}(c^{-6}), \end{aligned} \tag{1}$$

where $M$ and $\vec{J}$ being the mass and angular momentum of the Sun, $Q(r,\theta) = 1 - J_2\frac{R^2}{r^2}\frac{3\cos^2\theta - 1}{2}$, with $J_2$ being the quadrupole moment of the Sun and $R$ being its radius. $r$ is the distance between the observer and the center of the Sun. $\beta, \gamma, \delta$ are the PPN parameters and in general relativity they are all equal to 1. The $M/r$ term in the $g_{00}$ equation is the Newtonian limit; the terms multiplied by the post-Newtonian parameters $\beta, \gamma$, are post-Newtonian terms. The term multiplied by the post-post-Newtonian

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parameter $\delta$ also enters the calculation of the relativistic light deflection (Nordtvedt, 1996).

This PPN expansion serves as a useful framework to test relativistic gravitation in the context of the LATOR mission. In the special case, when only two PPN parameters ($\gamma$, $\beta$) are considered, these parameters have clear physical meaning. Parameter $\gamma$ represents the measure of the curvature of the space-time created by a unit rest mass; parameter $\beta$ is a measure of the non-linearity of the law of superposition of the gravitational fields in the theory of gravity. General relativity, which corresponds to $\gamma = \beta = 1$, is thus embedded in a two-dimensional space of theories. The Brans-Dicke is the best known theory among the alternative theories of gravity. It contains, besides the metric tensor, a scalar field and an arbitrary coupling constant $\omega$, which yields the two PPN parameter values $\gamma = (1 + \omega)/(2 + \omega)$, and $\beta = 1$. More general scalar tensor theories yield values of $\beta$ different from one.

The most precise value for the PPN parameter $\gamma$ is at present given by the Cassini mission (Bertotti, Iess, and Tortora, 2003) as: $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$. Using the recent Cassini result (Bertotti, Iess, and Tortora, 2003) on the PPN $\gamma$, the parameter $\beta$ was measured as $\beta - 1 = (0.9 \pm 1.1) \times 10^{-4}$ from LLR (Williams, Turyshev, and Boggs, 2004). The next order PPN parameter $\delta$ has not yet been measured though its value can be inferred from other measurements. Below, we will discuss motivations for new precision gravity experiments.

### 1.2. Tensor-Scalar Theories of Gravity

Recent theoretical findings suggest that the present agreement between general relativity and experiment might be naturally compatible with the existence of a scalar contribution to gravity. The Eddington parameter $\gamma$, whose value in general relativity is unity, is perhaps the most fundamental PPN parameter, in that $\frac{1}{2}(1 - \gamma)$ is a measure, for example, of the fractional strength of the scalar gravity interaction in scalar-tensor theories of gravity (please consult (Turyshev, Shao, and Nordtvedt, 2006) and references therein). Within perturbation theory for such theories, all other PPN parameters to all relativistic orders collapse to their general relativistic values in proportion to $\frac{1}{2}(1-\gamma)$. This is why measurement of the first order light deflection effect at the level of accuracy comparable with the second-order contribution would provide the crucial information separating alternative scalar-tensor theories of gravity from general relativity and also to probe possible ways for gravity quantization and to test modern theories of cosmological evolution (Damour and Nordtvedt, 1993; Damour and Polyakov, 1994; Damour, Piazza, and Veneziano, 2002). The LATOR mission is designed to directly address this issue with an unprecedented accuracy.

In particular, Damour and Nordtvedt (1993) have found that a scalar-tensor theory of gravity may contain a "built-in" cosmological attractor mechanism toward general relativity. 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 (Turyshev, Shao, and Nordtvedt, 2004). They have estimated the likely order of magnitude of the left-over coupling strength at present time which, depending on the total mass density of the universe, can be given as $1 - \gamma \sim 7.3 \times 10^{-7}(H_0/\Omega_0^3)^{1/2}$, where $\Omega_0$ is the ratio of the current density to the closure density and $H_0$ is the Hubble constant in units of 100 km/sec/Mpc. Compared to the cosmological constant, these scalar field models are consistent with the supernovae observations for a lower matter density, $\Omega_0 \sim 0.2$, and a higher age, $(H_0 t_0) \approx 1$. If this is indeed the case, the level $(1-\gamma) \sim 10^{-6} - 10^{-7}$ would be the lower bound for the present value of PPN parameter $\gamma$ (Damour and Nordtvedt, 1993).

