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Fundamental physics

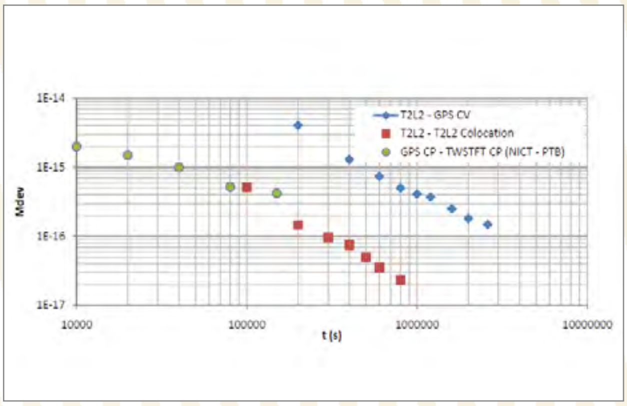

Fig. 1

Tests of gravity performed in the Solar System show a good agreement with general relativity. However some indications lead physicists to think this theory may not be the ultimate one. Its principles are not compatible with those of quantum mechanics. A theory solving this problem would represent a crucial step towards the unification of fundamental interactions. Several approaches have been suggested. All of them tend to lead to tiny 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. General relativity is also challenged by observations at larger galactic and cosmic scales which are presently explained by introducing new components, dark matter and dark energy, whose nature remains unknown.

The last two years have taken a leap. The PLANCK mission has confirmed the ΛCDM cosmological model and the GAIA astrometry mission launched in December 2013 will, among others, aim at determining the distribution of dark matter in our galaxy and testing modified gravity models. The Fundamental Physics dedicated missions PHARAO/ACES, MICROSCOPE and LISA PATHFINDER (precursor of e-LISA), will be launched in the 2015-2016 period. Such space missions based on optical interferometry, telemetry, clocks and accelerometry are designed to conduct high precision measurements of space, time and movement.

\\\\\\\\\\T2L2 on board JASON 2: Time Transfer by Laser Link

T2L2 allows the comparison of remote ultra-stable clocks. The instrument developed by CNES and Observatoire de la Côte d'Azur (OCA/GéoAzur) has been functioning on the JASON-2 satellite since June 2008. The principle of the experiment comes from laser ranging, using on ground a network of laser stations associated with high performance clocks and on board the T2L2 equipment designed to record the arrival time of laser pulses (linked to the local ultra-stable oscillator of the Doris system). Several laser ranging campaigns were conducted over the last two years together with calibration campaigns for laser and microwave techniques (GPS, TWSTFT). They demonstrated a frequency relative stability for the clock comparison down to 10^{-16} on the long term, and time accuracy better than 100 picoseconds (Fig. 1).

\\\\\\\\\\PHARAO/ACES: a space clock using cold caesium atoms to test relativity

The ESA ACES (Atomic Clock Ensemble in Space) mission, built around the Cs cold atom PHARAO clock, is planned to be launched in 2016 on one of the external nadir racks of the ISS Columbus module. By comparing signals from different ground atom clocks, it will monitor the relative variation of the fine structure constant α with an accuracy of 10^{-17} per year. The gravitational redshift will also be measured with an increased accuracy. The PHARAO flight model, developed under CNES responsibility, has been assembled and tested with the scientists (Observatoire de Paris/SYRTE and LKB) in the CNES premises in Toulouse (Fig. 2). The preparation of the science operation center has started in CADMOS in Toulouse. The SYRTE metrology laboratory in Paris has been recommended as a core institute to be equipped with one of the Microwave link ground terminal provided by ESA. Additional ground-to-ground clock comparison systems (GPS, TWSTFT, laser ranging station, optical fiber link) are available.

\\\\\\\\\\LISA PATHFINDER and e-LISA: laser interferometry for the detection of gravitational waves

The aim of e-LISA is to observe the Universe by means of gravitational waves. These are vibrations of the warped space-time produced in the most extreme environments, such as coalescence of supermassive black holes. They have been predicted by general relativity but they have never been detected directly. The "Gravitational Universe" has been selected by ESA as the theme for the *Cosmic Vision* L3 mission.

