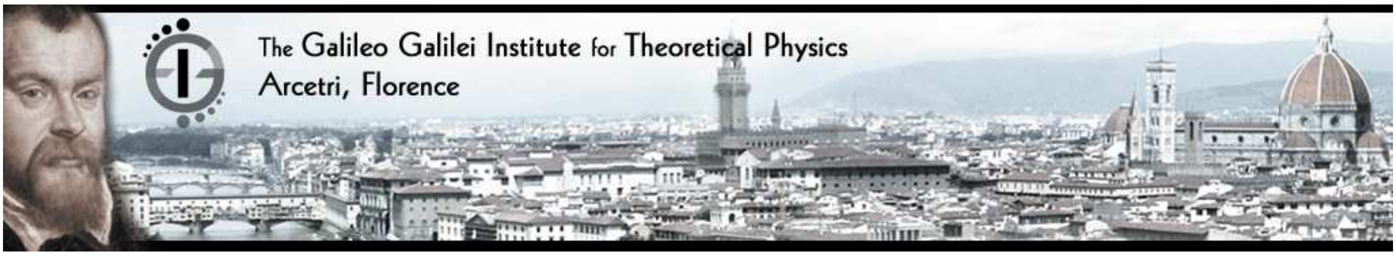

International Workshop

Advances in Precision Measurements and Experimental Gravitation in Space

Arcetri, Firenze 28^{th}–30^{th} September 2006

Organizing Committee:

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Part I

Oral Contributions

Alternative theories of gravity and cosmology

G. Veneziano

CERN, Switzerland

Alternatives to conventional gravity and cosmology, in particular those suggested by superstring theory, will be briefly reviewed with particular emphasis on their implications for precision tests in those areas of fundamental physics.

LISA Pathfinder and LISA

S. Vitale

University of Trento–INFN, Trento, Italy

The talk shortly overviews the architecture and the science of LISA, the gravitational wave observatory developed by ESA and NASA. It then discusses the accuracy required in the practical definition of the so called Transverse Traceless reference frame required by LISA to operate. This is the frame where coordinates are marked by geodesic moving particles and where the metric tensor oscillates with gravitational waves. The talk will show where we are with assessing the accuracy of such a construction on ground and, more important, where and how LISA Pathfinder, the dedicated ESA's mission with a launch in 2009, will bring us by a thorough experiment in space.

Alternatives to dark energy and dark matter and their implications

O. Bertolami

Instituto Superior Técnico, Departamento de Física, Av. Rovisco Pais, 1, 1049-001, Lisboa, Portugal

We discuss the motivation for high accuracy relativistic gravitational experiments in the Solar System to test alternative gravity models designed to get away with the need of dark energy and dark matter.

Testing General Relativity with Interplanetary Spacecraft

L. Iess

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Interplanetary missions offer an excellent opportunity to test general relativity (GR) and alternative theories of gravity either by measuring the effects of the sun on the propagation of photons or by precise determination of the ephemerides of solar system bodies. Those experiments rely on microwave radio links between a ground antenna and a distant spacecraft to provide accurate range and range rate measurements. Almost 30 years ago range measurements to the Viking landers near a solar conjunction confirmed the time delay predicted by GR. The experimental error in the PN parameter γ, affecting the space components of the solar metric relevant to this test, was 10^{-3}. Since then little progress was made in solar system tests, until the solar conjunction experiment of the Cassini mission was carried out in 2002. Thanks to the use of multifrequency radio link at X- and Ka-band (8.4 and 32.5 GHz), the propagation noise from to the solar corona was effectively cancelled in the Cassini experiment, leading to another, more stringent confirmation of GR at the level of 2.310^{-5}. While Viking made use range measurements, Cassini relied only on precise two-way range rate observables, determined with an accuracy of 3 micron/s over integration times between 1000 and 10000 s.

Future opportunities to measure the solar metric with better accuracies are provided by BepiColombo, the ESA mission to Mercury. In a further technological development, the radio science experiment of the mission (MORE, Mercury Orbiter Radioscience Experiment) will make use of dedicated onboard and ground hardware to set up a plasma cancellation system for both range and range rate measurements. In addition, an onboard accelerometer (ISA) will enable an accurate measurement of the strong non-gravitational accelerations acting on the spacecraft, a crucial quantity for the determination of the spacecraft orbit around the planet. Thanks to the use of a wideband (20 MHz) tone, the ranging system is designed for a target accuracy of 20 cm two-way, independently of the solar elongation angle. The combination of range and range rate measurements on the ground and accelerometer reading onboard will lead to a very accurate determination of the orbit of Mercury and therefore to the measurement of several PN parameters with improved accuracies.

Precision measurement based on ultracold atoms and molecules

Jun Ye

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We report our group's recent research efforts on precision test of fundamental physics using ultracold atoms and molecules.

In the first experiment, we will discuss recent progress on an optical atomic clock based on ultranarrow transitions in neutral strontium atoms tightly confined in a one-dimensional magic wavelength optical lattice. We demonstrate superior optical coherence without any deleterious effects from motional degrees of freedom, revealing optical resonance linewidths at the hertz level with excellent signal to noise ratio. The resonance quality factor of 2.4×10^{14} is the highest ever recovered in any form of coherent spectroscopy. The spectral resolution permits direct observation of the breaking of nuclear spin degeneracy for the $^1S_0$ and $^3P_0$ optical clock states of ^{87}Sr under a small magnetic bias field. We have also performed a detailed systematic study of the clock transition frequency, with the uncertainty reaching 10^{-15}. A phase-stabilized femtosecond optical frequency comb preserves optical coherence at the 0.3 Hz optical linewidth across the visible spectrum.

In the second experiment, cold, stable, ground state polar molecules are produced from Stark decelerators. Hydroxyl radicals (OH) and formaldehyde (H_2CO) molecules have been bunched in phase space, accelerated, slowed, or trapped. We demonstrate acceleration/deceleration of a supersonic beam of OH to a mean speed adjustable between 550 m/s to rest, with a translational temperature tunable from 1 mK to 1 K, corresponding to a longitudinal velocity spread from 2 to 80 m/s. These velocity-manipulated stable "bunches" contain 10^4 to 10^6 molecules at a density of 10^5 to 10^7 cm^{-3} in the beam. These slow, cold molecular packets are ideal for high resolution microwave spectroscopy. The lowest Λ-doublet lines of OH are measured with an order of magnitude improvement in accuracy. These results have led to improved understandings in the molecular structure. Comparing the laboratory results to those from OH megamasers in interstellar space will allow a sensitivity of 10^{-6} for measuring the potential time variation of the fundamental fine structure constant $\Delta\alpha/\alpha$ over 10^{10} years.

Atomic Clock Ensemble in Space

L. Cacciapuoti[1], N. Dimarcq[2], C. Salomon[3]

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Atomic Clock Ensemble in Space (ACES) is an ESA mission in fundamental physics that will operate a new generation of atomic clocks in the microgravity environment of the International Space Station. Fractional frequency instability and inaccuracy at the 10^{-16} level will be achieved for the on-board time base. The ACES clock signal, distributed on Earth via a microwave link, will be used for space-to-ground as well as ground-to-ground comparisons of atomic frequency standards. Based on these comparisons, ACES will perform fundamental physics tests and develop applications in time and frequency metrology, universal time scales, global positioning and navigation, geodesy, and gravimetry. After a description of the mission concept and its scientific objectives, the present status of ACES instruments and sub-systems will be discussed.

A Passion for Precision

T.W. Hänsch

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"*Very high precision physics has always appealed to me. The steady improvement in technologies that afford higher and higher precision has been a regular source of excitement and challenge during my carreer. In science, as in most things, whenever one looks at something more closely, new aspects almost always come into play. ...*" With these word from the book "*How the Laser happened*", Charles H. Townes expresses a passion for precision that is now shared by many scientists. Masers and lasers have become indispensible tools for precision measurements. During the past few years, the advent of femtosecond laser frequency comb synthesizers has revolutionized the art of directly comparing optical and microwave frequencies. Inspired by the needs of precision laser spectroscopy of the simple hydrogen atom, such frequency combs are now enabling ultraprecise spectroscopy over wide spectral ranges. Recent laboratory experiments are already setting stringent limits for possible slow variations of fundamental constants. Laser frequency combs also provide the long missing clockwork for optical atomic clocks that may ultimately reach a precision of parts in 1018 and beyond. Such tools will open intriguing new opportunities for fundamental experiments including new tests of special and general relativity. In the future, frequency comb techniques may be extended into the extreme ultraviolet and soft xray regime, opening a vast new spectral territory to precision measurements. Frequency combs have also become a key tool for the emerging new field of attosecond science, since they can control the electric field of ultrashort laser pulses on an unprecedented time scale. The biggest surprise in these endeavours would be if we found no surprise.

Recent advances in atomic frequency standards and precision measurements

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In recent years, the pace of research into atomic frequency standards has quickened considerably. Caesium cold atom fountain microwave standards have become well–established at a number of national measurement laboratories, and have been used to contribute to international atomic time (TAI). Additionally the development of a micro–gravity cold caesium standard within the ESA ACES programme has been underway for some years, and is close to fruition. On the optical frequency front, a great deal of progress has been made in a relatively short period of time, brought about primarily by the development of the optical frequency comb [1,2]. This has enabled the absolute frequencies of a number of cold trapped ion optical frequency standards to be measured at the part in 10^{15} level, close to the limiting uncertainty of the caesium fountain frequency comb reference [3,4,5]. Indeed, the recent absolute frequency measurement of the single Hg^+ ion demonstrates a trapped ion reproducibility below the limiting uncertainty of the Cs standard [5]. In addition cold neutral atoms trapped within far off–resonant optical lattices are beginning to demonstrate their capability as future high accuracy optical frequency standards [6,7,8]. Here, recent measurements have shown agreement between laboratories in the US, Japan and France differing only by a few Hz (1 in 10^{14}).

This presentation will review the state of art in single trapped ion and cold atom lattice optical standards. In particular the progress of the single cold ion systems of $^{199}Hg^+$, $^{171}Yb^+$ and $^{88}Sr^+$ quadrupole clock transitions will be outlined. Recent developments with the Al^+ system, whereby quantum logic ideas are utilised to achieve clock state read–out in the absence of fluorescence from an Al^+ cooling transition, will also be discussed. On the neutral atom lattice front, the ability to confine single atoms in arrays of optical lattice

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[2] S. Diddams, R. Jones, J. Ye, S. Cundiff, J.L. Hall, J.K. Ranka R.S. Windeler, R. Holzwarth, T. Udem and T.W. Haensch, Phys. Rev. Lett. 84 5102 (2000)

[3] Margolis et al., Science 306 1355 (2004)

[4] T. Schneider, E. Peik, and Chr. Tamm, Phys. Rev. Lett. 94, 230801 (2005)

[5] W.H. Oskay et al., Phys. Rev. Lett. 97 020801 (2006)

[6] H. Katori et al., Phys. Rev Lett. 91 173005 (2003)

[7] A.D. Ludlow et al., Phys. Rev Lett. 96 033003(2006)

[8] Z.W. Barber et al., Phys. Rev Lett. 96 083002 (2006)

trapping sites offers the potential for enhanced signal–to–noise and stability as well as frequency accuracy afforded by the isolation of a single atom per lattice site, and significant achievements with both Sr and Yb lattice systems have been made [6,7,8].

The development of high accuracy optical frequency standards brings with it opportunities for much improved precision measurements. In particular the measurement of absolute frequency ratios between different atomic clock systems over a period of time gives information about possible time variation of the fine structure constant. Recent frequency measurements of trapped ion and Cs fountain combinations have reduced the uncertainty in a possible rate of change of a to below 1 part in 10^{15} per year. As the standards improve, the potential exists to reduce this level further. In particular the opportunity of measuring the quadrupole and octupole clock transitions in $^{171}Yb^+$, where a degree of common mode rejection should be available, will be discussed. Additionally, options for clock operation within ground and space segments will be outlined.

An Accurate Optical Lattice Clock with ^{87}Sr Atoms

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The recent advent of optical lattice clocks opens a promising way towards frequency standards with improved accuracy [1]. With a large number of atoms probed in the Lamb-Dicke regime these clocks combine the advantages of traditional optical standards which use either a trapped single ion or a large number of free falling neutral atoms. A crucial concern however is the level of cancellation of the effects of the trapping potential on the clock transition. The first order perturbation is intrinsically cancelled by tuning the lattice to the "magic wavelength", but this is not the case for higher order terms. Theoretical predictions indicate that these effects should be compatible with a 10^{-18} accuracy goal [2], but do not properly account for two photon resonances at the vicinity of the magic wavelength. In Sr, the $5s5p\,^3P_0 \rightarrow 5s7p\,^1P_1$ and $5s5p\,^3P_0 \rightarrow 5s4f\,^3F_2$ transitions lie respectively 7×10^{-2} nm and 5 nm away from the magic wavelength.

We report the observation of higher order effects in such a clock using strontium atoms. Non linear frequency shifts of several kHz are observed by operating the clock at a very high trapping intensity of 4×10^5 W/cm^2 and by tuning the trap laser some 100 MHz away from the $P \rightarrow F$ resonance. No effect of the $P \rightarrow P$ transition could be observed to within the present accuracy of our measurements. When tuning the laser at the magic wavelength, which we determine to be 813.428 (1) nm, higher order effects are compatible with zero to within a few Hz. This demonstrates that they will not constitute a limitation to the accuracy at the 10^{-18} level for a Sr optical lattice clock operated at a reasonable lattice depth in the range of 10^3 W/cm^2 [3].

We have also performed a full accuracy evaluation of the clock. The clock transition frequency is determined to be 429 228 004 229 879 (5) Hz with a fractional uncertainty that is comparable to state-of-the-art optical clocks with neutral atoms in free fall. The two previous measurements of this transition [1,4] were found to disagree by about 2×10^{-13}, *i.e.* almost four times the combined error bar and 4 to 5 orders magnitude larger than the claimed ultimate accuracy of this new type of clocks. Our measurement is in perfect agreement with one of these two values and essentially solves this problem.

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[3] P. Lemonde and P. Wolf, Phys. Rev. A **72**, 033409 (2005).

[4] A. D. Ludlow *et al.*, Phys. Rev. Lett. **96**, 033003 (2006).

Fundamental Physics Tests Using Rubidium And Cesium Fountains

F. Chapelet[1] S. Bize[1], P. Wolf[1,2], P. Rosenbusch[1], P. Laurent[1], G. Santarelli[1], M.E. Tobar[3], C. Salomon[4], A. Clairon[1]

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Atomic clocks and ultra stable oscillators have proven to be highly useful tools to test fundamental principle of physics such as Einstein Equivalence Principle. Over the years, the development of atomic fountains at SYRTE has opened new possibilities for refined fundamental tests. In this paper, we will summarize the results obtained over the past few years using a cryogenic sapphire resonator oscillator and an ensemble of 3 rubidium and cesium fountains.

A brief description of a test of Lorentz Invariance in the photon sector performed with the cryogenic oscillator will be given [1]. Then, a second kind of test based on comparing atomic transition frequencies in different atomic species as a function of time will be described. Such comparisons are sensitive to a putative variation of fundamental constants involved atomic transitions such as the fine structure constant. Here, a comparison between ^{87}Rb and ^{133}Cs hyperfine transition will be described. This comparison currently constraints the stability of a combination of fundamental constants at the level of 5×10^{-16} per year [2]. Together with several other similar tests involving optical clocks, these experiments constrain the stability of the electroweak interaction and of the strong interaction independently. Finally, FO2 fountain has also been used to carry out an experiment which tests Lorentz Invariance by searching for a dependence on the quantization axis orientation of a particular combination of Zeeman transitions in Cs [3]. Within the theoretical framework of the Standard Model Extension (SME), it can be shown that this experiment is sensitive to a largely unexplored region of the SME parameter space, corresponding to first measurements of four proton parameters and improvements by 11 and 13 orders of magnitude on the determination of four others.

Recent progress in the development of atomic fountains will reported. Prospects for improving the above tests of fundamental physical laws will be discussed.

