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Fundamental Physics

Tests of gravity performed in the solar system show a good agreement with Einstein's theory of general relativity. However there are some indications which have led physicists to think that this theory may not be the ultimate one, among which, its principles are not compatible with those of quantum mechanics. A theory which would solve this problem would be a crucial step towards the unification of fundamental interactions.

Several approaches have been proposed. All of them involve minute violations of various aspects of the Einstein Equivalence Principle, which is the basis of general relativity, such as a drift of fundamental constants or a violation of the universality of free fall. The theory of general relativity is also challenged by observations at larger galactic and cosmic scales, which are currently explained by introducing unknown components: dark matter and dark energy. They might as well be interpreted as modifications of gravity laws.
In order to conduct highly precise experiments in space to test assumptions and predictions of general relativity theory, physicists are building the instruments needed to measure time, distance and movement directly in a very accurate and stable way.

PHARAO/ACES: a space clock using cold caesium atoms

The ESA ACES (Atomic Clock Ensemble in Space) mission, built around the PHARAO clock based on laser-cooled caesium atoms, is to be launched in 2015 for installation on one of the external nadir racks of the European Columbus module of the ISS. By comparing signals from different ground-based atomic clocks, it will monitor the relative variation of the fine structure constant α with an accuracy of 10^{-17} per year. The gravitational redshift, another of the most fascinating effects predicted by general relativity, will also be measured more accurately.

The PHARAO clock (based on hyperfine transitions between electronic states of caesium atoms) was proposed to CNES and ESA by the Kastler-Brossel laboratory at ENS Paris and the SYRTE laboratory at the Observatoire de Paris. It is being developed under CNES responsibility (Fig. 1). The performance tests of the clock engineering mode were completed in 2010. The flight models of the clock subsystems (caesium tube, laser source, etc.) have almost been completed.

Significant progress has been made for the ground segment based on the best ground-based atomic clocks and the Pharao transportable atomic fountain, coupled with microwave link (MWL) terminals, along with improved data processing algorithms.

T2L2: Time Transfer by Laser Link

T2L2 is a joint experiment being conducted by OCA (Observatoire de la Côte d'Azur/Géoazur) and CNES to compare clock signals using laser pulses instead of microwave signals. It was launched with the Jason-2 altimetry mission in June 2008. The instrument designed as a technological opportunity for a nominal life time of two years is still functioning perfectly. Ground-to-space time transfer has demonstrated noise levels of some tens of picoseconds (see detailed results in the following pages).

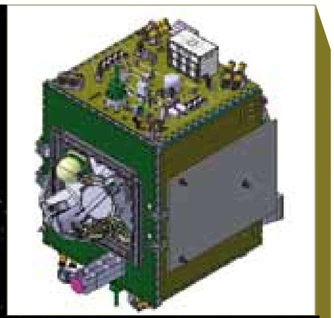
LISA Pathfinder and NGO: interferometry for the detection of gravitational waves

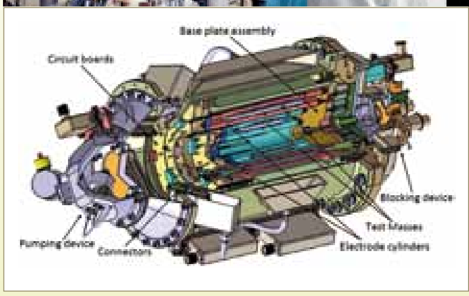
The ESA technology mission LISA Pathfinder (Fig. 2), planned for 2014, will pave the way for the future NGO (New Gravitational Observatory) mission, a one million kilometre laser interferometer. The aim of NGO is to observe the universe by means of gravitational waves. These are vibrations of warped space-time produced in the most extreme conditions, such as the coalescence of supermassive black holes. They have been predicted by general relativity theory but have never been detected directly. Their observation would complement the information given by telescopes which observe electromagnetic waves.
The French contribution to the Technology Package of LISA Pathfinder is the laser modulator, which has already been delivered. The project is being led by the APC laboratory, at the Paris-Diderot University, which will also be involved in the ground segment and the data analysis through the François Arago Centre.
The LISA-France group made up of about ten French laboratories has made progress in simulating the astrophysical sources. R&T activities have also been conducted, mainly on laser stabilisation and simulation of the interferometry signals by APC, SYRTE and OCA/Artemis.
After NASA dropped out of the LISA mission, France has been involved in drafting the new NGO mission scenario, as a candidate for the large L1 mission under the ESA Cosmic Vision programme.

