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ScienceDirect
Advances in Space Research 39 (2007) 230–235
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

OPTIS – A Satellite test of Special and General Relativity

H. Dittus [a], C. Lämmerzahl [a,*], A. Peters [b], S. Schiller [c]

[a] Centre of Applied Space Technology and Microgravity (ZARM), University of Bremen, Am Fallturm, D-28359 Bremen, Germany
[b] Humboldt-University Berlin, Hausvogteiplatz 5-7, D-10117 Berlin, Germany
[c] Institute of Experimental Physics, Heinrich-Heine-University, Universitätsstraße 1, D-40225 Düsseldorf, Germany

Received 1 August 2003; received in revised form 24 February 2007; accepted 26 February 2007

Abstract

OPTIS has been proposed as a small satellite platform in a high elliptical orbit (apogee 40,000 km, perigee 10,000 km) and is designed for high precision tests of foundations of Special and General Relativity. The experimental set-up consists of two ultrastable Nd:YAG lasers, three crossed optical resonators (monolithic cavities), an ensemble of atomic clocks, an optical comb generator, laser tracking devices and a drag-free control system. OPTIS enables improved tests of (1) the isotropy and (2) constancy of the speed of light, (3) special relativistic time dilation, (4) the universality of the gravitational redshift by comparison of various clocks, can measure (5) the absolute value of the gravitational redshift, (6) the Lense–Thirring effect and (7) the perigee advance and (8) can make a test of a hypothetical Yukawa part in the gravitational potential. To avoid any influence from atmospheric drag, solar radiation, or Earth albedo, the satellite needs drag-free control to depress the residual acceleration down to 10^{-14} m/s^2 in the frequency range between 10^{-2} and 10^{-3} Hz. Precise thermal control must be used to stabilize the cavity temperature to within one part in 10^7 at time scales of 100 s and to one part in 10^5 on the orbit time scale.

Keywords: Special relativity; General relativity; Isotropy of the speed of light; Constancy of speed of light; Gravitational redshift; Lense–Thirring effect; Doppler effect

1. Introduction

Special and General Relativity are at the basis of our understanding of space and time. Both theories are linked by the fact that the validity of Special Relativity is necessary for the validity of General Relativity. New results from canonical quantum gravity and string theories predict deviations from Special and General Relativity and their fundamental hypotheses which gives motivation to improve the experimental tests. Loop gravity and string theory predict modifications of the Maxwell equations (Gambini and Pullin, 1999; Ellis et al., 1999; Alfaro et al., 2001) which would lead to an anisotropic speed of light and to a dispersion in vacuum, thus violating the postulates of Special Relativity. Quantum gravity, e.g., predicts a violation of the Universality of Gravitational Redshift (Damour and Polyakov, 1997, 2000). Although the magnitude of the violations is too small to be within the range of experimental capabilities in the near future, it opens up a theoretically justifiable possibility for violations of fundamental principles. Since we do not know the "true" theory of quantum gravity, we cannot know the "true" parameters and their predicted range of violations. Theoretical investigations are speculations as long as they have not been proven experimentally.

A space mission provides several advantages: the relatively high velocity change along an elliptical orbit, the shorter period of the velocity modulation as compared with the 24 h period of the Earth rotation, a large change of the gravitational potential between perigee and apogee of the satellite orbit, the weightlessness environment minimizing distortions of the optical resonators, the possibility to vary the satellite spin rate to eliminate systematic errors, and the

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[*] Corresponding author.
E-mail addresses: dittus@zarm.uni-bremen.de (H. Dittus), laemmerzahl@zarm.uni-bremen.de (C. Lämmerzahl), achim.peters@physik.hu-berlin.de (A. Peters), step.schiller@uni-duesseldorf.de (S. Schiller).

0273-1177/$30 © 2007 Published by Elsevier Ltd on behalf of COSPAR.
doi:10.1016/j.asr.2007.02.074

long integration time of more than 6 months (Lämmerzahl et al., 2001; Lämmerzahl et al., 2004).