Regarding the LISA PATHFINDER preparatory mission foreseen in July 2015, the various simulation campaigns of science and technology operations performed at ESAC

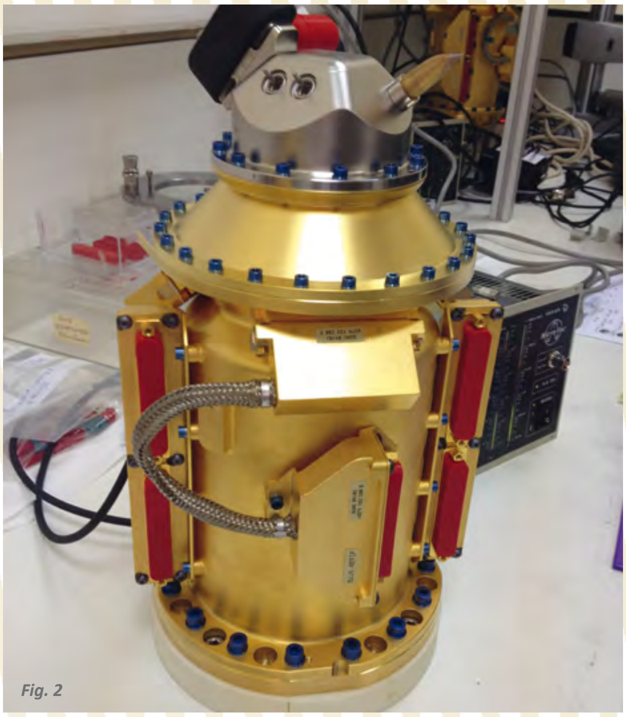

Fig. 2

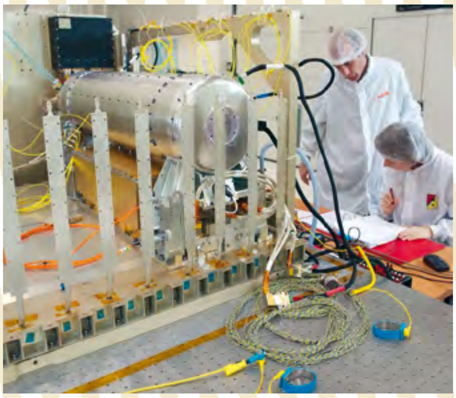

Fig. 3a

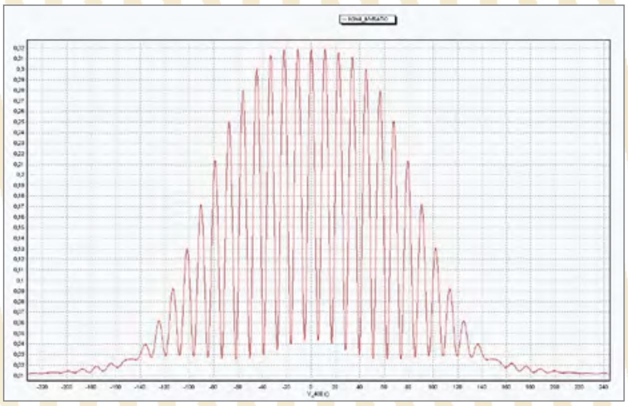

Fig. 3b

were supported by the complementary data center (Centre François Arago, APC, Paris), which was contributing off-line data analysis. French participation to the future e-LISA Data Processing Center was also investigated through a CNES assessment study.

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

MICROSCOPE is a CNES project of small satellite based on the use of the Myriade platform, and managed with ONERA and OCA/Géoazur in cooperation with ESA, DLR and ZARM. It aims at testing the Equivalence Principle between inertial and gravitational mass with an unprecedented resolution of 10^{-15}. The measurements will be performed using two ultra-sensitive differential electrostatic accelerometers consisting of a pair of concentric proof masses. The two flight models built at ONERA were delivered in July 2014 (Fig. 2). 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 presents two main functions enabling this mission on a low orbit around the Earth: the attitude control which minimizes the perturbations due to the gravity gradient and the drag-free control using a cold gas micro propulsion system which ensures the conditions of a pure free fall for the proof masses. The satellite is to be launched together with *SENTINEL-1B*, as of February 2016.