More recently, Damour, Piazza, and Veneziano (2002) have estimated $\frac{1}{2}(1 - \gamma)$, within the framework compatible with string theory and modern cosmology, which basically confirms the previous result (Damour and Nordtvedt, 1993). This recent analysis discusses a scenario when a composition-independent coupling of dilaton to hadronic matter produces detectable deviations from general relativity in high-accuracy light deflection experiments in the solar system. This work assumes only some general property of the coupling functions (for large values of the field, i.e. for an "attractor at infinity") and then only assume that $(1 - \gamma)$ is of order of one at the beginning of the controllably classical part of inflation. It was shown in (Damour, Piazza, and Veneziano, 2002) that one can relate the present value of $\frac{1}{2}(1 - \gamma)$ to the cosmological density fluctuations. They found that even for the simplest inflationary potentials the level of the expected deviations from general relativity is $\sim 0.5 \times 10^{-7}$. Note that these predictions are based on the scalar-tensor extensions of gravity that are consistent with, and indeed often part of, present cosmological models.

Over the recent decade, the technology has advanced to the point that one can consider carrying out direct tests in a weak field to second order in the field strength parameter ($\propto G^2$). Although any measured anomalies in first or second order metric gravity potentials will not determine strong field gravity, they would signal that modifications in the strong field domain will exist. The converse is perhaps more interesting: if to high precision no anomalies are found in the lowest order metric potentials, and this is reinforced by finding no anomalies at the next order, then it follows that any anomalies in the strong gravity environment are correspondingly quenched under all but exceptional circumstances.

### 1.3. Cosmological Motivations for New Tests

Recent astrophysical measurements of the angular structure of the cosmic microwave background (please consult (Spergel et al., 2006) and references therein) have placed stringent constraints on the cosmological constant $\Lambda$ and also have led to a revolutionary conclusion: the expansion of the universe is accelerating. This completely unexpected discovery demonstrates the importance of testing the important ideas about the nature of gravity. Given the challenge of this problem, a number of authors considered the possibility that cosmic acceleration is not due to some kind of stuff, but rather arises from new gravitational physics (see discussion in (Peebles and Ratra, 2003; Carroll et al., 2004)). In particular, some extensions to general relativity in a low energy regime (Carroll et al., 2004) were shown to predict an experimentally consistent universe evolution without the need for dark energy. These dynamical models are expected to produce measurable contribution to the parameter $\gamma$ in experiments conducted in the solar system also at the level of $1-\gamma \sim 10^{-7}-5\times10^{-9}$, thus further motivating the relativistic gravity research. Therefore, the PPN parameter $\gamma$ may be the only key parameter that holds the answer to most of the questions discussed above. Also an anomalous parameter $\delta$ will most likely be accompanied by a '$\gamma$ mass' of the Sun which differs from the gravitational mass of the Sun and therefore will show up as anomalous $\gamma$ (see discussion in (Nordtvedt, 2003)).

The analyses discussed above not only motivate new searches for very small deviations of relativistic gravity in the solar system, they also predict that such deviations are currently present in the range from $10^{-5}$ to $5\times10^{-8}$ for $\frac{1}{2}(1-\gamma)$, i.e. for observable post-Newtonian deviations from general relativity predictions and, thus, should be easily detectable with LATOR. 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.

### 1.4. 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, Shao, and Nordtvedt, 2004). With its focus on gravity's action on light propagation it complements other tests which rely on the gravitational dynamics of bodies. The idea behind this experiment is to use a combination of independent time-series of highly accurate measurements of the 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). Such a combination of observables is unique and enables LATOR to significantly improve tests of relativistic gravity.

