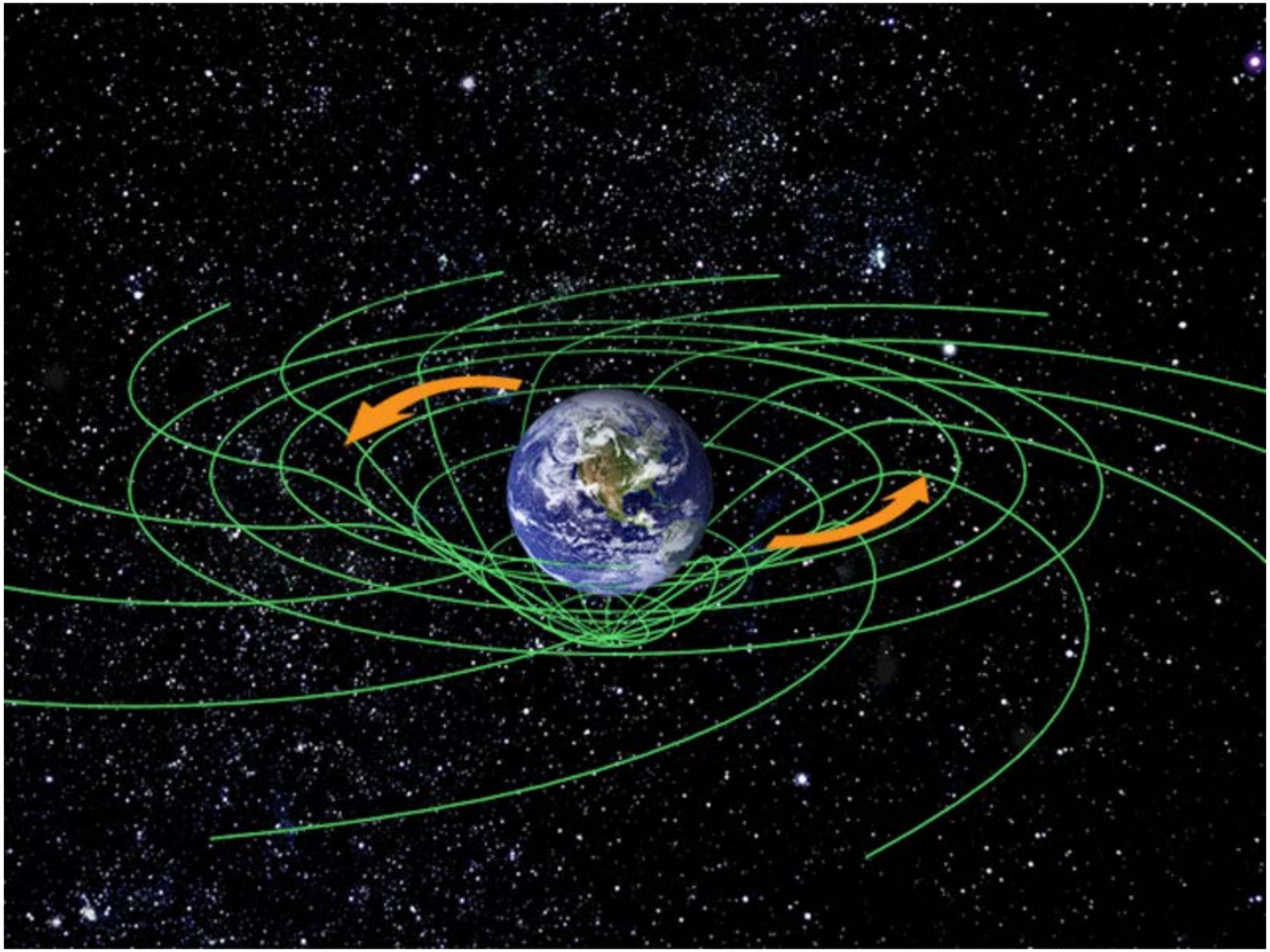
Frame Dragging



Frame Dragging

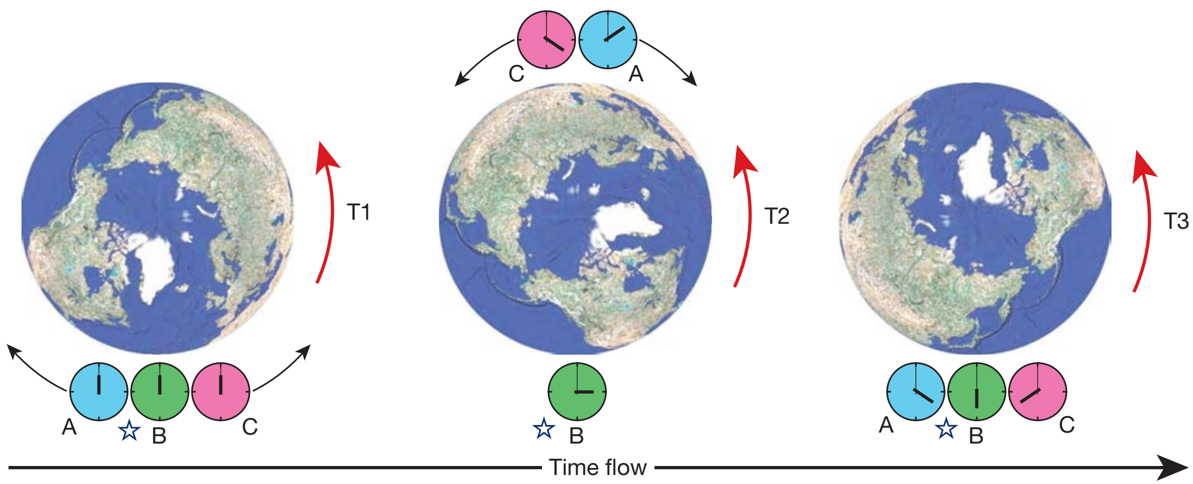
An **Inertial Frame** is a frame that is not accelerating (in the sense of proper acceleration that would be detected by an accelerometer).

In Einstein's theory of General Relativity inertial reference frames are influenced and dragged by the distribution and flow of mass– energy in the Universe.

The dragging of inertial frames by the motion and rotation of nearby matter is called **frame-dragging**.

Frame Dragging and Time Travel

Frame-dragging has an intriguing influence on the flow of time around a spinning body.



The object co-rotating with the Earth will take longer than a object counter-rotating on the same orbit to get back to the same point with respect to a distant star.

Frame Dragging and Time Travel

For example, around the spinning Earth, the difference between the travel times of two pulses of electromagnetic radiation counter-propagating at the same radius would be:

$$\Delta t = \frac{8\pi G J_{Earth}}{c^4 r}$$

The spin time delay must be taken into account in the modeling of relative time delays between images observed by gravitational lensing.

Frame Dragging and Time Travel

For example, around the spinning Earth, the difference between the travel times of two pulses of electromagnetic radiation counter-propagating at the same radius would be:

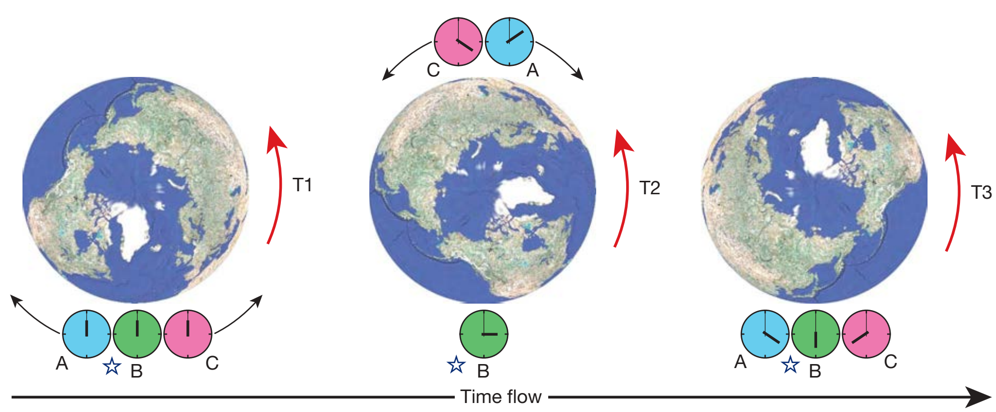
$$\Delta t = \frac{8\pi\times 6.674\times 10^{-11} Nm^2 kg^{-2}\times 7.2\times 10^{33} kg\ m^2 s^{-1}}{(3\times 10^8 m/s)^4\times(6.371\times 10^6 m)} \sim 2.34\times 10^{-16} s$$

The spin time delay must be taken into account in the modeling of relative time delays between images observed by gravitational lensing.

Frame Dragging and Time Travel

For time-travel into the future using frame dragging there is no need for the object to move near the speed of light.

For example, if two twins meet again, having flown arbitrarily slowly around the whole Earth in opposite directions on the equatorial plane and exactly at the same altitude, the difference in their ages due to the Earth's spin would be approximately 10^{-16} s.



Lense –Thirring Effect

In 1918, Lense and Thirring formulated the weak-field and slow-motion description of frame dragging on the orbit of a test particle around a spinning body.

Lense-Thirring precession can be thought of as the dragging of inertial frames around rotating masses. The rotation twists the surrounding space, perturbing the orbits of nearby masses.

Attempts to measure **frame-dragging of the accretion disks of black holes** have resulted in inconclusive results because of the complexity the disks.