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

The STE-QUEST mission proposal designed to test the Einstein Equivalence Principle with quantum sensors (atom clock and atom interferometer) was preselected by ESA in the competition for the *Cosmic Vision* M3 mission. STE-QUEST was finally withdrawn due to the inadequate technology readiness level of the atom interferometer. R&T activities are going on to improve the instrument maturity and 0*g* experiments under parabolic flights (ICE) will be conducted with two different atom species to test the equivalence principle at quantum level (see paper of P. Bouyer *et al.*).

Navigation data analysis and gravitation in the Solar System

The precise measurement of the gravitational field of the Sun and the planets is a strategic issue for fundamental physics. Improvement of probe trajectory, reference systems and planetary ephemeris can originate from it. French scientists have been involved in a specific scientific use of the navigation data, for example on CASSINI and MESSENGER (see paper of A. Fienga *et al.*), and are now participating in the JUICE radioscience experiment 3GM, Gravity & Geophysics of Jupiter and Galilean Moons. Its high precision Doppler and range measurements are quite interesting for fundamental physics tests.

[Fig. 1]
Relative frequency stability for clock comparison as a function of integration time, for microwave methods GPS, TWSTFT and T2L2. T2L2-T2L2 colocation (red squares) means two laser stations distant from about 40 m, connected to the same clock, so the clock is compared to itself via the JASON-2 satellite. © OCA Géoazur

[Fig. 2]
MICROSCOPE differential accelerometer flight model built in ONERA. © ONERA

[Fig. 3a]
PHARAO flight model under testing in CNES premises (gold: laser source, silver: caesium tube). © CNES

[Fig. 3b]
First signal of the PHARAO clock flight model (Ramsey fringes). © LKB/Syrte/CNES

Laboratory contribution

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Fundamental physics

ICE atom Interferometric Inertial Sensing in microgravity: toward a test of the universality of free fall

Accéléromètre ICE à ondes de matière en microgravité : vers un test de l'universalité de la chute libre

➔ **Abstract:** The ICE (Interferometrie atomique à sources Cohérentes pour l'Espace) experiment tests the universality of free fall using atom interferometry in microgravity. An ultra-stable transportable apparatus, consisting of a fiber-based laser system for cooling both rubidium and potassium atoms, has been built and operated in parabolic flight onboard the NOVESPACE ZERO-*G* aircraft.
We are presenting inertial measurements from both rubidium and potassium and describing progress toward the achievement of a dual-species interferometer.

➔ **Résumé :** L'expérience ICE (Interférométrie atomique à sources Cohérentes pour l'Espace) teste l'universalité de la chute libre par interférométrie atomique en microgravité. Un dispositif ultra-stable et transportable, utilisant un laser fibré pour refroidir les atomes de rubidium et potassium et fonctionnant en vol parabolique à bord de l'avion ZERO-*G* de NOVESPACE, a été construit.
Nous présentons les mesures inertielles faites avec le rubidium et le potassium et les progrès réalisés en vue d'un interféromètre double espèce.

Over the past 20 years, atom interferometers have emerged for precision measurements of both fundamental constants and inertial effects. They have been used, for example, to make precise and absolute measurements of local gravity, Earth rotation rate and the gravitational constant, *G* [1]. Interesting uses emerge in inertial navigation, geophysics and tests of fundamental physics such as the universality of free fall (UFF). Precise tests of the UFF with matter waves are of key importance to understanding gravity at the quantum scale. Such tests use two atom interferometers that measure the relative acceleration between two atomic species in free fall in the Earth gravitational potential. The ICE experiment is designed to generate interferometer signals from laser-cooled samples of ^{39}K and ^{87}Rb onboard the NOVESPACE A-300 ZERO-*G* aircraft. While in parabolic flight, the experiment is in free fall (Fig. 1) and this microgravity environment allows for interrogation times on the order of 10 s. Since the sensitivity of atom interferometers to acceleration scales as the square of this time, measurements on this timescale could theoretically detect changes in acceleration at the level of 10^{-11} *g*.

In order to laser-cool ^{87}Rb and ^{39}K, two independent laser sources are required at 780 and 767 nm. These wavelengths are generated by frequency-doubling the output of two C-band telecom lasers operating at 1 560 and 1 534 nm [2]. By using these fiber-based lasers the system is largely insensitive to optical misalignment due to vibrations or structural deformation. The frequency of both lasers is stabilized by locking them to an optical frequency comb that operates over both telecom wavelengths. After amplification and frequency-doubling, the light at 780 and 767 nm passes through a series of acousto-optic modulators in free-space (which act as frequency shifters and high-speed optical switches) before being sent through optical fibers toward the vacuum chamber.