[Fig. 1]

[Fig. 2]

[Fig. 3]





[Fig. 4a]

[Fig. 4b]

[Fig. 5]

MICROSCOPE: putting the universality of free fall to the test with accelerometers

MICROSCOPE is a CNES project for a small satellite using the MYRIADE platform equipment (Fig. 3), to be conducted jointly with ONERA and OCA/Géoazur in cooperation with ESA, DLR and ZARM. It aims to test the Equivalence Principle (EP) between inertial and gravitational mass with an unprecedented resolution of 10^{-15}. The measurements will be taken using two ultra-sensitive, differential, electrostatic accelerometers built at ONERA, consisting of a pair of concentric test masses (Fig. 4a & 4b). The orbital motion of the masses will be observed with subatomic precision at an altitude of about 720 km, on a quasi-polar, sun-synchronous circular orbit. The satellite offers two main functions for this mission on a low orbit around the Earth: i) the attitude control system which minimises perturbations due to the gravity gradient and ii) the drag-free control using a micro-propulsion system which ensures pure free fall conditions for the test masses.

After the change of the micro-propulsion system from caesium FEEPs (Field Effect Electric Propulsion) to cold gas thrusters, provided by ESA, the project was approved for implementation in December 2011. The satellite is due to be launched in 2016.

STE-QUEST: quantum sensors for Space-Time Explorer and Quantum Equivalence Principle Space Test

Following ACES and MICROSCOPE, STE-QUEST (Fig. 5) is designed to test the Einstein Equivalence Principle with quantum sensors, namely a rubidium clock and a rubidium atom interferometer.

These instruments will monitor the evolution of both the internal and external degrees of freedom of the freely falling atoms, establishing a direct link between the clock measurement of the gravitational redshift and the atom interferometry measurement of the free motion of atomic matter waves. The highly elliptical orbit will improve the measurement of the gravitational redshift. The proposal has been preselected by ESA in the framework of the M3 mission of the Cosmic Vision Programme. France is participating in the consortium for both instruments (rubidium clock and atom interferometer). A number of R&D activities have already been performed with the completion of the ICE (Interférométrie Cohérente dans l'Espace) prototype, tested in parabolic flight in the Airbus A-300 Zero-G (see results in the following pages).

[Fig. 1] - The PHARAO clock being integrated in the Toulouse Space Centre. © CNES/Hervé Piraud

[Fig. 2] - Artist impression of LISA Pathfinder and its propulsion module after separation. © ESA

[Fig. 3] - New configuration of the Microscope satellite (about 1m3, 280 kg, 140 W). The cold gas propulsion system is located on two opposite panels (upper and lower panels in the picture). Most of the flight equipment comes from the Myriade microsatellite family, except for the micro-propulsion system and the deorbiting system.

[Fig. 4a] - Cut-away view of the differential accelerometer. © ONERA courtesy

[Fig. 4b] - Engineering model of the two differential accelerometers (one for the EP test with two different test masses Pt and Ti, and one for reference with the same Pt masses) during vibration tests in 2011.

[Fig. 5] - Principle of STE-QUEST measurements – gravitational redshift. A two-way link compares the clock on-board the STE-QUEST spacecraft (Vsc) with two clocks on the ground (V1 et V2). The link transfers the clock signals in both directions (space-to-ground and ground-to-space) allowing the received signal to be compared with the local clock at both ends. © ESA

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Fundamental Physics

Laboratory contribution

Time Transfer by Laser Link, T2L2

Transfert de temps par lien Laser, T2L2

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Abstract

The Time Transfer by Laser Link (T2L2) equipment has been embarked onboard the Jason-2 space mission in 2008. The objectives are both technological and scientific, with the goal to demonstrate time transfer with an accuracy better than 100 ps. This paper shows that the purpose of synchronization to better than 100 ps by this technique is feasible and potentially even better results should be expected and should help validate the accuracy of other synchronization techniques.