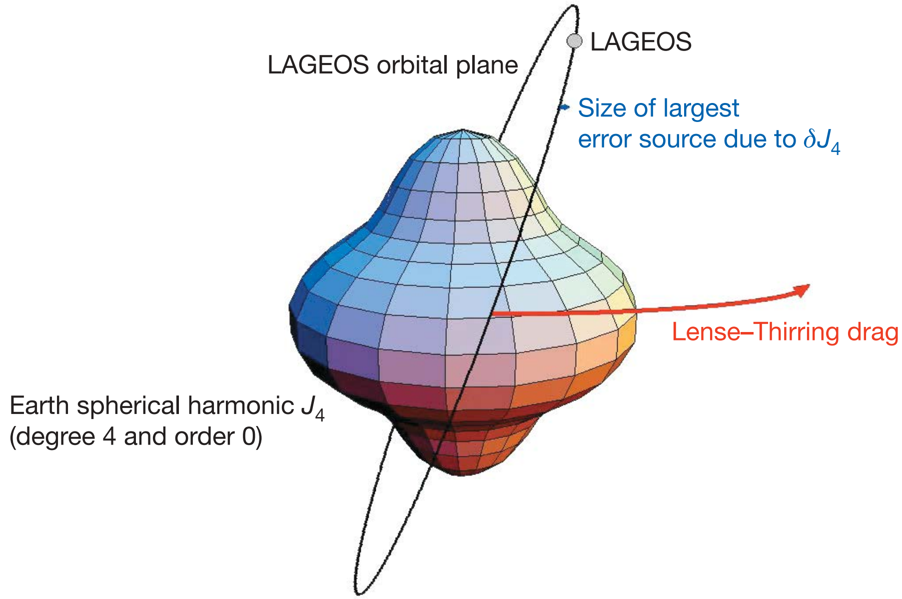
The Earths gravitational field even though much weaker also **produces frame dragging**. We will describe attempts to measure frame dragging by the Earths field.

Frame Dragging in Weak Gravitational Field

The precession, with rate Ω_{L-T}, of the longitude of the nodal line of a test-particle, that is, of its orbital angular momentum vector, is:

$$\vec{\Omega}_{L-T} = \frac{2G\vec{J}}{c^2 a^3 (1 - e^2)^{3/2}}$$

Where J is the angular momentum of the central body, *a* the semi-major axis of the orbiting test-particle and *e* its orbital eccentricity.

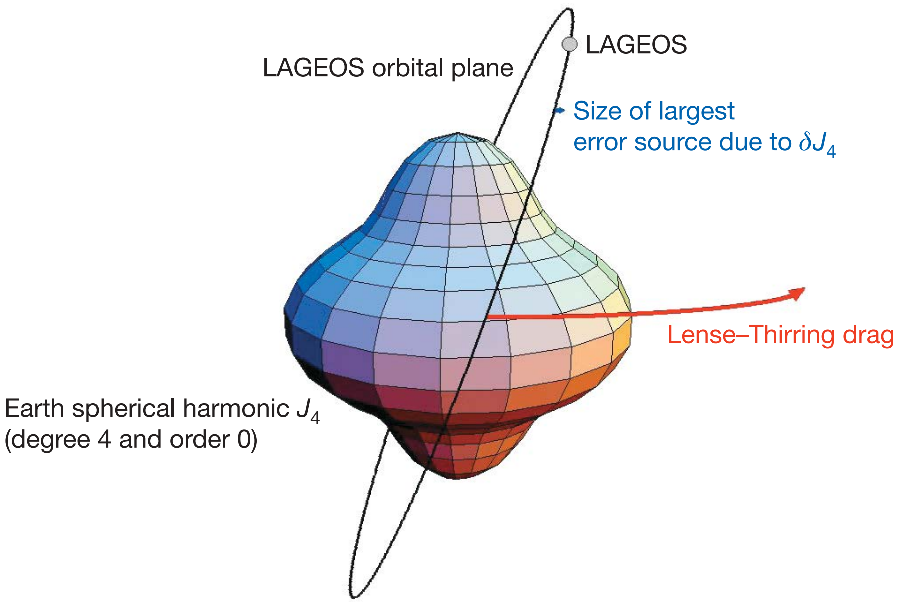


Frame Dragging in Weak Gravitational Field

The precession, with rate Ω_{L-T}, of the longitude of the nodal line of a test-particle, that is, orbiting around the Earth at a low orbit is:

$$\vec{\Omega}_{L-T} = \frac{2G\vec{J}}{c^2 a^3 (1-e^2)^{3/2}} \to \Omega_{L-T}$$

$$\approx \frac{2\times (6.674\times 10^{-11} Nm^2 kg^{-2})\times 7.2\times 10^{33} kg\, m^2 s^{-1}}{(3\times 10^8 m/s)^2 (6.371\times 10^6 m)^3} \approx 7\times 10^{-4} arcsec/day$$

