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CURRENT STATUS OF THE FRAME DRAGGING EXPERIMENTS*

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We present a brief history of the proposed satellite experiments to detect effects of frame dragging in the general theory of relativity and discuss recent data.

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1. Introduction

In a paper presented at the International Conference on Theories of Relativity and Gravitation held in 1962 in Warsaw and Jabłonna, Schiff [1] lamented over the state of experimental tests of general theory of relativity. "There is a striking difference between the experimental bases of the special and general theories of relativity. Special relativity has been amply verified in several aspects ... The situation is completely different with general relativity. Here, there are thus far only three so called 'crucial tests': the gravitational red shift, the deflection of starlight passing close to the sun, and the precession of the perihelia of the orbits of the inner planets, especially Mercury". In the past 45 years the experimental foundations of general theory of relativity has been improved in part due to the technological advances and in part due to discoveries of new types of astronomical objects.

The discovery of binary pulsars opened up a possibility of testing predictions of general theory of relativity in experiments beyond the Solar System. Indirectly the effects of emission of gravitational waves have been not only detected but shown to agree with theoretical predictions. The recent advances in testing general relativity are thoroughly discussed by Cliford Will

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in a review article posted at Living Reviews in Relativity [2]. Despite all these advances and new attempts the Lense–Thirring effect has not been yet satisfactory tested.

2. The Lense–Thirring effect

Let us consider a gyroscope with the angular momentum $\vec{S}_0$ as measured by a comoving observer moving in the gravitational field of the Earth. In Newton theory of gravity the angular momentum of a freely moving gyroscope remains constant. As shown for the first time in 1918 by Lense and Thirrinig [3] in general theory of relativity the angular momentum $\vec{S}_0$ of a gyroscope as measured by a comoving observer moving in the gravitational field of the Earth would change in time according to

$$\frac{d\vec{S}_0}{dt} = \vec{\Omega} \times \vec{S}_0 \,, \tag{1}$$

$$\vec{\Omega} = \frac{1}{2mc^2}\vec{F} \times \vec{v} + \frac{3GM}{2c^2r^2}\left(\frac{\vec{r}}{r} \times \vec{v}\right) + \frac{GI}{c^2r^3}\left[\frac{3\vec{r}}{r}(\vec{\omega} \cdot \frac{\vec{r}}{r}) - \vec{\omega}\right] , \tag{2}$$

where m is the mass of the gyroscope, $\vec{r}$ is its position vector with respect to the center of mass of the Earth, $\vec{v} = d\vec{r}/dt$ is its velocity vector, $\vec{F}$ is any non-gravitational force that may be applied to the center of mass of the gyroscope, and M, I and $\vec{\omega}$ are the mass, moment of inertia, and rotation angular velocity vector of the Earth.

The first term in Eq. (2) describes the effect of an external non-gravitational force $\vec{F}$ acting on the center of mass of the gyroscope. This is the so called Thomas precession. The second term has been for the first time introduced and discussed by de Sitter and now it is called the de Sitter precession or the geodetic precession. It is a general relativistic effect and appears even if the central body does not rotate. The third term arises from the rotation of the central body and it causes the gyroscope to precess even when the gyroscope is not moving. It is called the Lense–Thirring effect or the effect of dragging of inertial frames.

3. The Gravity Probe B

Already at the Warsaw Conference Schiff proposed to use satellites to measure the geodetic precession (de Sitter precession) and the Lense–Thirring effect [1]. Schiff estimated that if a gyroscope is placed in a satellite at a moderate altitude on an Earth bound orbit the geodetic precession will be about 7 arcs per year while the Lense–Thirring precession will be about 0.1 arcs per year.