[1]P. Wolf *et al.*, Phys. Rev. Lett. **90**, 060402 (2003), P. Wolf *et al.*, Phys. Rev. D **70**, 051902(R) (2004)

[2]H. Marion *et al.*, Phys. Rev. Lett. **90**, 150801 (2003)

[3]P. Wolf *et al.*, Phys. Rev. Lett. **96**, 060801 (2006)

The $^{171}Yb^+$ single-ion optical frequency standard at 688 THz

E. Peik[1], B. Lipphardt[1], H. Schnatz[1], T. Schneider[1,2], Chr. Tamm[1]
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A single laser-cooled ion confined in a radiofrequency trap is a nearly ideal reference for an optical frequency standard. Three of these systems ($^{88}Sr^+$, $^{171}Yb^+$, $^{199}Hg^+$) are now considered as secondary representations of the SI second in the optical frequency range.

We report recent investigations on the 688 THz $^{171}Yb^+$ frequency standard which is based on the $^2S_{1/2}(F=0) \rightarrow {}^2D_{3/2}(F=2)$ electric-quadrupole transition at 436 nm.[1] In order to overcome the accuracy and stability limitations associated with measurements relative to a microwave frequency reference, we have investigated systematic frequency shifts by comparing two $^{171}Yb^+$ standards directly and have observed their frequency difference with and without externally applied perturbations. The instability of the frequency difference was $\sigma_y(100\text{s}) = 9 \times 10^{-16}$, allowing the resolution of sub-hertz frequency shifts within a few minutes. [2]

These observations permit absolute measurements of the $^{171}Yb^+$ reference transition frequency with a systematic uncertainty contribution of the $^{171}Yb^+$ standard that is significantly smaller than in previous measurements. In a recent absolute frequency measurement based on a erbium-doped fiber laser comb generator,[3] also the statistical uncertainty which is dominated by the instability of the Cs fountain standard was significantly reduced by long continuous averaging intervals of up to 36 h. The result of the new measurements is consistent with our previous results and yields the $^{171}Yb^+$ transition frequency with a statistical uncertainty of 0.6×10^{-15} and a systematic uncertainty of 3.1×10^{-15}.

In the future, we plan optical frequency ratio measurements with other transition frequencies in order to enable a more sensitive search for possible temporal variations of the fine structure constant.

This work was in part funded by the Deutsche Forschungsgemeinschaft through SFB 407.

[1]T. Schneider, E. Peik, Chr. Tamm, Phys. Rev. Lett. **94**, 230801 (2005)

[2]E. Peik, T. Schneider, Chr. Tamm, J. Phys. B: At .Mol .Opt. Phys. **39**, 145 (2006)

[3]F. Adler, K. Moutzouris, A. Leitenstorfer , H. Schnatz, B. Lipphardt, G. Grosche, F. Tauser, Optics Expr. **12**, 5872 (2004)

Fiber frequency dissemination with resolution below 10^{-17}

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The expected stability and accuracy of the new generation of ultra-stable optical frequency standards is in the range 10^{-16}–10^{-18}. Thus, the way to compare distant optical clocks with such a level of performance is a severe problem, since the GPS and, in a near future, the Galileo systems will, by far, not be able to transfer data from one clock to the other one without degrading the standard. In this paper we present an alternative method based on an ultra-stable fiber optical link which allows transferring radio frequency reference signal between two research laboratories. The link is composed of two 43 km twin optical fibers of the urban telecommunications network that connect the LPL to the LNE-SYRTE. The phase/frequency stability of the transferred signal is degraded by mechanical vibrations and temperature variations along the fiber. To correct these deleterious effects we develop a compensation system which acts directly on the fiber length with a variable optical delay line.

We have already demonstrated a distribution of reference signal at 100 MHz over 86 km with a frequency stability of 10^{-14} at 1 s and 10^{-17} at one day integration time [1,2]. Two frequency standards separated by 43 km, one in the IR domain (CO_2/OsO_4 at 30 THz) and the other in the microwave domain (CSO at 12 GHz) have been compared with a resolution of $3 \cdot 10^{-14}$ at 1s [3]. To improve the frequency stability and to further extend the distribution distance, the compensation system has been upgraded to 1 GHz and the length was increased to 86 km and then to 186 km.

The optical compensation system of the 86 km link is obtained cascading the two twin fibers between LPL and LNE-SYRTE. By this way, the two ends are located at LPL. At each fiber end, an electronic system synthesizes the RF signal to be sent to the other end, 1 GHz for the forward signal and 900 MHz for the return signal to avoid the effect of parasitic reflections as well as the

[1]C. Daussy et al, Phy. Rev. Lett. 94, 203904 (2005)
[2]F.Narbonneau et al, in arXiv:physics/0603125, in press Rev. of Scient. Instr. (2006)
[3]F.Narbonneau et al, EFTF Procedings 2005

Stimulated Brillouin Scattering. Each RF signal modulates the beam intensity of a 20 mW, DFB laser diode at 1.55 mm. This modulation is detected with a fast photodiode at the other end of the fiber. Mechanical and temperature variation along the fiber perturbs the propagation delay across the fiber. In order to remove this parasitic variation we use a round trip phase correction technique.

To remove the effect of the perturbation cumulated along the link, we perform a comparison between the reference phase signals at the input with the phase signal after one round trip. This leads to the generation of an error signal applied to two delay lines. The delay lines at the LOCAL input of the link cancel out the variations of propagation delay. The fast and small variation corrections are applied with 15 meters of piezoelectrically stretched fiber (correction range of about 15 ps). The fiber is wrapped around a cylindrical PZT. The slow corrections are applied by heating 4 km of optical fiber wrapped around a copper wheel with 150 ps/°C and 6 ns dynamic range. We measure relative stability of the compensated link by analyzing phase variation between the 1 GHz at local end and the 1 GHz at remote end. The compensation system can potentially reach -120 dB at 1 Hz but the attenuation along the fibre degrades the signal to noise ratio at receiver and limits the compensation at -105 dB at 1 Hz.

During first measurements, we have observed a randomly instability of the loop and large phase fluctuations on the long term which maintained the instability above a few parts in 10^{-17}. These two effects are due to the polarization mode dispersion, PMD, of the 86 km link. The PMD is induced by the birefringence of the optical fiber due to the asymmetry of the core. This PMD is varying in time when the asymmetry is due to mechanical stress induced by vibrations or by temperature variations. Moreover, the direction of the fast and slow axes of the link changes randomly in time. The solution used in this work is to scramble the polarization directly at the emitted source at a frequency higher than the cut off frequency loop.

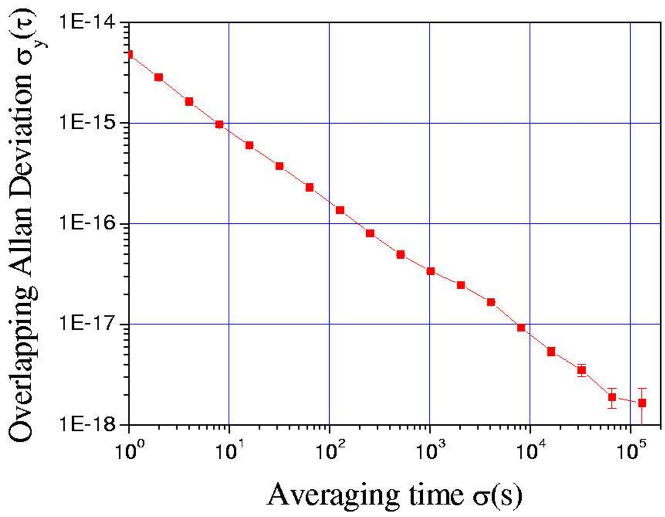

Figure 1: *Fractional frequency stability of the compensated 86 km link.*

Figure 1 shows the ADEV calculated from the phase data measured on the compensated link and filtered with low-pass filter of 3 Hz. We obtain residual frequency stabilities of the link of $5 \cdot 10^{-15}$ at 1 second integration time and $2 \cdot 10^{-18}$ at one day integration time. With minor changes of the setup, we demonstrated similar results on the link extended to 186 km by adding 100 km of fiber spools. In order to extend the time-frequency transfer on continental distances, a new scheme must be considered and will be shortly presented.

T2L2 on Jason-2: First results of the engineering model

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The new generation of optical time transfer T2L2 (Time Transfer by Laser Link) has recently been accepted as a passenger instrument of the Jason 2 satellite. The main function of T2L2 is to allow comparison and follow-up of distant clocks, either of an embarked clock relative to a ground clock or of two (or more) ground clocks. The project will be launched in mid 2008.

T2L2 is the follow-on mission to LASSO (LAser Synchronization from Stationary Orbit) with performances improved by two orders of magnitude: expected time stability is better than 1ps over 1000s (one pass) and better than 10ps over one day. The means used to establish the link between the clocks are the timing and the transmission of laser pulses. The Jason 2 host system is based on a T2L2 space payload connected to a quartz oscillator (DORIS) and on a network of laser telemetry stations equipped with clocks.

The T2L2 objectives are threefold. The first one is in-orbit functioning and performance validation, the second one is time and frequency metrology and fundamental physics tests, and the third one is a contribution to the Jason-2 core mission.

The experimental results recently obtained on the T2L2 engineering model are very promising. After a quick remind of mission hypothesis and objectives, we will present the performances measured.

Navigation, Gravitation and Cosmology with Cold Atom Sensors

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Interference with Bose-Einstein-Condensates on Atom Chips

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[2]*Atominstitut Österreichischer Universitäten, TU-Wien, Vienna, Austria*

Atom chips[1] promise manipulation of matter waves with high precision. Our exceptionally smooth atom chips potentials[2] [3] allow to experiment with continuous 1 mm long 1d condensates at strong transversal confinement (>10kHz) and extreme aspect ratio up to 10000. In these atom chip traps we employ RF induced adiabatic potentials[4] to split a 1d condensate along its long axis. Bringing the two split clouds together one completes an interferometer and observes interference between the two ensembles (Fig. 1). The RF potentials allow unprecedented precise control enabling a coherent splitting process as demonstrated by the deterministic and stable phase of the interference[5].

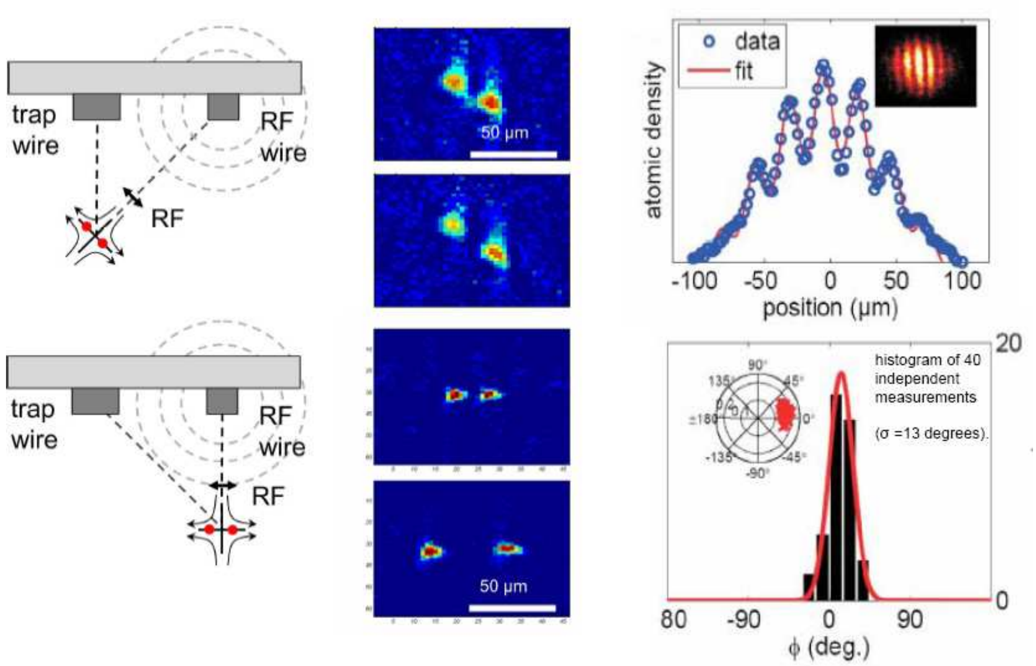

Figure 1: *Splitting an trapped atomic cloud with RF induced double well potential.* (left) *The orientation of the RF defines the orientation of the splitting.* (right) *The two split clouds interfere with a stable narrow phase distribution.*

[1]For review see: R. Folman *et al.* , Adv. At. Mol. Opt. Phys. **48**, 263 (2002).
[2]S. Groth *et al.*, Appl. Phys. Lett. **85**, 2980 (2004).
[3]P. Krüger *et al.*, cond-mat/0504686 (2005); S. Wildermuth *et al.*, Nature **435**, 440 (2005)
[4]I. Lesanovsky *et al.*, Phys. Rev. A **73**, 033619 (2006).
[5]Th. Schumm *et al.*, Nature Physics **1**, 57 (2005).

The interference pattern itself is sensitive probe of the order parameter in the 1d quantum gas:

- It allows precise separation between 'condensed' and 'thermal' component
- Adjusting the barrier between the separated ensembles we study tunnel coupling and phase locking between two 1d condensates and employ phase noise thermometry[6] to measure the local temperature.
- Coherently splitting into two widely separated isolated 1d systems with a fixed phase between them, we investigate the dynamics of phase fluctuations in the order parameter of a 1d quantum gas.
- Preparing completely separated independent 1d condensates the interference allows us to study the dynamics of establishing an order parameter when going through the 'phase transition' in a finite 1d system.

From our experiments we analyze under which conditions trapped quantum gases can be used for precision interference experiments.

In a second experiment we implemented optical lattices on an atom chip [7] and observed coherent Bloch oscillations close to the chip surface (see Fig. 2). We analyze the prospects to make precision force measurements at μm distance from macroscopic objects.

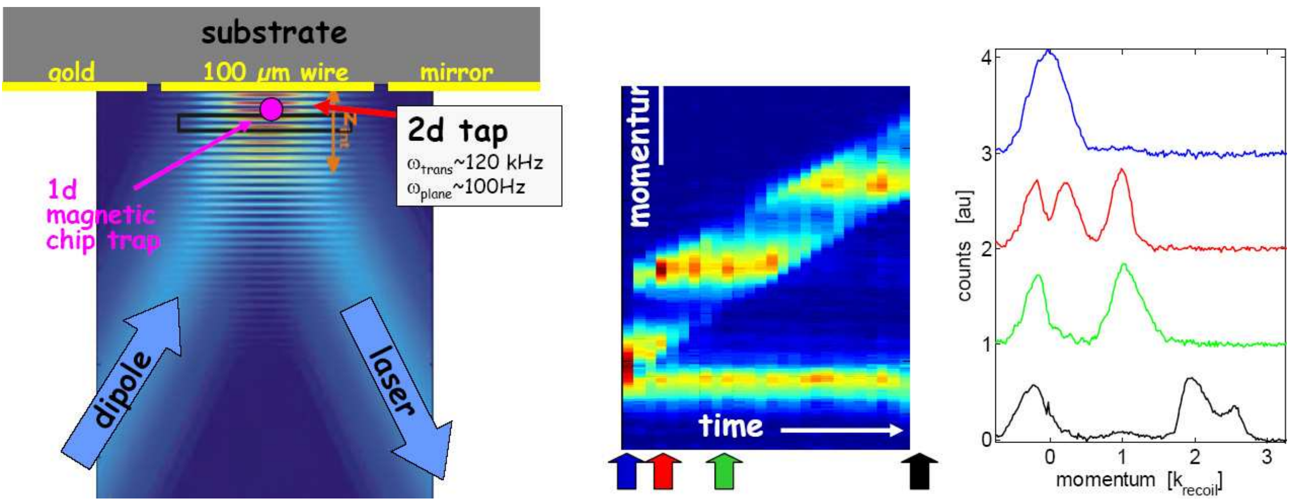

Figure 2: (left) *An optical lattice close to the chip surface by Reflecting a fare detuned laser beam from the chip surface creates an optical lattice.* (right) *Bloch oscillations observed in the optical lattice close to the atom chip surface*

Supported by EU projects ACQP, SCALA, AtomChips, the DFG, and DIP.