2. Experimental goals of OPTIS

OPTIS is an ensemble of precise optical experiments originally proposed as a small satellite mission on a high elliptical orbit. With OPTIS, an improvement of (1) the Michelson–Morley test of the isotropy of the speed of light (see Müller et al. (2003)), (2) the Kennedy–Thorndike test of the constancy of the speed of light (see Wolf et al. (2002)), (3) a Doppler measurement measuring the special relativistic time dilation (see Saathoff et al. (2003)), (4) clock comparison tests of the universality of the gravitational redshift (see Bauch and Weyers (2002)), (5) the measurement of the absolute gravitational redshift (see Vessot et al. (1980)), (6) a measurement of the Lense–Thirring effect (see Ciufolini (2004)) and of (7) the perihelion advance (see Will (2006)) and, finally, (8) a search for a Yukawa part of the Newtonian gravitational potential (see Fischbach and Talmadge (1999)). The improvement of these measurements is projected to reach up to three orders of magnitude. Michelson–Morley experiments test the isotropy of light propagation (the difference in the velocity of light in different directions), Kennedy–Thorndike experiments aim to test the hypothetical dependence of the velocity of light on the velocity of the laboratory (satellite) with respect to the cosmic background. Gravitational Redshift experiments testing the principle of Local Position Invariance (LPI) are carried out by comparing clocks of different physical nature in varying gravitational potentials. The experimental equipment consists of three lasers, three orthogonal optical cavities in one block, a femtosecond laser comb generator, an atomic clock, e.g. H-maser or multi-species trapped ion clock, for further tests of the Universality of Gravitational Redshift comparing two different atomic clocks. Table 1 gives an overview of the mission science goals compared to up-to-date laboratory results.

A schematic view of the experiment is shown in Fig. 1. For the Michelson–Morley experiment two crossed resonators are needed to measure the relative frequency of two laser waves locked to the cavities. For the Kennedy–Thorndike experiment, only one of the resonators is needed: a hypothetical phase shift of the cavity frequency due to the velocity change of the satellite along the orbit can be observed by comparing the cavity frequency with the atomic clock frequency. Also the Gravitational Redshift of the cavity clocks with respect to the Gravitational Redshift of the atomic clocks can be measured.

3. Theoretical description

According to common test theories (an overview is given in Lämmerzahl et al. (2002), Lämmerzahl (2006) and Amelino-Camelia et al. (2005)), the orientation and velocity dependence of the speed of light can be parameterized by

$$c(v,\theta) = c_0\left(1 + A\frac{v^2}{c_0^2} + B\frac{v^2}{c_0^2}\sin^2(\theta) + O\left(\frac{v^4}{c_0^4}\right)\right). \qquad (1)$$

This means that all anomalous terms vanish for vanishing velocity with respect to the cosmological preferred frame. θ is the angle between the cavity axis and the velocity vector with respect to the preferred frame. c_0 is the light speed with respect to the preferred frame, and an expansion v^2/c_0^2 has been used for simplicity. If Special Relativity holds, then the parameters A and B vanish. A Michelson–Morley experiment can set an upper limit for B, a Kennedy–Thorndike test sets upper limits for $A + B\sin^2(\theta)$.

3.1. Isotropy of space

The electromagnetic wave-vector magnitude k in a cavity with length L is given by $k = n\pi/L$ and the frequency f of an out-coupled wave is determined by $f = c(\theta)k/(2\pi) = c(\theta)n/(2L)$. In order to test the isotropy of space, or equivalently, the isotropy of the velocity of light, one rotates two orthogonal cavities 1 and 2 along the axis perpendicular to them. The eventual resulting relative phase shift is determined by

$$\frac{\delta_\theta f}{f} = \frac{f(\theta+\pi/2) - f(\theta)}{f(\theta)} = 1 + B\frac{v^2}{c_0^2}(1 - 2\cos^2(\theta)). \qquad (2)$$

The best experiments carried out so far yielded $|B| < 5\times10^{-9}$ (Braxmaier et al., 2002; Brillet and Hall, 1979). In a satellite experiment, systematic errors can be

Table 1
The scientific objectives of OPTIS: projected accuracies for the OPTIS experiments compared with current laboratory tests

Test	Method	Present accuracy	OPTIS accuracy
Isotropy of speed of light	Cavity–cavity comparison	1.5×10^{-9}	10^{-12}
Constancy of speed of light	Cavity–clock comparison	7×10^{-7}	10^{-8}
Time dilation – Doppler effect	Laser link	2×10^{-7}	10^{-9}
Universality of the gravitational redshift I	Cavity–clock comparison	1.7×10^{-2}	10^{-4}
Universality of the gravitational redshift II	Clock–clock comparison	2.5×10^{-5}	10^{-7}
Absolute gravitational redshift	Time transfer	1.4×10^{-4}	10^{-8}
Lense–Thirring effect	Laser tracking	0.3	10^{-3}
Einstein perigee advance	Laser tracking	3×10^{-3}	6×10^{-4}
Test of Newton potential	Laser tracking	10^{-5}	10^{-12}

