

Nicolae Sfetcu: Modern Tests of Relativistic Gravitational Theories

Modern Tests of Relativistic Gravitational Theories

Nicolae Sfetcu

25.09.2019

Sfetcu, Nicolae, "Modern Tests of Relativistic Gravitational Theories", SetThings (September 25, 2019), URL = <https://www.setthings.com/en/modern-tests-of-relativistic-gravitational-theories/>

Email: nicolae@sfetcu.com



This work is licensed under a Creative Commons Attribution-NoDerivatives 4.0 International. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nd/4.0/>.

A partial translation of

Sfetcu, Nicolae, "Epistemologia gravitației experimentale – Raționalitatea științifică", SetThings (1 august 2019), MultiMedia Publishing (ed.), ISBN: 978-606-033-234-3, DOI: 10.13140/RG.2.2.15421.61925, URL = <https://www.setthings.com/ro/e-books/epistemologia-gravitatiei-experimentale-rationalitatea-stiintifica/>

SHAPIRO DELAY	3
GRAVITATIONAL DILATION OF TIME.....	4
FRAME DRAGGING AND GEODETIC EFFECT	5
TESTING OF THE PRINCIPLE OF EQUIVALENCE	8
SOLAR SYSTEM TESTS	13
BIBLIOGRAPHY	14

Dicke and Schiff established a framework for testing general relativity,¹ including through null experiments and using the physics of space exploration, electronics and condensed matter, such as the Pound-Rebka experiment and laser interferometry. The gravitational lens tests and the temporal delay of light are highlighted by parameter γ of the PPN formalism, equal to 1 for general relativity and with different values in other theories. The BepiColombo mission aims to test the general theory of relativity by measuring the gamma and beta parameters of the PPN formalism.²

¹ L. I. Schiff, "On Experimental Tests of the General Theory of Relativity," *American Journal of Physics* 28, no. 4 (April 1, 1960): 340–343, <https://doi.org/10.1119/1.1935800>.

² C. Brans and R. H. Dicke, "Mach's Principle and a Relativistic Theory of Gravitation," *Physical Review* 124, no. 3 (November 1, 1961): 925–935, <https://doi.org/10.1103/PhysRev.124.925>.

Shapiro Delay

The gravitational delay (Shapiro delay), according to which the light signals require more time to pass through a gravitational field than in the absence of that field, has been successfully tested.³ In the PPN formalism, the gravitational delay is highlighted by the parameter γ , which encodes the influence of gravity on the geometry of space.⁴

Irwin I. Shapiro proposed this test becoming "classic", predicting a relativistic delay in the return of radar signals reflected on other planets. The use of the planets Mercury and Venus as targets before and after they were eclipsed by the Sun confirmed the theory of general relativity.⁵ Later the Cassini probe was used for a similar experiment.⁶ The measurement of the PPN gamma parameter is affected by the gravitomagnetic effect caused by the orbital motion of the Sun around the barycentre of the solar system. The very long basic interferometry allowed the corrections of this effect in the field of movement of Jupiter⁷ and Saturn.⁸

³ Irwin I. Shapiro, "Fourth Test of General Relativity," *Physical Review Letters* 13, no. 26 (December 28, 1964): 789–791, <https://doi.org/10.1103/PhysRevLett.13.789>.

⁴ Irwin I. Shapiro et al., "Fourth Test of General Relativity: New Radar Result," *Physical Review Letters* 26, no. 18 (May 3, 1971): 1132–1135, <https://doi.org/10.1103/PhysRevLett.26.1132>.

⁵ Shapiro et al., 1132–1135.

⁶ Sergei M. Kopeikin and Edward B. Fomalont, "Gravimagnetism, Causality, and Aberration of Gravity in the Gravitational Light-Ray Deflection Experiments," *General Relativity and Gravitation* 39, no. 10 (October 1, 2007): 1583–1624, <https://doi.org/10.1007/s10714-007-0483-6>.

⁷ Kopeikin and Fomalont, 1583–1624.

⁸ Ed Fomalont et al., "Recent VLBA/VERA/IVS Tests of General Relativity," *Proceedings of the International Astronomical Union* 5, no. S261 (April 2009): 291–295, <https://doi.org/10.1017/S1743921309990536>.

Gravitational dilation of time

Gravity influences the passage of time. Processes close to a massive body are slower.⁹ The gravitational redshift was measured in the laboratory¹⁰ and using astronomical observations.¹¹ The gravitational dilation of the time in the gravitational field of the Earth was measured using atomic clocks,¹² being verified as a side effect of the functioning of the Global Positioning System (GPS).¹³ Tests in stronger gravitational fields need binary pulsars.¹⁴ All the results are in accordance with general relativity, but also with other theories where the principle of equivalence is valid.¹⁵

The gravitational dilation of time coexists with the existence of an accelerated frame of reference, except for the center of a concentric distribution of matter in which there is no accelerated frame of reference, although it is assumed that here time is dilated.¹⁶ All physical phenomena undergo in this case the same time dilation, in accordance with the principle of equivalence. The time dilation can be measured for photons that are emitted on Earth, curved near the Sun, reflected on Venus, and returned to Earth along a similar path. It is observed that the speed of light in the vicinity of the Sun is lower than c . The phenomenon was measured experimentally using atomic clocks on the plane, where time dilations occur also due to the differences of height less than 1 meter and were tested experimentally in the laboratory.¹⁷ Other test modes are through the Pound-Rebka experiment, observations of the white dwarf Sirius B spectra, and experiments with time signals sent to and from Mars soil with the Viking 1.