Résumé

L'instrument de transfert de temps par lien laser T2L2 a été embarqué sur la mission d'océanographie Jason-2 en 2008. Ces objectifs sont reliés aux applications du transfert de temps de haute performance (moins de 100 ps d'exactitude). L'article montre que l'objectif de synchronisation à mieux que 100 ps par cette technique est réaliste et que des résultats encore meilleurs devraient pouvoir contribuer à valider l'exactitude d'autres techniques de synchronisation.

The comparison of distant clocks and the distribution of stable and accurate time scales have important applications in metrology and fundamental physics. The rapid progress of frequency standards in the optical domain is demanding additional efforts for improving the performances of existing time and frequency transfer links. Clock comparison systems in the microwave domain are essentially based on GPS and two-way satellite time and frequency transfer (TWSTFT) [1][2]. T2L2 is an optical link presently on board the Jason-2 satellite at 1 335 km [3].

Instrument, principle and ground network

The T2L2 on-board hardware consists in a corner cube retro-reflector (CCR), a photodetection system, and an event timer connected to the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) time scale. Laser pulses fired toward T2L2 by the current Satellite Laser Ranging (SLR) stations are time tagged in the DORIS time scale. At the same time, the CCR reflects the laser pulse toward the ground stations providing precise ranging information (level of arround 30 picoseconds).

The T2L2 instrument permanently record the incoming energy and the arrival date of laser pulses at 532 nm; the only requirement for SLR systems is to provide date with a picosecond resolution. From 2008 to 2012, several SLR stations switched to the new CRD format following ILRS recommendations; in addition since the mid of 2010, some stations started using a high performance clock (such as hydrogen Maser). New laser format and higher time stability (of the order of 1-2 ps over 1 000 s) of ground clocks led to numerous possibilities in term of time transfer between SLR stations notably in Europe where Jason-2 is in a common view mode. Since 2008, 24 SLR stations have been participating to the mission.

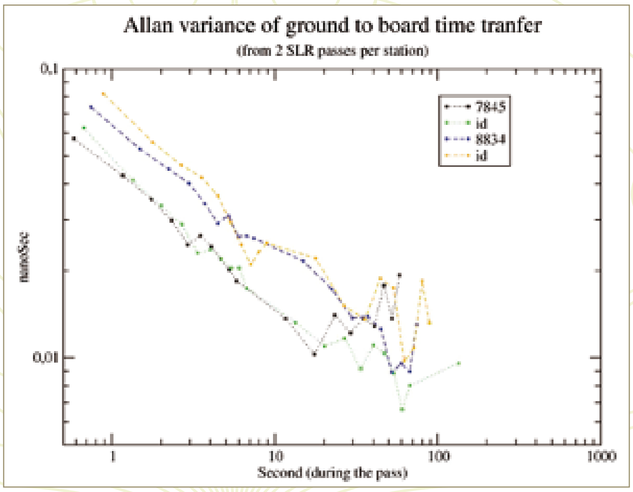
Ground to space time transfer

The ground to space time transfer is the corner stone of the T2L2 principle [4]. It consists in measuring the delay between the ground and onboard clocks when Jason-2 passes in the field of view of a SLR station. The correlation is made between the ground dates and onboard dates in order to identify a set of « triplets » consisting in 3 components: the start date (in the ground time scale) of the laser pulse, its onboard arrival date (in the DORIS time scale), and the range (time of flight of the light travel).

On a daily basis, CNES acquires and processes the onboard raw data (between 50 000 and 200 000 dates), whereas OCA downloads the SLR full rate data and produces the triplets; the resulting data base includes triplets, instrumental corrections, and statistics (available on the T2L2 Web site: https://t2l2. oca.eu/).