In previous work [3], we demonstrated the operation of a cold ^{87}Rb interferometer during parabolic flight and performed sensitive measurements of the plane's acceleration. In a single-species interferometer, the acceleration of the atoms is measured relative to a mirror that retro-reflects the interrogation light. On the plane, the high level of vibrations and residual acceleration (~50 m*g*) causes this reference mirror to move significantly during the interrogation time of the interferometer. As a result, the phase of the interferometer is randomized by the mirror vibrations and can span multiple interference fringes. We showed that this randomization can be reversed with a high degree of accuracy by using a correlation procedure with measurements from a mechanical accelerometer attached to the reference mirror. This enabled us to detect inertial effects 300 times below the level of vibrations onboard the aircraft. These measurements were primarily limited by the non-linearity and intrinsic noise of the mechanical accelerometer and we anticipate further improvement to airborne inertial measurements using state-of-the-art accelerometers.

Ultimately, our goal is to make simultaneous measurements from the two atomic species in microgravity. 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. So we have constructed a compact titanium vacuum system consisting of a six-beam laser-cooling configuration for both 780 nm and 767 nm light. This setup can generate sources of cold ^{87}Rb and ^{39}K samples at temperatures of 2 μK and 15 μK, respectively, each with approximately 10^8 atoms. 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 a mirror. In this way, mirror vibrations are common to both

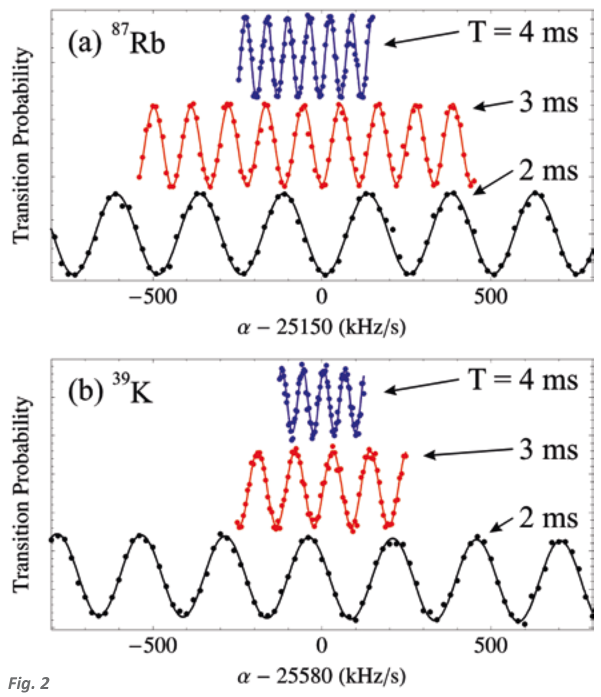

Fig. 2

interferometer signals, and many sources of measurement noise can be rejected to a high degree. In addition, a high-sensitivity mechanical accelerometer is attached to this mirror and is combined with the output of the two interferometers to further reduce noise due to lower-frequency vibrations and mirror drift. This technique is effective at removing phase noise even if no vibration isolation system is used.

In Fig. 2, we present some preliminary interferometer fringes measured in the lab separately with ^{87}Rb and ^{39}K. Here, measurements of the gravitational acceleration are performed by chirping the frequency difference between counter-propagating Raman beams and finding the chirp rate, α, that exactly compensates for the Doppler shift due to the falling atoms. This value of α corresponds to the central fringe that remains fixed for all values of T — the time separating light pulses of the interferometer. These results, along with other recent tests performed in parabolic flight [4], represent an important step toward the first mobile dual-species interferometer and a test of the UFF at the 10^{-11} level.

