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HYPER : ATOM INTERFEROMETRY IN SPACE

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The objective of the HYPER project is to use the very high sensitivity of the atomic interferometry in space for research in fundamental physics This project is sustained by many scientists in the atomic physics community [1] and by ESA. After a short introduction, the second part will describe the recent development in atom interferometry. The third part is dedicated to the description of the mapping of the Lense-Thirring effect with an atomic gyroscope.

1 Introduction

Inertial Sensors are useful device in both science and industry. Higher precision sensors could find practical scientific applications in the areas of general relativity [2], geodesy and geology. Important applications of such devices occur also in the field of navigation, surveying and analysis of structures. Matter-wave interferometry has recently shown its potential to be an extremely sensitive probe for inertial forces [3]. First, neutron interferometers have been used to measure the rotation of the earth [4] and the acceleration due to gravity [5] in the end of the seventies. In 1991, atom interference techniques have been used in proof-of-principle work to measure rotations [6] and accelerations [7]. In the following years, many theoretical and experimental works have been performed to investigate this new kind of inertial sensors [8]. Some of the recent works have shown very promising results leading to sensitivity comparable to other kind of sensors, as well for rotation [9] as for acceleration [10].

2 Inertial sensors based on atom interferometer: basic principal

We present here a summary of recent work with light-pulse interferometer-based inertial sensors. We first outline the general principles of operation of light-pulse interferometers. This atomic state interferometer [11,12] uses two-photon velocity selective Raman transitions [13], to manipulate atoms while keeping them in long-lived ground states.

2.1 Principle of a light pulse matter-wave interferometer

Light-pulse interferometers work on the principle that when an atom absorbs or emits a photon momentum must be conserved between the atom and the light field. Consequently, an atom which emits (absorbs) a photon of momentum $\hbar k_{eff}$ will receive a momentum impulse of $\delta p = -\hbar k_{eff}(+\hbar k_{eff})$. When a resonant traveling wave is used to excite the atom, the internal state of the atom becomes correlated with its momentum: an atom is in its ground state $|1\rangle$ with momentum p (labeled $|1,p\rangle$) is coupled to an excited state $|2\rangle$ of momentum ($|2, p+\hbar k_{eff}\rangle$) [11]. A precise control of the light-pulse duration allows a complete transfer from one state (for example $|1,p\rangle$) to the other ($|2, p+\hbar k_{eff}\rangle$) in the case of a π pulse and a 50/50 splitting between the 2 states in the case of a $\pi/2$ pulse (half the duration of a π pulse).

We use a $\pi/2 - \pi - \pi/2$ pulse sequence to coherently divide, deflect and finally recombine an atomic wavepacket. The first $\pi/2$ pulse excites an atom initially in the $|1,p\rangle$ state into a coherent superposition of states $|1,p\rangle$ and $|2, p+\hbar k_{eff}\rangle$. If state $|2\rangle$ is stable against spontaneous decay, the two wavepackets will drift apart by a distance $\hbar kT/m$ in time T. Each wavepacket is redirected by a π pulse which induces the transitions $|1,p\rangle \rightarrow |2, p+\hbar k_{eff}\rangle$ and $|2, p+\hbar k_{eff}\rangle \rightarrow |1,p\rangle$. After another interval T the wavepacket once again overlap. A final pulse causes the two wavepackets to interfere. The interference is detected, for example, by measuring the number of atoms in the $|2\rangle$ state. We obtain large wavepacket separation by using laser cooled atoms and velocity sensitive stimulated Raman transitions [13] to drive the transitions.

2.2 Application to Earth-based inertial sensors

Inertial forces manifest themselves by changing the relative phase of the de Broglie matter waves with respect to the phase of the driving light field, which is anchored to the local reference frame. The physical manifestation of the phase shift is a change in the number of atoms in, for example, the state $|2\rangle$, after the interferometer pulse sequence as described above.

If the 3 light pulses of the pulse sequence are only separated in time, and not separated in space (*i.e.* if the velocity of the atoms is parallel to the laser beams), the interferometer is in a gravimeter or accelerometer configuration . In a uniformly accelerating frame with the atoms, the frequency of the driving laser changes linearly with time at the rate of $-k_{eff}.a$. The phase shift arises from the interaction between the light and the atoms [8] and can be written:

$$\Delta\phi = \phi_1(t_1) - 2\phi_2(t_2) + \phi_3(t_3) \tag{1}$$

where $\phi_i(t_i)$ is the phase of light pulse i at time t_i relative to the atoms. If the laser beams are vertical, the gravitationally induced chirp can be written:

