S. Léon, Fundamental Physics Program Manager
CNES, 2 place Maurice Quentin, 75039 Paris, France.

Fundamental Physics

Gravitation is a very weak interaction. However, it is long ranged and always attractive, and responsible for the structure of the Universe. It is described by Einstein's theory of general relativity which has just been confirmed to an unprecedented level, thanks to the direct detection of gravitational waves by the LIGO ground-based detectors. The next step will be to use space to characterize gravity with further accuracy.

Gravity has not revealed all its secrets. The theory of general relativity is of geometric and classical nature. It is incompatible with quantum theories, which describe the other fundamental interactions, *i.e.*, electromagnetic, strong and weak nuclear forces. Its relation to the quantum world remains unclear and may have to do with the mystery of dark matter and dark energy, which account for 96% of the Universe's matter and whose nature is entirely unknown.

CNES's Fundamental Physics program was created twenty years ago to test the laws of gravitation thanks to very precise distance, time and movement measurements. New space instruments, laser links, interferometers, clocks and accelerometers are being developed and will soon yield results. This approach to fine metrology in the Solar System is designed to test the foundations of general relativity. It complements cosmology space missions and experiments on particle physics which are carried out at CERN.

The equivalence principle is the basis of the theory of general relativity. It implies that in a gravitational field, all bodies fall in the same way regardless of their composition (this is the universality of free fall). It also means that time passes in the same way regardless of the type of clock, but depending on the gravitational field and the movement of the clock. Thanks to this principle, a geometric description of gravitation was formulated as a curvature of space-time. The new theories which aim to unify general relativity and the standard model of particle physics violate this principle at a very low level. This is what the MICROSCOPE and ACES experiments will investigate.

MICROSCOPE

On April 22, 2016, the 300 kg-CNES MICROSCOPE microsatellite was launched on a circular sun-synchronous orbit at 707 km altitude to test the universality of free fall with an expected precision of 10^{-15} (two orders of magnitude better than for a ground experiment). In space, it is possible to study the relative motion of two bodies in almost perfect and permanent free fall, shielded from perturbations encountered on Earth, over the course of several months. Two concentric cylindrical test masses made of different materials – titanium and platinum – placed in a differential electrostatic accelerometer built by ONERA are minutely controlled to maintain them motionless with respect to the satellite. If the equivalence principle is confirmed, the two masses will be subjected to the same control acceleration. If different accelerations have to be applied, it will mean that the principle has been violated. A second accelerometer with two identical platinum masses will be used as a reference. ESA provided the microsatellite with cold gas microthrusters which can compensate tiny perturbations (including solar radiation pressure). The success of the mission relies on performing the acceleration measurements lower than 8. 10^{-15} ms^{-2}. The mission was submitted by the DMPH[1] and the Géoazur laboratory[2] which were joined by ZARM[3] and DLR. In 2015, the project was open to new scientific participations on data processing including other applications for geodesy and aeronomy.

PHARAO

CNES is the prime contractor of the cesium PHARAO clock using laser-cooled atoms. It was submitted by the SYRTE[4] and LKB[5] laboratories and delivered to ESA on July 25, 2014. It will be part of the ACES payload mounted externally on one of the external nadir racks of the ISS Columbus module, for at least 18 months, starting in 2017. ACES accommodates two atomic clocks (PHARAO and the Space Hydrogen Maser), a microwave ground-space frequency and time transfer unit and a laser link. ACES will perform a planet-scale comparison of various ground clock signals using different atoms and transitions in the microwave or optical domain. Clock comparisons will enable the search for a possible drift of the fundamental fine structure constant, measure Einstein's effect on redshifts according to the gravitational potential and test the anisotropy of the speed of light. The PHARAO frequency stability is expected to reach 10^{-16} over a few days. Clock comparisons will be performed with a precision of about ten picoseconds.