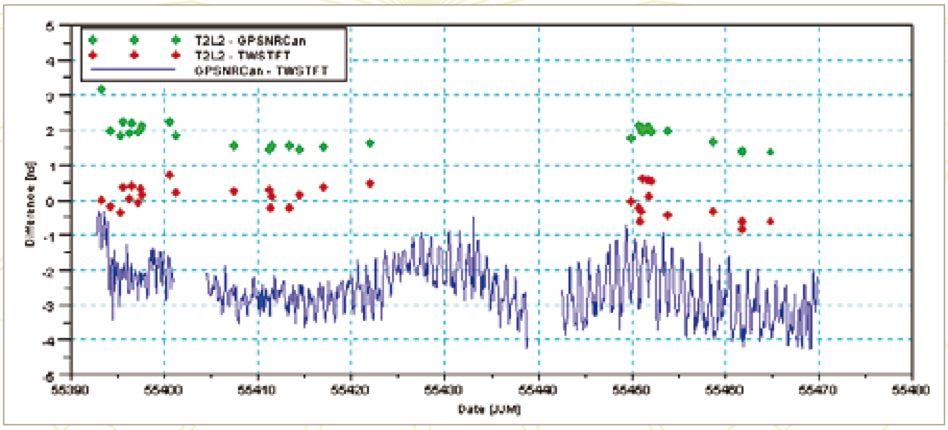
The second step of the data processing is to apply a fine and robust (mathematical sense) filter to each set of identified triplets.

[Fig. 1]



[Fig. 1]
Time Deviation of ground to space time transfers of Wettzell (Germany) and Grasse (France) SLR stations.

[Fig. 2]



[Fig. 2]
Comparison between T2L2, GPS and Two Ways on the link OP-OCA: T2L2-GPS (green), T2L2-TWSTFT (red) and TWSTFT-GPS (blue) (Arbitrary offset removed).

Because the expected performance of the ground to space time transfer essentially depends on the quality of both onboard and ground clocks (plus instrumental corrections and noises), we have selected three kinds of situation, which can be described thanks to the overall root mean square (RMS) of the clock differences over a pass : *i)* RMS > 20 ns, *ii)* RMS > 2-5 ns, and *iii)* RMS < 0.2 ns.

These cases roughly correspond to the use of, respectively: a resolution of 100 ns for the pulse start dates, the use of ground clocks like Rubidium, Quartz, etc., and finally the use of Cesium or H-Maser clocks. We characterize the time stability of each ground to space time transfer using the Time Deviation estimator $\sigma_x(\tau)$, which reach the level of 6-10 ps at 30-40 seconds for all passes of the third mentioned case.

Ground experiments and campaigns

Several experiments and campaigns were conducted since 2010, in particular between the Paris Observatory (where the French Transportable Laser Ranging Station (FTLRS) was deployed in May-October, 2010) and our fixed SLR station in Grasse (MeO), between FTLRS and MeO in Grasse (April-May, 2010) where both SLR systems used the same ground clocks, and finally from Tahiti (with FTLRS and Moblas-8, that have been connected to a same ground H-Maser clock, April-October, 2011). In addition, a dedicated calibration kit has been transported to Tahiti, Wettzell and Herstmonceux (UK) in order to in situ measure the 1-way time calibration of each station. These experiments allowed to assess a sub nanosecond accuracy and showed that GPS, TWSTFT and T2L2 ground to ground time transfer are consistent within 2 ns over 2 months.

Time transfer measurements involving T2L2 and SLR were published in several meeting (EFTF, PTTI). The time stability of the T2L2 ground to ground transfer is of 8-15 ps over 100 s, when the accuracy of the synchronization between ground clocks is better than 100 ps (thanks to measurements provided by the T2L2 calibration kit). In 2012, we plan to distribute through ILRS the T2L2 data in the CRD format, to pursue the calibration campaigns for SLR stations, and to compare the T2L2 time transfer with GPS, in term of accuracy.

References

[1] Jiang, Z., Petit, G., (2009), Combination of TWSTFT and GNSS for accurate UTC time transfer, *Metrologia,* **46** (3), 305-314.

[2] Ray, J., Senior, K., (2005), Geodetic techniques for time and frequency comparisons using GPS phase and code measurements, *Metrologia,* **42** (4), 215-232.