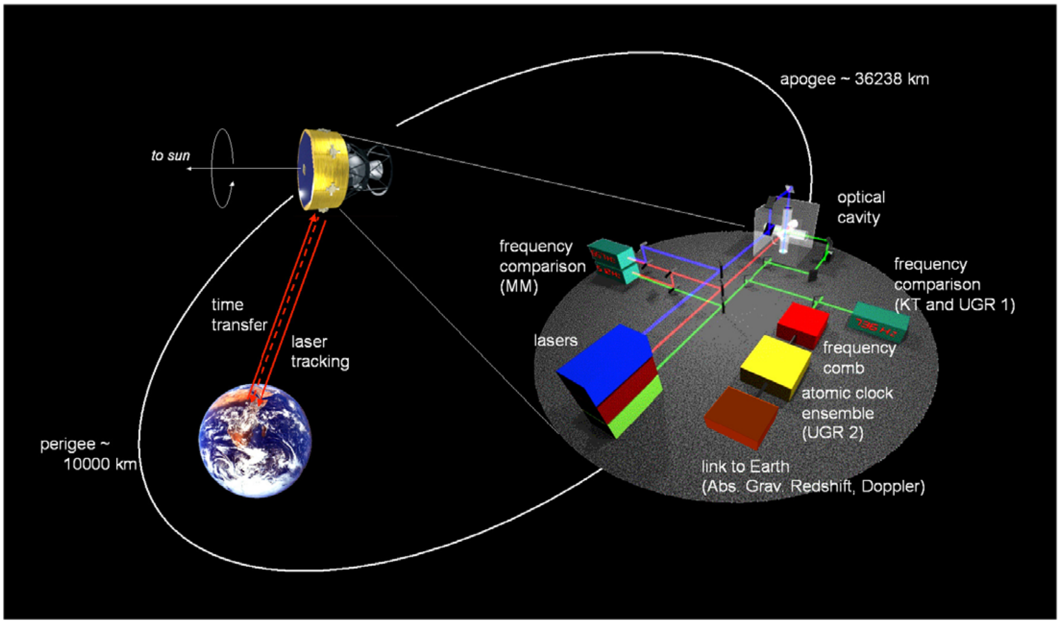

Fig. 1. The mission scenario (apogee and perigee heights measured from Earth's surface).

eliminated by varying the spin rate of the satellite. For OPTIS it is planned to change the spin rate of the sun-pointing satellite between 10^{-2} Hz and 10^{-3} Hz.

3.2. Independence of the light speed from the velocity of the satellite

A hypothetical dependence of the light speed from the velocity v of the laboratory (satellite) can be tested by a periodic velocity variation and searching for a corresponding frequency shift of an optical cavity resonance. In Earth-based experiments, the rotation of the Earth or the orbital motion of the Earth around the sun could be used. The Earth rotation gives a daily periodical velocity change of ±300 m/s, the Earth rotation around the sun results in an annual velocity variation of ±30 km/s related to the Earth velocity of 377 km/s with respect to the cosmic background. Along its elliptical orbit, the tangential velocity of OPTIS will vary between +7 km/s and −4 km/s over half the orbital period $T_{\mathrm{orbit}}/2 \approx 7$ h. So, the advantage compared to a terrestrial experiment using the rotation of the Earth is significant.

The frequency difference between the frequency given by the optical resonator and the atomic clock (where the latter is assumed to be independent of the velocity with respect to the cosmological background) is

$$\frac{\delta_v f}{f_0} = \frac{f(v)}{f_0}\,\frac{c(v+\Delta v)-c(v)}{c(v)} = \frac{f(v)}{f_0}\cdot 2\frac{\Delta v}{v}\,\frac{v^2}{c_0^2}\left(A + B\sin^2(\theta)\right) \tag{3}$$

Experiments set the upper limit to $A = 1.9 \pm 2.1 \times 10^{-5}$ (assuming $B = 0$ from Michelson–Morley test).