$$\Delta\phi = -k_{eff}.gT^2 \tag{2}$$

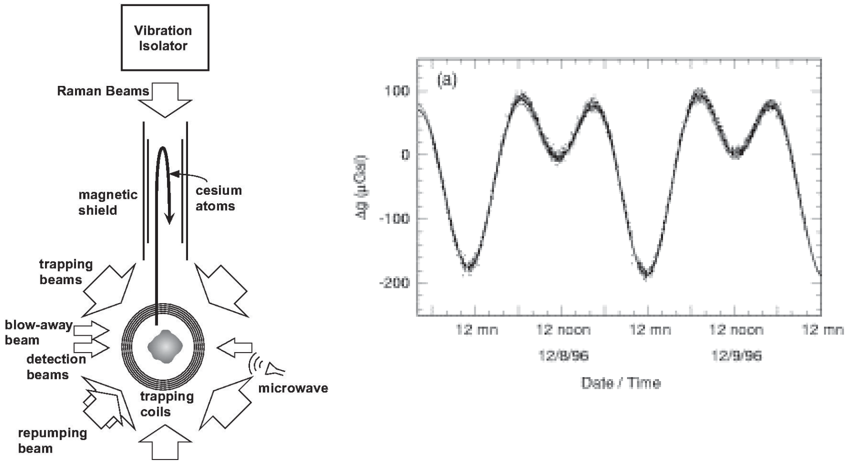

Figure 1. Principle of the atom-fountain-based atom gravimeter achieved in S. Chu (Nobel 1998) group at Stanford. Left shows a two days recording showing the variation of gravity (top curve). The accuracy enable to resolve ocean loading effects (curve i and ii correspond to residual compare to models with or without ocean loading taken into account).

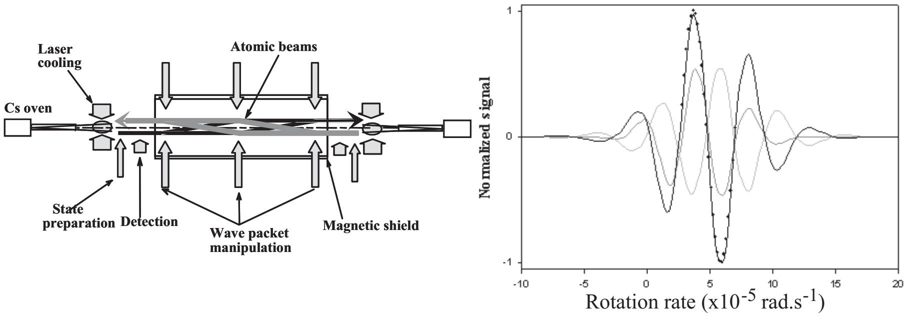

Figure 2. Schematic of the atomic Sagnac interferometer at Yale [9] on left. Individual signals from the outputs of the two interferometer(gray lines), and difference of the two signals corresponding to a pure rotation signal (black line) versus rotation rate.

It should be noted that this phase shift does not depend on the atomic initial velocity or on the mass of the particle. Recently, atomic gravimeter with comparable accuracy than best corner cube has been achieved [10].

The main limitation of this kind of gravimeter on earth is is due to spurious acceleration from the reference platform. Measuring gravity gradient may allow to overcome this problem. indeed, by using the same reference platform for two independent gavimeters enable to extract gravity fluctuations. Such apparatus [14], using two gravimeters as described above but shearing the same light pulses, has shown a sensitivity of $3.10^{-8}s^{-2}.Hz^{-1/2}$ and as a potentiel on earth up to $10^{-9}s^{-2}.Hz^{-1/2}$.

If the laser beams are separated in space (i.e. if the atomic velocity is perpendicular to the direction of the laser beams), the interferometer which is formed is in a Mach-Zenhder configuration. In this case, the interferometer is also sensitive to rotations, as in the Sagnac geometry [15] for light interferometers . For a Sagnac loop enclosing area A, a rotation Ω produces a phase shift:

$$\Delta\phi_{Sagnac} = \frac{4\pi}{\lambda v_L}\Omega.A \tag{3}$$

where λ is the particle wavelength and v_L its longitudinal velocity. The area A of the interferometer depends on the distance between two pulses L and recoil velocity $V_T = \hbar k/m$:

$$A = L^2\frac{V_T}{V_L} \tag{4}$$

Thanks to the use of massive particle, atomic interferometer can achieve very high sensitivity. An atomic gyroscope [9] using thermal caesium atomic beams ($v_L \sim 300m.s^{-1}$) and with a overall interferometer length of $2m$ has demonstrated a sensitivity of $6.10^{-10}rad.s^{-1}.Hz^{-1/2}$. The apparatus consists on a double interferometer using two counter-propagating sources of atoms and shearing the same lasers which enables to discriminate between rotation and acceleration.

Improvements of an atomic Sagnac interferometer relies on the increase of the enclosed surface which is determined by the ratio of the atomic beam velocity v_L to the velocity v_T of both atomic waves relative to each other due to the beam splitting process. Therefore using cold atomic source (with velocity dispersion close to the recoil velocity) will enable to achieve a ratio of v_T/v_L close to unity. The improvements with HYPER will follow precisely this philosophy and will benefit from the space environment, which enable very long interaction time (few seconds) and low spurious vibrational level. Presently first prototypes based on atomic fountains of laser cooled atoms are under construction in a joint project of LPTF, IOTA and LHA in Paris as well as at the IQO in Hannover.