The LATOR's primary mission objective is to measure the key post-Newtonian Eddington parameter $\gamma$ with an accuracy of a part in $10^9$. When the light deflection in solar gravity is concerned, the magnitude of the first order effect as predicted by general relativity for the light ray just grazing the limb of the Sun is $\sim 1.75$ arcsecond (asec). The effect varies inversely with the impact parameter. The second order term is almost six orders of magnitude smaller resulting in $\sim 3.5$ microarcseconds ($\mu$as) light deflection effect, and which falls off inversely as the square of the light ray's impact parameter (see discussion in (Turyshev, Shao, and Nordtvedt, 2006) and references therein). The relativistic frame-dragging term is $\pm 0.7$ $\mu$as, and contribution of the solar quadrupole moment, $J_2$, is sized as 0.2 $\mu$as (using theoretical value of the solar quadrupole moment $J_2 \simeq 10^{-7}$). The small magnitudes of the effects emphasize the fact that, among the four forces of nature, gravitation is the weakest interaction; it acts at very long distances and controls the large-scale structure of the universe, thus, making the precision tests of gravity a very challenging task.

We shall now discuss the LATOR mission in more details.

## 2. OVERVIEW OF LATOR

The Laser Astrometric Test of Relativity (LATOR) is a space-based experiment that is designed to significantly improve the tests of relativistic gravity in the solar system. If the Eddington's 1919 experiment was performed to confirm the Einstein's general theory of relativity, LATOR is motivated to search for physics beyond the Einstein's theory of gravity with an unprecedented accuracy (Turyshev, Shao, and Nordtvedt, 2006). In fact, this mission is designed to address the questions of fundamental importance to modern physics by searching for a cosmologically-evolved scalar field that is predicted by modern theories of gravity and cosmology, and also by superstring and brane-world models. LATOR will also test the cosmologically motivated theories that attempt to explain the small acceleration rate of the Universe (so-called 'dark energy') via modification of gravity at very large, horizon or super-horizon distances.

The LATOR test will be performed in the solar gravity field using optical interferometry between two micro-spacecraft. Precise measurements of the angular position of the spacecraft will be made using a fiber coupled multi-chanelled optical interferometer on the ISS with a 100 m baseline. The primary objective of the LATOR mission will be to measure the gravitational deflection of light by the solar gravity to accuracy of 0.1 picoradians (prad), which corresponds to ~10 picometers (pm) on a 100 m interferometric baseline. A combination of laser ranging among the spacecraft and direct interferometric measurements will allow LATOR to measure deflection of light in the solar gravity by a factor of more than 30,000 better than had recently been accomplished with the Cassini spacecraft. In particular, this mission will not only measure the key PPN parameter $\gamma$ to unprecedented levels of accuracy of one part in $10^9$; it will also reach ability to measure the next post-Newtonian order ($\propto G^2$) of light deflection resulting from gravity's intrinsic non-linearity and a number of corresponding effects to very significant