Fig. 1 and 2: Integration of the Microscope satellite at the Guiana Space Center.
© CNES/ESA/Arianespace/Optique Vidéo CSG/S.Martin, 2016

T2L2

The Time Transfer by Laser Link instrument was developed by both CNES and Géoazur. It was initially scheduled as part of the ACES project but launched on board JASON-2 in June 2008 [1, 2, 3, 4]. T2L2 uses laser pulses and an onboard time-tagging system combined with the DORIS ultra-Stable Oscillator. It showed a 200-picosecond uncertainty for time comparison between two distant clocks. The instrument is still in operation. The performances of a ground-to-space optical link with coherent detection are also studied by the SYRTE, Géoazur and Lagrange(6) Laboratories as well as DOTA(7). The ability to compensate the effects of atmospheric turbulence was analyzed as part of an STE-QUEST(8) type of mission scenario with an elliptic orbit. [5] A station for atmospheric turbulence characterization was set up at OCA's(9) Calern site. This work is also relevant to optical telecommunications.

PHARAO

The cold atom clock PHARAO has paved the way for studies on inertial sensors using matter wave interferometry: the ICE prototype, which has already been used in the Airbus ZERO-G, now allows simultaneous trapping of two atomic species, namely rubidium and potassium. The development of metrology based on quantum technologies is confirmed; various applications are considered, including the test of the equivalence principle by atom interferometry or geodesy using clocks.

LISA PATHFINDER

Launched in December 2015, ESA's LISA PATHFINDER mission will demonstrate the technological feasibility of critical technologies for the future L3 gravitational wave detection mission. The French contribution, through CNES, the APC laboratory(10) and the LISA-France group(11), consisted in providing the acousto-optic modulator of the optical bench and in data processing through the François Arago Center(12) (Université Paris-Diderot). Efforts are now focused on the L3 mission.

Other data from missions including ESA's GAIA astrometry mission, navigation data from probes in the Solar System and GNSS data are also exploited for Fundamental Physics tests.

REFERENCES

[1] Exertier, P., *et al.* (2014), Time Transfer by Laser Link: Data analysis and validation to the ps level, *Advances in Space Research*, **54**, 2371-85.

[2] Samain, E., *et al.* (2014), Time Transfer by Laser Link (T2L2): characterization and calibration of the flight instrument, *Metrologia*, **51**, 503-15.

[3] Samain, E., *et al.* (2015), Time Transfer by Laser Link: a complete analysis of the uncertainty budget, *Metrologia*, **52**, 423-32.

[4] Laas-Bourez, M., *et al.* (2015), Accuracy validation of T2L2 time transfer in co-location, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, **62(2)**, 255-65.

[5] Robert, C., *et al.* (2016), Impact of turbulence on high-precision ground-satellite frequency transfer with two-way coherent optical links, *Phys Rev A*, **93(3)**, 033860, DOI: 10.1103/PhysRevA.93.033860.

(1) *ONERA's Physics and Instrumentation Department.*

(2) *Géoazur, CNRS, Université de Nice Sophia Antipolis, Observatoire de la Côte d'Azur, Université Pierre et Marie Curie, IRD.*

(3) *Center of Applied Space Technology and Microgravity, University of Bremen.*

(4) *SYstèmes de Référence Temps-Espace, Observatoire de Paris, CNRS, Université Pierre et Marie Curie, Laboratoire National de Métrologie et d'Essais.*

(5) *Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Ecole Normale Supérieure de Paris, Collège de France, CNRS.*

(6) *Laboratoire Lagrange, CNRS, Observatoire de la Côte d'Azur, Université de Nice Sophia Antipolis.*

(7) *ONERA's Theoretical and Applied Optics department.*

(8) *Space-Time Explorer and QUantum Equivalence Space Test.*

(9) *Observatoire de la Côte d'Azur.*

(10) *AstroParticule et Cosmologie, CNRS, Université Paris Diderot, CEA, Observatoire de Paris.*

(11) *LISA France gathers several French laboratories (APC, ARTEMIS, CEA/IPht, IAP, LAPP, LPC2E, LUTH, ONERA and SYRTE).*

(12) *The François Arago Center is managed by the APC laboratory and backed by the IPGP within the Space Campus of Université Paris 7.*

S. Léon, Fundamental Physics Program Manager
CNES, 2 place Maurice Quentin, 75039 Paris, France.

Fundamental Physics

ICE measures the local differential acceleration between two atomic species

Quantum sensors, based on the wave nature of matter for detecting inertial forces with high accuracy and long-term stability, are highly relevant to Fundamental Physics in order to probe the interface between quantum mechanics and gravity. The ICE cold atom interferometer has been designed to be used under reduced gravity level, in parabolic flight campaigns of the Airbus ZERO-G. For the first time, the ICE instrument has tested the weak equivalence principle (Universality of Free Fall) by measuring the local differential acceleration between two atomic species, *i.e.*, rubidium and potassium.