[3] Samain, E., Weick, J., Vrancken, P., et al., (2008), Time Transfer by Laser Link - the T2L2. Experiment on JASON-2 and Further Experiments, *International J. Modern Phys.* D, **17** (7), 1043-1054.

[4] Exertier, P., Samain, E., Bonnefond, P., and Guillemot, Ph., (2010), Status of the T2L2/Jason2 Experiment, *Adv. Space Res.*, **46**, Issue 12, 1559-1565.

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Fundamental Physics

Laboratory contribution

Matter-wave inertial sensing in microgravity: towards a test of the Universality of Free Fall

Senseur inertiel à ondes de matière en microgravité : vers un test du principe d'équivalence

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Abstract

We present the development and results of an airborne atom interferometer designed to test the Universality of Free Fall in parabolic flights. We have built a compact and robust fiber-based laser system for two-species atomic cooling.
We show that combining the atom interferometer with an auxiliary mechanical accelerometer allows for very efficient vibration rejection even in a noisy environment.
We used this technique to carry out precision acceleration measurements in the plane.

Résumé

Nous présentons le développement d'un interféromètre atomique embarqué dans la perspective de réaliser un test du principe d'équivalence lors de vols paraboliques. Nous avons construit un système laser compact permettant de refroidir deux espèces atomiques.
Nous avons montré qu'il est possible de s'affranchir des vibrations dans l'avion, en combinant l'interféromètre atomique avec un senseur classique, et de réaliser des mesures d'accélération de haute précision dans l'avion avec ce dispositif.

Atom interferometers (AIs) have demonstrated excellent performances in the field of precision inertial sensing and are promising candidates both for applications such as inertial navigation or geophysics and for tests of fundamental physics such as that of the Universality of Free-Fall (UFF) [1]. In the effort of understanding gravity at the quantum scale, testing the UFF with matter-waves is of key importance and several extensions to the theory of General Relativity predict its violation. A test of the UFF with cold atoms will consist of two atom interferometers measuring the relative differential acceleration between two atomic species with different masses as they fall in the Earth's gravitational potential. In this respect, microgravity will allow for longer interrogation times and increased sensitivity.

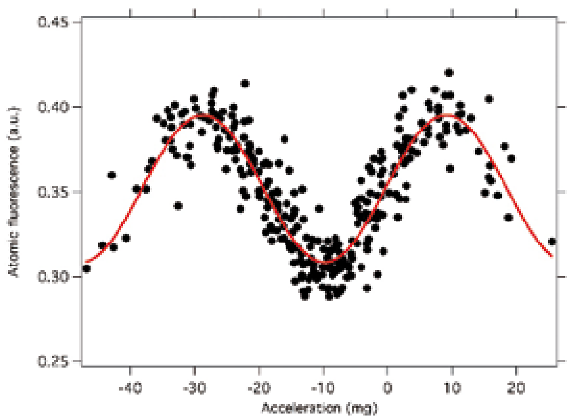
We present the results of an experiment designed to test the UFF by measuring the relative accelerations of ^{87}Rb and ^{39}K atoms in the Novespace A-300 Zero-G aircraft carrying out ballistic flights where 20 s parabolas (0*g*) are alternated with standard (1*g*) flight phases. The experimental apparatus is made of a dual-wavelength laser source, a vacuum chamber in which the atoms are laser-cooled and interrogated, and a reference oscillator used to generate all the necessary RF and microwave frequencies.

The wavelengths needed for cooling and interrogating ^{87}Rb and ^{39}K are around 780 and 767 nm respectively. We generate these wavelengths by frequency-doubling light from C-band telecom lasers operating at 1 560 and 1 534 nm [2]. This way, we take advantage of the robustness and compactness of fibered telecom components to build a laser system, which is intrinsically insensitive to misalignments caused by vibrations or structural deformations. We use a self-referenced fibered optical frequency comb to stabilize the frequency of both lasers. The lasers are amplified in an Erbium-Doped Fiber Amplifier and frequency-doubled to 780 and 767 nm in free-space before being sent to the vacuum chamber through optical fibers (Fig. 1).

