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A TEST OF THE ONE-WAY ISOTROPY OF THE SPEED OF LIGHT FROM THE T2L2 SPACE EXPERIMENT

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Abstract.
The Time Transfer by Laser Link (T2L2) space experiment that is currently flying on-board Jason-2 (1335 km of altitude) provides an opportunity to make a test of the isotropy of the speed of light using one-way propagation on a non-laboratory scale. Following the general framework given by Mansouri & Sexl (1977), which permits violations of Einstein special relativity, we study the problem of deducing the isotropy of the speed between two clocks as the orientation path varies relative to an inertial reference frame. The short term stability of the T2L2 ground-to-space time transfer has been established at 5-6 ps at 60 seconds between a hydrogen maser and the on-board oscillator on use for the Jason-2 satellite. Nevertheless, during the satellite pass above a laser ranging station (of around 1000 seconds), the stability of the space oscillator is decreasing in $\tau^{3/2}$ that clearly impacts the expected performance of the present test. We thus give insights into certain modelling issues and processes, including time transfer problems which have a bearing on the global error budget. Our goal is to achieve an accuracy of $\frac{\delta c}{c} \approx 2 - 3.10^{-9}$ locally with a scope for improvement by cumulating numerous passes over the same laser ranging station.

Keywords: Isotropy of the speed of light, free space laser, clocks.

1 Introduction

The Newtonian universal law of gravity and mechanics form the framework of what we need to compute and measure in Newtonian systems. All systems of coordinates we use are equivalent or interchangeable, as long as they move with a constant velocity; furthermore, transformations between time scales and coordinate systems are linear functions or angular rotations. Einstein proposed the theory of Special Relativity (SR) to explain several effects that seemed to contradict Newtonian physics and mechanics. It deals with motions in inertial reference frames. He generalised the principle by stating that all inertial frames are totally equivalent for the performance of all physical experiments. The constancy (isotropy) of the velocity of light in inertial reference frames, which was first tested in the classic Michelson-Morley experiment, is a fundamental postulate of the SR theory.

Advances in technology have made possible new experimental tests; in particular, clock comparison is one major category of experiments for probing the SR theory and Lorentz invariance. Additionally, space is one of the most likely places where some manifestations, i.e. anisotropy of the one-way velocity of light, or variation of fundamental constants may be investigated. While providing access to greater variation of gravitational potentials, greater velocities, and full orientation coverage, space also mimics the well-understood and controlled laboratory environment. Thus, clock experiments in space will set new limits on Einstein's gravitational redshift and fundamental Lorentz symmetry; clocks enable science and open the door of chronometric geodesy.

In order to study the significance of a given experimental test of relativity, it is useful to employ a general framework. The work of Mansouri & Sexl (1977) gives a kinematic background, which assumes the existence of a preferred frame S' where space and light speed are isotropic while, in an inertial frame S moving with velocity w with respect to S', the one-way speed of light is no longer isotropic. From this formalism, the goal is to express one-way propagation from a source to a receiver (where the coordinates are expressed in the frame S) in terms of measurable quantities. The Time Transfer by Laser Link (T2L2) instrument, which was launched

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in 2008 on-board the altimeter satellite Jason-2 (altitude of 1335 km), is one of the space experiments that actually enables both two-way and one-way laser ranging (Samain et al. 2008). Considering the design of the mission (repeatability, altitude, etc.) and technological aspects both on the ground and on board − very short laser pulses (20 ps), ground hydrogen maser(s), and picoseconds resolution and precision of event timers −, we study the potential performance of T2L2.

In Section 2, we start explaining the principle of T2L2 experiment then we discuss the main limiting factors of the present test of SR, notably about the stability induced by the on-board oscillator. We discuss the overall accuracy, of $\frac{\delta c}{c} \approx 2 - 3.10^{-9}$, that we expect from T2L2 data once modeled the behavior of the oscillator.

2 Time Transfer by Laser Ranging

The optical space time transfer allows to synchronise remote ground clocks that equip laser ranging stations of the ILRS (International Laser Ranging Service) network (Pearlman et al. 2002). A series of space missions have embarked a detector (mostly at 532 nm) and a sub-nanosecond event timer in addition to the reference clock of the spacecraft in view of very different objectives: navigation, fundamental physics and Time & Frequency (TF) metrology. Examples of time transfer by laser ranging mission that may be given include: LAser Synchronization from Stationary Orbit (LASSO) (Fridelance & Veillet 1995) and more recently Laser Time Transfer (LTT) (Fumin et al. 2008). Depending on the mission, the embarked clock can be a Rubidium, as e.g. on GNSS-Beidou or an Ultra Stable Oscillator (USO) as it is the case on the Lunar Reconnaissance Orbiter spacecraft orbiting the Moon (Mao et al. 2014) or on T2L2/Jason-2 (Samain et al. 2008). Additionally in 2018, the ESA project ACES on the ISS is the only one project which will deploy a cold atom clock in space together with a high accurate optical link (European Laser Transfer, ELT) in a single photon mode (Schreiber et al. 2009).

In all these experiments, the principle consists in measuring the propagation time of a light signal transmitted from one point on the ground to another in space; it is measured directly by comparing the phases of both clocks using the adopted laser time transfer system. Behind, the expected result of the potential test of SR simply lies in the ratio $\delta c/c$, where δc corresponds to the deviation of the speed (in the moving geocentric frame) in a preferred direction of space.