3.3. Gravitational Redshift experiment

Within the framework of Einstein's General Relativity, the comparison of two identical clocks with frequency f_0 located in different gravitational potentials $U(x_1)$ and $U(x_2)$ yields

$$f(x_2) = f(x_1)\cdot\left(1 - \alpha_{\mathrm{clock}}\frac{U(x_2)-U(x_1)}{c_0^2}\right). \tag{4}$$

The Gravitational Redshift is universal, i.e. it is independent on the type of clock implying that for all clocks, $\alpha_{\mathrm{clock}} = 1$. If General Relativity is not correct, $\alpha_{\mathrm{clock}} \neq 1$ in Eq. (4) may follow. If two different clocks are displaced together in a gravitational potential, a relative frequency shift

$$\frac{\delta f_1}{f_1} - \frac{\delta f_2}{f_2} = (\alpha_{\mathrm{clock1}} - \alpha_{\mathrm{clock2}})\frac{U(x_2)-U(x_1)}{c_0^2} \tag{5}$$

would be measured. The relative frequency shift is proportional to the difference of the gravitational potential relative to the initial position.

With GP-A, an experiment on a ballistic rocket flight, $|\alpha_{\mathrm{H\text{-}maser}} - 1| < 10^{-4}$ has been determined by comparing a H-maser on the rocket with a H-maser on Earth (Vessot et al., 1980). Best tests of a comparison between a cavity clock (microwave cavity) and an atomic cesium clock has yielded $\alpha_{\mathrm{Cs\text{-}clock}} - \alpha_{\mathrm{cavity}} < 2 \times 10^{-2}$ (Turneaure et al., 1983).

The difference of the gravitational potential in the high elliptical orbit is $\Delta U/c^2 \sim 3 \times 10^{-2}$, about three orders of magnitude larger than the difference of the Sun potential on the surface of the Earth over the course of a day. This is the fundamental reason for the improvement possible by the OPTIS mission.

4. Science payload

The main experimental subsystems of OPTIS are optical resonators, ultra-stable lasers, an optical frequency comb, and an ultra-stable atomic clock. These components are interconnected and supplemented by the locking and stabilization electronics, the optical bench, the drag-free attitude and orbit control system including a reference sensor, and a high precision thermal control system.

The optical resonators are the central part of the set-up. Three crossed standing wave resonators are implemented by optically contacting six highly reflecting mirrors to a monolithic spacer block with three orthogonal holes. The block is made from a low expansion glass ceramic (ULE: with thermal expansion coefficient $\alpha < 10^{-9}\,\mathrm{K}^{-1}$). With a technically feasible finesse of 2.5×10^5 and a length of 10 cm each, these resonators should exhibit line widths of 6 kHz. Ageing will cause a continuous shrinking of the ceramic material resulting in frequency drifts of typically 5–50 kHz/d. However, for the Michelson–Morley experiment, the monolithic structure of the resonator block guarantees a high degree of common mode rejection in the differential frequency measurement of the lasers locked to the resonators. For the Kennedy–Thorndike experiment and the clock comparison test, on the other side, any frequency shift may be critical. Calculations show that the unpredictable part of the shift has to stay below 10^{-13} over the signal half period ($T_{\mathrm{orbit}}/2 = 7$ h).

The resonator length is influenced by the accelerations at the level of 1 nm/g_0 (g_0 is the average gravitational acceleration on the Earth surface) for a resonator length of about 25 cm. This results in the requirement for a maximum level of $2 \times 10^{-9}\,\mathrm{m/s^2}$ for random and residual acceleration onboard the satellite.

For OPTIS, three Nd:YAG diode-pumped lasers with high intrinsic frequency stability, narrow line width and high-intensity stability are ideal. Such lasers have been space qualified and are state-of-the-art technology.

For comparing the frequencies of the atomic clock standard and the lasers, it is necessary to correct the microwave frequency of the atomic clock (10^9 Hz) to the optical range (10^{15} Hz). This can be achieved by means a femtosecond-optical comb generator (Diddams et al., 2000). To this end, the repetition rate (1 GHz) of a mode-locked femtosecond-laser is locked to the atomic clock. Its optical spectrum – a "comb" of frequencies spaced exactly at the repetition rate – is broadened to more than one octave by passing the pulses through a special optical fibre. By stabilizing the beat-note between the two sections of the comb, the absolute frequency of each component of the comb relative to the time standard is determined. Finally, by measuring the beat-note between the optical frequency of the cavity-stabilized lasers and the closest frequency peak of the comb with a fast photo-detector, a direct comparison of both frequencies with very high accuracy is possible. Compact diode-laser-pumped comb generators with reasonably low power consumption are under development.