These very challenging estimates have not discouraged a group of physicists at Stanford University headed by L. Schiff and low temperature expert William Fairbank to start thinking about measuring the Lense–Thirring effect in a satellite experiment. At that time it was clear that to measure the geodetic precession and the Lense–Thirring effect it will be necessary to break several technological barriers. Not only sufficiently accurate gyroscopes have not existed at that time but also techniques to measure angles with fraction of arc second precision and nobody has yet placed a telescope is space. In 1962 Brian Josephson postulated that Cooper pairs could tunnel through a tin layer of dielectric that separates two superconductors. A year later Josephson junction was experimentally tested and applied to measure a very weak magnetic field. Soon it become clear that the Superconducting Quantum Interference Device (SQUID) could measure very small changes in the orientation of gyroscope's spin axis. However, SQUIDs to operate require a very low temperature. Despite all these technical challenges in 1964 NASA provided funding for the so called Gravity Probe B experiment with the prime goal to measure the relativistic effect of dragging of inertial frames and the group at Stanford started designing the gyroscopes. In 1973 NASA successfully launched a drag-free satellite achieving residual acceleration of the order of 5×10^{-12}g during whole two years long mission. In 1980 after a detailed review of technological possibilities NASA decided to proceed with planing the flight program. The Challenger disaster in 1986 slowed down the progress in designing and testing components for the GP-B mission and in 1995 NASA cancels Shuttle tests completely. These unforseen complications have note slowed down the development of different components of the GP-B satellite. In 1996 the Dewar for 2441 liters of superfluid helium has been manufactured and tested. By 1999 the four gyroscopes (see Fig. 1), their quartz encloser and the telescope have been manufactured and ground tested.

Fig. 1. One of the GP-B gyroscopes with housing.

The gyroscopes used in GP-B experiment are the roundest objects ever made — these quartz spheres are polished to within 0.01 microns of perfect sphericity. During the next four years all components and the whole satellite went through a standard sequence of ground pre launch tests. Finally on April 20, 2004, the GP-B satellite was successfully launched from the Vandenberg Air Force Base in California. After the satellite and all its systems underwent initialization and tests and all 4 gyroscopes have been spined up and aligned on August 28, 2004, the GP-B began collecting data. During the next 50 weeks the satellite transmitted over a terabyte of data. On August 15, 2005, the GP-B Mission Operations team finished collecting the data and begun a set of calibration tests of the gyroscopes, the telescope and SQUID readouts that lasted until the liquid helium was exhausted at the end of September, 2005.

Already during the initiation phase of the mission after the gyroscopes were spun up it was noticed that the polhode motion of the gyroscopes rotors, which was expected to exhibit a constant pattern throughout the experiment period, was changing over time, significantly complicating the calibration of the gyroscope readout angels. During the post-experiment instrument calibration testing, the spin axes of the gyroscopes were found to be affected by small classical torques, known as "misalignment torques", whose effects must be rigorously separated from the relativity measurements. Later tests indicated that these unexpected effects are caused by larger than anticipated electrostatic patches on the rotor's surface. The GP-B data analysis team is now working to devise the best method for separating the disturbance torques from the relativity signal. The final results are expected to be announced in May 2008.

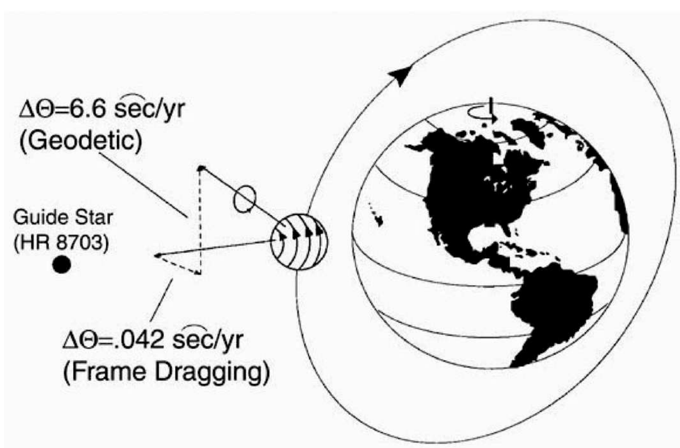

Fig. 2. Trajectory of the GP-B satellite and expected relativistic precession effects.

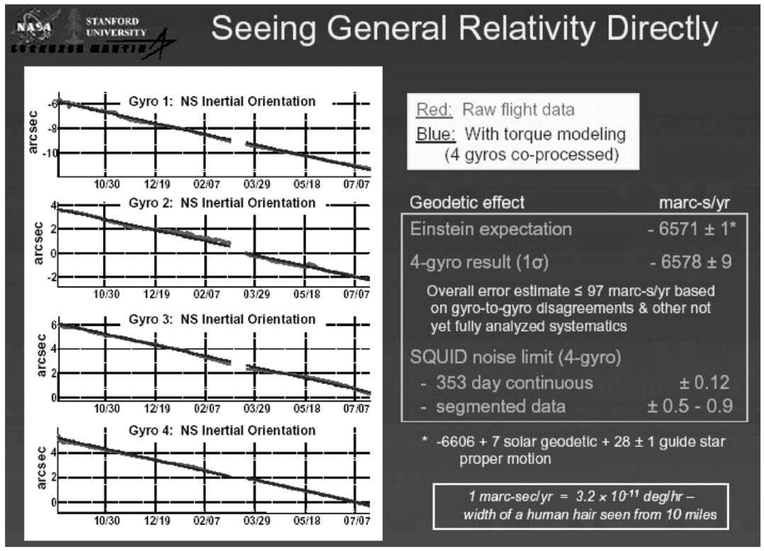

Fig. 3. Preliminary results of the GP-B mission.