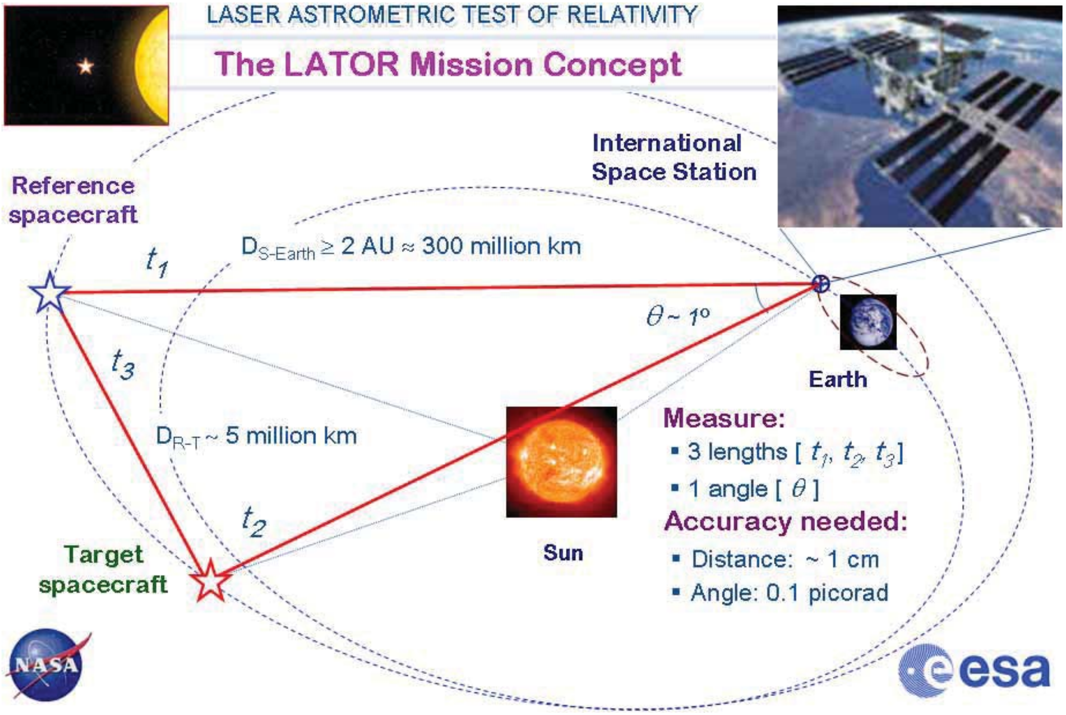

*Figure 1. The overall geometry of the LATOR experiment.*

level of accuracy.

The first order effect of light deflection in the solar gravity caused by the solar mass monopole is $\alpha_1 = 1.75$ arcseconds (Turyshev, Shao, and Nordtvedt, 2004), which corresponds to an interferometric delay of $d \simeq b\alpha_1 \approx 0.85$ mm on a $b = 100$ m baseline. Using laser interferometry, we currently are able to measure distances with an accuracy (not just precision but accuracy) of $\leq 1$ pm. In principle, the 0.85 mm gravitational delay can be measured with $10^{-10}$ accuracy versus $10^{-4}$ available with current techniques. However, we use a conservative estimate for the delay of 5 pm which would produce the measurement of $\gamma$ to accuracy of 1 part in $10^9$ (rather than 1 part in $10^{-10}$), which would be already a factor of 30,000 accuracy improvement when compared to the recent Cassini result (Bertotti, Iess, and Tortora, 2003). Furthermore, we have targeted an overall measurement accuracy of 5 pm per measurement, which for $b = 100$ m this translates to the accuracy of 0.1 prad $\simeq$ 0.01 $\mu$as. With 4 measurements per observation, this yields an accuracy of $\sim 5.8 \times 10^{-9}$ for the first order term. The second order light deflection is approximately 1700 pm and, with 5 pm accuracy and $\sim$ 400 independent data points, it could be measured with accuracy of $\sim$ 1 part in $10^4$, including first ever measurement of the PPN parameter $\delta$. The frame dragging effect would be measured with $\sim$ 1 part in $10^3$ accuracy and the solar quadrupole moment can be modestly measured to 1 part in 200, all with respectable signal to noise ratios. Covariance studies performed for the LATOR mission (Plowman and Hellings, 2005; Turyshev, Shao, and Nordtvedt, 2006) confirm the design performance parameters and also provide valuable recommendations for further mission developments.

The LATOR experiment uses the standard technique of time-of-fight laser ranging between two micro-spacecraft whose lines of sight pass close by the Sun and also a long-baseline stellar optical interferometer (placed above the Earth's atmosphere) to accurately measure deflection of light by the solar gravitational field in the extreme proximity to the Sun (Turyshev, Shao, and Nordtvedt, 2004). Figure 1 shows the general concept for the LATOR missions including the mission-related geometry, experiment details and required accuracies.

We shall now consider the LATOR mission architecture.

### 2.1. Mission Design: Evolving Light Triangle

The LATOR mission architecture uses an evolving light triangle formed by laser ranging between two spacecraft (placed in $\sim$1 AU heliocentric orbits) and a laser transceiver terminal on the International Space Station (ISS), via European collaboration. The objective is to measure the gravitational deflection of laser light as it passes in extreme proximity to the Sun (see Figure 1). To that extent, the long-baseline ($\sim$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 $1^\circ$, which will be accomplished by a small maneuver immediately after their launch (Turyshev, Shao, and Nordtvedt, 2004, 2006). This separation