⁹ Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler, *Gravitation* (W. H. Freeman, 1973).

¹⁰ R. V. Pound and G. A. Rebka, "Apparent Weight of Photons," *Physical Review Letters* 4, no. 7 (April 1, 1960): 186, <https://doi.org/10.1103/PhysRevLett.4.337>.

¹¹ M. A. Barstow et al., "Hubble Space Telescope Spectroscopy of the Balmer Lines in Sirius B," *Monthly Notices of the Royal Astronomical Society* 362, no. 4 (October 1, 2005): 1134–1142, <https://doi.org/10.1111/j.1365-2966.2005.09359.x>.

¹² Hans C. Ohanian and Remo Ruffini, *Gravitation and Spacetime* (Norton, 1994).

¹³ Neil Ashby, "Relativity in the Global Positioning System," *Living Reviews in Relativity* 6, no. 1 (January 28, 2003): 1, <https://doi.org/10.12942/lrr-2003-1>.

¹⁴ Michael Kramer, "Millisecond Pulsars as Tools of Fundamental Physics," in *Astrophysics, Clocks and Fundamental Constants*, ed. Savely G. Karshenboim and Ekkehard Peik, Lecture Notes in Physics (Berlin, Heidelberg: Springer Berlin Heidelberg, 2004), 33–54, https://doi.org/10.1007/978-3-540-40991-5_3.

¹⁵ Ohanian and Ruffini, *Gravitation and Spacetime*.

¹⁶ Einstein derived these effects using the principle of equivalence as early as 1907, cf. Albert Einstein, "Über Das Relativitätsprinzip Und Die Aus Demselben Gezogene Folgerungen, in Volume 2: The Swiss Years: Writings, 1900-1909 Page 432 (468 of 692)," 1907, <https://einsteinpapers.press.princeton.edu/vol2-doc/468>.

¹⁷ Pound and Rebka, "Apparent Weight of Photons," 186.

Frame dragging and geodetic effect

In general relativity, the apsides of the orbits (the point on the orbit of the body closest to the center of mass of the system) will have a precession, forming an orbit different from an ellipse, the shape of the rose. Einstein predicted this move. Relativistic precessions have been observed for all planets that allow accurate measurements of precession (Mercury, Venus and Earth),¹⁸ and in binary pulsar systems where it is larger by five orders of magnitude.

A binary system that emits gravitational waves loses energy. Thus, the distance between the two orbital bodies decreases, as does their orbital period. At the level of the solar system, the effect is difficult to observe. It is observable for a near binary pulsar, from which very precise frequency radio pulses are received, allowing measurements of the orbital period. Neutron stars emit large amounts of energy in the form of gravitational radiation. The first observation of this effect is due to Hulse and Taylor, using a binary pulsar PSR1913+16 discovered in 1974. This was the first, indirect, detection of gravitational waves.¹⁹

The relativity of the direction has several relativistic effects,²⁰ such as the geodetic precession: the direction of the axis of a gyroscope in free fall in curved space will change compared to the direction of light received from distant stars.²¹ For the Moon-Earth system, this effect was measured using the laser reflected on the Moon,²² and more recently with the help of the test masses on board the Gravity Probe B.²³

Near a rotary table, there are gravitometric or frame dragging effects. In the case of rotating black holes, any object that enters the ergosphere rotates. The effect can be tested by its influence on the

¹⁸ Ohanian and Ruffini, *Gravitation and Spacetime*, 406–7.

¹⁹ R. A. Hulse and J. H. Taylor, “Discovery of a Pulsar in a Binary System,” *The Astrophysical Journal Letters* 195 (January 1, 1975): L51–L55, <https://doi.org/10.1086/181708>.

²⁰ Roger Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, Reprint edition (New York: Vintage, 2007).

²¹ Ohanian and Ruffini, *Gravitation and Spacetime*, sec. 7.8.

²² Kenneth Nordtvedt, “Lunar Laser Ranging - a Comprehensive Probe of Post-Newtonian Gravity,” *ArXiv:Gr-Qc/0301024*, January 7, 2003, <http://arxiv.org/abs/gr-qc/0301024>.

²³ C. W. F. Everitt et al., “Gravity Probe B: Final Results of a Space Experiment to Test General Relativity,” *Physical Review Letters* 106, no. 22 (May 31, 2011): 221101, <https://doi.org/10.1103/PhysRevLett.106.221101>.

orientation of free fall gyros.²⁴ Tests were performed using the LAGEOS satellites,²⁵ with the Mars Global Surveyor probe around Mars,²⁶ confirming the relativistic prediction.