For the Kennedy–Thorndike experiment and the Gravitational Redshift experiment, the cavity clock is compared with a clock standard of different physical nature. The reference clock may be based on the frequency related to the difference of two energy levels in an atomic or molecular system. Atomic clocks such as hydrogen masers are available in space qualified form. The whole set-up must be stable and isolated from vibrations to prevent frequency fluctuations induced by mechanically induced Doppler shifts. Even small displacements of less than 1 μm of the laser beams result in substantial frequency shifts. Therefore, the complete bench has a well designed monolithic structure.

A difficult technical task is the temperature stability requirement of ±20 μK for the Michelson–Morley experiment with respect to random fluctuations over one spin period of 100–1000 s and ±100 nK for temperature variations modulated by the satellite spin. For the Kennedy–Thorndike experiment, the requirements are ±200 μK and ±10 μK, respectively. Thermal modelling showed that the satellite surface can be stabilized only to a temperature variation of some Kelvin. Active high precision temperature control and multi-layer isolation is required in addition.

5. Orbit and satellite

Experimental requirements result in the following specifications:

- Drag-free attitude and orbit control (AOCS) is needed for all six degrees of freedom. To attain an accuracy of $10^{-11}\,\mathrm{m/s^2}$ within the signal bandwidth of 10^{-2}–10^{-3} Hz, thrust control must be possible down to 0.1 μN. Therefore the satellite needs an inertial reference sensor consisting of a cubic test mass whose movements are measured and compensated capacitively with respect to all degrees of freedom (Toboul, 2001). Apart from the sensing electrodes, servo-control electrodes surround the test mass and compensate its movement relative to the satellite structure. The servo-control signal is also used for AOCS via ion thrusters (Field emission electrical propulsion, FEEP) able to be controlled very precisely on the level required. Pointing accuracy needs a star sensor with a resolution of at least 10 arcsec.

- The minimum perigee height is determined by (1) the FEEP maximum thrust and (2) the constraints to avoid charging of the reference sensor by interactions with highly energetic protons when the satellite passes the van Allen belt. This demand is contrasted by the requirement for the Kennedy–Thorndike experiment to fly the satellite in a low orbit in order to attain high tangential (in-orbit) velocities. A perigee of 10,000 km seems to be an appropriate compromise. Although the orbit height reduces the tangential velocity variations of the satellite by a factor of 2.8 compared with a low-Earth circular orbit, it is still 20 times higher than for Earth-based experiments.
- The strong temperature stability requirement during integration times of more than 100 s can only be realized on orbits with rare eclipse intervals.
- The mission time should be at least 6 months.
- For the Gravitational Redshift test, the orbit eccentricity a should be as large as possible. An apogee height of about 40,000 km should be attained realistically and gives us $\varepsilon = 0.41$.

In general, OPTIS is designed to be launched as a microsatellite with limited technological performance. Considering all experimental requirements technological feasibility, launch capability, and design philosophy, the optimum solution is to launch the satellite in a high elliptical orbit, attainable via a geo-transfer orbit (GTO) by lifting the perigee. In our scenario, the satellite is first launched as an auxiliary payload into the GTO with an apogee of 35,800 km and a perigee of only 280 km. An additional kick-motor will lift the satellite in its final orbit with a perigee of about 10,000 km.

The satellite has cylindrical shape, with a height and a diameter of about 1.5 m. It spins around its cylindrical axis which is always Sun pointing. The front facing the Sun is covered by solar panels. Behind the front plate serving as a thermal shield, on-board electronics and thrusters control are located. Four clusters of FEEPs for fine (drag-free) AOCS as well as three clusters of cold gas thrusters for coarse AOCS and first acquisition operation are mounted circumferentially. The satellite total mass is about 250 kg, including about 100 kg experimental payload. The total power budget is estimated to be less than 250 W.

6. Conclusion

The proposed OPTIS mission is capable of making considerable improvements of up to three orders of magnitude for tests of foundations of Special and General Relativity. It is designed to be a low-cost mission and is based on using recent laboratory developments in optical technology, in particular highly stable cavities, stabilized lasers, optical combs. The advantages of the OPTIS satellite test compared to Earth-based tests are the larger periodic velocity changes, the low residual acceleration environment (microgravity, drag-free controlled), the long integration time, a variable spin rate to eliminate systematic errors, and the large difference of the gravitational potential between apogee and perigee.

Acknowledgement

The authors gratefully acknowledge the support from the Deutsches Zentrum für Luft- and Raumfahrt (DLR), Bonn, Germany.

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