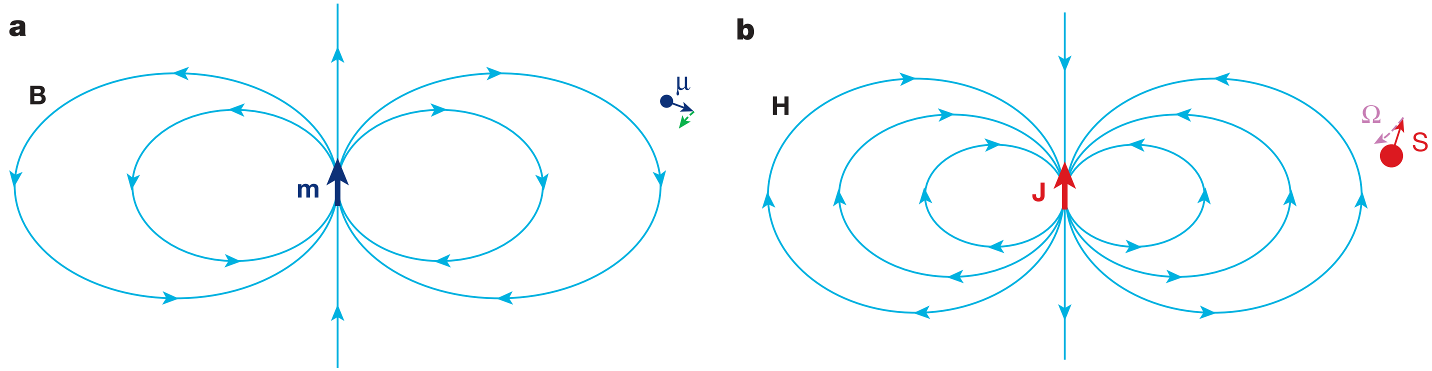


Gravitomagnetic Analogy of General Relativity with Electrodynamics.

Analogous to an accelerating charge producing a magnetic field, an accelerating mass produces certain “gravitomagnetic” effects.

For weak gravitational fields there is an analogy between the equations that govern the forces on a **spinning electric charge** (magnetic moment μ) moving through a magnetic field and the forces on a spinning mass moving through the field of a rotating mass.

The magnetic dipole will feel a force due to the magnetic field and rotate. In a similar manner the spinning mass will experience a force and precess.



Gravitomagnetic Effects

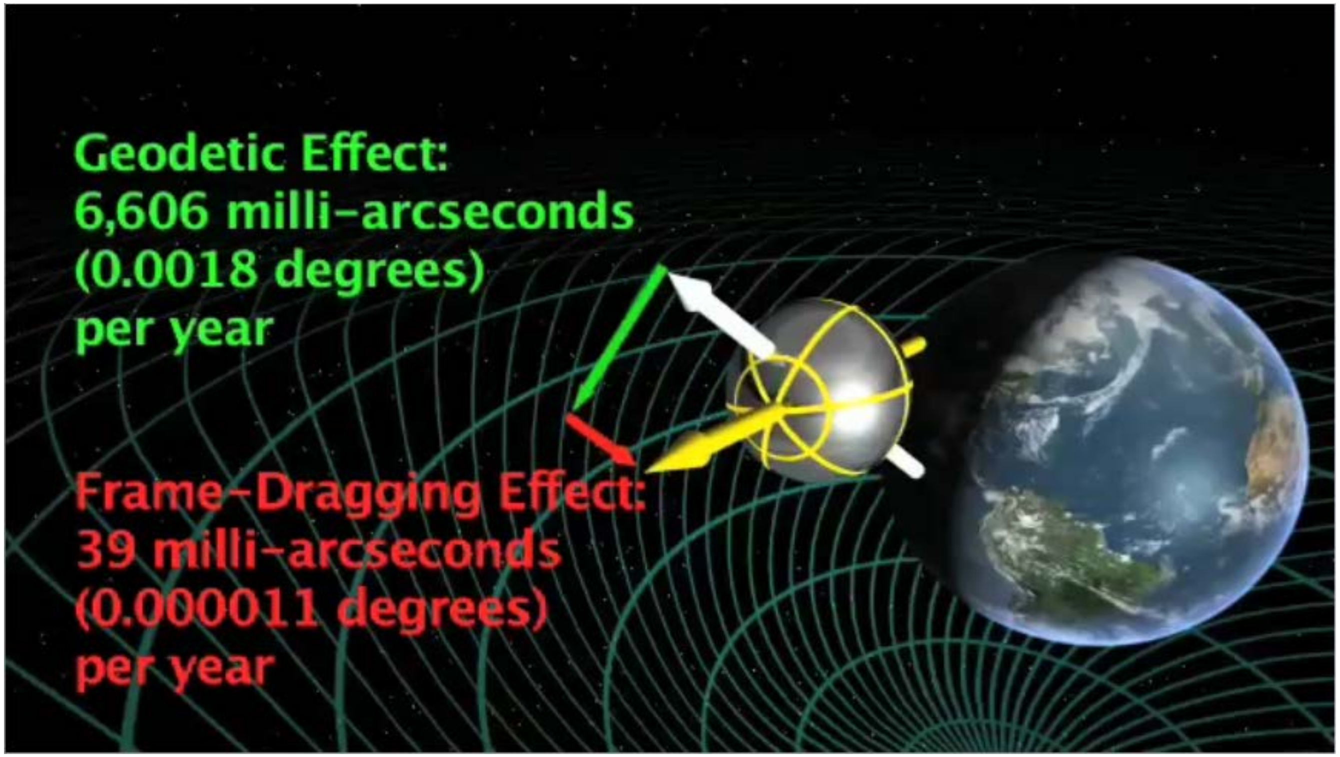
Three gravitomagnetic effects are:

(i) the **precession of a gyroscope** in orbit about a rotating mass,

(ii) the **precession of orbital planes** in which a mass orbiting a large rotating body constitutes a gyroscopic system whose orbital axis will precess, and

(iii) the **precession of the pericenter** of the orbit of a test mass about a massive rotating object

Gravity Probe B satellite attempted to measure effects (i) and (ii)
The LAGEOS satellites attempted to measure effect (ii)



$$\vec{\Omega}_S = \frac{G}{c^2}\left[\frac{3(\vec{J}\cdot\hat{r})\hat{r} - \vec{J}}{r^3}\right] \qquad \vec{\Omega}_{\text{geodetic}} = -\frac{3GM}{2c^2r^2}\vec{v}\times\hat{r}$$

Where J is the angular momentum of Earth, r is the position unit vector of the gyro, r is the distance of the gyro from Earth, M is the mass of the Earth and v is the velocity of the gyroscope.

The Gravity Probe B EXPERIMENT

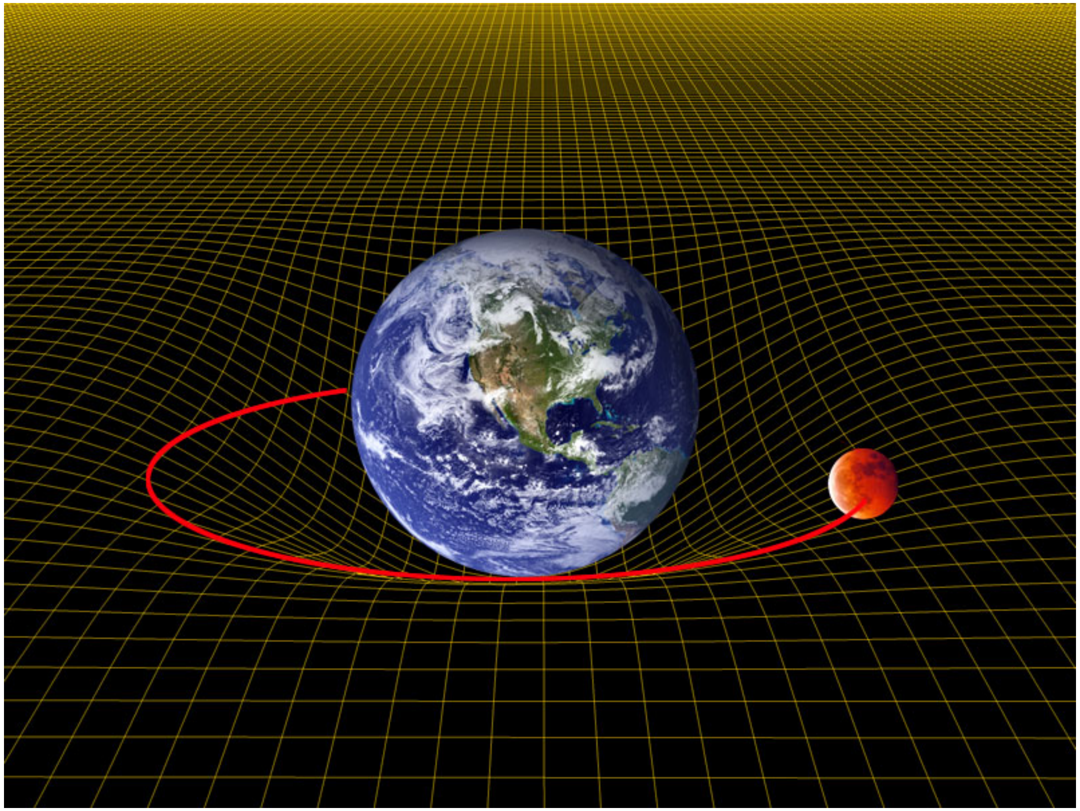
Measuring the Warping & Twisting of Spacetime with Gyroscopes

Soundtrack by Ray Lynch. Used with Permission.