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[7] D. Gallego, Diplomarbeit Univ. Heidelberg (2005).

Quantum sensors for fundamental tests and applied sciences

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The IQ develops several atomic sources and quantum sensors to be used in fundamental physics and applied sciences. The talk will give an overview on our activities covering the development of a magnesium optical clock; the realisation of inertial sensors based on ultra-cold Rubidium and the design of the quantum matter facility QUANTUS, which in future will serve to investigate degenerate gases in microgravity environment. Main emphasis will be given to our dual atom interferometer CASI which serves to study the potential of ultracold atoms for high-resolution rotation sensors. In the final stage, the set-up will serve for comparisons with the large ring laser gyroscope in Wettzell, Germany, with an area of 16 m^2.

QUANTUS – Experiments with Bose-Einstein condensates in microgravity

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Weightlessness promisses to substantially extend the science of quantum gases towards nowadays inaccessible regimes of low temperatures, macroscopic dimensions of coherent matter-waves, and enhanced duration of unperturbed evolution. Targeting the long-term goal of studying cold quantum gases on a space platform, we currently focus on the implementation of an ^{87}Rb Bose-Einstein-condensate (BEC) experiment under microgravity condition at the ZARM drop tower in Bremen (Germany).

Special challenges in the construction of the experimental setup are posed by a low volume of the drop capsule ($< 1\,m^3$) as well as critical vibrations during capsule release and peak decelerations of up to 50 g during recapture at the bottom of the tower. All mechanical and electronic components have thus been designed with stringent demands on miniaturization, mechanical stability and reliability. Additionally, the system provides extensive remote control capabilities as it is not manually accessible in the tower 2 hours before and during the drop.

This talk will discuss the prospects of Bose-Einstein condensates in microgravity and present first results of the experimental implementation at the ZARM drop tower in Bremen.

The project is funded by the German Space Agency (DLR) within grant DLR 50 WM 0346.

New transportable atom inertial sensors and their applications to space experiments

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Atomic quantum sensors are a major breakthrough in the technology of time and frequency standards as well as ultra-precise sensing and monitoring of accelerations and rotations. They apply a new kind of optics based on matter waves. Today, atomic clocks are the standard for time and frequency measurement at the highest precisions. Inertial and rotational sensors using atom interferometers have already shown similar potential for replacing state-of-the-art sensors in other fields.

For example, a 6 axis inertial sensor has been demonstrated at LNE-SYRTE[1]. The direction of sensitivity of the setup is defined by the direction of the Raman interrogation laser with respect to the atomic trajectory. As illustrated in Fig. 1, with a classical three pulses sequence ($\pi/2 - \pi - \pi/2$), a sensitivity to vertical rotation Ω_z and to horizontal acceleration a_y is achieved by placing the Raman lasers horizontal and perpendicular to the atomic trajectory[2] (Fig. 1a). The same sequence, using vertical lasers, leads to the measurement of horizontal rotation Ω_y and vertical acceleration a_z (Fig. 1b). Thanks to the specific setup of the GOM, it is possible to have access to the other components of acceleration and rotation which lie along the horizontal direction of propagation of the atoms (x axis).

[1]B. Canuel *et al.*, *Phys. Rev. Lett.* **97**, 010402 (2006)
[2]T.L. Gustavson, P. Bouyer, M.A. Kasevich. *Phys. Rev. Lett.* **78**, 2046 (1997).

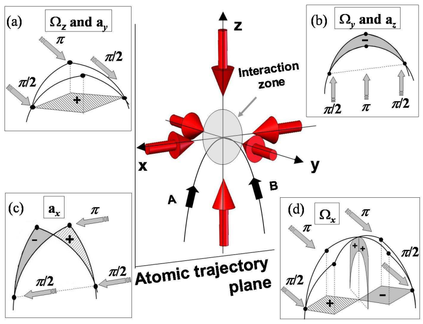

Figure 1: *6-axis inertial sensor principle. The atomic clouds are launched on a parabolic trajectory, and interact with the Raman lasers at the top. The four configurations (a)-(d) give access to the 3 rotations and the 3 accelerations.*

With Bose-Einstein condensates, also refered as atom lasers, the traditional experiments with atom interferometers can be greatly improved. Testing of fundamental principles, studies of atomic properties, applications as inertial sensors, and measurements of fundamental constants can benefit from the brightness (intensity and small momentum spread) of these coherent sources. In addition, the coherence properties of condensates may also allow BEC based atom interferometers to approach the Heisenberg detection limit[3]. This corresponds to a measurement precision which scales like $1/N$ for N atoms and not like $1/\sqrt{N}$ as for independent measurements on N atoms. We will report on the development of a 0-g coherent atom interferometer (ICE) that will be used to test the ultimate performances of atom accelerometers in space[4].

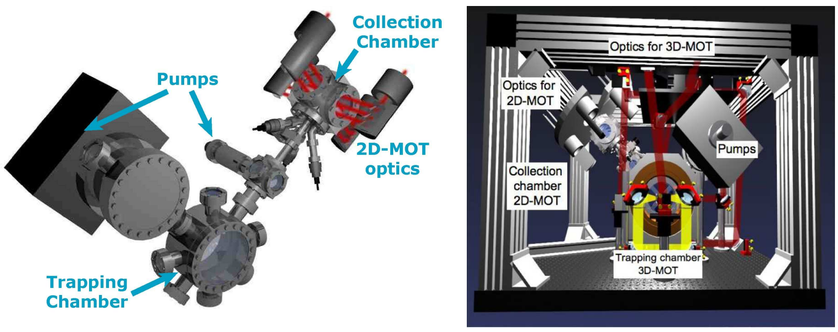

Figure 2: ***Left****: Artist's impression of the ICE vacuum system. Atoms are transferred from the collection chamber, using a 2D-MOT, to the trapping chamber, where they are collected in a 3D-MOT and an optical-dipole trap (FORT).* ***Right****: The ICE mechanical structure with optics and light paths represented.*

[3]P. Bouyer and M. Kasevich. *Phys. Rev.* **A 56**, R1083 (1997).
[4]R. Nyman *et al.*, to appear in App. Phys. B. See also `http://ice-space.fr`.

Comparison between optical interferometry and matter-wave interferometry, towards new sensors and clocks using matter-wave cavities for ground and space applications

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A new framework is proposed to compare and unify photon and atom optics, which rests on the quantization of proper time. A common wave equation written in five dimensions[1] reduces both cases to 5D-optics of massless particles. The ordinary methods of optics (Lagrange invariant, Fermat principle, symplectic algebra and ABCD matrices[2,3]....) are used to solve this equation in practical cases. The various phase shift cancellations, which occur in atom interferometers, and the quantum Langevin twin paradox for atoms, are then easily explained and will be discussed. As a specific application, a novel concept of multi-D gravito-inertial sensors and optical clocks based on matter-wave cavities[4] will be analyzed.

[1] Ch.J. Bordé, Phil. Trans. Roy. Soc. A, Base units of the SI, fundamental constants and modern quantum physics, **363**, 2177-2201 (2005).

[2] Ch.J. Bordé, Atomic clocks and inertial sensors, Metrologia, **39**, 435-463 (2002).

[3] Ch.J. Bordé, Quantum theory of atom-wave beam splitters and application to multidimensional atomic gravito-inertial sensors, GRG, **36**, 475-502 (2004).

[4] F. Impens, P. Bouyer and Ch.J. Bordé, Matter-wave cavity gravimeter, Appl. Phys. B (2006), in press.

Gravity tests by atom interferometry: Measurement of G and test of Newtonian law at micrometric distances

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Experiments we are performing using atom interferometry to determine the gravitational constant G[1] and test the Newtonian gravitational law at micrometric distances[2] will be presented. Prospects for future experiments in ground laboratories and in space will also be discussed.

[1]A. Bertoldi, G. Lamporesi, L. Cacciapuoti, M. de Angelis, M. Fattori, T. Petelski, A. Peters, M. Prevedelli, J. Stuhler, and G. M. Tino, "Atom interferometry gravity-gradiometer for the determination of the Newtonian gravitational constant G", to be published in Eur. Phys. J. D, preprint arXiv:physics/0606126

[2]G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, "Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale", Phys. Rev. Lett. 97, 060402 (2006)

A new determination of the fine structure constant with cold rubidium atoms

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[2]*present adress : National Institute of Standards and Technology 100 Bureau Drive, Stop 8424 Gaithersburg, MD 20899-8424*
[3]*INM-CNAM, 292 rue Saint Martin 75141 PARIS Cedex 03 France*

We have recently measured the recoil velocity of ^{87}Rb using Bloch oscillations in a vertical accelerated optical lattice. Then the ratio h/m_{Rb} and therefore the fine structure constant α can be determined. Our value of α^{-1} is 137.03599884(91), in good agreement with the last CODATA estimation.

The fine structure constant α has been measured with various experiments in different fields of physics. But, only accurate measurements contribute significantly to the CODATA determination of the best estimate of α because of the weighting with the square of their uncertainty. In the latest CODATA adjustments, α has been determined to great extent by only one experiment [1,2]. Therefore, other precise determinations are needed to increase the reliability of the estimated value.

A competitive method, respect with g-2 experiment, to determine α is the h/m_X one with cold atoms X. The determination is based on the well known equation [3]:

$$\alpha^2 = \frac{2R_\infty}{c}\frac{A_r(X)}{A_r(e)}\frac{h}{m_X} \tag{1}$$

where the uncertainty on α is limited by the one on h/m_X. All the other terms are known with a very small uncertainty: 8×10^{-12} for the Rydberg constant R_∞ [4,5] and 4.4×10^{-10} for the electron relative mass $A_r(e)$ [2]. The relative atomic mass of X ($A_r(X)$) is known with a relative uncertainty less than 2×10^{-10} for Cs and Rb atoms [6].

[1]P. Mohr and B.N. Taylor, *Rev. Mod. Phys.*, Vol 72, n°2 (2000)
[2]P. Mohr and B.N. Taylor, *Rev. Mod. Phys.*, Vol 77, n°1 (2005)
[3]B. Taylor, *Metrologia.* **31**, 181 (1994)
[4]C. Schwob et al., *Phys. Rev. Lett.* **82**, 4960 (1999)
[5]Th. Udem et al. *Phys. Rev. Lett.* **79**, 2646 (1997)
[6]M. P. Bradley et al., *Phys. Rev. Lett.* **83**, 4510 (1999)

In this kind of experiment, the value of the ratio h/m_X is determined by measuring the atomic velocity recoil v_r and the wave-vector of the light k. v_r is the velocity acquired by an atom initially at rest when it absorbs a photon of momentum $\hbar k$.

The experiment has been precisely described in previous papers [7]. It deals with ^{87}Rb atoms trapped with a magneto-optic trap (MOT) and cooled down to around 3 v_r with an optical molasses. The experiment is done in vertical geometry to provide a long laser-atom interaction time. Its principle is quite simple. Two photon velocity selective Raman pulses are used to select an initial narrow velocity class ($v_r/15$) and at the end of the sequence to probe the final velocity distribution. The photon momentum transfers are achieved between these two Raman pulses with Bloch oscillations. To increase the number of momenta transferred, all the atoms are pre-accelerated, also with Bloch oscillations and the initial velocity class is selected in the moving atomic cloud. The second acceleration is used to decelerate the atoms so that at the end of the sequence the atoms are almost at rest. We transfer about 900 recoil momenta with a measured efficiency of 99.97% per recoil. The acceleration is done up and then down. Therefore the resulting differential measurement is independent of g value to the first order [8].

We have achieved 72 measurements of α^{-1} with a relative statistical uncertainty on the mean value of 4.4 ppb.

We have carefully studied systematic effects. Their contribution to the relative uncertainty on α^{-1} is 5.0 ppb. The two major systematic effects come from the laser beams parameters and the second order Zeeman effect.

Finally our determination of α^{-1} is 137.03599884(91) $[6,7\times10^{-9}]$. This value is in good agreement with the two latest competitive determinations $\alpha^{-1}(Cs) =$ 137.0360001(11) $[7.7\times10^{-9}]$ [9] and $\alpha^{-1}(a_e) =$ 137.035999710(96) $[0.7\times10^{-9}]$ [10].

For next determination, a more rigorous control of the systematic effects will be done by studying before the data acquisition the beams parameters with a wave front analyser and by building a new magnetically shielded vacuum chamber. A 2D MOT will be used to fill a 3D MOT located in a new cell made of titanium. The latest developments of the experiment will be presented.

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[7] R. Battesti *et al., Phys. Rev. Lett.* **92**, 253001 (2004)

[8] P. Cladé, Thèse de doctorat, 2005, Conservatoire National des Arts et Metiers, http://tel.ccsd.cnrs.fr/tel-00010730

[9] A. Wicht et al., *Physica Scripta* **T102**, 82 (2002)

[10] G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio and B. Odom, submitted to Phys. Rev. Lett.

Phase Noise due to vibrations in Mach-Zehnder atom interferometers

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We have built an atom interferometer of the Mach-Zehnder type [1], with a supersonic beam of lithium seeded in argon and elastic Bragg diffraction on laser standing waves at $\lambda = 671$ nm. We have optimized the fringe visibility by a series of experiments testing its sensitivity to the main alignment defects and our results [1], which will be presented on the poster, are in good agreement with a previous theoretical analysis [2].

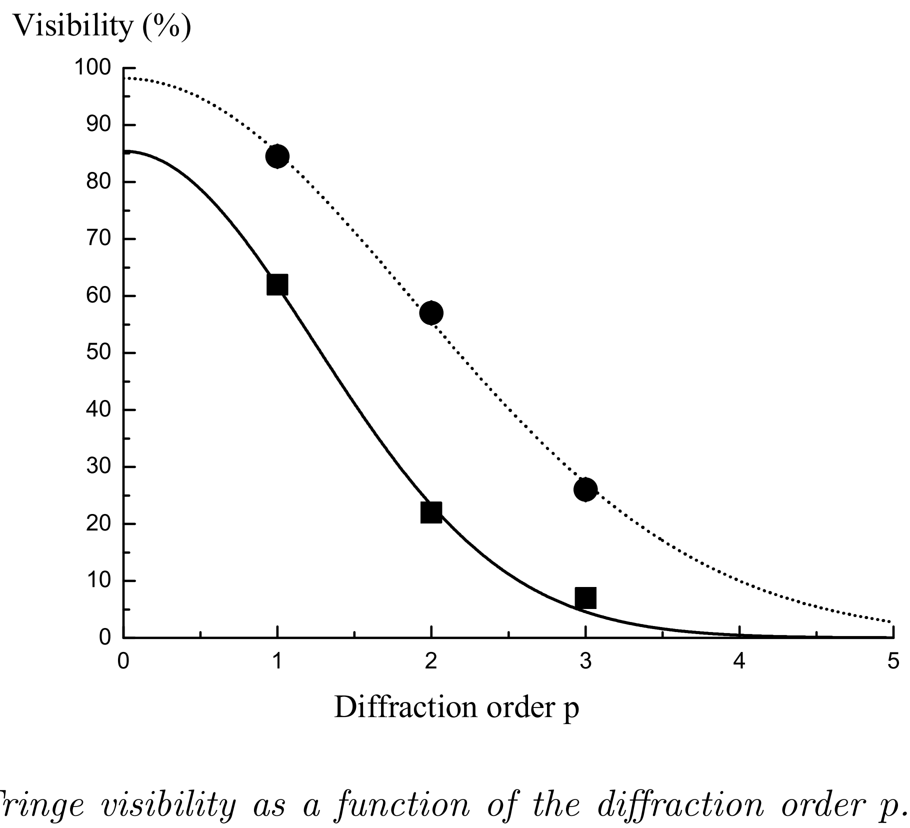

Figure 1: *Fringe visibility as a function of the diffraction order p. Our measurements (round dots) and those of Giltner et al.* [3] *(squares) are well fitted by Gaussian functions of the diffraction order p.*

[1]A. Miffre et al., *Eur. Phys. J.* D **33**, 99 (2005)
[2]C. Champenois et al., *Eur. Phys. J.* D **5**, 363 (1999)

The fringe visibility decreases when the diffraction order p increases, with $\mathcal{V} = 84.5 \pm 1\%$ when $p = 1$, $\mathcal{V} = 54\%$ when $p = 2$ and $\mathcal{V} = 26\%$ when $p = 3$. A similar decrease was previously observed by Giltner et al. [3]. This decrease is well represented by a Gaussian function of the order p (see Fig. 1), a behavior which is expected in the presence of a phase noise.

