The Laser Astrometric Test Of Relativity Mission

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The First Test of General Theory of Relativity

Gravitational Deflection of Light: Solar Eclipse 1919

Possible outcomes in 1919:
Deflection = 0;
Newton = 0.87 arcsec;
Einstein = 2 x Newton = 1.75 arcsec

Eddington’s telegram to Einstein, 1919

Einstein and Eddington, Cambridge, 1930
Gravitational Deflection of Light is a Well-Known Effect Today
35 Years of Relativistic Gravity Tests

Techniques for Gravity Tests:

Radar Ranging:
- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Cassini, MGS, MO accuracy ~few meters
- VLBI, GPS, etc.

Laser:
- LLR, SLR, etc.

Designated Gravity Missions:
- LLR (1969 - on-going!!)
- GP-A, ’76; LAGEOS, ’76,’92; GP-B, ’04; LISA, 2014

New Engineering Discipline – Applied General Relativity:
- Daily life: GPS, geodesy, time transfer;
- Precision measurements: deep-space navigation & astrometry (SIM, GAIA,...).

A factor of 100 in 35 years is impressive, but is not enough for the near future!
LASER ASTROMETRIC TEST OF RELATIVITY

Challenges to General Relativity

Fundamental Physics Challenges:

- Appearance of space-time singularities;
- Classical description breaks down in large curvature;
- Quest for Quantum Gravity → GR modification;
- Cosmology: accelerating Universe, *dark energy*?!

Alternative Theories of Gravity:

- Grand Unification Models, Standard Model Extensions;
- Inflationary cosmologies, strings, Kaluza-Klein theories;
  Common element: scalar partners – dilaton, moduli fields...

If scalar exists, how to observe it?

- Search for violations of the Equivalence Principle;
- Look for modification of large-scale gravity phenomena;
- Test for variability of fundamental constants (*G*, *α*, …);
- Gravity tests at short and solar system scales

As a fundamental theory, GR must be tested to the highest level
**Laboratory for Relativistic Gravity Experiments: Our Solar System**

**Strongest gravity potential**

\[ \frac{GM_{\text{Sun}}}{c^2 R_{\text{Sun}}} \sim 10^{-6} \]

**Most accessible region for gravity tests in space:**
- ISS, LLR, SLR, free-fliers

**We need a dedicated mission to explore accuracies better than** $10^{-6}$
Theoretical Motivation for New Gravity Tests

Long-range massless [or low-mass] scalar:

The low-energy limit of the String Theory in ‘Einstein Frame’ (Damour-Nordtvedt-Polyakov 1993) suggests:

\[ S = -\frac{1}{16\pi G} \int d^4x \sqrt{-g} \left( R - 2g^{mn}\nabla_m\phi\nabla_n\phi \right) + S_M[\psi_M, A(\phi)g_{mn}] \]

Expansion \( A(\phi) \) around background value \( \phi_0 \) of the scalar leads:

\[ \ln A(\varphi) = \ln A(\varphi_0) + \alpha_0(\varphi - \varphi_0) + \frac{1}{2}k_0(\varphi - \varphi_0)^2 + \mathcal{O}(\Delta \varphi^3) \]

Slope \( \alpha_0 \) measures the coupling strength of interaction between matter and the scalar.

\[ \gamma - 1 = \frac{-2\alpha_0^2}{1 + \alpha_0^2} \approx -2\alpha_0^2 \]

\[ \beta - 1 = \frac{\alpha_0^2k_0}{2(1 + \alpha_0^2)^2} \approx \frac{1}{2}\alpha_0^2k_0 \approx \frac{1}{4}(1 - \gamma)k_0 \]

Scenario for cosmological evolution of the scalar (Damour, Piazza & Veneziano 2002):

\[ \gamma - 1 \sim 7.3 \times 10^{-7} \left( \frac{H_0}{\Omega_0^3} \right)^{\frac{1}{2}} \implies \gamma - 1 \sim 10^{-5} - 10^{-7} \]

The unit curvature, PPN parameter \( \gamma \) – the most important quantity to test.
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The LATOR Mission Concept

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International Space Station

Reference spacecraft

Target spacecraft

Earth

DS-Earth ≥ 2 AU ≈ 300 million km

D_{R-T} \sim 5 \text{ million km}

\theta \sim 1^\circ

Measure:
- 3 lengths [t_1, t_2, t_3]
- 1 angle [\theta]

Accuracy needed:
- Distance: \sim 1 \text{ cm}
- Angle: 0.1 \text{ picorad}

Euclid is violated in gravity:
\cos \theta \neq \left( t_1^2 + t_2^2 - t_3^2 \right) / 2t_1t_2

Geometric redundancy enables a very accurate measurement of curvature of the solar gravity field

Accurate test of gravitational deflection of light to 1 part in 10^8
Sizes of the Effects & Needed Accuracy

<table>
<thead>
<tr>
<th>Effect</th>
<th>Analytical Form</th>
<th>Value (µas)</th>
<th>Value (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Order</td>
<td>$2(1 + \gamma) \frac{M}{R}$</td>
<td>$1.75 \times 10^6$</td>
<td>$8.487 \times 10^8$</td>
</tr>
<tr>
<td>Second Order</td>
<td>$(2(1 + \gamma) \beta \frac{3\delta}{4}\pi + 2(1 + \gamma)^2) \frac{M^2}{R^2}$</td>
<td>$3.5$</td>
<td>$1702$</td>
</tr>
<tr>
<td>Frame-Dragging</td>
<td>$\pm 2(1 + \gamma) \frac{J}{R^2}$</td>
<td>$\pm 0.7$</td>
<td>$\pm 339$</td>
</tr>
<tr>
<td>Solar Quadrupole</td>
<td>$2(1 + \gamma)J_2 \frac{M}{R^3}$</td>
<td>$0.2$</td>
<td>$97$</td>
</tr>
</tbody>
</table>