The Gravity Probe B
EXPERIMENT

The Drag-Free Satellite

Geodetic Effect



The Geodetic effect (the missing inch) represents the warpage by the Earth of the local spacetime in which it resides.

The Gravity Probe B
EXPERIMENT

The Missing Inch

Kip Thorne
Feynman Professor of Theoretical Physics
Caltech

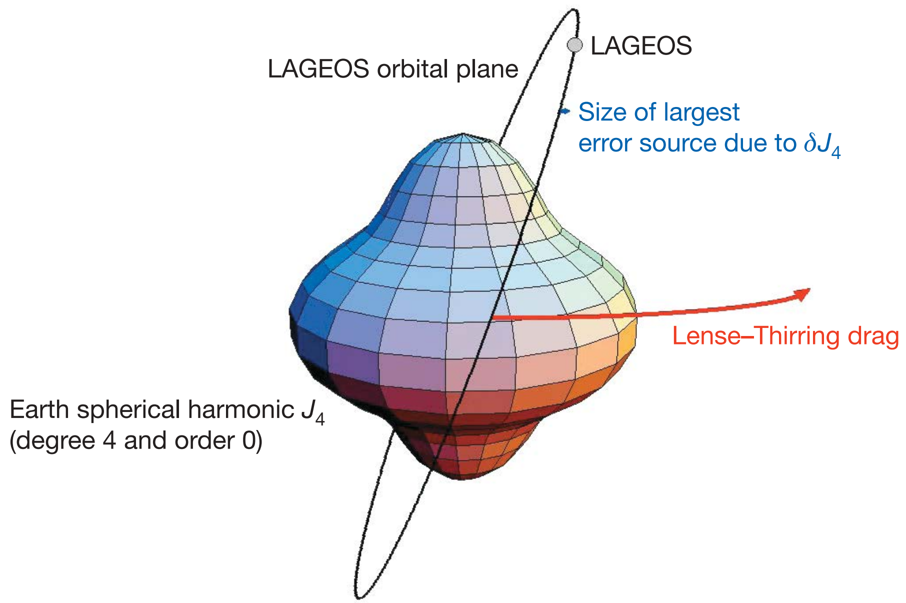
GP-B Pre-launch Press Conference
NASA Headquarters, April 2, 2004

Experimental Tests of Frame-Dragging

The LAGEOS Satellites

Frame-dragging is extremely small for Solar System objects, so to measure its effect on the orbit of a satellite we need to measure the position of the satellite to extremely high accuracy.

Laser-ranging is the most accurate technique for measuring distances to satellites such as the **LAGEOS** (laser geodynamics satellite).



Experimental Tests of Frame-Dragging

The LAGEOS Satellites

Determining accurate distances to satellites using laser-ranging:

Short laser pulses are emitted from Earth and then reflected by the LAGEOS satellites. By measuring the total round-trip travel time the distances to LAGEOS satellites are determined with a precision of a few millimeters.

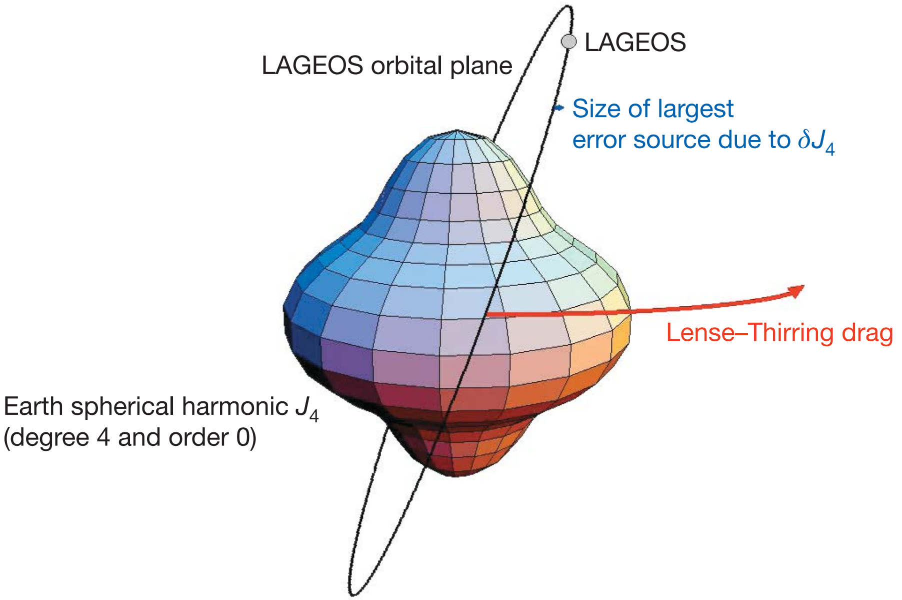
LAGEOS was launched by NASA in 1976 and LAGEOS2 was launched by the Italian Space Agency and NASA in 1992, at altitudes of approximately 5,900 km and 5,800 km respectively.