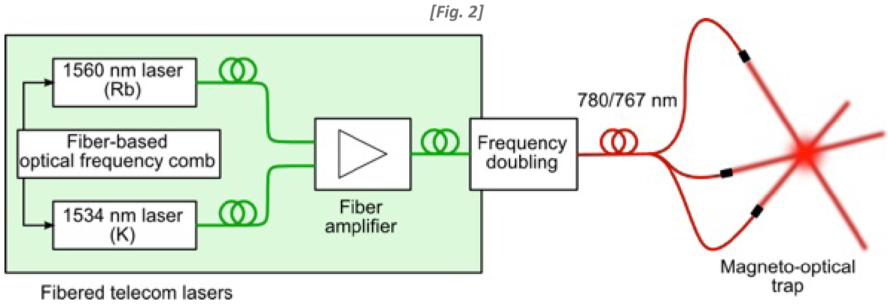
The source was successfully used in flight to cool the atoms in a two-species magneto-optical trap. Further improvements on the frequency-doubled telecom laser system will come from the use of fibered waveguide nonlinear crystals, which will allow for the creation of a fully fibered laser source for onboard atom interferometry.

Using this laser source we have carried out precision acceleration measurements with ^{87}Rb atoms in the plane [3]. The AI measures the relative acceleration between the atoms and a mirror retroreflecting the interrogating laser beam, which is attached to the experiment.

[Fig. 1]



[Fig. 2]



[Fig. 1]
Architecture of the frequency-doubled telecom laser source. Two lasers at 1 560 and 1 534nm are stabilized on a frequency comb. They are amplified and frequency-doubled to the cooling wavelengths of 780 and 767 nm for Rb and K respectively.

[Fig. 2]
Atom interferometer signal recorded during 5 parabolas, showing the sensitivity of the atom interferometer to the acceleration of the plane, recorded by an external accelerometer attached to the experiment.

The high level of residual acceleration in the aircraft (50 mg) causes the interferometer to scan many fringes, meaning that the instrument no longer operates in a region where it is reciprocal, and where the atomic signal can be inverted unambiguously to extract the acceleration. In order to recover the full sensitivity of the atomic sensor, we combine it with an external mechanical accelerometer attached to the mirror, which provides a coarse acceleration measurement used to retrieve the fringe on which the AI operates. The atomic sensor gives a fine reading of the acceleration on the fringe (Fig. 2). With this hybrid sensor we could detect inertial effects more than 300 times lower than the typical acceleration fluctuations in the aircraft, benefitting both from the mechanical accelerometer's large dynamic range and from the high sensitivity of the AI. The overall sensitivity of the measurement was mainly limited by the nonlinearities and intrinsic noise of the mechanical accelerometer. Using state of the art accelerometers and an improved version of the AI should enable sub-µg airborne acceleration measurements.

In the perspective of UFF tests, additional vibration rejection will occur when the two atom interferometers are operated at the same time.

We have demonstrated this by using our single-species AI in a 4-pulse differential configuration. In this regime, two interferometers with opposite scale factors are operated one after the other, and this leads to the rejection of low frequency accelerations with a single species setup.

These results open the way for a test of the UFF in the plane at the 10^{11} level [4] and are an important step in the preparation of ESA's STE-Quest M-class mission, which has been pre-selected in the frame of the Cosmic Vision program. STE-Quest will aim at testing the Equivalence Principle, including the UFF with a precision of one part in 10^{15}, in a dedicated satellite. Frequency-doubled telecom laser systems are good candidates for the development of a space borne source. Furthermore, the use of external accelerometers will help to reject background vibration noise even if no vibration isolation system is used.

References

[1] Cronin, A. D. et al., (2009), Optics and interferometry with atoms and molecules, *Rev. Mod. Phys.*, **81**, 1051–1129.

[2] Ménoret, V. et al., (2011), Dual-wavelength laser source for onboard atom interferometry, *Opt. Lett.*, **36**, 21.

[3] Geiger, R. et al., (2011), Detecting inertial effects with airborne matter-wave interferometry, *Nat. Commun.*, **2**, 474.

[4] Varoquaux, G. et al., (2009), How to estimate the differential acceleration in a two-species atom interferometer to test the equivalence principle. *N. Journ. Phys.*, **11**.