[Fig. 1]
Members of the ICE team performing atom interferometry experiments during the microgravity phase of a parabolic flight onboard the NOVESPACE A300 ZERO-G aircraft. From top to bottom: B. Barrett, B. Battelier, P.-A. Gominet. © LP2N

[Fig. 2]
Acceleration-sensitive interferometer fringes measured in the lab with 87Rb (a) and 39K (b). Here, the fringes are obtained by scanning the frequency chirp rate, α, between Raman beams for T = 2, 3 and 4 ms. The sensitivity to the gravitational acceleration scales as T^2, where T is the time between interferometer pulses. © LP2N

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Laboratory contribution

Fundamental physics

The MESSENGER mission: new INPOP planetary ephemerides and constraints for theories of gravitation

La mission MESSENGER : de nouveaux éphémérides planétaires et validations de la relativité générale

➔ **Abstract:** From the analysis of the tracking data of the Mercury orbiter, MESSENGER, a new planetary ephemerides INPOP13a was built and possible violations of General Relativity (GR) were measured with the PPN parameters β and γ. INPOP13a gives an orbit of Mercury 25 times more accurate than the previous ephemerides and the validation of GR is improved by a factor 4 for β and 2 for γ in comparison to the previous best estimates [1-2].

➔ **Résumé :** Par l'analyse des données de navigation de l'orbiter de Mercure, Messenger, une nouvelle éphéméride planétaire INPOP13a a été construite et de possibles violations de la Relativité Générale (RG) ont été déterminées avec les paramètres PPN β et γ. INPOP13a donne une orbite de Mercure 25 fois plus précise que les éphémérides précédentes et la validation de la RG a été améliorée d'un facteur 4 pour β et 2 pour γ par rapport aux tests précédents [1-2].

Mercury is the smallest and the less explored planet of the Solar System. It is also the closest planet to the Sun. This proximity makes the study of its dynamics a fundamental input for testing general relativity. The effect of general relativity is indeed for Mercury orbit the strongest among all planets in the Solar System (43 arcseconds per century of perihelia advance). Despite its proximity, until recently, Mercury had only been visited three times by the Mariner 10 spacecraft in the seventies (twice in 1974 and once in 1975).

The MESSENGER spacecraft launched in 2004 by NASA in the frame of the *Discovery* program of Solar System exploration was the first probe to orbit Mercury since March 18, 2011. The main goal of the mission is to map Mercury surface and to study its inner structure.

Researchers of the CNES CESDN (Consortium pour l'Exploitation Scientifique des Données de Navigation), a consortium for the use of spacecraft navigation data for science exploitation, have studied the spacecraft orbit using more than one and a half year of navigation data samples. This work allows to set up a new planetary ephemeris and to perform new tests for general relativity [3].

Several models of gravitation are presently under consideration aiming to solve some major problems of quantic physics and cosmology such as the existence of dark matter or our understanding of the gravitation mechanism at large and quantic scales. Up to now, CESDN studies have tested the PPN (Parametrized Post-Newtonian) formalism described by Will (1993) [4]. This formalism describes the non-linear equations of motion of GR as developments of Newton universal law of gravity. Many parameters are used to calibrate possible violations of GR in this framework. The most common ones are the parameter β describing the non-linearity of gravity, usually scaled at one for GR, and the parameter γ for deflection of light per unit of mass, scaled at one in GR.

In studying the motions of natural and artificial objects in the Solar System, the CESDN researchers provide new limits confirming or denying the proposed models.

The INPOP (Intégrateur Numérique Planétaire de l'Observatoire de Paris) team working together since 2003 for the construction of the INPOP planetary ephemerides is the only team in the world to address these questions by the construction of spacecraft and planetary orbits with the use of raw navigation data of space missions [1-3].

MESSENGER data are regular and accurate at a level never reached before. The team has built up the most accurate ephemerides of Mercury (Fig. 1) called INPOP13a. These publicly distributed ephemerides[1] introduce an improvement of a factor 10 on the estimation of Mercury positions but also an improvement of the Earth orbit as well as new estimations of Earth perturbing asteroid masses. They also have obtained new constraints on PPN parameters of light deflection γ and of gravity non-linearity β (Fig. 2).

In a paper recently published in Astronomy and Astrophysics [3], the obtained accuracy gives an improvement of about a factor 4 for the parameter β in comparison to previous estimations obtained by the team in 2010 [1]. For the parameter γ, the 2003 Cassini experiment published in Nature [2] gave a possible maximum violation to general relativity of about 4.10^{-5}. The present study reduces the possible range of such violation by a factor 2.