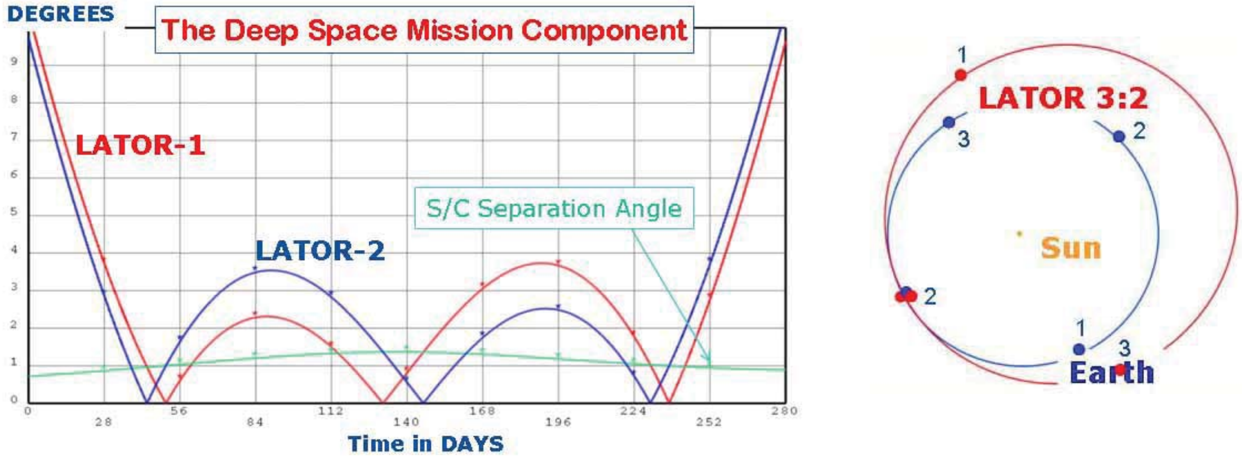

*Figure 2. Left: The Sun-Earth-Probe angle during the period of 3 occultations (two periodic curves) and the angular separation of the spacecraft as seen from the Earth (lower smooth line). Time shown is days from the moment when one of the spacecraft are at 10 distance from the Sun. Right: View from the North Ecliptic of the LATOR spacecraft in a 3:2 resonance. The epoch is taken near the first occultation.*

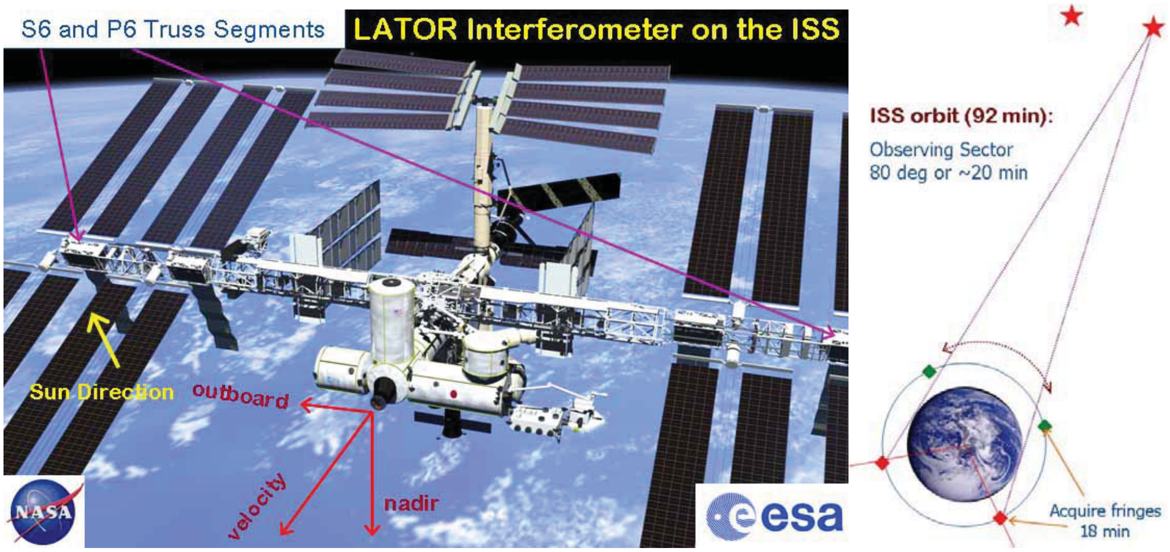

*Figure 3. Left: Location of the LATOR interferometer on the ISS. To utilize the inherent ISS Sun-tracking capability, the LATOR optical packages will be located on the outboard truss segments P6 and S6 outwards. Right: Signal acquisition for each orbit of the ISS; variable baseline allows for solving fringe ambiguity.*

would permit differential astrometric observations to an accuracy of $\sim 10^{-13}$ radians needed to significantly improve measurements of gravitational deflection of light in the solar gravity.