3 Latitudinal mapping of the gravitomagnetic effect with HYPER

The Lense-Thirring effect consists on a precession of a local referential frame (realized by inertial gyroscopes) and non-local referential realized by direction of fixed stars. This Lenth-Thirring precession is given by:

$$\Omega_{LT} = \frac{GI}{c^2}\frac{3(\omega.r)r - \omega r^2}{r^5} \tag{5}$$

The high sensitivity of atomic Sagnac interferometer for rotation rates will enable HYPER to measure the latitudinal structure of the gravitomagnetic or Lense-Thirring effect while the satellite orbits around the Earth. In a Sun-synchronous, circular orbit at 700 km altitude, HYPER will detect how the direction of the Earth's drag varies over the course of the near-polar orbit as a function of the latitudinal position θ:

$$\begin{pmatrix} \Omega_x \\ \Omega_y \end{pmatrix} \propto \frac{3}{2}\begin{pmatrix} sin(2\theta) \\ cos(2\theta) - \frac{1}{3} \end{pmatrix} \tag{6}$$

with $\overrightarrow{J} \| \overrightarrow{e_y}$, $\theta \equiv arcos(r.e_x)$ the coordinate system, spanned by e_x and e_y, defines the orbital plane.

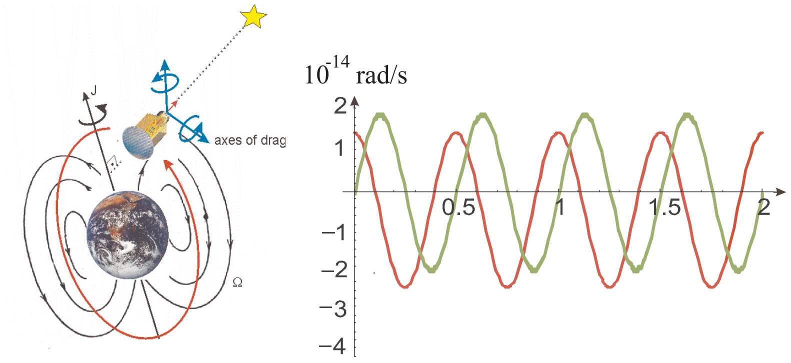

Figure 3. Schematic of the measurement of the Lense-Thirring effect. The black lines visualise the vector field of the Earth's drag Ω_{LT}. The sensitive axes of the two ASUs are perpendicular to the pointing of the telescope. The direction of the Earth's drag varies over the course of the orbit showing the same structure as the field of a magnetic dipole. Due to this formal similarity the Lense-Thirring effect is also called gravitomagnetic effect. The modulation of the rotation rate Ω_{LT} due to Earth's gravitomagnetism as sensed by the two orthogonal ASUs in the orbit around the Earth appears at twice the orbit frequency.

HYPER carries two atomic Sagnac interferometers, each of them is sensitive to rotations around one particular axis and a telescope used as highly sensitive star-tracker ($10^{-9}rad$ in the 0.3 to 3 Hz bandwidth). The two units will measure the vector components of the gravitomagnetic rotation rate along the two axes perpendicular to the telescope pointing which is directed to a guide star. The drag variation written above describes the situation for a telescope pointing in the direction perpendicular to the orbital plane of the satellite. The orbit, however, changes its orientation over the course of a year which has to be compensated by a rotation of the satellite to track continuously the guide star. Consequently the pointing of the telescope is not always directed parallel to the normal of the orbital plane. According to the equation, the rotation rate signal will oscillate at twice the frequency of the satellites revolution around the Earth. The modulated signals have the same amplitude (3.75x$10^{-14}rad.s^{-1}$) on the two axes but are in quadrature. The resolution of the atomic Sagnac units is about $10^{-12}rad.s^{-1}$ for a drift time of about $3s$. Repeating this measurement every 3 seconds the ASU's will reach after 3 hours the level of $10^{-14}rad.s^{-1}$, in the course of one year the level of $2.10^{-16}rad.s^{-1}$, i.e. a hundredth of the expected effect.

4 Conclusion

Previous experiments measuring the gravitational acceleration of Earth and its gradient or rotations have been demonstrated to be very promising. Sensitivities better than $1 nrad.s^{-1}.Hz^{-1/2}$ for rotation measurements and $2.10^{-8} g.Hz^{-1/2}$ for gravity measurement have already been obtained. The sensitivity of matter-wave interferometers for rotations and accelerations increases with the measurement time and can therefore be dramatically enhanced by reducing the atomic velocity. Laser cooling can efficiently reduce the speed of the atoms but cannot circumvent the acceleration due to gravity. On the ground the 1-g gravity level sets clear limitations to the ultimate sensitivities. HYPER-precision atom interferometry in space opens up entirely new possibilities for research in fundamental physics with unprecedented precision. The cold atom interferometers carried by HYPER will be accommodated in a drag-free spacecraft in a low-Earth, Sun-synchronous orbit. The primary scientific objectives of the HYPER mission are to test General Relativity by mapping (latitudinal) structure (magnitude and sign) of the Lense-Thirring effect, to determine the fine structure constant by measuring the ratio of Planck's constant to the atomic mass and to test the equivalence principle on individual atoms, a complement to other space tests of the equivalence principle using massive bodies (STEP, MICROSCOPE).

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