The first frame dragging effect was derived in 1918 by Josef Lense and Hans Thirring and is known as the *Lense-Thirring effect*. They predicted that the rotation of a massive body would distort the spacetime metric, causing the orbit of a nearby test particle to precess. In order to detect it, it is necessary to examine a very massive body or to construct a very sensitive instrument. The *linear dragging of the frames* appears by applying the RG principle to the linear momentum. It is very difficult to verify.²⁷ *Increasing of the static mass* is another effect, an increase in the inertia of a body when other masses are placed nearby. Einstein states that it derives from the same equation of general relativity. It is a small effect, difficult to confirm experimentally.

Several costly proposals were made, including in 1976 by Van Patten and Everitt,²⁸ for a special space mission to measure the Lense-Thirring precession of a pair of spacecrafts to be placed in Earth's polar orbits with non-dragging devices. In 1986 Ciufolini proposed the launch of a passive geodesic satellite in an orbit identical to that of the LAGEOS satellite. The tests were started using the LAGEOS and LAGEOS II satellites in 1996.²⁹ The accuracy of the tests is controversial. Neither did the Gravity Probe B experiment achieve the desired accuracy.³⁰

In the case of stars orbiting near a supermassive black hole, the frame dragging should cause the orbital plane of the star to precess around the axis of rotation of the black hole, an effect that could be detected in the following years by astrometric monitoring of the stars in the center of the Milky Way galaxy.³¹

²⁴ Ohanian and Ruffini, *Gravitation and Spacetime*, sec. 4.7.

²⁵ Lorenzo Iorio, "An Assessment of the Systematic Uncertainty in Present and Future Tests of the Lense-Thirring Effect with Satellite Laser Ranging," *Space Science Reviews* 148, no. 1–4 (December 2009): 363–381, <https://doi.org/10.1007/s11214-008-9478-1>.

²⁶ Lorenzo Iorio, "On the Lense-Thirring Test with the Mars Global Surveyor in the Gravitational Field of Mars," *Open Physics* 8, no. 3 (January 1, 2010): 509–513, <https://doi.org/10.2478/s11534-009-0117-6>.

²⁷ Albert Einstein, "The Meaning of Relativity," Princeton University Press, 1921, <https://press.princeton.edu/titles/484.html>.

²⁸ R. A. Van Patten and C. W. F. Everitt, "Possible Experiment with Two Counter-Orbiting Drag-Free Satellites to Obtain a New Test of Einstein's General Theory of Relativity and Improved Measurements in Geodesy," *Physical Review Letters* 36, no. 12 (March 22, 1976): 629–632, <https://doi.org/10.1103/PhysRevLett.36.629>.

²⁹ Iorio, "An Assessment of the Systematic Uncertainty in Present and Future Tests of the Lense-Thirring Effect with Satellite Laser Ranging," 363–381.

³⁰ Everitt et al., "Gravity Probe B."

³¹ Ohanian and Ruffini, *Gravitation and Spacetime*, sec. 7.8.

Relativistic jets can provide evidence for frame dragging.³² The gravitomagnetic model developed by Reva Kay Williams predicts the high energy particles emitted by quasars and active galactic nuclei, the extraction of X and γ rays and $e^- e^+$ relativistic pairs, jets collimated around the polar axis, and asymmetric jets formation.

³² For a distant observer, jets sometimes seem to move faster than light, but this is an optical illusion that does not violate the principles of relativity.

Testing of the principle of equivalence

At the beginning of the 17th century Galileo developed a principle similar to that of equivalence when he showed experimentally that the acceleration of a body due to gravity is independent of its mass quantity. Kepler emphasized the principle of equivalence through a thought experiment, what would happen if the Moon were stopped in orbit and dropped to Earth.

The principle of equivalence has historically played an important role in the law of gravity. Newton considered it from the opening paragraph of the *Principia*. Einstein also relied on this principle in general relativity. Newton's principle of equivalence states that the "mass" of a body is proportional to its "weight" (the **weak equivalence principle**, WEP). An alternative definition of WEP is that the trajectory of a body in the absence of forces is independent of its internal structure and composition. A simple WEP test is the comparison of the acceleration of two bodies of different composition in an external gravitational field. Other high-precision experiments include from Newton, Bessel and Potter's pendulum experiments to the classical torsion measurements of Eotvos,³³ Dicke,³⁴ and Braginsky.³⁵ There are several projects to improve the values measured with the help of satellites.

The **Einstein Equivalence Principle** (EEP) is stronger and more comprehensive, stating that the WEP is valid, and the results of local non-gravitational experiments are independent of the speeds of the appropriate reference frames and the place and time they are performed. The independence of the frame of reference is called local Lorentz invariance, and independence of its internal structure and composition is called local position invariance.