We have developed [4] a dynamical model to describe the motion and vibration of the rail supporting the three diffraction gratings (or the laser standing wave mirrors in the case of laser diffraction). This model enables us to evaluate the phase noise of the interferometer if we know the vibration spectrum of its support. Starting from a measurement of this spectrum, we explain a large fraction of the phase noise deduced from the visibility dependence with the diffraction order (see Fig. 1).

It is interesting to note that three different terms contribute to this phase noise, a term proportional to the instantaneous bending of the rail, a Sagnac term due to the rotation of the rail (proportional to the atom time of flight T from one grating to the next) vibration of the rail and an acceleration term proportional to T^2. In our experiment, the rail is very stiff so that the dominant phase noise is due to the Sagnac term and this term can be reduced by using a more efficient suspension of the rail.

The present analysis gives access to an understanding of inertial phase noise in Mach-Zehnder atom interferometers and it should be an important step towards the reduction of this phase noise. If we are able to fully eliminate the phase noise induced by vibrations, we may hope to observe atom interference effects with a much improved fringe visibility and it will also be possible to work either with diffraction orders $p \gg 1$ or with considerably slower atoms.

[3] D. M. Giltner et al., *Phys. Rev. Lett.* **75**, 2638 (1995)

[4] A. Miffre et al., accepted for publication in *Appl. Phys.* B and in *EuroPhysics Lett.*

Short range forces and the Casimir effect

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The search for deviations from Newton's gravitation law has been a recurrent issue for the last three decades. Initially motivated by the possibility for deviations from standard gravity due to new forces with couplings of order of the gravitational one [1], this search has more recently been encouraged by unification models which predict the existence of forces which can be up to 10^5 times stronger than gravity with ranges between 1μm and 100μm [2]. Even if its results have not met the initial hopes of observing a "fifth force", this search has generated an impressive progress of tests of the gravitation law in the laboratory or in the solar system. It has led to a largely improved knowledge of this law narrowing the remaining open windows for new hypothetical forces.

The hypothetical extra-gravitational force is often parametrized by a Yukawa range λ and a coupling strength α such that the corresponding potential is:

$$V_{\text{Newton}}(d) + V_{\text{Yukawa}}(d) = -\frac{GM_aM_b}{d}\left(1 + \alpha e^{-d/\lambda}\right) \tag{1}$$

The Newton and Yukawa potentials have been written for two point masses M_a and M_b at a distance d from each other, and the coupling strength is defined with respect to Newtonian gravity. The current limits in the (λ, α) plane (see for instance [3]), summarize the considerable progress achieved during the last decades, thanks to a variety of laboratory experiments and solar system observations. At the same time, windows remain open for deviations of standard gravity in the submillimeter range or for scales larger than the size of planetary orbits [4]. In this paper, we focus our attention on the submillimeter window.

The accuracy of short range tests has recently been much improved for Cavendish experiments performed at smaller distances. The best limits for distances of the order of $\simeq 100\mu$m have been recently obtained by the group of Adelberger at the University of Washington using torsion balances and rotors [5,6]. Similar experiments have been performed with microresonators in the

[1] Fischbach E and Talmadge C L 1999 *The search for Non-Newtonian gravity* (AIP/Springer-Verlag, New York) and references therein.

[2] Long J C, Chan H W and Price J C 1999 *Nucl. Phys.* **B 539** 23

[3] Coy J, Fischbach E, Hellings R, Talmadge C and Standish E M 2003, private communication

[4] Jaekel M-T and Reynaud S 2005 *Int. J. Mod. Phys.* **A 20** 2294

[5] Smith G L *et al.* 2000 *Phys. Rev.* **D 61** 022001

[6] Hoyle C D *et al.* 2001 *Phys. Rev. Lett.* **86** 1418

groups at Boulder [7] and Stanford [8] and they have started to explore distances below 100μm, where however difficulties arise from the stringent requirements to maintain the surfaces parallel during the rotation.

For even lower distances, of the order or smaller than one micrometer, the hypothetical new forces have to be measured against a large background coming from the Casimir force [9]. The latter has been measured with increasing accuracy during the last years by various groups using atomic force microscopes or microresonators whose motion is monitored by means of capacitively or optically coupled displacement transducers [10,11,12,13,14].

Hypothetical forces would appear as experiment/theory differences in precise measurements of the Casimir force. As far as an accurate theory-experiment comparison is aimed at, the accuracy of theory is as crucial as the precision of experiments. If the target is a given accuracy, say at the 1 % level, the theoretical prediction has to be mastered at this level as well as the experimental measurement. This requires to take into account the real conditions of the experiments which differ from the ideal situation often assumed in the theory of the Casimir effect. Most experiments are performed with a plane-sphere geometry rather than the original plane-plane geometry. Temperature corrections to be added to the vacuum contribution play an important role when the plate separation is above 1μm. Finite conductivity and roughness of the metallic plates used in the experiments provide the major corrections for the distances of the order of a few hundred nanometers probed by the most accurate experiments [15]. The spatial variations of the surface potential also affect the force measurement [16].

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[13] Bressi G, Carugno G, Onofrio R and Ruoso G 2002 *Phys. Rev. Lett.* **88** 041804

[14] Decca R S, Lopez D, Fischbach E and Krause D E 2003 *Phys. Rev. Lett.* **91** 050402

[15] Lambrecht A and Reynaud S 2000 *Eur. Phys. J.* **D8** 309

[16] Speake C C and Trenkel C 2003 *Phys. Rev. Lett.* **90** 160403

Thermal effects of the Casimir forces on ultra-cold gases

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The Casimir-Polder force characterizes the surface-atom force originating from the fluctuations of the electromagnetic field. Such a force and its cousin, the van der Waals force, are not only fascinating scientifically but also important technologically because of their relevance for instance to atomic force microscopy and to MEMS.

Recent theoretical work by the Trento team[1,2] has focused on the temperature dependence of the force both at equilibrium[1] and out of thermal equilibrium[2]. In particular, when the temperature of the surface is different from the temperature of free space, the force is predicted to decay more slowly at large distances and to exhibit a stronger dependence on the temperature.

By positioning a Rb-87 Bose-Einstein condensate a few microns from a dielectric surface and resonantly exciting it into a mechanical dipole oscillation, the JILA team has recently observed changes in the collective oscillation frequency that result from the spatial variations in the force[3,4]. By heating the dielectric surface to 600K while the surrounding environment is kept near room temperature (310K), clear evidence of non-equilibrium effects have been illustrated[4]. The magnitude of the effect is measured in both this non-equilibrium configuration and also in a room temperature equilibrium configuration. Both measurements agree with the theoretical predictions, marking the first conclusive demonstration of the temperature dependence of the Casimir-Polder force.

Future perspectives for accurate measurements of the surface-atom force using Bloch oscillations[5] will be also discussed.

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Study of a quantum-limited force measurement through quantum Langevin equations

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We study the detection of weak coherent forces by means of an optomechanical device formed by a highly reflecting isolated mirror shined by an intense and highly monochromatic laser field. Radiation pressure excites a vibrational mode of the mirror, inducing motional sidebands of the incident field, which are then measured by heterodyne detection. We determine the sensitivity of such a scheme and show that the use of an entangled meter state improves the detection, even in the presence of damping and noise acting on the mechanical mode.

Requirement for measuring the gravitational time delay between drag–free spacecraft

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A possible mission is described in which the gravitational time delay due to the Sun is measured between a spacecraft near the Sun-Earth L1 point and another spacecraft that passes behind the Sun. The L1 spacecraft would contain an atomic clock based on cooled atoms, similar to those developed for possible use in the ACES or PARCS experiments on the International Space Station. The assumed spectral amplitude of the fractional frequency noise is $1 \times 10^{-13}/\sqrt{Hz}$ at frequencies down to $4 \times 10^{-7} Hz$. The distant spacecraft would have a 1.5 year period orbit with an eccentricity of 0.24, the same as the orbits for the distant spacecraft in the LATOR mission. Thus there would be 3 passes of the line of sight to the distant spacecraft by the Sun during a roughly 6 month period centered on 1.5 years after launch. The main strength of the time delay determination would come from observations during periods of about 20 days around the 3 conjunctions.

Two other technology developments would be needed, in addition to adapting a high-stability atomic clock for use in a small spacecraft. One is an improved disturbance reduction system (DRS) to reduce acceleration noise for test masses in the two spacecraft to below $1 \times 10^{-13} m/s^2/\sqrt{Hz}$ at frequencies down to $4 \times 10^{-7} Hz$. This will require careful attention to minimizing fluctuations in temperature gradients within the DRS, as well as other sources of spurious forces. Based on calculations related to the DRS for the LISA mission, this appears to be achievable. The performance of a similar DRS at frequencies down to 10^{-3} Hz will be tested on the LISA Pathfinder mission.

The other needed technology development is a method for measuring the round trip travel time between the two spacecraft in terms of the L1 atomic clock to an accuracy of 0.1 or 0.2 picosecond. Measurements to this accuracy over more than 2 AU distances with conventional pulsed laser timing measurements appear to be very difficult. The suggested new approach is to put roughly 60 GHz sidebands on a cw laser beam, and use the phase of the 120 GHz beat between the sidebands as the observable for determining the travel time. This requires having a similar system on the distant spacecraft for phase locking the onboard 60 GHz signal source to the phase of the received 120 GHz beat before a similar signal is sent back to the L1 spacecraft.

An idealized simulation of the kind of gravitational time delay measurement discussed above has been done. For the first and third of the 3 conjunctions with the Sun, the rate of motion of the line of sight with respect to the Sun is 0.7 solar radii per day. It is assumed that measurements are made from 10 days to 2 days before conjunction and for a similar period after conjunction. Thus measurements within 0.4 solar radii of the limb are not included. Actually measurements would be made over a longer period to refine the orbits for both spacecraft, but the problem of orbit determination has not yet been considered. Equal contributions to the error budget for the gravitational time delay are assumed from the clock noise, the DRS performance, the travel time measurement system, and the orbit determination part of the problem. With these assumptions, a fractional uncertainty of about 1×10^{-8} is found for the gravitational time delay.

Proposal for a Gravity Explorer Satellite Mission

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The performance of optical clocks has strongly progressed in recent years, and accuracies and instabilities of 1 part in 10^{18} are expected in the near future. The operation of optical clocks in space provides new scientific and technological opportunities. In particular, an earth-orbiting satellite containing an ensemble of optical clocks of different types (atomic, molecular, nuclear) allows a precision measurement of the gravitational redshift, navigation with improved precision, mapping of the earth's gravitational potential by relativistic geodesy, and frequency distribution for earth and space. In this talk I will outline details of an optical clock satellite mission devoted to these goals [1].

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MICROSCOPE status, mission definition and recent instrument development

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The two pairs of the electrostatic inertial sensors integrated at the centre of the MICROSCOPE satellite will includes the four masses of the space experiment aiming at the test of the Equivalence Principle with an accuracy of 1 part over 1015. The scientific payload takes advantage in orbit of the very soft environment on board the specific micro satellite developed in Cnes. Peculiar attention has been paid for the thermal stability of the instrument case, up to 1 mK, for the instrument pointing in the Earth gravity field and gradient, better than 1 rad, and for the orbital motion. The specific drag compensation system will maintain the inertial sensor outputs in a very weak range by counteracting the surface forces of the satellite, like radiation pressures, thanks to the permanent and accurate actuation of its twelve thrusters.

The two recently performed reviews concerning the definition of the MICROSCOPE satellite and of its scientific instrument have detailed the specifications of each major elements, assessing the mission expected performance.

The SAGE (Space Accelerometer for Gravitation Experiment) instrument is presently under development. Test results of the electronics units, necessary for the control of the test mass at 10 pico meters, are presented as well as the status of the silica core production. One inertial sensor laboratory model is also under test for the fine characterisation of its operation.

"Galileo Galilei" (GG) space experiment to test the Equivalence Principle to 10^{-17}: design, error budget and relevance of experimental results with the GGG prototype

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The small satellite "Galileo Galilei-GG" is designed to test the Equivalence Principle (EP) to 10^{-17}. The GG space project has been included in the National Aerospace Plan of ASI (Agenzia Spaziale Italiana) for the next three years. It is crucial for the goal of the mission that the test masses are large (to reduce thermal noise), that their coupling is weak (to increase sensitivity to differential effects), and that rotation is fast (to modulate the signal at high frequency and reduce noise). In GG all these needs can be met by arranging the masses (including the outer spacecraft shell) in a nested cylinder configuration, the symmetry axis being also the axis of rotation and the plane perpendicular to it the sensitive plane where an EP violation signal from the Earth could be detected. Because of axial symmetry, fast rotation provides signal modulation as well as passive stabilization of the satellite, no motor or active system being required because of angular momentum conservation. The rotating test masses can be large, in spite of the extremely small effects they ought to be sensitive to, because the system is in supercritical dynamical regime, which ensures self centering. In addition, axial symmetry helps eliminating or reducing many disturbances −primarily the dangerous radiometer effect− with no need for cryogenics.

According to the error budget completed during GG mission Studies to Phase A level, the scientific goal can be reached with a total satellite mass at launch of $\simeq 250\,kg$ only.

By using the rotation/symmetry axis to suspend the system, so as to withstand local gravity and detect differential effects in the horizontal plane, a 1-g version of the accelerometer ("GG on the Ground-GGG") has been built to full scale. On ground the coupling of the test cylinders is much stiffer than it can be in absence of weight, a motor is needed to maintain rotation and the test masses are disturbed by terrain tilts, the rotor not being an isolated system like in space.

GGG has proved: i) high Q; ii) self-centering of the test cylinders; iii) long term stability (disproving past speculations of strong instability); iv) sensitivity to differential displacements of the test cylinders at the nanometer level. These results are directly relevant to the scientific target of the space experiment and strongly complement numerical simulations performed at Phase A level Studies of the GG mission.

Gravity Probe B: Testing General Relativity with Orbiting Gyroscopes

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The NASA-Stanford University Gravity Probe B mission was launched on 20 April 2004 to perform two highly accurate tests of two predictions of General Relativity - the geodetic and frame-dragging effects. This is done by measuring the spin axis drift of near-perfect gyroscopes in orbit caused only by the motion of the gyroscopes through curved space-time near Earth. Building an instrument to make this measurement was confoundingly difficult and has resulted in arguably the most sophisticated scientific satellite developed to date. This talk examines the design of the spacecraft and its science instrumentation, discusses many novel technologies developed to build the instrument, reviews spacecraft performance on orbit, and discusses the state of the post-flight data analysis. The scientific results of Gravity Probe B are planned to be announced in Spring, 2007.

Is physics within the Solar system really understood?

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Progress in physics always has been stimulated by observations which could not been explained within the presently standard physical theories. Perhaps the situation of gravitational physics today is similar. At first, the theoretical inconsistency of quantum mechanics and General Relativity (in particular the problem of time and the singularities occuring in General Relativity) makes a new theory combining these two universal theories necessary. Furthermore, there are observations which at least until now and after many years of studies, have not yet found any convincing explanation. These observations are (i) dark energy which is necessary – under the assumption of the validity of Einstein's equations – to describe the accelerated expansion of the universe and (ii) dark matter which – again under the assumption of General Relativity – is necessary to account for the galactic rotation curves, for observed gravitational lensing of light, and for the structure formation in the early universe. Of a slightly weaker observational basis is (iii) the Pioneer anomaly, an unexplained constant acceleration of the Pioneer 10 and 11 spacecraft, (iv) the flyby anomaly, an unexplained increase of the velocity of a series of spacecrafts after Earth Gravity Assists, (v) the recently realized increase of the Astronomical Unit defined by the distance of the planets from the Sun by approximately 10 m per century, and (vi) the quadrupole and octupole anomaly which describes the correlation of the low l contributions of the Cosmic Microwave Background to the orientation of the Solar system.