In the mean-time, however, on April 14, 2007 and on July 11, 2008 at the GR18 Conference in Sydney Francis Everitt presented preliminary results of the GP-B mission. The geodetic precession of GP-B gyroscopes predicted by the Einstein general theory of relativity is 6571 ± 1marc-sec/yr while the 1σ 4 gyroscopes result is 6578 ± 9marc-sec/yr with the estimated total error of 97marc-sec/yr. In conclusion we see that even the preliminary results confirm the general relativistic geodetic precession effect with accuracy of the order of 1%. There are only very preliminary results concerning the Lense–Thirring effect, at the GP-B internet site they say that "In our September 25, 2007 status update, we reported that the trapped flux mapping technique had resulted in a dramatic improvement in the determinations of the polhode phase and angle for each gyroscope throughout the entire 353-day experiment period. Applying these results to a central 85-day stretch of data, from December 12, 2004 through March 4, 2005, we obtained a robust and stable measurement of the frame-dragging effect with a reasonable (30%) error level. We are in process of progressively extending the analysis to increasingly long time intervals in order to reach the full experiment accuracy, potentially to an error margin of less than 5%. Also important is the completion of the study of — and if necessary elimination of — any remaining systematic effects that may bias the results of the experiment". Let us hope that soon we will have a robust confirmation of the Lense–Thirring effect.

4. Other satellite and astrophysical measurements of the Lense–Thirring effect

Two years after the launch of the first sputnik Yilmaz [4] realized that a satellite orbiting the Earth could be regarded as a gyroscope and proposed to use polar orbit satellites to detect the geodetic and Lens–Thirring precession. In 1974 Van Patten and Everitt [5] proposed to use two counter orbiting polar orbit drag-free satellites to measure the effect of relativistic dragging of inertial frames. However, in the seventies there was no hope to get funds for such demanding satellite mission. In 1976 in connection with the International Geophysics Year NASA launched a small, very heavy satellite equipped with 426 special mirrors to reflect laser signals. This LAser GEOdynamic Satellite (LAGEOS) of only 60 cm in diameter, weighting 411 kg was placed on an almost circular orbit with perigee of 5839 km and apogee of 5947 km and it orbited the Earth in 225.5 min. In 1984 Ciufollini [6] suggested that the achieved accuracy in determination of LAGEOS orbit is sufficient to measure the effects of relativistic dragging of inertial frames. In 1989 Ciufollini [7] performed a detailed analysis of possible errors and have shown that tracking two non-polar laser ranged satellites over a period of 3 years should allow to detect effects of relativistic dragging of inertial frames with an error smaller than about 10%.

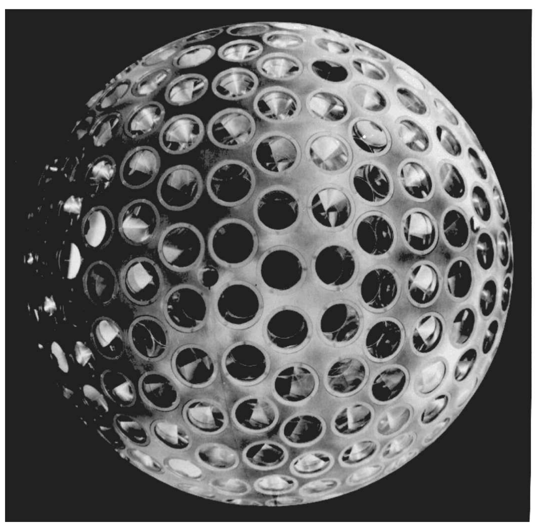

Fig. 4. The LAGEOS satelite.