**LATOR 1994 Proposal:**
- Ground-based interferometer [B = 30km]
- Limited capabilities due to atmosphere

$\frac{(M/R)^2}{2}$ term $\sim 0.2\%$ accuracy [B =100 m]:
- $0.02 \mu$as $\Rightarrow 0.1$ picorad $\sim 10\text{pm}$

**LATOR 2004 (all in space):**
- Interferometer on the ISS [B = 100m]
- Technology exists as a result of NASA investments in astrometric interferometry

1 hour integration in 0.5 arcsec seeing

The key technologies are already available – SIM, TPF, Starlight, KI
To utilize the inherent ISS sun-tracking capability, the LATOR optical packages will be located on the outboard truss segments P6 & S6 outwards.
Recent JPL Team X Mission Study:

The Deep Space Mission Component

Launch: 2009-10
Spacecraft: SA-200S/B
Vehicle: Delta II (any date)
Orbit: 3:2 Earth Resonant
Duration: ~2 years
1st Occultation: in 15 months

JPL Team X study demonstrates feasibility of LATOR as a MIDEX
Full aperture ~15cm narrow band-pass filter; corner cube [baseline metrology];
Steering flat; off-axis telescope w/ no central obscuration [for metrology];
Coronagraph; ½ plane focal plane occulter; Lyot stop;
Fibers for each target (1 on S/C and 2 on the ISS).
The LATOR 100mm receiver optical system is located one each of two separate spacecraft to receive optical communication signals from a transmitter on the ISS.
Out-of-field solar radiation (SR) will fall on the narrow band pass filter and primary mirror. Scattering from these optical surfaces will put some SR into the FOV of the two focal planes.

The narrow band pass filter and primary mirror optical surfaces need to be made optically smooth to minimize narrow angle scattering. This may be difficult for the relatively steep parabolic aspheric primary mirror surface.

The field stop will eliminate direct out of field solar radiation at the two focal planes, but it will not eliminate narrow angle scattering from the filter and primary mirror.

The Layot stop will eliminate out of field diffracted solar radiation at the two focal planes.

Baffle vanes may be needed several places in the optical system.
The straight edge of the “D”-shaped CCD field stop is tangent to both the limb of the Sun and the edge of APD field stop (pinhole).

There is a 2.68 arcsecond offset between the straight edge and the concentric point for the circular edge of the CCD field stop (“D”-shaped aperture)

The APD field of view and the CCD field of view circular edges are concentric with each other.
Two LATOR interferometers will perform differential astrometry with distant spacecraft working in a 'chopping' regime.

- Laser Xmitter beacon for 2 spacecraft (2 beams)
- Interferometer receiver
- Interferometer on the ISS
- Baseline

Launching in 2006 by NASA

Laser Astrometric Test of Relativity
Observing Sector 80 deg or ~20 min

Acquire fringes 18 min

Transmitters on S/C and ISS broadcast in wide beam mode [50 urad, depending on attitude knowledge of the ISS, and S/C]

Receivers use long (<100sec) integration time to find beacons 2AU away; after finding beacons, narrow transmitted beam to ~5 urad (diff limit)

It takes ~18 minutes for the narrow beam to travel 2 AU; as soon as “bright” narrow beam is received, observations start.

Fringe ambiguity:

Laser Astrometric Interferometer has N*I ambiguity, which is resolved by varying the baseline length over ~30%.

Change of effective baseline length achieved by ISS flying with constant attitude wrt the Earth rather than wrt inertial space.
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Fundamental Physics with LATOR:

A 21\textsuperscript{st} Century version of Michelson-Morley Experiment

Only Existing Technologies are sufficient:

- Laser Nav/Comm over interplanetary distances
- Redundant optical truss for Nav and attitude control
- Precise spatial acquisition, tracking and fine beam-pointing
- Signal acquisition on a noisy background (i.e. Sun)
- Vibration isolation for extended structures at a picometer level

Toward Centennial of General Relativity (2015):

- 1919: Light deflection during solar eclipse: \(| 1 - \gamma | \leq 10^{-1} \)
- 1980: Viking – Shapiro Time Delay: \(| 1 - \gamma | \leq 2 \times 10^{-3} \)
- 2003: Cassini – Doppler \([\text{d(Time Delay)}/\text{dt}]\): \(| 1 - \gamma | \leq 2.3 \times 10^{-5} \)
- 2011: LATOR – Astrometric Interferometry: \(| 1 - \gamma | \leq 10^{-8} - 10^{-9} \)

LATOR is the ultimate test of GR in the Solar System:

A factor of >3,000 improvement in the light deflection tests

- PPN parameters: \(\gamma\) to 1 part in \(10^8\); direct measure of \(\delta, \beta\) to 1%
- Solar physics: solar \(J_2\) (\(~10\%) ; mass, atmosphere
- Will search for cosmological remnants of scalar field

The LATOR Mission is important and it should be done!
Thank You!