The schematic of the LATOR experiment is quite simple and is given in Figure 1. Two spacecraft are injected into a heliocentric solar orbit on the opposite side of the Sun from the Earth. The triangle in the figure has three independent quantities but three arms are monitored with laser metrology. Each spacecraft equipped with a laser ranging system that enable a measurement of the arms of the triangle formed by the two spacecraft and the ISS. According to Euclidean rules this determines a specific angle at the interferometer; LATOR can measure this angle directly. In particular, the laser beams transmitted by each spacecraft are detected by a long baseline ($\sim$ 100 m) optical interferometer on the ISS. The actual angle measured at the interferometer is compared to the angle calculated using Euclidean rules and three side measurements; the difference is the non-Euclidean deflection signal (which varies in time during spacecraft passages), which contains the scientific information. This built-in redundant–geometry optical truss eliminates the need for drag-free spacecraft for high-accuracy navigation (Turyshev, Shao, and Nordtvedt, 2004, 2006).

The uniqueness of this mission comes with its geometrically redundant architecture that enables LATOR to measure the departure from Euclidean geometry ($\sim 8 \times 10^{-6}$ rad) caused by the solar gravity field, to a very high accuracy. 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 precise measurement of this departure constitutes the primary mission objective.

To enable the primary objective, LATOR will place two spacecraft into a heliocentric orbit, to provide conditions for observing the spacecraft when they are behind the Sun as viewed from the ISS (see Figures 2,3). An orbit with a 3:2 resonance with the Earth was found to uniquely satisfy the LATOR orbital requirements (Turyshev, Shao, and Nordtvedt, 2004, 2006). For this orbit, 13 months after the launch, the spacecraft are within $\sim 10^\circ$ of the Sun with first occultation occurring 15 months after launch (Turyshev, Shao, and Nordtvedt, 2004). At this point, LATOR is orbiting at a slower speed than the Earth, but as LATOR approaches its perihelion, its motion in the sky begins to reverse and the spacecraft is again occulted by the Sun 18 months after launch. As the spacecraft slows down and moves out toward aphelion, its motion in the sky reverses again, and it is occulted by the Sun for the third and final time 21 months after launch. For more details, please consult (Turyshev, Shao, and Nordtvedt, 2006). We shall now consider the basic elements of the LATOR optical design.

### 2.2. General Principles of Optical Design

A single aperture of the interferometer on the ISS consists of three 20 cm diameter telescopes (see Figure 4 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 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 5 pm.

The spacecraft are identical in construction and contain a relatively high powered (1 W), stable (2 MHz per hour $\sim$500 Hz per second), small cavity fiber-amplified laser at 1064 nm. Three quarters of the power of this laser is pointed to the Earth through a 15 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 toward the other spacecraft. In addition to the two transmitting telescopes, each spacecraft has two receiving telescopes. The receiving telescope, which points toward the area near the Sun, has laser line filters and a simple knife-edge coronagraph to suppress the Sun's 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 camera. This telescope is used to initially point the spacecraft directly toward 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 toward the other spacecraft may be used for this purpose part of the time, reducing hardware complexity. Star trackers with this construction were 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 spacecraft while they are on their way to assume the orbital position needed for the experiment.

The LATOR experiment has a number of advantages over techniques that use radio waves to measure gravitational light deflection. 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. The use of the 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. In addition, the short wavelength allows much more efficient links with smaller apertures, thereby eliminating the need for a deployable antenna. Finally, the use of the ISS will allow conducting the test above the Earth's atmosphere—the major source of astrometric noise for any ground based interferometer. This fact justifies LATOR as a space mission.