Precise tests of the universality of free fall (UFF) or Einstein's weak equivalence principle (WEP) with matter waves are key to understanding gravity at the quantum scale. They use two atom interferometers which measure the relative acceleration between two atomic species in free fall in the Earth's gravitational potential. The ICE experiment [1] has been designed to generate interferometer signals from laser-cooled samples of two atom species ^{39}K and ^{87}Rb. It has been used under a reduced gravity level on board the Novespace ZERO-G Aircraft. During an aircraft parabolic flight, the experiment is in free fall. This microgravity environment should enable longer interrogation times for the atoms, on the order of 10 s. Since the sensitivity of atom interferometers to acceleration scales as the square of the interrogation interval T, measurements on this timescale could theoretically detect changes in acceleration at the level of 10^{-11} g.

Simultaneous acceleration measurements with the two atomic species in microgravity have recently been made (see Fig. 1). A three Raman pulse interferometer for both Rb and K has been achieved. The phases of the fringes obtained from the measurements of the respective population probabilities are directly linked to the mean acceleration of the two species. The differential phase can be extracted directly from the fringes or from the elliptical parametric representation of the two signals [1]. This constitutes the first quantum test of the weak equivalence principle in a free-falling vehicle.

Since the two interferometer signals originate from atomic sources that occupy the same space, many systematic effects related to a precise test of the UFF can be eliminated. The Raman beams at 780 nm and 767 nm are combined on the same optics before being aligned through the atomic cloud and retro-reflected off of a reference mirror. In this way, mirror vibrations are common to both interferometer signals [2, 3] and many sources of measurement noise can be rejected to a high degree. In addition, a high-sensitivity mechanical accelerometer (Colibrys SF3600) is attached to this mirror and its signal is combined with the output of the two interferometers to further reduce noise due to low-frequency vibrations and mirror drift. This technique is effective at removing phase noise even if no vibration isolation system is used.

The ICE experiment has been developed jointly by LP2N at the Institut d'Optique Graduate School, SYRTE at the Paris Observatory and ONERA/DMPh, with the support of CNES. The ultimate goal is to perform the experiment aboard a dedicated satellite. The French science community has been part of the STE-QUEST (Space Time Explorer - QUantum Equivalence principle Space Test) mission proposal which was initially submitted to the ESA Cosmic Vision M3 call in 2010, and in a simplified version to the M4 call in 2015.