Experimental Tests of Frame-Dragging

The Lense–Thirring drag of the orbital planes of LAGEOS and LAGEOS2 is ~**0.031 arcsec per year**, corresponding at the LAGEOS altitude to ~ 1.9 m/yr.

The main perturbation of the orbital planes on the LAGEOS satellites is due to the Earth's deviations from spherical symmetry.

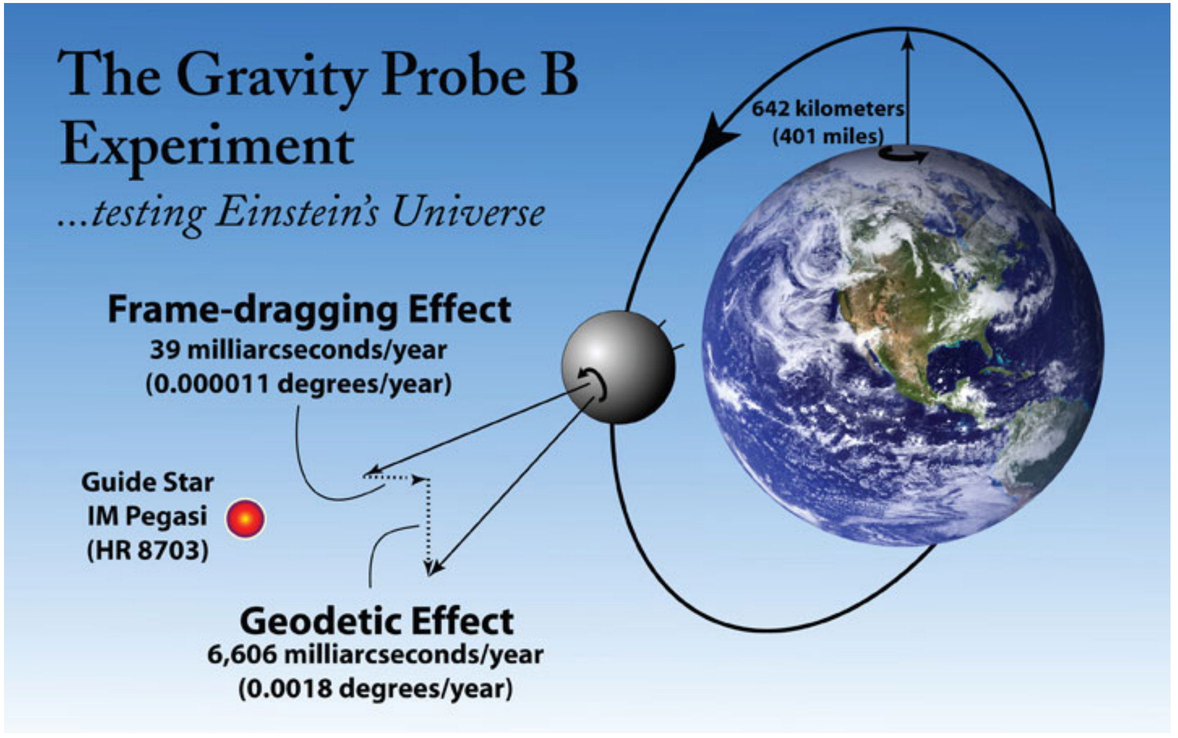
Accurate measurements of the Earth's gravitational field performed by the **GRACE satellites** have reduced the orbital uncertainties due to the modeling errors in the non-spherical Earth's gravitational field to only a few per cent of the Lense–Thirring effect.



Shown are the Lense–Thirring drag (red arrow) and its uncertainty (blue arrow) produced by the uncertainty in the Earth's mass distribution.

There is an ongoing debate about the true size of the systematic errors of the LAGEOS measurements of the L-T drag.