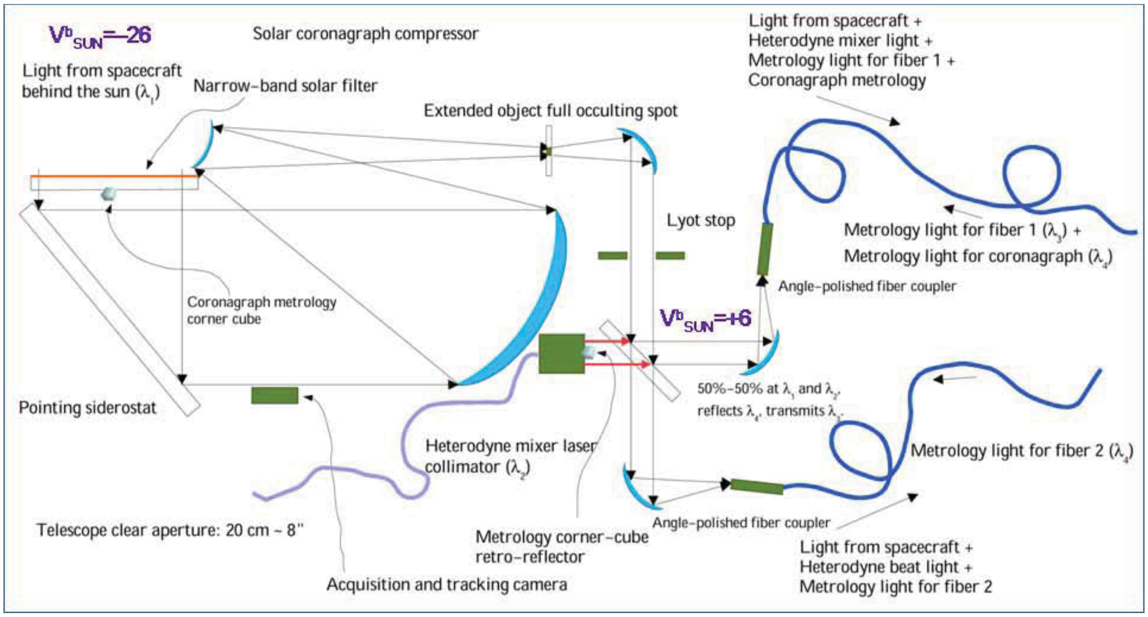

*Figure 4. Basic elements of optical design for the LATOR interferometer: The laser light (together with the solar background) is going through a full aperture ($\sim$ 20cm) narrow band-pass filter with $\sim 10^{-4}$ suppression properties. The remaining light illuminates the baseline metrology corner 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 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.*

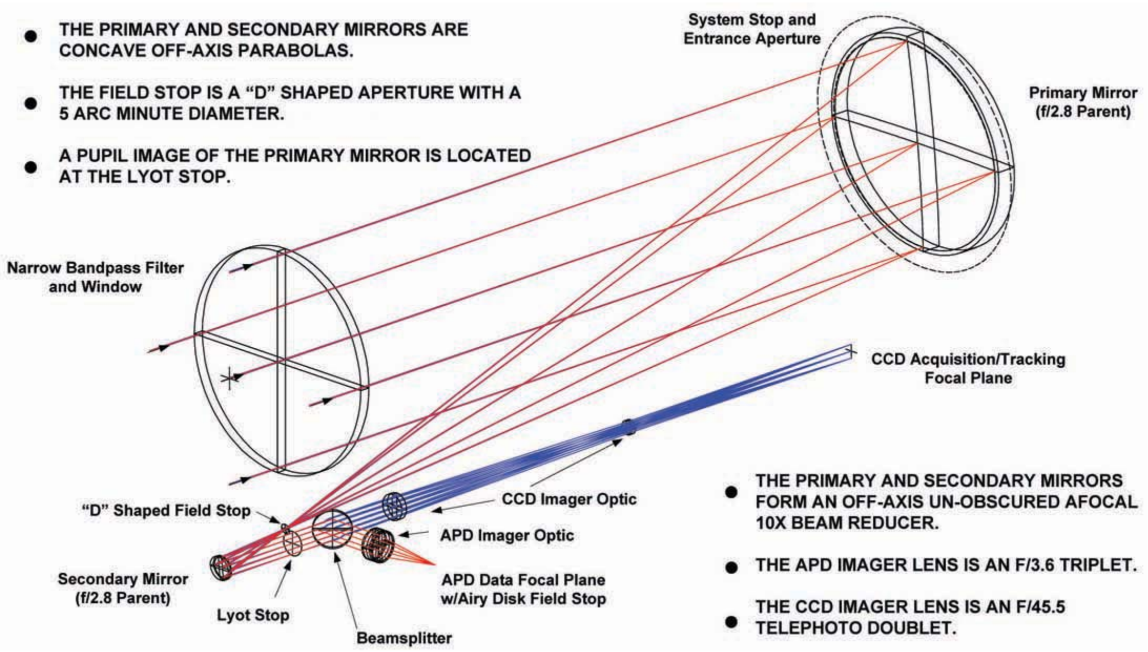

*Figure 5. LATOR receiver optical system layout.*

## 2.3. 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 1. The receiver optical system captures optical communication signals form a transmitter on the ISS, which orbits the Earth. To support the primary mis-