In 1992 NASA and Italian Space Agency launched LAGEOS II satellite. LAGEOS II is slightly lighter than LAGEOS, with mass of 400 kg and it was placed on a similar circular orbit with perigee of 5616 km and apogee of

5912 km and an inclination of 52.7 degree. The small size and high density of these passive satellites were chosen to minimize the effect of solar wind and to assure that the satellites are moving on a very stable orbits. The positions of both LAGEOS satellites are determined by several tracking stations placed all over the globe which use laser beams that reflect from the satellites and allow to measure their position with the accuracy of about 1–3 cm. The LAGEOS satellites are used to monitor the motion of the Earth's tectonic plates, measure the Earth's gravitational field and erratic changes in position of the Earth's axis of rotation, and determine changes in the Earth's rotational period. Using the orbital parameters LAGEOS satellites and Eq. (2) it turns out that the Lense–Thirring drag of their orbital planes is about 31 milliarcseconds per year.

In 2004 Ciuffolini and Pavlis [8] reported results of their analysis of eleven years of positioning data of the LAGOES satellites. In their analysis and error estimates they have used more accurate model of the Earth's gravitational field that was prepared with the help of new data collected by the twin GRACE satellites which were launched by NASA in 2002. Ciuffolini and Pavlis have found that the observed residual nodal longitudes of the LQGEOS satellites is 47.9 mas/yr while the theoretical prediction of the general relativistic Lense–Thirring effect is 48.2mas/yr and their estimated systematic error is about ±10%. In a review paper published in 2007 Ciuffolini [10] states that "After 2004, other accurate Earth gravity models have been published using longer GRACE observations. The LAGEOS analyses have been recently repeated with these models [9], over a longer period and by using different orbital programs independently developed by NASA Goddard and the GeoForschungsZentrum (GFZ) Potsdam, have improved the precision of the 2004 LAGEOS determination of the Lense–Thirring effect. No deviations from the predictions of the general theory of relativity have been observed".

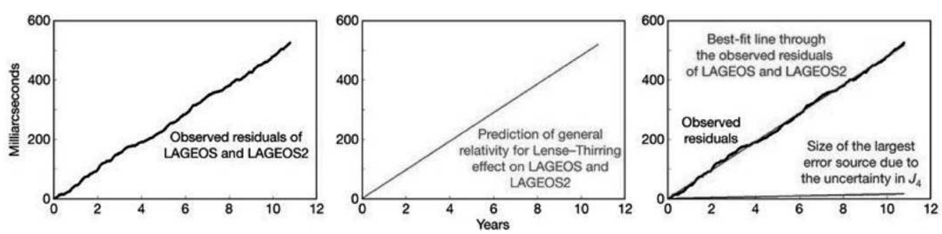

Fig. 5. Relativistic effects measured by the LAGEOS satellites.

The results of Ciuffolini and Pavlis and in particular their estimates of errors have been recently challenged by Iorio [11], who questions the estimated errors of the even zonal harmonics J_l of the Earth's geopotential. According to Iorio the more realistic estimate of error of the present determination of the Lense–Thirring effect is as large as about 25%.

The Apollo astronauts have placed on the Moon's surface several high quality mirrors that could bounce back laser signals send from the Earth. Over the years the precision of determination of the distance between the Moon and the Earth has substantially improved, now it is in the millimeter range, allowing very accurate determination of the Moon's orbit around the Earth. The geodetic precession of the Moon's orbit is about 2 arcseconds per century. This effect has been measured with the Lunar Laser Ranging technique [12] with the accuracy of about 0.6% .

When in 2004 the first double pulsar system PSR J0737-3039 was discovered [13] it immediately became clear that it will provide a unique opportunity to test several different general relativistic effects. By 2006 several relativistic effects have been observed and measured in this system [14]. This list includes periastron advance ($16.89947(68)^0$/yr), gravitational redshift parameter (0.3856(26) ms), Shapiro delay parameter (0.99974(-39, +16)), transversal Shapiro delay parameter (6.21(33) μs) and mass functions of both neutron stars. Combination of these relativistic effects allows to determine masses of both neutron stars, they are $m_A = 1.3381 \pm 0.0007 M_\odot$ and $m_B = 1.2489 \pm 0.0007 M_\odot$. Orbits of both pulsars should precess with respect to the total angular momentum, for the binary system PSR J0737-3039 the expected angular velocity of precession is $\Omega = 0.87^0/\mathrm{yr}$. This geodetic precession should cause a slow change in the shape of the pulse profile. Unfortunately such a change has not yet been observed for the binary system PSR J0737-3039. For possible relativistic effects in other binary pulsar systems see the review "Testing General Relativity with Pulsar Timing" by Stairs [15] on The Living Reviews on Relativity site.

I would like to warmly thank Francis Everitt and Ignazio Ciuffolini for providing their recent data.

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