These six phenomena, including Dark Energy and Dark Matter which at this stage are nothing more than a synonym for these observations, had neither found any convincing interpretation or solution nor culminated into a finally convincing theory. Lacking any explanation until now, these phenomena have the potential to be of importance for a new physics.

In this talk we describe all these unexplained observations, state the open questions, and suggest new observations and new missions in order to obtain better data for a better analysis of these phenomena. We lay emphasize on the Pioneer and the flyby anomaly. While the Pioneer anomaly has been discussed widely during the last five years, the discussion of the flyby anomaly just started. A first error analysis shows that neither drag forces nor errors in the gravitational field of the Earth nor charging of the spacecraft can be held responsible for the velocity increase during flybys. Furthermore, no reasonable model for an even hypothetical description of the flyby anomaly has been found. Emphasize is laid on the proposal to make precise observations of the next flybys to be carried through by Rosetta at Mars and at the Earth. In particular the Mars flyby has the potentiality to provide independent confirmation of this effect.

Fundamental Physics with Gaia

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In the last 1-2 decades we witnessed a very impressive progress in accuracy of astrometrical (positional) observations: the accuracy of astrometric VLBI in radio band and HIPPARCOS in optical band is 50–100 times better than astrometric accuracy available 20 years ago. This progress is expected to continue even faster due to the space astrometry projects Gaia [1] and SIM [2] to be launched within several years from now. The positional accuracy should attain the level of 1 microarcsecond, which is the angle at which an observer in Europe would see the thickness of a sheet of paper on which this book in printed if the book is demonstrated from New Zealand. This accuracy which we could not dream of 20 years ago makes it possible to boost our knowledge in many fields of astronomy and also in gravitational physics. Especially promising for gravitational physics is Gaia because of its 10^9 objects observed as close as 40° from the Sun. In this paper we deal mostly with relativistic experiments with Gaia, although the relativistic modelling and the relativistic experiments for other space astrometry missions can be considered in a similar way.

The relation between Gaia and the theory of relativity is twofold. First, very detailed and consistent general-relativistic modelling is indispensable for the success of the mission. At the accuracy level of 1 microarcsecond it is impossible to interpret the observational data in a purely Newtonian way or even in a way deliberately combining elements of Newtonian and relativistic physics. From the very beginning all scope of the data models should be constructed in the framework of general relativity. This includes consistent general-relativistic models for

- the reference systems to be used for the data processing (this includes also the relativistic astronomical times scales and their relation to the Gaia proper time),
- the translational motion of the solar system (solar system ephemerides),
- the system of astronomical constants used in various parts of the data processing chain,

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[2]Shao, M. 1998, in Astronomical Interferometry, ed. R.D. Reasenberg, Proc. SPIE, 3350, 536

- the translational and rotational motion of the satellite itself,
- the influence of rotational motion of the satellite on optical imaging within the satellite,
- the process of signal detection within the satellite (this includes aberration of the light),
- the light propagation from the source to the satellite (this includes gravitational light deflection, which includes at least the effects of the monopole and quadrupole components of the gravitational fields of solar system bodies as well as the gravitomagnetic field due to their translational motion),
- the motion of the observed sources (relativistic definitions of parallax, proper motion etc. should be adopted).

On the other hand, virtually all of the relativistic effects included in the model can be used to test general relativity itself. A series of tests of relativity is planned within the REMAT (Gaia collaboration for RElativistic Models and Tests):

- a test of the Local Positional Invariance using the onboard clock of Gaia,
- a test of the Local Lorentz Invariance using the aberration of light,
- several versions of the gravitational light deflection test due to the monopole gravitational fields of the solar system bodies (including stability checks, checks for higher-order deflection terms and alternative angular patterns),
- a first-ever measurement of the acceleration of the solar system relative to remote sources (e.g. quasars),
- constraints on the flux of ultra-low frequency gravitational waves,
- dedicated tests to detect the gravitational light deflection due to quadrupole field of Jupiter and due to translational motion of the giant planets,
- dedicated tests from the motion of the 500000 asteroids which are expected to be detected by Gaia (perihelion precession due to the Schwarzschild (monopole) field of the Sun, constraints on the time derivative of the gravitational constant, independent determination of the quadrupole moment of the Sun, tests of the Strong Equivalence Principle with the Trojan and other resonant asteroids, detection of the non-Schwarzschild effects in the motion of asteroids, etc.).

In order to optimize the Gaia data processing chain to get the maximal possible merit for fundamental physics a series of large-scale numerical simulations is planned within REMAT.

General Relativistic Astrometry: the RAMOD project

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Gravitational waves detectors based on matter wave interferometry

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Matter wave interferometry is a rapidly growing field of physics. This relatively young technology allows new experiments to emerge, and inject new life into existing ones[1]. Matter wave based inertial sensors are today in competition with the best inertial sensors based on laser interferometry or other technologies.

The aim of our work is to calculate the sensitivity of such matter wave interferometers to gravitational waves. We brought out the necessary main characteristic (atom velocity, arm lenght, flux) in order to reach the sensitivity of existing (Virgo) or planned (LISA) laser interferometers. Most generally, whatever the boundary conditions, we show that sensitivities similar to LISA or Virgo can be achieved with small interferometers (less than 1 meter) if the atom flux is high enough depending on the velocity of the atoms[2].

The major interest in building such matter wave interfometers is their small dimension which permits to cool them to very low temperatures to fight the thermal noise.

[1] A. Miffre, M. Jacquey, M. Büchner, G. Trénec, J. Vigué, "Atom interferometry", Physica Scripta, Volume 74, Issue 2, pp. C15-C23 (2006).

[2] P. Delva, M.-C. Angonin, P. Tourrenc, "A comparison between matter wave and light wave interferometers for the detection of gravitational waves", Physics Letters A, Volume 357, Issues 4-5, Pages 249-254 (2006).

Two exotic uses of LISA

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Apart from the regular optimal use of LISA for detecting sources, some special operation regimes exist. We present firstly the coronographic LISA, for occultation of a given source, and secondly a discussion of the detection of passing asteroids by LISA.

Probing Planck Scale Physics, Cosmic Acceleration and Equivalence Principle using Atom Interferometry

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The relation between gravity and space time quantum physics is undergoing renewed interest with the development of new theories such as string theory. Although quantum gravity was recognised about 30 years ago by Richard Feynman, it is only now that experiments are being proposed. In addition to quantum gravity, such experiments also probe zero point energy fluctuations of all elementary fields.

Quantum interference produces a diffusion in the wave function of the system, at the Planck scale quantum gravity fluctuates on the time scale equal to the Planck time. The Planck scale is where it is thought all forces unify into one including gravity at this scale the gravitational field is as strong as the strong, weak, and electromagnetic.

However, it is possible that fluctuation of space time on the scale of the Planck time could be detected using atom interferometers. Percival et al [1] has suggested an atom wave experiment which is analogous to the Brownian motion experiments.

In an atom interferometer, an atomic wavepacket is split into two that follow different paths before recombining. The phase change of each wavepacket is proportional to the proper time along its path, resulting in a interference pattern when the wavepackets recombine. The detection of the decoherence due to spacetime fluctuations on the Planck scale would provide experimental access to quantum gravity effects analogous to accessing to atomic scales provided by Brownian motion.

There is an important cut-off parameter λ for quantum gravity theories in terms of a theory-dependent parameter determined by the amplitude of zero point gravitational fluctuations.

Previous estimates implied [1] that experiments using caesium atom interferometers by [2] and fullerene C_{70} molecule interferometer by [3] set a lower bound of to be of order 10, outside the theoretical limits of 10^2–10^6.

Recently discovered conformal structure of canonical gravity [4, 5] makes possible a new approach to the gravitational decoherence near the Planck scale.

This leads to a new formula for λ [6]: The same experiments now yield a lower bound of λ to be of order 10^4, well within the theoretical limits.

This suggests that the sensitivities of advanced matter wave interferometers may well be approaching the fundamental level due to quantum spacetime fluctuations and that investigating Planck scale physics using matter wave interferometry may become a reality in the near future.

Further improved measurements will confirm and refine the upper bound of λ. A HYPER style atom interferometer in space can provide such improvements.

As well as causing quantum matter waves to loss coherence at small scales, the conformal gravitational field is responsible for cosmic acceleration linked to inflation and the cosmological constant problem.

The sensitivity of matter wave interferometry in space to spacetime inertia also makes it a sharp tool for testing the equivalence principle by using atoms of different mass.

Furthermore additional objectives of the mission are:

Map the latitudinal structure (magnitude and sign) of the Lense-Thirring effect induced by the Earth's rotation and predicted by the General Relativity with a measurement accuracy of 3–5 %.

Determine, independently from Quantum Electro-Dynamics theories, the fine structure constant with a measurement accuracy improvement of one order of magnitude with respect to the present experimental results.

The successful completion of this mission would demonstrate for the first time the superior performance of cold atom matter-wave interferometer instruments, which are extremely sensitive to rotations and accelerations. The mission might therefore lead the way to a novel generation of inertial sensors and gyroscopes that would be needed to enable other future missions. The scientific objectives given above are only feasible in space, where the potential of cold-atom matter-wave interferometry sensors can be fully exploited thanks to the provision, via drag free satellite control, of an environment almost totally free of disturbing accelerations, such as those due to gravity on Earth.

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Studies of quantum states of neutrons in the earth's gravitational field

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Gravitationally bound quantum states of matter were observed recently for the first time thanks to the unique properties of ultra-cold neutrons (UCN). The neutrons were allowed to fall towards a horizontal mirror which, together with the Earth's gravitational field, provided the necessary confining potential well. In this paper we discuss the current status of this experiment and its possible improvements. This phenomenon and the related experimental techniques could be applied to various domains ranging from the physics of elementary particles and fields, to surface studies , to the foundations of quantum mechanics, and to various experimental technics and methods.

Conceptual problems in interpretation of searches for variation of fundamental constants and other 'new physics'

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The last decade was marked in physics by an impresive fast progress in quantum optics and atomic physics. Meanwhile, we still have experienced a strong shortage with data on fundamental problems, such as quantum gravity and possible extention of the Standard model of the electroweak and strong interactions.

There are a number of atomic experiments trying to observe various fundamental effects ranging from the electron's EDM to possible variation of α and other fundamental constants or violation of most basic symmetries.

The experiments either involve a certain model, or pretend to be model-independent. I my talk I will discuss certain details of phenomenology and will show that the interpretation is not free of various concectual problems.

Progress in the Laser-Enabled Tests of Gravity in the Solar System

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Optical technologies are critical for fundamental physics research in the solar system. As an illustration, possible improvements in the laser-enabled tests of various gravitational phenomena are considered. Motivated by the anticipated accuracy gains, we discuss technology that enabled the recent renaissance in lunar laser ranging (LLR)[1,2] and consider future relativistic gravity experiments with precision laser ranging over interplanetary distances. Thus, accurate ranging to the Moon and Mars will provide significant improvements in several gravity tests, namely the equivalence principle, geodetic precession, PPN parameters β and γ, and possible variation of the gravitational constant G. Other tests will become possible with development of an optical architecture that would allow proceeding from meter to centimeter to millimeter range accuracies on interplanetary distances. We also consider proposed experiments that rely on a combination of technologies and briefly discuss LATOR[3,4] mission.

We emphasize that existing capabilities in laser ranging, optical interferometry and metrology, in combination with precision frequency standards, atom sensors, and drag-free technologies are critical for the space-based tests of fundamental physics; as a result, of the recent progress in these disciplines, the entire area is poised for major advances. Looking to the future of space exploration, what characteristics are desired for the next generation of ranging devices, what is the optimal architecture that would benefit both space exploration and fundamental physics, and what fundamental issues can be investigated? We will attempt to address these questions.

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

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General post-Minkowskian expansions of time delays and frequency shifts

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We present a general method enabling to determine the post-linear expansions of gravitational time delays and frequency shifts of electromagnetic signals without solving the differential equations of null geodesics.

Gravitomagnetism and its measurement

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After an introduction on frame-dragging and gravitomagnetism, we describe some phenomena due to the spin of a body on test-gyroscopes, test-particles, clocks and electromagnetic waves. We then review the main experimental attempts and efforts to measure gravitomagnetism, including the NASA Gravity Probe-B space experiment dedicated to detection of frame-dragging. In particular we present the latest results in the accurate measurement of gravitomagnetism of Earth and Lense-Thirring effect by analyzing the orbits of the LAGEOS laser-ranged satellites using the Earth's gravity field models generated by the space mission GRACE. The status of the new laser ranged satellite LARES is finally briefly described.

The INFN-LNF Space Climatic Facility for the LARES mission and the ETRUSCO project

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Gravity is studied in detail in Near Earth Orbits (NEO) using laser-ranged test masses tracked with few mm accuracy by ILRS. The two LAGEOS satellites have been used to measure frame dragging (a truly rotational effect predicted by GR) with 10% error. A new mission and an optimized satellite, LARES (I. Ciufolini PI), is in preparation to reach an accuracy of 1% or less on frame dragging, to measure some PPN parameters, to test the $1/r^2$ law in very weak field and, possibly, to test select models of unified theories (using the perigee). This requires a full thermal analysis and characterization of the test mass and an accurate knowledge of the asymmetric thermal thursts due to radiation emitted by Sun and Earth. A Space Climatic Facility (SCF) has been built at INFN-LNF to perform this experimental program on LAGEOS and LARES prototypes. The SCF consists of a 2m $\times$ 1m cryostat kept at appropriate pressure and temperatures, equipped with simulators of the Sun and Earth e.m. radiation and a versatile thermometry system made of discrete probes and an infrared digital camera. The SCF has been partly funded by the INFN Astroparticle Physics committee (CSNII) for LARES and mainly by the LNF for LARES and other future projects in the fields of space physics and technology.

A complete laser-optical characterization of the LARES prototypes is in preparation on a dedicated optical bench at LNF (kindly made available by G. Giordano). This includes far field diffraction pattern (FFDP) measurements in absolute units and timing laser-ranging tests, to be carried out in close cooperation with ILRS, NASA-GSFC and the Univ. of Maryland at College Park (UMCP). Ultimately, these test will be carried out with the prototypes inside the SCF.

The commissioning of the SCF is well underway. A LAGEOS prototype built at LNF (a 3 × 3 retro-reflector array) has been thermally analized in great detail and will be tested in the summer 2006. A prototype of LARES has been built based on an original design developed at LNF. The results of the thermal simulations and the experimental measurements will be presented.

The experimental facilities setup for LARES are also well suited to the thermo-optical characterization of the retro-reflector arrays proposed for the next Global Navigation Satellite System constellations (GNSS), i.e. the US GPS-3 and the EU GALILEO, in which INFN-LNF proposes to work, again in cooperation with ILRS, NASA-GSFC and UMCP.

Answering a call for proposals for the 2006-2008 study by ASI, INFN-LNF has also proposed to use its facilities to participate in the design and test of the laser-ranged test masses for the Deep Space Gravity Probe mission (DSGP), which is being conceived to accurately verify the Pioneer effect, as well as to perform important (inter)planetary science investigations. The expertise gained in the thermal analysis will also be used in the re-analysis of the PIONEER 10 and 11 spacecraft data. This research effort, led by the PI S. Turyshev of NASA-JPL, will be done together with the Pioneer Explorer Collaboration.

This activity concerning GNSS and PIONEER/DSGP has been presented to the INFN Technology Research Committe (CSNV) in the summer of 2006 under the name of ETRUSCO project (Extra Terrestrial Ranging to Unified Satellite COnstellations, where the "unification" concept refers to the proposed combined use of laser ranging in addition to microwave ranging).

Both the LARES mission and the ETRUSCO project are truly international and inter-agency initiatives with partners in the US, Russia and the EU. [1]

Figure 1: *The logo of the INFN-LNF Space Climatic Facility.*

[1]Presented by C. Cantone at the Intern. Workshop on "ADVANCES IN PRECISION TESTS AND EXPERIMENTAL GRAVITATION IN SPACE", Florence, Italy, Sep. 2006.