The special relativity benefited from a series of experiments that subsequently contributed to the acceptance of the GR:

- Michelson-Morley experiment and subsequent equivalent experiments,³⁶
- Ives-Stillwell, Rossi-Hall, other tests of time dilation,³⁷

³³ Roland V. Eötvös, Desiderius Pekár, and Eugen Fekete, "Beiträge Zum Gesetze Der Proportionalität von Trägheit Und Gravität," *Annalen Der Physik* 373 (1922): 11–66, 68, <https://doi.org/10.1002/andp.19223730903>.

³⁴ R. H. Dicke, *Gravitation and the Universe*, 1969, <http://adsabs.harvard.edu/abs/1969grun.book.....D>.

³⁵ V. B. Braginsky and V. I. Panov, "Verification of the equivalence of inertial and gravitational mass," *Soviet Journal of Experimental and Theoretical Physics* 34 (1972): 34, 463–466, <https://istina.msu.ru/publications/article/4687588/>.

³⁶ A. Brilliet and J. L. Hall, "Improved Laser Test of the Isotropy of Space," *Physical Review Letters* 42 (February 1, 1979): 42, 549–552, <https://doi.org/10.1103/PhysRevLett.42.549>.

³⁷ F. J. M. Farley et al., "The Anomalous Magnetic Moment of the Negative Muon," *Il Nuovo Cimento A* (1965-1970) 45, no. 1 (September 1, 1966): 45, 281–286, <https://doi.org/10.1007/BF02738104>.

- independence of the speed of light from the source speed, using X-ray binary stellar sources, and high energy pions,³⁸
- isotropy of light speed.³⁹

In recent years, scientists have begun to look for apparent violations of the Lorentz invariance resulting from certain quantum gravity models. A simple modality, embodied in the c_2 formalism, assumes that the electromagnetic interactions suffer a slight violation of the Lorentz invariance by changing the velocity of the electromagnetic radiation c relative to the limiting speed of the testing particle of particles,⁴⁰ trying to select a preferred universal resting frame, possible of cosmic background radiation.⁴¹ Through the Michelson-Morley experiments the speed of light is verified; the Brilliet-Hall experiment⁴² used a Fabry-Perot laser interferometer; in other experiments, the frequencies of the oscillators of the electromagnetic cavity in different orientations were compared with each other or with the atomic clocks, depending on the orientation of the laboratory.⁴³

The principle of local position invariance can be tested by the gravitational redshift experiments. The first such experiments were the Pound-Rebka-Snider series from 1960 to 1965, which measured the frequency change of the gamma radiation photons. The most accurate standard redshift test was the Vessot-Levine rocket experiment in June 1976.⁴⁴ A "null" redshift experiment conducted in 1978 tested whether the relative rate of two different clocks depends on position. The most recent experiments have used laser cooling and trapping techniques to obtain extreme clock stability and compared the hyperfine transition Rubidium-87,⁴⁵ the ionic quadrupole

³⁸ T. Alväger et al., "Test of the Second Postulate of Special Relativity in the GeV Region," *Physics Letters* 12, no. 3 (October 1, 1964): 12, 260–262, [https://doi.org/10.1016/0031-9163\(64\)91095-9](https://doi.org/10.1016/0031-9163(64)91095-9).

³⁹ null Krisher et al., "Test of the Isotropy of the One-Way Speed of Light Using Hydrogen-Maser Frequency Standards," *Physical Review. D, Particles and Fields* 42, no. 2 (July 15, 1990): 42, 731–734.

⁴⁰ Clifford M. Will, "The Confrontation between General Relativity and Experiment," *Living Reviews in Relativity* 17, no. 1 (December 2014): 4, <https://doi.org/10.12942/lrr-2014-4>.

⁴¹ C. H. Lineweaver et al., "The Dipole Observed in the COBE DMR 4 Year Data," *The Astrophysical Journal* 470 (October 1, 1996): 470, 38–42, <https://doi.org/10.1086/177846>.

⁴² Brilliet and Hall, "Improved Laser Test of the Isotropy of Space," 42, 549–552.

⁴³ Paul L. Stanwix et al., "Test of Lorentz Invariance in Electrodynamics Using Rotating Cryogenic Sapphire Microwave Oscillators," *Physical Review Letters* 95, no. 4 (July 21, 2005): 040404, <https://doi.org/10.1103/PhysRevLett.95.040404>.

⁴⁴ R. F. C. Vessot et al., "Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser," *Physical Review Letters* 45, no. 26 (December 29, 1980): 45, 2081–2084, <https://doi.org/10.1103/PhysRevLett.45.2081>.