Experimental Tests of Frame-Dragging

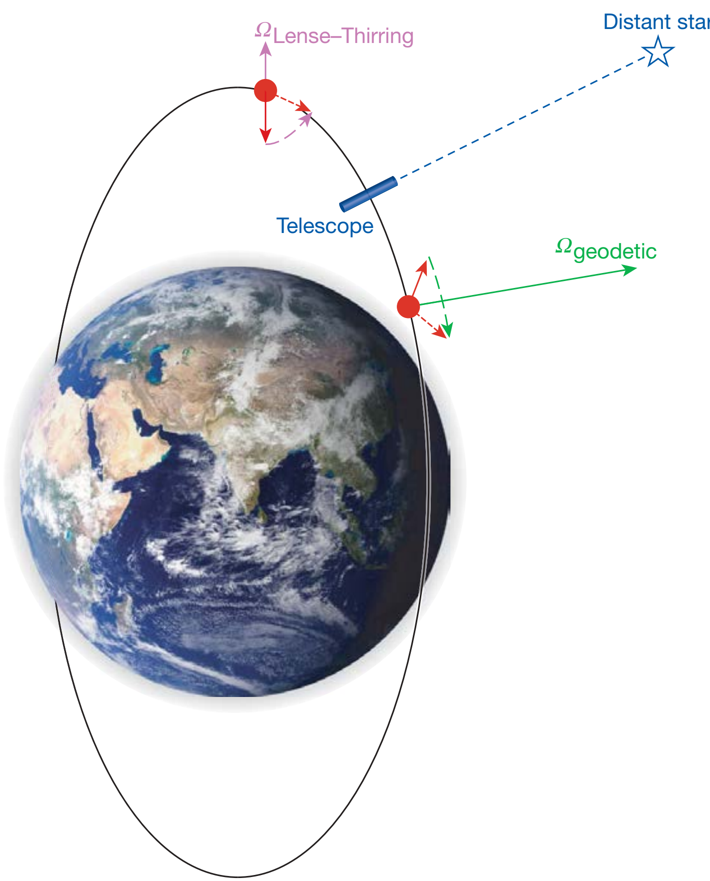


Gravity Probe B spacecraft was launched in April 2004 in a polar orbit.

Gravity Probe B carried four gyroscopes and one telescope, and was designed to measure the relativistic precessions of the four test-gyroscopes with respect to the distant star IM Pegasi.

Experimental Tests of Frame-Dragging

The violet arrow displays frame-dragging of the Gravity Probe B gyroscopes by the Earth's spin, Ω_{L-T}, (~0.039 arcsec per year rotation of Gravity Probe B's spin axis around Earth's angular momentum $\hat{J}$).

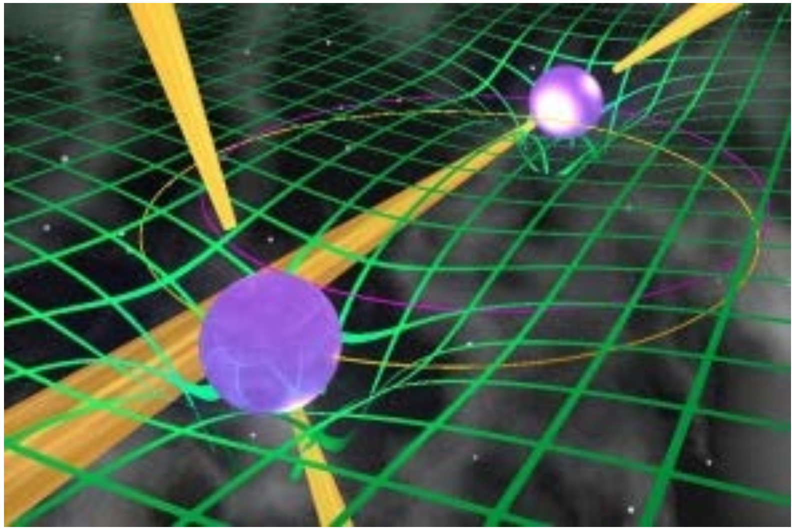


The green arrow represents the geodetic precession, $\Omega_{geodetic}$. Its theoretical value is ~ 6.6 arcsec per year about an axis orthogonal to the Gravity Probe B orbital plane.

Unfortunately due to unexpected large drifts of the gyroscopes' spin axes the geodetic precession was only measured to a precision of 1.5% (10^{-5} expected) and the error on the measurement of frame dragging Ω_{L-T} was relatively large.

Experimental Tests of Frame-Dragging

The geodetic precession of the spin axis of a binary pulsar, a spin-orbit frame-dragging effect, has been observed in the binary system PSRB1534+112, where its measured value has been reported to be ~ 0.44° (+0.48,-0.12) per year in agreement with the GR prediction of 0.52° per year.



Since 1974, a number of binary pulsars have been discovered and they provide extraordinary astrophysical laboratories for testing the general theory of relativity via the measurement of their orbital parameters.

Frame Dragging near a Kerr Black Hole