Pioneer anomaly and Post-Einsteinian theory

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Although experimental tests of gravity performed in the solar system show a good agreement with General Relativity (GR), the latter is challenged by observations at larger scales and also by the Pioneer anomaly, which might be pointing at some anomalous behaviour of gravity within the solar system. An extension of GR has been introduced which, while preserving the metric nature of the theory, modifies the coupling between curvature and stress tensors through two running coupling constants, differing in the sectors of traceless and traced tensors. It has been shown that while preserving the compatibility with existing gravity tests, this new framework has the capability to account for the Pioneer anomaly. It furthermore provides a basis for a more complete quantitative analysis of the Pioneer data, with the possibility to assess extended metric theories as the appropriate description of gravity within the solar system.

The Pioneer anomaly and the motion of the outer planets of the Solar System

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The so-called Pioneer anomaly[1] consists of an unexpected, almost constant and uniform acceleration $A_{\rm Pio}$ directed towards the Sun of $(8.74 \pm 1.33) \times 10^{-10}$ m s^{-2} detected in the data of both the spacecraft Pioneer 10 and Pioneer 11 after they passed the threshold of 20 Astronomical Units (AU), although it might also have started to occur after 10 AU only, according to a recent analysis of the Pioneer 11 data[2]. Latest communications with the Pioneer spacecraft, confirming the persistence of such an anomalous feature, occurred when they reached 40 AU (Pioneer 11) and 70 AU (Pioneer 10).

Such a feature has recently attracted considerable attention because of the possibility that it is a signal of some failure in the currently accepted Newton-Einstein laws of gravitation; indeed, at present no convincing explanations of it in terms of some non-gravitational effects peculiar to the spacecraft themselves have yet been found.

If the Pioneer anomaly is of gravitational origin, it must then fulfil the equivalence principle, which is presently tested at a 10^{-12} level and lies at the foundations of the currently accepted theories of gravity. In its weak form, it states that different bodies fall with the same accelerations in a given external gravitational field. As a consequence, an extra-gravitational acceleration like $A_{\rm Pio}$ should also affect the motion of any other object moving in the region in which the Pioneer anomaly manifested itself. Thus, the outer planets Uranus, Neptune and Pluto are ideal candidates to perform independent and clean tests of the hypothesis that the Pioneer anomaly is due to some still unexplained features of gravity. Indeed, their paths lie at the edge of the Pioneer anomaly region or entirely reside in it because their semimajor axes a, which fix the size of their Keplerian ellipses, are 9.53 AU, 19.19 AU, 30.06 AU, and 39.48 AU, respectively, and their eccentricities e, which determine the shape of their ellipses, are close to zero yielding to nearly circular orbits. Moreover, astronomical objects of the size of planets are not affected at all by any possible disturbing accelerations of non-gravitational origin which are proportional to their area-to-mass ratio $S/M \propto 1/R$, where R is the planet's radius.

[1] J.D. Anderson, *et al.*, "Indication, from Pioneer 10/11, Galileo, and Ulysses Data, of an Apparent Anomalous, Weak, Long-Range Acceleration", , *Phys. Rev. Lett.*, **81**, 2858-2861, 1998; J.D. Anderson, *et al.*, "Study of the anomalous acceleration of Pioneer 10 and 11", *Phys. Rev. D*, **65**, 082004, 2002.

[2] M.M. Nieto, and J.D. Anderson, "Using Early Data to Illuminate the Pioneer Anomaly", *Class.Quant.Grav.* **22**, 5343-5354, 2005.

It turns out that under the action of an acceleration like $A_{\rm Pio}$ the argument of perihelion ω, which is an angle in the orbital plane determining the position of the point of planet's closest approach to the Sun, would slowly change its location after each full orbital revolution at a rate of

$$\frac{d\omega}{dt} = -A_{\rm Pio}\sqrt{\frac{a(1-e^2)}{GM_{\odot}}}, \tag{1}$$

where G is the Newtonian gravitational constant and $M_{\odot}$ is the mass of the Sun. For Uranus, which is the only outer planet having completed a full orbital revolution over the time span for which modern observations are available, eq. (1) yields a rate of -83.58 arcseconds per century, respectively with an uncertainty of 12.71 arcseconds per century due to the error in $A_{\rm Pio}$ of 1.33×10^{-10} m s^{-2}. The Russian astronomer E.V. Pitjeva has recently processed almost one century of data of all types in the effort of continuously improving the EPM2004 planetary ephemerides. Among other things, she also determined residual advances of the perihelia of the inner and outer[3] planets as fit-for parameters of a global solution in which she contrasted, in a least-square way, the observations (ranges, range-rates, angles like right ascension α and declination δ, etc.) to their predicted values computed with a complete suite of dynamical force models including all the known Newtonian and Einsteinian features of motion. Thus, any unmodelled force, as it would be the case for a Pioneer-like one if present in Nature, is entirely accounted for by the so-obtained residual perihelia advances. For the perihelion of Uranus she found an extra-rate of just $+0.57 \pm 1.30$ arcseconds per century. The quoted uncertainty is only the mere formal, statistical error: the realistic one might be up to $10-30$ times larger. Even in this case, the presence of unexpected precessions as large as that predicted for Uranus by eq. (1) is completely ruled out.

This result is consistent with the findings of Iorio and Giudice[4] in which the time-dependent patterns of the true observable quantities $\alpha\cos\delta$ and δ induced by a Pioneer-like acceleration on Uranus, Neptune and Pluto have been compared with the residuals determined by Pitjeva[5] for the same quantities and the same planets over a time span of about 90 years. While the former ones exhibited well defined polynomial signatures yielding shifts of hundreds of arcseconds, the latter ones did not show any particular patterns, being almost uniform strips constrained within ± 5 arcseconds.

[3]E.V. Pitjeva, "Some Relativistic Effects from Observations of Planets and Spacecraft", abstract submitted to *Eleventh Marcel Grossmann Meeting on General Relativity*, 23-29 July, Freie Universität Berlin, 2006a; private communication 2006b.

[4]L. Iorio, and G. Giudice, "What do the orbital motions of the outer planets of the Solar System tell us about the Pioneer anomaly?", *New Astron*, **11**, 600-607, 2006.

[5]E.V. Pitjeva, "High-Precision Ephemerides of Planets-EPM and Determination of Some Astronomical Constants", *Sol. Sys. Res.*, **39**, 176-186, 2005.

"GAUGE, a cosmic vision proposal: GrAnd Unification And Gravity Explorer"

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GAUGE (GrAnd Unification and Gravity Explorer) is a proposal to the Cosmic Visions programme at ESA. The proposal is for a drag-free spacecraft platform onto which is attached a number of modular experiments. The possible complement of experiments is designed to address a number of key issues at the interface between gravity and unification with the other forces of nature. At present we are considering

- a test of string-dilaton theories using a high precision equivalence principle experiment
- a G measurement
- a $\frac{1}{r^2}$ test of extra dimensions
- an axion-like mass-spin coupling search
- measurement of quantum decoherence from space-time fluctuations at the Planck scale

All the experiments involve precision displacement sensing of proof-masses. There are now a number of available technologies for this sensing, including magnetic (SQUIDS), optical (laser interferometry) and cold atom (matter-wave interferometers). Possibilities for combining/rationalising these technologies across the experiments will be discussed.

A plausible mission concept is to use the LISAPathfinder (LISAPF) spacecraft bus, including its inertial sensor, to provide a drag-free quiet environment for all the experiments. This will be launched into a low-earth sun-synchronous orbit with a VEGA launch vehicle. The fixed solar panels will on the top of the spacecraft facing the Sun. They provide a shadowed eclipse-free environment for the experiments which will be attached to the other side of the spacecraft. A modular design of the experiments in principle allows each of them to have independent thermal control; there could in principle be a mix of low-temperature and 'room-temperature' experiments.

A final choice between the experiments will require a trade-off between scientific grasp, complexity, cost and technology readiness. All of these will need to studied during an assessment study phase.

LISA and its possible Successors

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LISA will pioneer gravitational wave detection in space, but the community is already thinking about successor missions. I will survey the science LISA addresses, the technology required, and likely science goals of future mission proposals. The basic design of LISA as a multi-spacecraft laser interferometer is still the only feasible technology, so future mission concepts simply improve on the technology: more powerful lasers, larger mirrors. But these add significant cost, so that radical new ideas, based perhaps on matter wave interferometry, have an opportunity if they can reduce the power requirements. Multiple spacecraft will still be likely to be needed for direction-finding.

Part II

Poster Session

The MICROSCOPE mission performance and critical features

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The test of the Equivalence Principle, to be performed on board the MICROSCOPE satellite, requires not only outstanding resolution for the inertial sensors at low frequencies about 10-3 Hz and below but also the satellite environment variations to be extremely well controlled, in order to achieve a test resolution of 10-15. The fine analysis of the in-orbit experiment emphasizes a short number of effects ranging from the instrument electrical and mechanical design to the instrument thermal insulation and to the satellite attitude pointing; these effects dominate over the long list of impeding elements that may limit the performance of the mission. The MICROSCOPE instrument SAGE is presently under development. One inertial sensor lab model has been successfully integrated and tested. This helps to confirm the validity of the sensor operation model. Besides electronics units have been tested and satellite subsystems defined. The paper will evaluate by the existing results the expected performance of the experiment.

Testing General Relativity by micro-arcsecond light bending parameters

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The ESA astrometric mission Gaia[1] will be able to carry out general relativistic tests by means of both global and differential astrometric measurements. This will open a unique opportunity to put in practice methods of relativistic astrometry mainly devoted to model the celestial sphere with the precepts of GR[2]. Global tests will be done through the full astrometric reconstruction of the celestial sphere, while the differential experiments will be implemented in the form of repeated Eddington-like measurements, i.e., comparing the evolution of the relative distances in stellar fields observed in the vicinity of a giant planet like Jupiter. Results based on simulated observations show that Gaia can provide two new fully independent determinations of the most fundamental PPN parameter, i.e. γ, to an accuracy of up to $\sim 10^{-7}$ and, for the first time, the measurement of the bending effect due to the quadrupole moment with a 3σ confidence level[3]. Further simulations of selected differential experiments by using GSCII catalogue and realistic error model, show how to improve the Gaia capabilities to detect the quadrupole light deflection and to perform new independent measurements of relativistic effects at the micro-arcsecond level of accuracy.

[1] *The three-Dimensional Universe with Gaia*, 2004, ESA-SP-576

[2] de Felice, F.,Crosta, M. T., Vecchiato, A., Lattanzi, M. G., and Bucciarelli, B., 2004, APJ 607, 580-595; Klioner, S. A.,2003, Astron.J. 125, 1580-1597.

[3] Crosta, M.T., and Mignard, F., 2006, Class. Quantum Grav. 23,4853-4871

ACES MicroWave Link Data Analysis

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The ACES mission (Atomic Clock Ensemble in Space) is an ESA project which aims at installing on board the International Space Station (ISS) an ensemble of ultrastable clocks and comparing them to ground based clocks with a frequency stability over one day and an overall accuracy of $\Delta f/f = 10^{-16}$. The scientific goals of ACES include several tests of fundamental physics (e.g. tests of general and special relativity, search for variation of fundamental constants).

The space clock will be compared to ground clocks using a microwave link (MWL), which is specified to have a time stability of less than 0.3 ps (over one 300 s ISS pass) and 5 ps over 1 day integration time, which is much better than the performance of time transfer techniques commonly used (GPS,TWSTFT). The MWL concept relies on a two-way technique using 3 frequencies (one up-link and two down-links) in order to reject or reduce a number of perturbing effects (position errors, ionospheric delays, internal delays, etc). It will provide six independent observables (PRN-code and carrier phase measurements at each of the three frequencies) each averaged to one point per second.

In this work we describe a fully relativistic model that we have developed to combine the MWL raw observables together with orbitography data in order to obtain the products of scientific interest (clock phase differences, range, ionospheric parameters, etc) with uncertainties that are compatible with the specifications of the MWL. We then show a simulation taking into account noise and biases on some of the fundamental parameters (orbitography, internal delay callibrations) and determine the maximum upper limits that can be tolerated. Finally we compare those results to realistic estimates of ISS orbitography errors.

Inertial forces measurement with cold atoms interferometry

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We have realized a device based on cold atom interferometry to achieve precision inertial measurements. In contrast with previous similar atomic setups [1,2,3], emphasis was placed on the long term stability and compactness of the device through the use of laser cooled atoms, as previously shown with the field of atomic clock. The expected improvement in stability will enable to consider applications in inertial navigation, geophysics and tests of general relativity as the equivalence principle or Lense-Thirring effect[4]. The expected sensitivity resulting from our geometry is 30 nrad.s^{-1}.$Hz^{-1/2}$ for rotation measurements and 4. 10^{-8} m.s^{-2}.$Hz^{-1/2}$ for acceleration measurements.

Cesium atoms are loaded as a vapor into two independent magneto-optical traps for 125 ms. The two cesium clouds are launched into two opposite parabolic trajectories using moving molasses at 2.4 $m.s^{-1}$, with an angle of 8^o with respect to the vertical direction. At the top of their trajectory, the atoms interact with three Raman lasers pulses, equivalent to beam splitters (for $\pi/2$ pulses) and mirrors (for π pulses), thus generating an interferometer. After this interaction sequence, the transition probability depends on the atomic phase difference accumulated between the two arms of the interferometer. This phase difference can be due to inertial effect like accelerations along the Raman laser direction or rotations around the normal to the plan defined by the laser and the velocity of the atoms. Raman transitions permit the detection of the internal states of the atoms by fluorescence imaging. The use of two atomic sources allows to discriminate between the acceleration and rotation.

First measurements obtained with this setup led to a sensitivity of 4.7 10^{-6} m.s^{-2} for accelerations and 2.2 10^{-6} rad.s^{-1} for rotations, averaged over one

[1]F. Riehle, et al, Phys. Rev. Lett. 67, 177 (1991).
[2]T.L. Gustavson, et al, Class. Quantum. Grav. 17, 1 (2000).
[3]D. E. Pritchard et al, Phys. Rev. Lett. 78, 760 (1997).
[4]ESA Assessment Study Report ESA SCI 10 (2000).

second[5]. The sensitivity was limited by the low number of detected atoms and the weak contrast of atomic fringes. This contrast value could be attributed to the temperature of the two atomic sources ($\sim 3\ \mu K$). To reach better performances, the entire cooling system was re-designed to increase the number of launched atoms, optimize the atomic temperatures and improve the control of atomic trajectories. With these modifications, we are now able to launch 10^6 atoms in the pure quantum state $|6S_{1/2}, F = 3, m_f = 0 >$, with a temperature of $\sim 1\ \mu K$, corresponding to a velocity dispersion of about 2 V_{recoil}. The contrast has consequently, improved by a factor two. Furthermore, it is now possible to independently control both atomic sources in order to have a correct overlap the two atomic trajectories. In this manner, we can evaluate some systematics linked to these inaccuracies of overlapping (for example, wave front distortion of Raman-laser[6], Zeeman quadratic effects and light shift). We can also confirm the rejection value of acceleration and rotation signals is better than 40 dB. Thus, the accuracy of the rotation measurement is evaluated at about 2% of the projection of the Earth's rotation rate. The sensitivity is now 2.3 10^{-6} m.s^{-2} for acceleration and 5.9 10^{-7} rad.s^{-1} for rotation, averaged over one second. These measurements are limited by vibrations for the acceleration signal, and by the laser phase noise for the rotation measurement. In our set-up the Raman lasers can also be turned to the vertical direction allowing measurement of the second projection of the Earth's rotation rate. In this configuration the laser phase noise impacts the acceleration signal. The sensor is being characterized and optimized in this configuration to reach an optimum sensitivity.

[5] B. Canuel et al. , Phys. Rev. Lett. 97, 010402 (2006)
[6] J. Fils et al., Eur. Phys. J. D. 36, 257 (2005).