⁴⁵ H. Marion et al., "A Search for Variations of Fundamental Constants Using Atomic Fountain Clocks," *Physical Review Letters* 90, no. 15 (April 18, 2003): 90, 150801–1–4, <https://doi.org/10.1103/PhysRevLett.90.150801>.

transition Mercury-199,⁴⁶ the atomic transition with Hydrogen 1S- 2S,⁴⁷ or an optical transition in Ytterbium-171,⁴⁸ against hyperfine ground-state transition in Cesium-133.⁴⁹

The Einstein equivalence principle is part of the hard core of Einstein's research program, since the existence of EEP implies gravity as a phenomenon in "curved spacetime". It turns out that the only theories of gravity that can fully incorporate EEP are those that satisfy the postulates of "metric theories of gravity", respectively:⁵⁰

1. Spacetime has a symmetrical value.
2. The trajectories of free-falling bodies are geodesic of this metric.
3. In the free-falling local reference frames, the non-gravitational laws of physics are those written in the language of special relativity.

In 1960, Schiff developed the hypothesis that any complete, self-consistent theory of gravity that embodies strong equivalence principle (SEP) necessarily embodies EEP (the validity of SEP itself guarantees the validity of local Lorentz and position invariance). In this case, it follows, based on the energy conservation hypothesis, that Eotvos experiments are direct empirical bases for EEP. The first successful attempt to prove Schiff's conjecture more formally was made by Lightman and Lee,⁵¹ using a framework called "THEμ formalism" which includes all metric theories of gravity and many non-metric theories, which uses the rate of falling of a "tested" body consisting of interacting charged particles.

Empirical evidence supporting the Einstein principle of equivalence states that the only theories of gravity that hope to be viable are metric theories, or possibly theories that are metric outside of very weak or short-lived non-metric couplings (as in string theory).⁵²

There may be other gravitational fields besides metric ones, such as scalar or vector fields, which mediate how matter and non-gravitational fields generate gravitational fields and produce the metric; but once the metric is determined, it only acts backwards in the manner prescribed by the EEP. Thus, all metric theories of gravity can be divided into two fundamental classes: "purely

⁴⁶ S. Bize et al., "Testing the Stability of Fundamental Constants with the 199Hg+ Single-Ion Optical Clock," *Physical Review Letters* 90, no. 15 (April 18, 2003): 90, 150802–1–4, <https://doi.org/10.1103/PhysRevLett.90.150802>.

⁴⁷ M. Fischer et al., "New Limits to the Drift of Fundamental Constants from Laboratory Measurements," *Physical Review Letters* 92, no. 23 (June 10, 2004): 92, 230802–1–4, <https://doi.org/10.1103/PhysRevLett.92.230802>.

⁴⁸ E. Peik et al., "New Limit on the Present Temporal Variation of the Fine Structure Constant," *Physical Review Letters* 93, no. 17 (October 18, 2004): 93, 170801–1–4, <https://doi.org/10.1103/PhysRevLett.93.170801>.

⁴⁹ Will, "The Confrontation between General Relativity and Experiment."

⁵⁰ Will.

⁵¹ A. P. Lightman and D. L. Lee, "Restricted Proof That the Weak Equivalence Principle Implies the Einstein Equivalence Principle," *Physical Review D, Particles Fields* 8, no. 2 (1973): 8, 364–376, http://inis.iaea.org/Search/search.aspx?orig_q=RN:5098997.

⁵² Will, "The Confrontation between General Relativity and Experiment."

dynamic" and "previously geometric."⁵³ In a "purely dynamic metric theory" the gravitational fields have the structure and evolution determined by the partially coupled differential field equations. A "previously geometric" theory contains "absolute elements", fields or equations whose structure and evolution are given *a priori* and are independent of the structure and evolution of the other fields of theory. General relativity is a purely dynamic theory.

The **strong equivalence principle** states that: WEP is valid for all bodies, and the result of any local testing experiment is independent of the speed of the apparatus and the place and time of the experiment.

Compared to WEP, SEP includes gravitational sources (planets, stars) and experiments involving gravitational forces (Cavendish experiments, gravimetric measurements). Note that WEP includes EEP as a special case where local gravitational forces are ignored. If the WEP is strictly valid, there must be only one gravitational field in the universe, the metric g , but there is no rigorous evidence of this statement so far.

The Einstein equivalence principle can be tested, in addition to WEP tests, by looking for the variation of dimensionless constants and mass ratios.

The strong equivalence principle implies that gravity is geometric by nature and does not contain additional associated fields. Thus, SEP says that a measurement of a flat space surface is absolutely equivalent to any other flat space surface in any other part of the universe. Einstein's theory of general relativity is the only theory of gravity that satisfies the strong equivalence principle.

The SEP can be tested by searching for a variation of Newton's gravitational constant G , or a variation of the mass of the fundamental particles. These would result from deviations from the law of gravitational force from general relativity, especially deviations from inverse-quadratic proportionality, which can be explained by the existence of the fifth force. Other sought effects are the Nordtvedt effect, a "polarization" of the orbits of the solar system due to the gravitational acceleration of self-generation at a rate different from the normal matter, sought by the Lunar Laser Ranging experiment. Other tests include studying the deflection of radiation from radio sources far from the sun measured with very long basic interferometry or measuring the change in frequency of signals to and from the Cassini spacecraft.