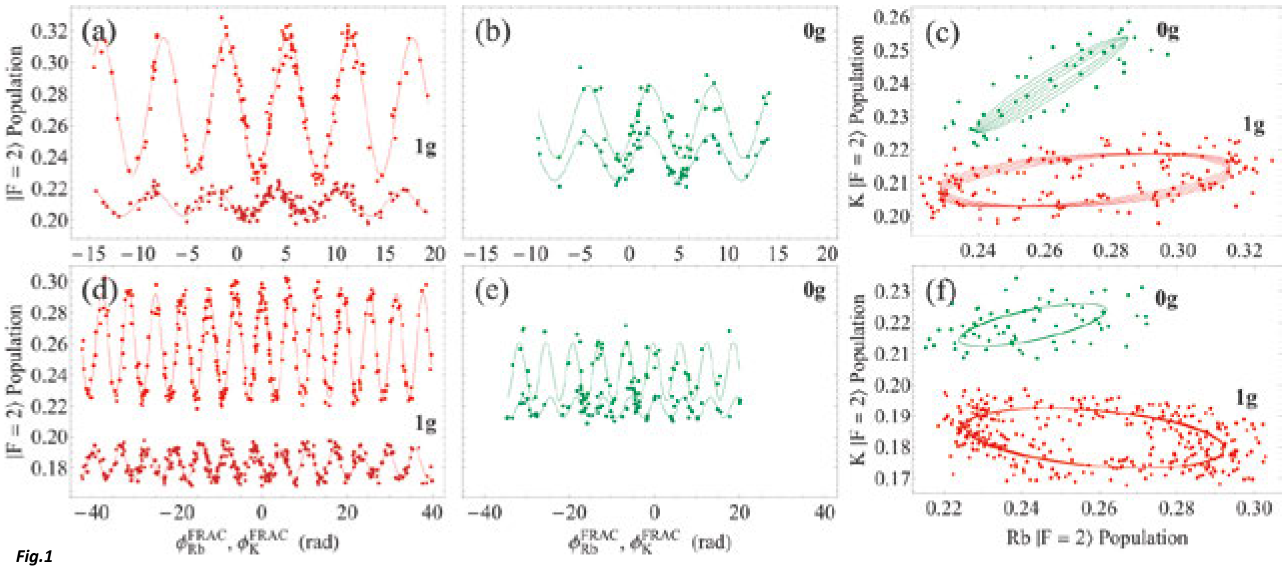

Fig.1

Fig. 1: Simultaneous K-Rb interferometer fringes both 1g (red) and 0g phase of flight (green) for interrogation time T = 1 ms (a-c) and T = 2 ms (d-f). Plots (c) and (f) show correlations between population measurements for each interferometer. The solid lines are parametric representations of the corresponding fit functions shown in (a, b, d, e).

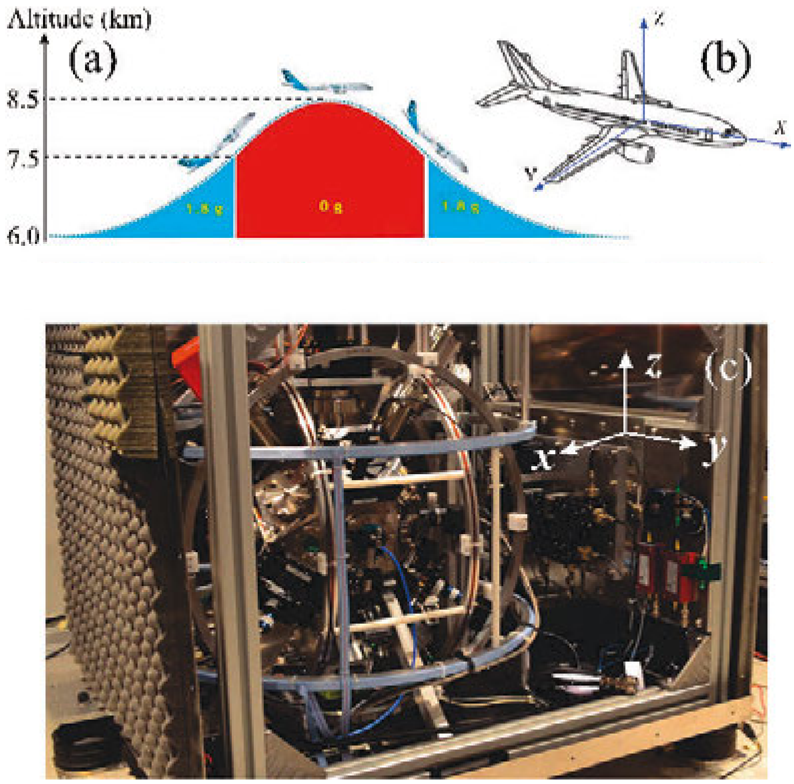

Fig.2

Fig. 2: (a) Basic trajectory of the Novespace Zero-G aircraft during parabolic flight. (b) Coordinate system onboard the aircraft. (c) The science chamber mounted onboard the aircraft. Samples of Rb and K are laser-cooled in a vapor-loaded magneto-optical trap contained within a titanium vacuum system and enclosed by a magnetic shield. Raman beams are aligned either along the horizontal or the vertical axis of the aircraft.

REFERENCES

[1] Barrett, B., *et al.* (2015), Correlative methods for dual-species quantum tests of the weak equivalence principle, *New. J. Phys.*, **17**, 085010.

[2] Varoquaux, G., *et al.* (2009), How to estimate the differential acceleration in a two-species atom interferometer to test the equivalence principle, *New J. Phys.*, **11**, 113010.

[3] Bonnin, A., *et al.* (2015), Characterization of a simultaneous dual-species atom interferometer for a quantum test of the weak equivalence principle, *Phys. Rev. A.*, **92(2),** 023626.