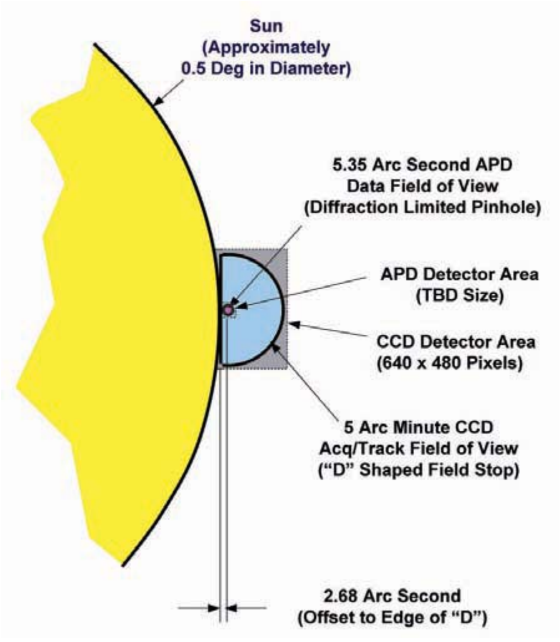

*Figure 6. LATOR focal plane mapping (not to scale).*

sion 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 receiver optical system successfully satisfied all the configuration and performance requirements (Plowman and Hellings, 2005; Turyshev, Shao, and Nordtvedt, 2006). 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.

Figure 6 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, Shao, and Nordtvedt, 2006).

## 3. CONCLUSIONS

The LATOR mission aims to carry out a test of the curvature of the solar system's gravity field with an accuracy better than 1 part in $10^9$. 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 (Turyshev et al., 2005).

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. With this mission testing theory to several orders of magnitude higher precision, finding a violation of general relativity or discovering a new long range interaction could be one of this era's primary steps forward in fundamental physics. 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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## REFERENCES

Bertotti, B., Iess, L., Tortora, P., 2003, Nature 425, 374

Carroll, S. M., Duvvuri, V., Trodden, M., and Turner, M., 2004, Phys. Rev. D70, 043528, astro-ph/0306438

Damour, T., Nordtvedt, K. L., 1993, Phys. Rev. Lett. 70, 2217; *ibid*, 1993, Phys. Rev. D48, 3436

Damour, T., Polyakov, A. M., 1994, Gen. Rel. Grav. 26, 1171; *ibid*, 1994, Nucl. Phys. B423, 532

Damour, T., Piazza, F., and Veneziano, G., 2002, Phys. Rev. Lett. 89, 081601, gr-qc/0204094; *ibid*, 2002, Phys. Rev. D66, 046007, hep-th/0205111.

Peebles, P. J. E., Ratra, B., 2003, Rev. Mod. Phys. 75, 559, astro-ph/0207347

Plowman, J. E., Hellings, R. W., 2006, Class. Quant. Grav. 23, 309, gr-qc/0505064

Nordtvedt, K. L., 2003, gr-qc/0301024.

Nordtvedt, K. L., 1996, Class. Quant. Grav. 13, A11

Spergel, D. N. et al., 2006, "Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology," submitted to ApJ

Turyshev, S. G., Shao, M., Nordtvedt, K. L., 2004, Class. Quant. Grav. 21, 2773, gr-qc/0311020; *ibid*, 2004, Int. J. Mod. Phys. D13, 2035, gr-qc/0410044

Turyshev, S. G., Dittus, H., Lämmerzahl, C., et al., 2005, gr-qc/0506104

Turyshev, S. G., Shao, M., Nordtvedt, K. L., 2006, gr-qc/0601035

Will, C. M., 1993, Theory and Experiment in Gravitational Physics, Cambridge University Press

Williams, J. G., Turyshev, S. G., Boggs, D. H., 2004, Phys. Rev. Lett. 93, 261101, gr-qc/0411113.