The pass of the satellite above a given laser ranging station, which potentially provides many directions of measurement, from the beginning to the end of the pass (around 140 degrees), is thus by itself a realisation of the test of SR.

The readings of a short laser pulse event (i) of around 20-30 ps is made by a H-maser (Hydrogen-maser) at emission (t_E) and reception (t_R) whereas the space clock records the arrival time of that pulse (τ_i) which thus is a proper time (Exertier et al. 2010). Einstein's second postulate would require that, for a series of measurements, the difference between the up and down links should be equal to a constant Δ_0 (initial clock offset) independent of the spatial orientation of each of the individual links. In that way, the time transfer equation is :

$$\Delta_i^E(t) = \tau_i - (t_E + 1way) + \Delta_0 + C + \Delta r \tag{2.1}$$

Where :

C are geometric and instrumental corrections

$1way$ is given by: $\frac{1}{2}(t_R - t_E - \Delta t_{Sagnac})$. The present Sagnac delay is caused by the motion of the receiver on the surface of the Earth due to the Earth's rotation during the time when the signal is on its way from the satellite. This delay is given by:

$$\Delta t_{Sagnac} = \frac{\bar{v}_E \bar{D}}{c^2}$$

Where :

- $\bar{v_E}$ the angular motion of the Earth
- $\bar{D}$: ground to spacecraft distance

Δr are relativistic corrections; for precision navigational systems operating in space on artificial satellites, three major systematic relativistic effects also need to be considered with regard to using the broadcast timing signal. Time dilation refers to the effect of the clock's velocity on its frequency; the effect of time dilation is given by:

$$\Delta t' = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Where :

- v is the velocity of the satellite
- c the speed of light in the vacuum.

Because the clocks, at an altitude of thousands of km, experience a gravity field less than clocks on Earth, the gravitational red shift causes them to run fast. This effect can be estimated roughly, assuming circular orbits for the satellites, from:

$$\Delta t' = \Delta t \, \frac{\Delta\Phi}{c^2} = \Delta t \, \frac{1}{c^2} \left[\frac{GM_E}{r} - (\frac{GM_E}{a_E}) \right]$$

Where :

- $\Delta\phi$ is the difference of potential between spacecraft and ground station,
- $\frac{GM_E}{r}$ the potential at the satellite
- $\frac{GM_E}{a_E}$ the geopotential of the Earth.

In order to precisely convert the elapsed on-board proper time to be compared to the ground time coordinate, these corrections have been integrated on a pass-by-pass level. The resulting stability of the ground-to-space time transfer link in addition to the typical propagation time are the primary parameters that constraint the performance of the SR test (Wolf 1995). As an example, when the T2L2 mission actually flights at 1335 km altitude, comparing to 450 km for ELT (on the ISS), it is not obvious that the ground-to-space stability of the latter has been improved by a factor 3 comparing to the former. On the other hand, the stability of the overall experiment (over a complete satellite pass above a laser ranging station) clearly depends on the on-board oscillator, which is an USO in case of T2L2/Jason-2 (3-5 10^{-13} between 10-100s, with an evolution in $\tau^{3/2}$ (Auriol & Tourain 2010)). Because of the small quantity we are looking for (an overall signal of a few ps) during the SR test, a deterministic model of the USO frequency is added to the above explained integration process (Belli et al. 2015). This model is essentially controlled by external data, such as temperature and level of particles flux (of around 85 MeV) both quantities being measured on-board. This avoids any empirical parameters that could absorb the SR test signal. An other source of instability which comes from the laser technology itself (pulse width, temperature of the optical bench, etc.) during a complete ground-to-space pass has been investigated by (Samain et al. 2014, 2015); the resulting analysis gave an error budget of 10-15 ps without bias. Thus, we will take into account at least three months of data from a dedicated laser ranging station, which roughly provides 60 passes per month.

Now the idea is to compare the phase readings of both clocks during a pass. Following the theoretical context given by Mansouri & Sexl (1977), to the lowest order in the velocity w of S relative to S' (CMB), the one-way experiment discussed here measures variation or anisotropy controlled by the amplitude:

$$A = \alpha w \cos\theta$$

where α is the coefficient in the expansion of the function in power of w^2, and θ is the angle between w and a direction relevant to the experiment in question, such as the propagation direction of light or the velocity vector of a moving clock. In SR, $\alpha = 0$, so that the anisotropy vanishes. For the velocity w, it is natural to choose the velocity of the Earth relative to the CMB; its amplitude and direction have been published many times. We will use the formalism:

$$c(\theta, w) = c \left[1 - \frac{(1+2\alpha)w}{c} \cos\theta + \mathcal{O}(c^3) \right] \tag{2.2}$$

3 Conclusion

Challenges of space deployment impose additional requirements on the reliability of the instruments and put pressure to minimise their mass, volume, and power requirements. A proposal for a new T2L2 instrument on the proposed E-GRASP mission (ESA, EE-9) takes place through the concerted efforts to be deployed for miniaturisation and space qualification.

Some other missions and projects have been designed to search for a variation of the fine-structure constant. The European Atomic Clock Ensemble in Space (ACES) is the only remaining space experiment based on clock tests, and is scheduled for launch in 2018. More recently, optical clocks have shown the potential for even greater precision than their microwave counterparts. Several mission proposals using optical clocks have already been proposed in the ESA Cosmic Vision program. In Europe, there is currently a great deal of work underway for potential future ESA projects on optical clocks and atom interferometry.

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