Evidence of the gravitomagnetic field of Mars

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The general relativistic gravitomagnetic Lense-Thirring effect consists of small secular advances of the along-track T and out-of-plane N parts of the orbit of a test particle freely falling in the gravitational field of a central rotating body. In terms of the usual Keplerian orbital elements such shifts can be expressed as

$$\left\{\begin{array}{lcl} \Delta T_{\rm LT} & = & a\sqrt{1+\frac{e^2}{2}}\left(\Delta\omega_{\rm LT}+\cos i\Delta\Omega_{\rm LT}\right), \\ & & \\ \Delta N_{\rm LT} & = & a\sqrt{1+\frac{e^2}{2}}\sin i\Delta\Omega_{\rm LT}. \end{array}\right. \quad (1)$$

where a, e, i, Ω, ω are the semimajor axis, the eccentricity, the inclination, the longitude of the ascending node and the argument of the pericentre, respectively, of the satellite's orbit. For equatorial orbits ($i = 0$ deg) only the along-track shift occurs, while for polar orbits ($i = 90$ deg) only the out-of-plane portion of the orbit is affected by the gravitomagnetic force.

Up to now, the Lense-Thirring effect on the orbit of a test particle has been tested only in the gravitational field of the Earth by analyzing the perigees and/or the nodes of the existing LAGEOS and LAGEOS II satellites[1][2], but their results have always been rather controversial for various reasons[3][4][5] The present-day accuracy might be $15 - 20\%$, according to, e.g., Ref. 5.

Rather unexpectedly, the space environment of Mars has recently yielded the opportunity of performing another, independent test of the Lense-Thirring

[1] I. Ciufolini, I., E.C. Pavlis, F. Chieppa, *et al.*, "Test of General Relativity and Measurement of the Lense-Thirring Effect with Two Earth Satellites", *Science*, **279**, 2100-2103, 1998.

[2] J.C. Ries, R.J. Eanes, B.D. Tapley, and G.E. Peterson, "Prospects for an Improved Lense-Thirring Test with SLR and the GRACE Gravity Mission", *Proceedings of the 13th International Laser Ranging Workshop, NASA CP 2003-212248*, ed. R. Noomen, S. Klosko, C. Noll, and M. Pearlman, (NASA Goddard, Greenbelt), 2003.; L. Iorio, and A. Morea, "The impact of the new Earth gravity models on the measurement of the Lense-Thirring effect", *Gen. Rel. Grav.*, **36**, 1321–1333, 2004; I. Ciufolini, and E.C. Pavlis, "A confirmation of the general relativistic prediction of the Lense-Thirring effect", *Nature*, **431**, 958–960, 2004.

[3] J.C. Ries, R.J. Eanes, and B.D. Tapley, "Lense-Thirring Precession Determination from Laser Ranging to Artificial Satellites", in: "*Nonlinear Gravitodynamics. The Lense–Thirring Effect*", ed. R. Ruffini, and C. Sigismondi, pp. 201-211, (World Scientific, Singapore), 2003.

[4] D. Lucchesi, "The Impact of the Even Zonal Harmonics Variations on the Lense-Thirring Effect Measurement with the Two LAGEOS Satellites ", *Int. J. of Mod. Phys. D*, **14**, 1989-2023, 2005.

[5] L. Iorio, "A Critical Analysis of a Recent Test of the Lense-Thirring Effect with the LAGEOS Satellites", *J. of Geodesy*, **80**, 128-136, 2006a.

effect[6]. Almost six years of range and range–rate data of the Mars Global Surveyor (MGS) orbiter, together with three years of data from Odyssey, have been used in order to precisely determine many physical properties of Mars[7] (gravity field, polar motion, orientation in space, etc.). As a by-product of such an effort, also the orbital path of MGS has been reconstructed very accurately[7]. The average Root-Sum-Square error of the residuals of the out-of-plane component of the MGS orbit amounts to 1.6 m over a 5-years time span ranging from 10 February 2000 to 14 January 2005. Neither the gravitomagnetic force was included in the suite of the dynamical force models used in the analysis, nor any empirical acceleration was fitted, so that such residuals account entirely for the gravitomagnetic force of Mars on MGS. It turns out that the average Lense-Thirring shift in the out-of-plane direction of MGS (it is in a polar orbit) over 5 years amounts just to 1.5 m: a discrepancy of 6%.

[6]L. Iorio, "Evidence of the gravitomagnetic field of Mars", *Class. Quantum Grav.* , at press, gr-qc/0606092, 2006b

[7]A.S. Konopliv, *et al.*, "A global solution for the Mars static and seasonal gravity, Mars orientation, Phobos and Deimos masses, and Mars ephemeris", *Icarus*, **182**, 23-50, 2006.

Atomic Clock Missions in Space: The Galileo On-board Clocks

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[3] *European Space Technology Centre, The Netherland*

The European Space Agency is supporting, since quite a few years, the development of space-qualified clocks, for scientific and navigation programmes. These developments received a strong acceleration after approval of the Galileo Navigation programme, with the objective to guarantee Europe with the technology independence in such a critical field. The In Orbit Validation (IOV) programme presently running is as well supported by the European Community. The Galileo Navigation payload adopts for the clocks a double redundant scheme, using two different technologies constituted by the Rubidium Atomic Frequency Standard (RAFS) and the Passive Hydrogen Maser (PHM). Use of this concept is dictated by the need to ensure an adequate degree of system reliability. Both clock technologies are now mature and qualified for space use. The clocks have a mission life of 12 years and shall perform in the harsh MEO orbit at about 23.000 Km altitude. Their stability is specified in order to guarantee the navigation accuracy, with clock correction data uploading from ground in longer than 8 hour intervals. After launch on end 2005 of GIOVE A, which embarked two rubidium clocks, the navigation signals are ongoing system test. The launch of GIOVE B, planned on end 2006, will allow flight testing of the master clock technology, i.e. the Passive hydrogen Maser.

Figure 1: *The RAFSis produced by Temex Neuchatel Time (CH), that is responsible for the clock performances and produces its physics, in cooperation*

with EADS Astrium (D), that provides the electronics. It represents the active redundant clock of Galileo payload, providing the reference signal in case of PHM failure. The RAFS is also available in a smaller version (RACM) including the only clock core and its essential electronic functions. The latter is more convenient for highly integrated scientific payloads.

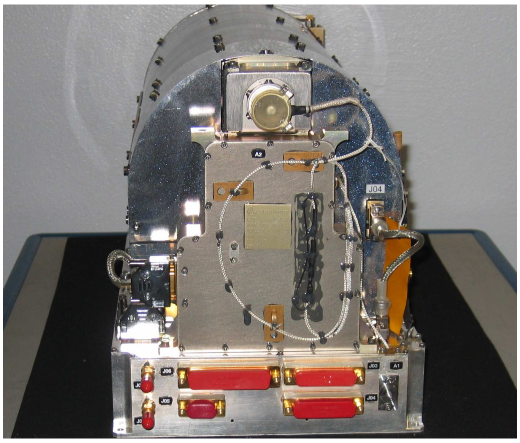

Figure 2: *The PHM is the master clock of the Galileo navigation payload. It is produced by Galileo Avionica (I), that is responsible for the clock performances and produces its electronics, in cooperation with Temex Neuchatel Time (CH), that provides the PHM physics. The PHM design privileges frequency stability and exhibits an excellent frequency drift.*

LISA and its precursor LISA Pathfinder (Status/Overview)

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The Laser Interferometer Space Antanna (LISA) is a joint ESA-NASA mission, designed to observe gravitational waves in the frequency regime from 0.1 mHz to 100 mHz. Whilst sources in the audio-band above appr. 1 Hz can be detected by ground-based observatories (LIGO,GEO,TAMA,etc.), many interesting sources, such as inspirals and mergers of supermassive black hole binaries, can be only detected in space, due to the seismic noise limitation of ground based detectors.

LISA is a cluster of 3 identical spacecraft, separated by 5 million kilometers, trailing the Earth by 20° in a equilateral triangle formation. Each spacecraft carries a set of two drag-free-controlled proof masses, whose relative positions are given only by gravitational radiation. These proof masses act as end mirrors of inter-spacecraft laser interferometers. The relative changes in separation of these proof masses will be measured with a shot noise limited sensitivity of $40\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 1 mHz.

In order to verify key technologies, like drag-free proof masses with a residual force noise of $3 \times 10^{-15}\,\mathrm{N}/\sqrt{\mathrm{Hz}}$ in the mHz range, and picometer precision interferometry in space, the LISA technology demonstrator *LISA Pathfinder* will be launched in 2009. *LISA Pathfinder* currently enters its Critical Design Review (CDR) phase in the ESA/NASA project time line, and its implementation phase has already begun.

This talk gives an overview of LISA and *LISA Pathfinder* with particular emphasis of the technology development and associated laboratory work.

A robust laser system for quantum gases under microgravity

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The QUANTUS collaboration targets the establishment of quantum gases under microgravity as a new research field, allowing to access the lowest ever temperatures and extremely long times of free evolution and observation with these quantum objects. Within a current pilot project an apparatus for Bose-Einstein condensation during free fall at the ZARM drop tower facility is under development. We present and analyze the laser system as a key component for the atom trapping and precooling stage. The miniaturized laser setup is designed to deliver frequency stable radiation under the conditions of a free fall experiment. We discuss the particular mechanical and temperature requirements as well as corresponding laboratory tests. Further developments towards a catapult operation stable version with lock stability beyond accelerations of 30g will be presented.

Matter-wave cavity gravimeter

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The use of cold atoms and atom optics has brought considerable improvements to the measurement of gravito-inertial effects in the last decade. Conversely, the improvements in the production and manipulation of Bose Einstein condensates have led to experimental realizations of quasi-continuous coherent matter-wave sources. We investigate here some possible applications of Bose-Einstein condensates to precision sensing and interferometry.

We propose a gravimeter based on a matter-wave resonant cavity loaded with a Bose-Einstein condensate and closed with a sequence of periodic Raman pulses. [1] The gravimeter sensitivity increases quickly with the number of cycles experienced by the condensate inside the cavity.

In order to stabilize the matter wave inside the cavity, we propose an original matter-wave focusing scheme: the matter wave is refocused thanks to Raman pulses of spherical wave-front. This method provides a lens whose focal length can be easily controlled through the relative positions of the waists of the laser and atomic beams. Furthermore, the momentum transfer achieved with this curved optical mirror is of higher efficiency than that obtained with usual focusing schemes based on a position-dependent light shift. [2]

The periodic sequence of optical Raman pulses levitating the atoms is the analog of a resonator in momentum space for the matter waves.

[1]F. Impens, P. Bouyer and Ch.J. Bordé, Matter-Wave Cavity Gravimeter, to appear in App. Phys. B (2006)

[2]G. Whyte, P. Öhberg and J. Courtial, Phys. Rev. A 69, 053610 (2004)

ACES, a Fundamental Physics Mission on the International Space Station

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Atomic Clock Ensemble in Space (ACES) is a mission that will demonstrate the high performance of a new generation of atomic clocks operated in microgravity conditions. A number of fundamental physic experiments will be conducted by comparing the ACES clock signal to a worldwide ensemble of ground clocks both in the microwave and the optical domain.

ACES is a complex payload, involving state-of-the-art instruments and subsystems, that will be accommodated on-board the International Space Station, on the nadir external facility of the Columbus module. The heart of the ACES payload is an atomic clock based on laser-cooled caesium atoms called PHARAO ("Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite"). The accuracy and long term stability of PHARAO (few part in 10^{16}) will be combined to the excellent medium term stability of a Space Hydrogen Maser (SHM) to establish the ACES time scale. The on-board clocks will be locked and compared to each other using an especially developed Frequency Comparison and Distribution Package (FCDP). The ultra-stable on-board reference signal will be world-wide distributed and compared to ground clocks through a dual-frequency two-way time and frequency transfer system operating in the microwave domain (MWL). The high stability of the MWL space-to-ground time transfer (0.3 ps over 300 s and 7 ps over 1 day) will also allow ground-to-ground comparisons of atomic frequency standards with a resolution better than 1 ps in common-view and better than 3 ps for non common-view comparisons separated by 1000 s.

Based on these comparisons, a number of fundamental physics experiments (tests of Einstein's theory of General Relativity and Standard Model Extension, search for a drift of fundamental constants, string theories, etc.) will be performed. Applications in time and frequency metrology, physics of the atmosphere, global positioning and navigation, geodesy, and gravimetry will be also developed.

After a general overview of the mission concept, ACES scientific objectives will be presented and discussed.

“Galileo Galilei on the Ground” (GGG): validation of the main featuers of the space experiment and current sensitivity

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GGG[1] is a $1-g$ version in the lab of the differential accelerometer designed to fly inside the small satellite GG with the purpose of testing the Equivalence Principle (EP) to 1 part in 10^{17}. It is a system of two co-axial, concentric test cylinders ($10\,kg$ each, as for the space instrument) weakly coupled to form a beam balance with the beam along the symmetry axis of the cylinders. The main novelty of the GGG instrument as compared to ordinary balances is that the centers of mass of the suspended bodies coincide; this is a crucial constraint for an instrument designed for EP testing in orbit around the Earth, where classical tidal effects between the bodies need to be minimized to possibly uncover a non classical differential effect due to an EP violation between test bodies of different composition. In this way the GGG instrument is sensitive to differential accelerations acting between the coupled test cylinders in the horizontal plane of the lab. The weaker the coupling and the better the balance of the bodies, the more sensitive the instrument is to such differential accelerations which are read by means of four capacitance plates located in between the cylinders at 90 deg from each other to form two capacitance bridges in two orthogonal directions of the plane. In addition, with the beam along the symmetry axis of the concentric test cylinders, it is natural to set the whole system in rotation around it so as to modulate the differential acceleration signal recorded by the bridges at the (fast) frequency of spin.

High frequency modulation has long been sought in experiments to test the equivalence principle, starting with Dicke’s suggestion for torsion balances to look for an EP violation in field of the Sun rather than of the Earth, so as to use the Earth’s rotation to provide a $24-hr$ modulation. High frequency modulation is well known to reduce $1/f$ electronics noise. In the GGG design, where the spin period is of the order of $1\,s$, it turns out to be extremely beneficial in reducing mechanical noise as well. This is because, due to very weak coupling and rapid spin, the GGG system is a rotor in *supercritical regime* and

[1] G. L. Comandi *et al.,* Dynamical Response of the Galileo Galilei rotor for a Ground test of the Equivalence Principle: theory, simulation and experiment. Part I: the normal modes, Rev. Sc. Instr. 77, 034501 (2006)

supercritical rotors are known to self center (thus providing very smooth and quiet rotation) and to be dominated by energy losses in the suspensions at the high frequency of spin, rather than at the low frequency of the coupling. Since losses are well known to be much lower for deformations at high frequencies, the GGG apparatus and its thermal noise are limited by relatively small losses.

In this presentation we report the experimental results obtained with the GGG prototype showing that macroscopic test bodies in rapid rotation can be used for measuring very small forces, with large masses and small losses ensuring reduced thermal noise also at room temperature and the fast spin providing the required high frequency modulation of the signal. We also show that the GGG experimental results are relevant for the goal of the GG experiment in space to test the Equivalence Principle to 10^{-17}.

Whirl control of macrocsocpic supercrtitical rotors enabling high accuracy tests of the Equivalence Principle: experimental results with GGG

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The GGG rotating differential accelerometer currently operated in the INFN lab of San Piero a Grado-Pisa is a prototype of a similar instrument designed to fly inside the small satellite "Galileo Galilei-GG" with the scientific goal of testing the Equivalence Principle to 1 part in 10^{17}. As illustrated in the presentation by G.L. Comandi, GGG is in essence a supercritical rotor. It differs from ordinary supercritical rotors only because of being a multi-body rather than a single-body system, which requires some more attention in operating it. Like all rotors GGG gives rise to "whirl motions" at the natural frequencies of the system once in supercritical regime, i.e. once the system spins at a frequency higher than its natural frequencies.