Quantum gravity theories, such as string theory and loop quantum gravity, predict violations of the weak equivalence principle. Currently, the tests of the weak equivalence principle have a degree of sensitivity so that the non-detection of an infringement is as profound as the discovery of an

⁵³ Will.

infringement. Discovering the violation of the principle of equivalence would provide an important guide to unification.⁵⁴

A formalism of non-gravitational laws of physics in the presence of gravity that incorporates the possibility of nonmetric (nonuniversal) and metric coupling is the TH formalism elaborated by Lightman and Lee.⁵⁵ It allows quantitative forecasting for experiment results.

⁵⁴ James Overduin et al., “The Science Case for STEP,” *Advances in Space Research* 43, no. 10 (May 15, 2009): 1532–1537, <https://doi.org/10.1016/j.asr.2009.02.012>.

⁵⁵ Lightman and Lee, “Restricted Proof That the Weak Equivalence Principle Implies the Einstein Equivalence Principle,” 8, 364–76.

Solar system tests

The dynamic environment of spacetime around Earth allows testing of gravitational theories, with geodetic satellites as test masses. An example is the LAGEOS satellites, launched for geodetic and geodynamic purposes, and for fundamental physical studies. LAGEOS satellites are used as a target for laser pulses sent from ground stations to calculate the instantaneous distance ("Satellite Laser Ranging" (SLR) technique). The determination of the orbit of the satellites requires models for the dynamics of the satellites, for the measurement procedures and for the transformations of the reference frames.⁵⁶ The models take into account geopotential, lunar and planetary disturbances, pressure of solar radiation and Earth's albedo, Rubin-cam and Yarkovsky-Schach effects, SLR station coordinates, ocean loading, earth orientation parameters and measurement procedure.⁵⁷ The models also include general relativistic corrections in the post-Newtonian parametric formalism (PPN).⁵⁸ The tests performed confirm the general relativity predictions (Schwarzschild precession, Lense-Thirring effect) and exclude an alternative theory (NLRI/Yukawa potential).

⁵⁶ Friedrich W. Hehl et al., "General Relativity with Spin and Torsion: Foundations and Prospects," *Reviews of Modern Physics* 48, no. 3 (July 1, 1976): 393–416, <https://doi.org/10.1103/RevModPhys.48.393>.

⁵⁷ Emil T. Akhmedov et al., "Experimental Tests of Quantum Gravity and Exotic Quantum Field Theory Effects," ResearchGate, 2014, https://www.researchgate.net/publication/274948108_Experimental_Tests_of_Quantum_Gravity_and_Exotic_Quantum_Field_Theory_Effects.

⁵⁸ Kenneth Nordtvedt Jr. and Clifford M. Will, "Conservation Laws and Preferred Frames in Relativistic Gravity. II. Experimental Evidence to Rule Out Preferred-Frame Theories of Gravity," *The Astrophysical Journal* 177 (November 1, 1972): 775–792, <https://doi.org/10.1086/151755>.