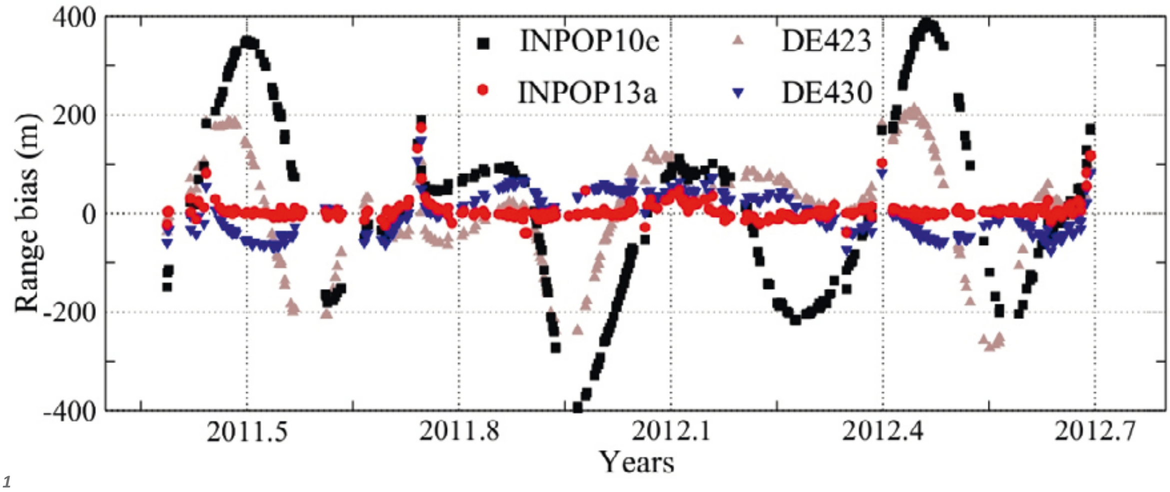

Fig. 1

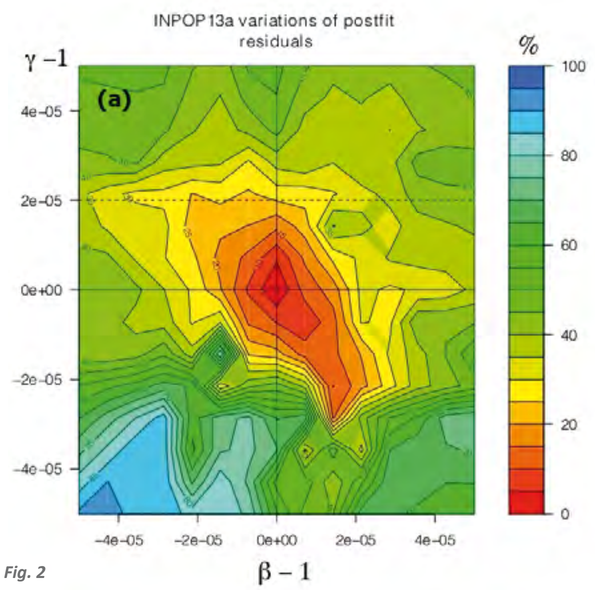

Fig. 2

[Fig. 1]
Differences in meters between the Earth-Mercury distance deduced from the observations of radio navigation of the spacecraft orbiting Mercury and planetary ephemerides INPOP13a (in red), INPOP10e (in black), and the US planetary ephemerides DE423 (gray) and DE430 (in blue). © Adapted from [4]

[Fig. 2]
Differences (%) between planet position residuals from INPOP13a (with β=1 and γ=1) and from ephemerides built with values of parameters β-1 (x-axis) and γ-1 (γ-axis). The zones of smallest differences (red and orange zones) give constraints for the β and γ parameters, acceptable at the level of accuracy of the planetary observations.© Adapted from [4]

Furthermore, this study shows that it was possible to produce a disentangled estimation of the parameters β and γ based on the analysis of spacecraft data and the construction of planetary ephemerides. The new estimations of β and γ give new constraints for alternative theories of gravitation.

Collaborations are installed in order to test other theories at the scale of the Solar System like MOND or tensor-scale theories [5] in particular with the Institut Astrophysique de Paris and Paris Observatory.

This work was supported by a PhD grant from CNES and the Région Franche-Comté, in the framework of the GRGS (Groupe de Recherche en Géodésie Spatiale) and of the CNES CESDN (Consortium pour l'Exploitation Scientifique des Données de Navigation).

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