Whirl motions are a known feature of supercritical rotors: losses in the system (due to inevitable losses in the suspensions, *i.e.* the mechanical quality factor is necessarily finite) will result in decreasing the rotation energy, hence the rotation speed (because the moment of inertia is constant), hence the rotation angular momentum; and since the total angular momentum is conserved, an orbital angular motion must arise, known as whirl motion, at the natural frequency/ies of the dynamical system. Two important facts can be proven. First, the suspensions are deformed at the (high) spin frequency, not at the natural (low) ones, hence losses at the spin frequency are the relevant ones, which is a very favorable situation because smaller losses are known to take place at higher frequencies. Second, the ratio between the orbital energy gained by the whirl motion and the spin energy lost by the rotor (per unit time) is equal –in modulus– to the ratio between the whirl (natural) frequency and the spin frequency, which by definition of a supercritical rotor is a number smaller, in fact much smaller, than 1:

$$\frac{\dot{E}_w}{\dot{E}_{rotor}} = -\frac{\omega_w}{\omega_{spin}} \tag{4}$$

As a result, only a correspondingly small fraction of the rotation energy lost by the rotor gives rise to whirl motion; all the rest can be shown to be dissipated as heat in the suspensions themselves.

In summary, whirl motions are a known instability of supercritical rotors but due to their physical properties they can be stabilized so as to allow the advantages of supercritical rotation to be exploited also in very fine measurements as in GG/GGG. In ordinary supercritical rotors whirl motions are damped passively. However, passive whirl damping is too rough for GGG since it is designed to perform very small force measurements. Instead, active whirl damping has been implemented in a closed control loop based on small capacitance sensors/actuators.

In this presentation we report the experimental results obtained in whirl damping during very long runs of the GGG prototype, and show how whirl signals can be separated out from much smaller differential effects such as the one of a possible Equivalence Principle violation. The relevance for the GG experiment in space of active whirl damping implemented in the lab is discussed. Altogether, theoretical analysis, nuemrical simulations and now long term experimental results disprove speculations made in the past that whirl motions would make the GG system highly unstable and fast rotation impossible to achieve in space experiments to test the Equivalence Principle.

Advances in new technologies for on-board and ground based optical atomic clocks for space applications

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In the last years, the advent of new techniques in the field of frequencies synthesis (frequency synthesizer or "frequency comb") and in laser cooling opened the way to a new generation of optical atomic clocks (OACs) based on "forbidden" optical transition in neutral atoms or ions. Such OACs take advantage of the very narrow linewidths (up to few Hz) of the optical transitions allowing to reach unprecedented levels of accuracy (near to 10^{-17} level) and stability (10^{-15} - 10^{-16} at 1s). The OACs technology is, at present, strongly under discussion. In particular, the great interest in OACs is related to both the fundamental physics involved in the experimental implementation of an atomic clock (e.g. ACES mission) and to the field of Global Navigation Satellite Systems (GNSS). Kayser Italia (KI) has been commissioned by the European Space Agency (ESA) and the Agenzia Spaziale Italiana (ASI) of two studies on OACs for respectively ground based and on-board applications. KI as Prime Contractor of the two projects is performing a selection, on the basis of a trade-off evaluation, of the most promising technologies, in collaboration with some of the laboratories leading the European research efforts on optical atomic clocks (LENS-Florence, Düsseldorf University and the Observatoire de Paris).

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Both the projects show a common background on the optical atomic clocks technology as well as common experimental setups, while differ considerably for the design guidelines. In particular, the design and implementation of OACs for ESA Deep Space Stations (DSS) take mainly care of maintenance and operation aspects, whereas the study for the ASI on-board OAC is driven by the typical requirements of a space-borne payload.

An experimental phase is related to the ESA project, for both neutral atoms and ions, in order to test several aspects as, for example, the laser sources stabilized on optical cavities for Sr atoms, the optimization of the short term stability, the design of laser subsystems for cooling and interrogations of clock ion, the construction of a linear RF trap for the confinement of the ions, the development of a reliable clock laser system for an Yb lattice clock and many others. The obtained results will contribute to the definition of the possible OAC system concepts, hence for each of them the implementation of a breadboard will be assessed. Furthermore, a preliminary design of the frequency distribution concept inside the DSS will be performed.

In the same way, the project for the OAC for on-board applications, commissioned by ASI, has as primary outcome the study of each single block of the clock (choice of the quantum frequency reference (QFR) transition, laser systems for cooling and interrogation, detection systems) in terms of final performances and system engineering. The selection will be performed through a direct comparison between neutrals and ions samples that appear to be, both, very promising in order to obtain high final performances of the clock. The final purpose is to identify the best candidate to be used as time reference provider on board the next generations of the Galileo GNSS.

QUANTUS – The quantum matter facility

W. Ertmer

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Microgravity is expected to be a decisive ingredient for the next leap for experiments testing the fundamental physics of gravity, relativity and theories beyond the standard model. A promising technique for such tests in the quantum domain are matter-wave sensors based on cold atoms or atom lasers, which use atoms as unperturbed microscopic test bodies for measuring inertial forces or as frequency references. For matter-wave interferometers and experiments with quantum matter (Bose-Einstein Condensates or degenerate Fermi gases) microgravity allows the extension of the unperturbed free fall of these test particles in a low-noise environment.

Microgravity will also help to establish a new scientific avenue in the research on degenerate quantum gases. They offer unique insights into a broad range of fundamental physics as well as prospects for novel quantum sensors. Microgravity will substantially extend the science of quantum gases towards nowadays inaccessible regimes at lowest temperatures, to macroscopic dimensions, and to unequalled durations of unperturbed evolution of these distinguished quantum objects.

With the launch of the development of a mobile BEC platform project for microgravity experiments in the drop tower and during parabolic flights within a pilot project, running since January 2004, the DLR took a major first step to establish this field of research in Germany. The pilot projects aims for a first technological demonstration of the feasibility of such experiments at the drop tower. The prospects of such an experiment, however, cover the study of quantum gases in the regime of unperturbed evolution with extremely large correlation length and longest unperturbed time of flight. The research will be performed with regard to scientific and technological aspects, from fundamental physical questions with low energy quantum phase transitions and the establishment of quantum correlations to measurements of highest precision in atom interferometric set-ups. QUANTUS comprises a battery-driven UHV-BEC experiment (10-11 mbar), which is based on an atom chip and remote controlled by a real time computer system. The experiment can trap more than 10^7 atoms in a mirror MOT from where about $3 \cdot 10^6$ atoms with 20 μK are transferred in the Joffe-Pritchard trap. Currently we optimise atom number, temperature and the lifetime in the Joffe-Pritchard trap, which is about 2.7 s.

The Quantus Team: The team of E.M. Rasel and W. Ertmer, Leibniz Universitt Hannover; Hj. Dittus and C. Lämmerzahl, Zarm Bremen; K. Bongs and K. Sengstock, University Hamburg; A. Peters, Humboldt Universität Berlin; R. Walser and W. Schleich; University Ulm; J. Reichel and T. Hänsch, ENS Paris & MPQ Germany

Atom interferometry gravity-gradiometer for the determination of Newtonian gravitational constant G

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We present a gravity–gradiometer based on atom interferometry, developed for a precise determination of the Newtonian gravitational constant G[1].

The interferometer is realized applying a sequence of $\pi/2 - \pi - \pi/2$ vertical Raman pulses on free falling cold ^{87}Rb atoms in an atomic fountain. The resulting phase contains information related to the local vertical acceleration. Two cold atomic clouds are launched upwards with a juggling scheme in order to have two displaced sensors in rapid sequence. The Raman pulses simultaneously act on both samples.

Heavy source masses are placed around the gradiometer region and accurately moved in two different positions along the vertical direction. The double differential measurement drastically reduces common mode spurious signals.

The apparatus has been already tested[2] using preliminary lead masses providing first results.

[1]M. Fattori, G. Lamporesi, T. Petelski, J. Stuhler and G. M. Tino, "Towards an atom interferometer determination of the Newtonian gravitational constant", Phys. Lett. A **318**, 184-191 (2003)

[2]A. Bertoldi, G. Lamporesi, L. Cacciapuoti, M. de Angelis, M. Fattori, T. Petelski, A. Peters, M. Prevedelli, J. Stuhler, and G. M. Tino, "Atom interferometry gravity-gradiometer for the determination of the Newtonian gravitational constant G", to be published in Eur. Phys. J. D, preprint arXiv:physics/0606126

Optical frequency standard with ultra-cold strontium atoms for earth and space applications

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We report on our progress toward the realization of an optical frequency standard referenced to strontium intercombination lines. For the ultimate performance of a clock based on strontium, the most interesting transition would seem to be the doubly-forbidden $^1S_0$-$^3P_0$ transition in either ^{87}Sr or ^{88}Sr isotopes [1,2].

For this we are preparing a new 698 nm stable laser source resonant with the $^1S_0$-$^3P_0$ transition for ^{88}Sr. Cascaded lock to two resonant cavities of increasing finesse ($3{\cdot}10^3$, $3{\cdot}10^5$) can be used to obtain sub-Hz linewidth [3]. While the lock to the first cavity with lower finesse is used to reduce the fast laser linewidth to below 100 Hz, the lock to the second ultrastable cavity will be used to reduce the linewidth to below 1 Hz. Reduced sensitivity of the cavity length to both thermal noise and acoustic noise is achieved by a specially cut of a 10 cm ULE spacer for symmetric horizontal suspension [4].

We also prepared an ultracold sample of Sr atoms. The atoms are first slowed and trapped on the strongly allowed 5s^2 $^1S_0$ - 5s5p $^1P_1$ transition, subsequently a second cooling stage is applied on the 5s^2 $^1S_0$ - 5s5p $^3P_1$ intercombination line finally obtaining more than 10^6 ^{88}Sr atoms at less than 1 μK[5]. The cold atoms can then be transferred into a pure optical dipole trap at magic wavelength for spectroscopy.

[1]M. Takamoto, F.-L. Hong, R. Higashi and H. Katori, "An optical lattice clock", Nature 435, 03541 (2005)

[2]A. V. Taichenachev and V. I. Yudin, C. W. Oates, C. W Hoyt, Z. W. Barber, and L. Hollberg,"Magnetic field-induced spectroscopy of forbidden optical transition with application to lattice-based optical atomic clocks", Phys. Rev. Lett. 96, 083001 (2006)

[3]B.C. Young, F.C. Cruz, W.M. Itano, J.C. Bergquist, "Visible lasers with subhertz linewidth", Phys. Rev. Lett. 82, 3799 (1999)

[4]N. Poli et. al., EFTF 2006 Conference abstract

[5]N. Poli, R. E. Drullinger, G. Ferrari, J. Leonard, F. Sorrentino, and G. M. Tino, "Cooling and trapping of ultracold strontium mixtures", Phys. Rev. A 71, 061403(R) (2005)

Expected limits on relative frequency stability (accuracy) of this reference lie at 10^{-15} at 1 s (10^{-17}) level.

While the study of optical frequency reference is of fundamental importance for a possible new definition of the SI second and for tests of theories, optical standards with this level of stability and accuracy could improve the performance of a number of earth and space-borne applications.

Satellite earth navigation and positioning systems (GPS, GALILEO) could reach level of sub-cm position accuracy, ultra-high phase stability signals for deep space antennas would allow a more precise determination of position of spacecraft, while new earth geodesy effects could be addressed.

Future Inertial Atomic Quantum Sensors (FINAQS)

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In recent years, matter wave interferometry has developed into a powerful tool for the ultra precise measurement of accelerations and rotations. It is used in various laboratories for experiments in the fields of fundamental physics and metrology.

FINAQS (Future Inertial Atomic Quantum Sensors), a collaboration of five European research groups, aims at developing new atomic quantum sensors based on coherent and brilliant atomic sources. For this purpose, we will implement new atom optics concepts, particularly the first gravimeter and quantum gyroscope using degenerate quantum gases. Another goal of FINAQS is extending the usefulness of atom interferometers to include practical applications, such as on-site high precision measurements of local gravity, which will benefit research in geology and seismology, amongst others. Each FINAQS partner will contribute its experience and designs to the development of the project.

We will present the current status of the key technologies that are developed or adapted from previous laboratory based experiments for the realization of two mobile and yet precise FINAQS quantum sensors.

ACES Payload Description and Design

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The Atomic Clock Ensemble in Space (ACES) Mission has applications to Fundamental Physics and to technology such as global Time & Frequency (T&F) comparison. The mission will be conducted on the International Space Station (ISS), Columbus External Payload Facility (CEPF), nadir looking location. The ACES payload is planned to be launched with a HTV. The on-orbit transfer from HTV to the CEPF, will be performed using the Space Station Robotic Systems.

The ACES payload carries two scientific instruments and a number of subsystems as outlined below:

The cold Caesium atom clock, PHARAO, (Projet d'Horloge Atomique Refroidissement d'Atomes en Orbite) funded and nationally developed by CNES. The Space Hydrogen Maser (SHM) designed by the Observatory of Neuchatel and originally funded by Switzerland via the ESA PRODEX Program but currently under the management of the ESA ACES project.

A Frequency Comparison and Distribution Package (FCDP), for on-board clock comparison between PHARAO and SHM, and distribution of the signal to the MWL

A MicroWave Link (MWL), for two-way time transfer between space and ground clocks with unprecedented accuracy. The MWL consists of a flight segment and a ground terminal. The ground terminals will be connected to ground clocks in laboratories world-wide.

Standard equipment for data, power, environmental control and mechanical support.

The ACES clock reference signal, which combines the PHARAO accuracy and the best stability of the two clocks, is controlled by means of the ACES servo loops.

The ACES mission is implemented under ESA responsibility and executed in cooperation with CNES. The Payload is being developed by an industrial team lead by Astrium (D) under ESA contract.

Ground based 2DoF test for LISA and LISA PF

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LISA will be an experiment devoted to the detection and observation of gravitational waves. It will consist of a constellation of three satellites 5 million km apart, on a solar orbit with the radius of 1 AU. A Michelson interferometer will measure how the distances between test masses on board each spacecraft change in time, signalling the arrival of GW. LISA will follow a precursor mission, called LISA Pathfinder. On-ground tests are required to study the couplings between LISA (and LISA PAthfinder) test masses and the spacecraft that host them. Very interesting and useful results have already been obtained with a 1 DoF torsion pendulum. In order to study the couplings that might act between two ore more degrees of freedom in measuring the position and acting on the position of each test mass, a many degrees of freedom facility is needed. Here we present a new 2 DoF double torsion pendulum, that will be used to test LISA Gravitational Reference Sensor (GRS) on the ground.

Cold Atom Sagnac Interferometer

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Matter-wave interferometry has a very high sensitivity for detecting accelerations and rotations, which makes it an ideal tool for applications in fundamental physics and metrology, such as tracking locally the rotation of the earth or measuring the relativistic Lense-Thirring effect[1].

In the project CASI (Cold Atom Sagnac Interferometer) a compact and transportable inertial sensor based on matter-wave interferometry is being realised to measure rotations and accelerations. To distinguish between them, we designed the apparatus to send two clouds of cold atoms in opposite direction through the same Mach-Zender-interferometer for a differential measurement. Each of the two atomic Rubidium sources has a two stage design, consisting of a 2D-MOT and a following 3D-MOT, to launch the cloud of cold atoms into the interferometer chamber. The laser detuning in the 3D-MOT is controlled by four custom build frequency generators which are all phase locked to a common reference, allowing precise control of the forward and vertical launch velocity of the atoms. The optical transitions used for the atom interferometer are based on Raman transitions between the two ground-states of ^{87}Rb and are driven by two MOPA systems stabilised to a very stable microwave reference.

The shotnoise limited sensitivity of the interferometer, when completed, is expected to be $2 \cdot 10^{-9}$ rad/s for $1 \cdot 10^{8}$ atoms per shot with a velocity of 3 m/s.

[1] C. Jentsch, T. Muller, E.M. Rasel, and W. Ertmer, Gen. Rel. Grav. 36(10), 2197(2004)

Design of the Cold Atom PHARAO Space Clock and Initial Test Results

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Abstract

We describe the cold atom clock PHARAO designed for microgravity operation. All elements of the PHARAO engineering model have been manufactured and delivered to CNES, the French space agency. We present the clock design, its main characteristics and initial science operation. PHARAO is one of the main components of the ACES payload which is scheduled to fly on board the International Space Station in 2011 [1].

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Part III

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