Bibliography

- Akhmedov, Emil T., Stephen James Minter, Piero Nicolini, and Douglas Singleton. “Experimental Tests of Quantum Gravity and Exotic Quantum Field Theory Effects.” ResearchGate, 2014.
https://www.researchgate.net/publication/274948108_Experimental_Tests_of_Quantum_Gravity_and_Exotic_Quantum_Field_Theory_Effects.
- Alväger, T., F. J. M. Farley, J. Kjellman, and L. Wallin. “Test of the Second Postulate of Special Relativity in the GeV Region.” *Physics Letters* 12, no. 3 (October 1, 1964): 260–62.
[https://doi.org/10.1016/0031-9163\(64\)91095-9](https://doi.org/10.1016/0031-9163(64)91095-9).
- Ashby, Neil. “Relativity in the Global Positioning System.” *Living Reviews in Relativity* 6, no. 1 (January 28, 2003): 1. <https://doi.org/10.12942/lrr-2003-1>.
- Barstow, M. A., Howard E. Bond, J. B. Holberg, M. R. Burleigh, I. Hubeny, and D. Koester. “Hubble Space Telescope Spectroscopy of the Balmer Lines in Sirius B.” *Monthly Notices of the Royal Astronomical Society* 362, no. 4 (October 1, 2005): 1134–42.
<https://doi.org/10.1111/j.1365-2966.2005.09359.x>.
- Bize, S., S. A. Diddams, U. Tanaka, C. E. Tanner, W. H. Oskay, R. E. Drullinger, T. E. Parker, et al. “Testing the Stability of Fundamental Constants with the 199Hg+ Single-Ion Optical Clock.” *Physical Review Letters* 90, no. 15 (April 18, 2003): 150802.
<https://doi.org/10.1103/PhysRevLett.90.150802>.
- Braginsky, V. B., and V. I. Panov. “Verification of the equivalence of inertial and gravitational mass.” *Soviet Journal of Experimental and Theoretical Physics* 34 (1972): 463–66.
<https://istina.msu.ru/publications/article/4687588/>.
- Brans, C., and R. H. Dicke. “Mach’s Principle and a Relativistic Theory of Gravitation.” *Physical Review* 124, no. 3 (November 1, 1961): 925–35. <https://doi.org/10.1103/PhysRev.124.925>.
- Brillet, A., and J. L. Hall. “Improved Laser Test of the Isotropy of Space.” *Physical Review Letters* 42 (February 1, 1979): 549–52. <https://doi.org/10.1103/PhysRevLett.42.549>.
- Dicke, R. H. *Gravitation and the Universe*, 1969. <http://adsabs.harvard.edu/abs/1969grun.book.....D>.
- Einstein, Albert. “The Meaning of Relativity.” Princeton University Press, 1921.
<https://press.princeton.edu/titles/484.html>.
- . “Über Das Relativitätsprinzip Und Die Aus Demselben Gezogene Folgerungen, in Volume 2: The Swiss Years: Writings, 1900-1909 Page 432 (468 of 692),” 1907.
<https://einsteinpapers.press.princeton.edu/vol2-doc/468>.
- Eötvös, Roland V., Desiderius Pekár, and Eugen Fekete. “Beiträge Zum Gesetze Der Proportionalität von Trägheit Und Gravität.” *Annalen Der Physik* 373 (1922): 11–66.
<https://doi.org/10.1002/andp.19223730903>.
- Everitt, C. W. F., D. B. DeBra, B. W. Parkinson, J. P. Turneare, J. W. Conklin, M. I. Heifetz, G. M. Keiser, et al. “Gravity Probe B: Final Results of a Space Experiment to Test General Relativity.” *Physical Review Letters* 106, no. 22 (May 31, 2011): 221101.
<https://doi.org/10.1103/PhysRevLett.106.221101>.
- Farley, F. J. M., J. Bailey, R. C. A. Brown, M. Giesch, H. Jöstlein, S. van der Meer, E. Picasso, and M. Tannenbaum. “The Anomalous Magnetic Moment of the Negative Muon.” *Il Nuovo Cimento A (1965-1970)* 45, no. 1 (September 1, 1966): 281–86.
<https://doi.org/10.1007/BF02738104>.
- Fischer, M., N. Kolachevsky, M. Zimmermann, R. Holzwarth, Th Udem, T. W. Haensch, M. Abgrall, et al. “New Limits to the Drift of Fundamental Constants from Laboratory Measurements.” *Physical Review Letters* 92, no. 23 (June 10, 2004): 230802.
<https://doi.org/10.1103/PhysRevLett.92.230802>.
- Fomalont, Ed, Sergei Kopeikin, Dayton Jones, Mareki Honma, and Oleg Titov. “Recent VLBA/VERA/IVS Tests of General Relativity.” *Proceedings of the International Astronomical Union* 5, no. S261 (April 2009): 291–95. <https://doi.org/10.1017/S1743921309990536>.

- Hehl, Friedrich W., Paul von der Heyde, G. David Kerlick, and James M. Nester. "General Relativity with Spin and Torsion: Foundations and Prospects." *Reviews of Modern Physics* 48, no. 3 (July 1, 1976): 393–416. <https://doi.org/10.1103/RevModPhys.48.393>.
- Hulse, R. A., and J. H. Taylor. "Discovery of a Pulsar in a Binary System." *The Astrophysical Journal Letters* 195 (January 1, 1975): L51–53. <https://doi.org/10.1086/181708>.
- Iorio, Lorenzo. "An Assessment of the Systematic Uncertainty in Present and Future Tests of the Lense-Thirring Effect with Satellite Laser Ranging." *Space Science Reviews* 148, no. 1–4 (December 2009): 363–81. <https://doi.org/10.1007/s11214-008-9478-1>.
- . "On the Lense-Thirring Test with the Mars Global Surveyor in the Gravitational Field of Mars." *Open Physics* 8, no. 3 (January 1, 2010). <https://doi.org/10.2478/s11534-009-0117-6>.
- Kopeikin, Sergei M., and Edward B. Fomalont. "Gravimagnetism, Causality, and Aberration of Gravity in the Gravitational Light-Ray Deflection Experiments." *General Relativity and Gravitation* 39, no. 10 (October 1, 2007): 1583–1624. <https://doi.org/10.1007/s10714-007-0483-6>.
- Kramer, Michael. "Millisecond Pulsars as Tools of Fundamental Physics." In *Astrophysics, Clocks and Fundamental Constants*, edited by Savely G. Karshenboim and Ekkehard Peik, 33–54. Lecture Notes in Physics. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004. https://doi.org/10.1007/978-3-540-40991-5_3.
- Krisher, null, null Maleki, null Lutes, null Primas, null Logan, null Anderson, and null Will. "Test of the Isotropy of the One-Way Speed of Light Using Hydrogen-Maser Frequency Standards." *Physical Review D, Particles and Fields* 42, no. 2 (July 15, 1990): 731–34.
- Lightman, A. P., and D. L. Lee. "Restricted Proof That the Weak Equivalence Principle Implies the Einstein Equivalence Principle." *Physical Review D, Particles Fields* 8, no. 2 (1973): 364–76. http://inis.iaea.org/Search/search.aspx?orig_q=RN:5098997.
- Lineweaver, C. H., L. Tenorio, G. F. Smoot, P. Keegstra, A. J. Banday, and P. Lubin. "The Dipole Observed in the COBE DMR 4 Year Data." *The Astrophysical Journal* 470 (October 1, 1996): 38. <https://doi.org/10.1086/177846>.
- Marion, H., F. Pereira Dos Santos, M. Abgrall, S. Zhang, Y. Sortais, S. Bize, I. Maksimovic, et al. "A Search for Variations of Fundamental Constants Using Atomic Fountain Clocks." *Physical Review Letters* 90, no. 15 (April 18, 2003): 150801. <https://doi.org/10.1103/PhysRevLett.90.150801>.
- Misner, Charles W., Kip S. Thorne, and John Archibald Wheeler. *Gravitation*. W. H. Freeman, 1973.
- Nordtvedt, Kenneth. "Lunar Laser Ranging - a Comprehensive Probe of Post-Newtonian Gravity." *ArXiv:Gr-Qc/0301024*, January 7, 2003. <http://arxiv.org/abs/gr-qc/0301024>.
- Nordtvedt, Kenneth, Jr., and Clifford M. Will. "Conservation Laws and Preferred Frames in Relativistic Gravity. II. Experimental Evidence to Rule Out Preferred-Frame Theories of Gravity." *The Astrophysical Journal* 177 (November 1, 1972): 775. <https://doi.org/10.1086/151755>.
- Ohanian, Hans C., and Remo Ruffini. *Gravitation and Spacetime*. Norton, 1994.
- Overduin, James, Francis Everitt, John Mester, and Paul Worden. "The Science Case for STEP." *Advances in Space Research* 43, no. 10 (May 15, 2009): 1532–37. <https://doi.org/10.1016/j.asr.2009.02.012>.
- Peik, E., B. Lipphardt, H. Schnatz, T. Schneider, Chr Tamm, and S. G. Karshenboim. "New Limit on the Present Temporal Variation of the Fine Structure Constant." *Physical Review Letters* 93, no. 17 (October 18, 2004): 170801. <https://doi.org/10.1103/PhysRevLett.93.170801>.
- Penrose, Roger. *The Road to Reality: A Complete Guide to the Laws of the Universe*. Reprint edition. New York: Vintage, 2007.
- Pound, R. V., and G. A. Rebka. "Apparent Weight of Photons." *Physical Review Letters* 4, no. 7 (April 1, 1960): 337–41. <https://doi.org/10.1103/PhysRevLett.4.337>.

- Schiff, L. I. "On Experimental Tests of the General Theory of Relativity." *American Journal of Physics* 28, no. 4 (April 1, 1960): 340–43. <https://doi.org/10.1119/1.1935800>.
- Shapiro, Irwin I. "Fourth Test of General Relativity." *Physical Review Letters* 13, no. 26 (December 28, 1964): 789–91. <https://doi.org/10.1103/PhysRevLett.13.789>.
- Shapiro, Irwin I., Michael E. Ash, Richard P. Ingalls, William B. Smith, Donald B. Campbell, Rolf B. Dyce, Raymond F. Jurgens, and Gordon H. Pettengill. "Fourth Test of General Relativity: New Radar Result." *Physical Review Letters* 26, no. 18 (May 3, 1971): 1132–35. <https://doi.org/10.1103/PhysRevLett.26.1132>.
- Stanwix, Paul L., Michael E. Tobar, Peter Wolf, Mohamad Susli, Clayton R. Locke, Eugene N. Ivanov, John Winterflood, and Frank van Kann. "Test of Lorentz Invariance in Electrodynamics Using Rotating Cryogenic Sapphire Microwave Oscillators." *Physical Review Letters* 95, no. 4 (July 21, 2005): 040404. <https://doi.org/10.1103/PhysRevLett.95.040404>.
- Van Patten, R. A., and C. W. F. Everitt. "Possible Experiment with Two Counter-Orbiting Drag-Free Satellites to Obtain a New Test of Einstein's General Theory of Relativity and Improved Measurements in Geodesy." *Physical Review Letters* 36, no. 12 (March 22, 1976): 629–32. <https://doi.org/10.1103/PhysRevLett.36.629>.
- Vessot, R. F. C., M. W. Levine, E. M. Mattison, E. L. Blomberg, T. E. Hoffman, G. U. Nystrom, B. F. Farrel, et al. "Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser." *Physical Review Letters* 45, no. 26 (December 29, 1980): 2081–84. <https://doi.org/10.1103/PhysRevLett.45.2081>.
- Will, Clifford M. "The Confrontation between General Relativity and Experiment." *Living Reviews in Relativity* 17, no. 1 (December 2014): 4. <https://doi.org/10.12942/lrr-2014-4>.