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► **To cite this version:**

Alexis Bonnin, Yannick Bidel, Jeanne Bernard, Cedric Blanchard, Malo Cadoret, et al.. Marine and Airborne Gravimetry with an Absolute Cold Atom Sensor. 2022 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL), May 2022, Avignon, France. <10.1109/INERTIAL53425.2022.9787747>. <hal-03739336>

HAL Id: hal-03739336

<https://hal.science/hal-03739336v1>

Submitted on 27 Jul 2022

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Marine and Airborne Gravimetry with an Absolute Cold Atom Sensor

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Abstract—Gravity field mapping from moving vehicles as ship or aircraft allows to cover large regional areas with a spatial resolution ranging from typically 1 to 10 km. In this paper, we present an absolute cold atom gravimeter capable of performing high performance measurements in such dynamical environments. The demonstrated stability and repeatability reached typically few $0.1 \times 10^{-5} \text{ m.s}^{-2}$ in a marine campaign [1] and few $1 \times 10^{-5} \text{ m.s}^{-2}$ in an airborne survey [2]. The intrinsic very high stability of this atom sensor allows to relax many operational constraints linked to drifts or calibration processes and to obtain repeatable and harmonized gravity maps on long time scales.

Index Terms—On-board gravimetry, cold atom inertial sensor

I. INTRODUCTION

Since more than twenty years, light pulse atom interferometers interrogating free-falling cold atomic samples has proven to be a very powerful technique to built high performance gravimeters. Those devices could then be used to produce gravity field maps which are of great interest in geodesy [3], geophysics [4], exploration [5] and navigation [6]. In that context, on-board measurements from a ship or an aircraft play a major role by filling the gap between static gravity measurements at given locations and satellite missions from which long wavelength components ($>200 \text{ km}$) can be extracted. They are also of great interest to cover coastal areas where discrepancies exist between terrestrial, marine, and satellite altimetry data.

In cold atom gravimeters, gravity is obtained from the acceleration measurement of a gas of cold atoms using

matter-wave interferometry [7]. In static configuration, this technology has reached extremely high performance: short term sensitivity of $5.7 \times 10^{-8} \text{ m.s}^{-2}.\text{Hz}^{-1/2}$ [8], long term stability of $0.05 \times 10^{-8} \text{ m.s}^{-2}$ [9], accuracy of $1.3 \times 10^{-8} \text{ m.s}^{-2}$ [10]. It is also commercialized since few years [11]. In dynamical environment, where only relative sensors were previously available, such gravimeters appear notably relevant as they contain no mechanical moving parts, they can work at repetition rates of 10 Hz and they perform accurate and stable measurements.

Here we report on the GIRAFE cold atom gravimeter which is the first sensor of his class that have performed absolute marine and airborne gravity surveys. After describing the basic principle of the sensor and the achieved static performance, the global precisions reached during three marine surveys and two airborne surveys will be presented and compared. These results sustain the stability and repeatability of the measurements over few years of operation.

II. SENSOR DESCRIPTION

The test mass is a collection of $\sim 10^6$ cold atoms of rubidium 87 generated from a magneto-optical trap. Its temperature is about $2 \mu\text{K}$, corresponding to a velocity dispersion of the atomic ensemble of about 1 cm.s^{-1} . After the atoms are released from the trap, they are prepared in a magnetically insensitive sub-state. During the free fall, the acceleration of the atoms is measured thanks to a Mach-Zehnder type atom interferometer [7] consisting of three laser pulses of duration 10-20-10 μs each separated by a time T . In our gravimeter,

the maximal duration of the interferometer is $2T = 40$ ms in a dynamical environment. The laser is retro-reflected on a mirror and phase modulated at 6.834 GHz [12] in order to drive two-photon stimulated Raman transitions between two internal states of the atoms. Each change of internal state is accompanied with a change of momentum by a quantity $\hbar\vec{k}_{\text{eff}}$, where $|\vec{k}_{\text{eff}}| \sim \frac{4\pi}{\lambda} \sim \frac{4\pi}{780 \text{ nm}}$ is the effective wave-vector of the two-photon Raman transition. This opens a physical area between the two arms of the interferometer making the final phase shift sensitive to inertial effects. At the interferometer output, the probability P of ending in one of the two internal state is estimated by counting the atom number in each state thanks to fluorescence detection. In the Mach-Zehnder type configuration, it is given by

$$P = P_0 + \frac{A}{2} \cos(\vec{k}_{\text{eff}} \cdot \vec{a} T^2) \quad (1)$$

where \vec{a} is the acceleration between the atoms and the retro-reflected mirror and P_0 and A are the fringe offset and amplitude. For $2T = 40$ ms the atomic sensor operates at a repetition rate of 10 Hz.

As shown in equation (1), an atom interferometer measures the projection of the atoms free-fall acceleration along the laser direction of propagation. That is why the sensor head needs to be gyro-stabilized vertically to actually measure gravity (*cf.* Fig. 1). For this purpose we use a two-axis gyro-stabilized gimballed platform (iMAR) that maintains the measurement axis align with gravity at the $100 \mu\text{rad}$ level.

This type of atomic sensor suffers from two main drawbacks: (i) there are measurements dead-times, while preparing and detecting the atomic sample, during which gravity is not measured, (ii) there is an ambiguity on the acceleration value as the observable P is a sinusoidal function of this physical quantity with a period of $\frac{\lambda}{2T^2} \sim 1 \times 10^{-3} \text{ m.s}^{-2}$ for $T = 20$ ms. To overcome these limitations the atomic sensor is hybridized with a classical accelerometer [13]: a force balanced Q-Flex accelerometer from Honeywell. First, we use this classical accelerometer to fill the measurement dead-times. This allows to avoid the deleterious effect of aliasing, especially in a dynamical environment where the sensor can experience a broad spectrum of accelerations. Second, we use the classical accelerometer measurement during the interferometer to provide a rough estimation of the acceleration which permit to solve the fringe ambiguity. On the other hand, the atom accelerometer is used to continuously track and estimate the bias and the scale factor of the classical accelerometer. This hybridization scheme works only if the correlation of the two acceleration signals given by the two sensor is of good quality within the range of $\frac{\lambda}{2T^2}$ (*cf.* Fig. 1). The algorithm optimizes this correlation by tuning the interrogation T within $\{2.5; 5; 10; 20\}$ ms. For instance, when the correlation quality decreases (because of accelerometric transfer function uncertainties, alignment defaults, non co-located measurements...), T is also decreased to relax the need of matching both acceleration signals but at the cost of sensitivity and precision loss. Details about this algorithm can

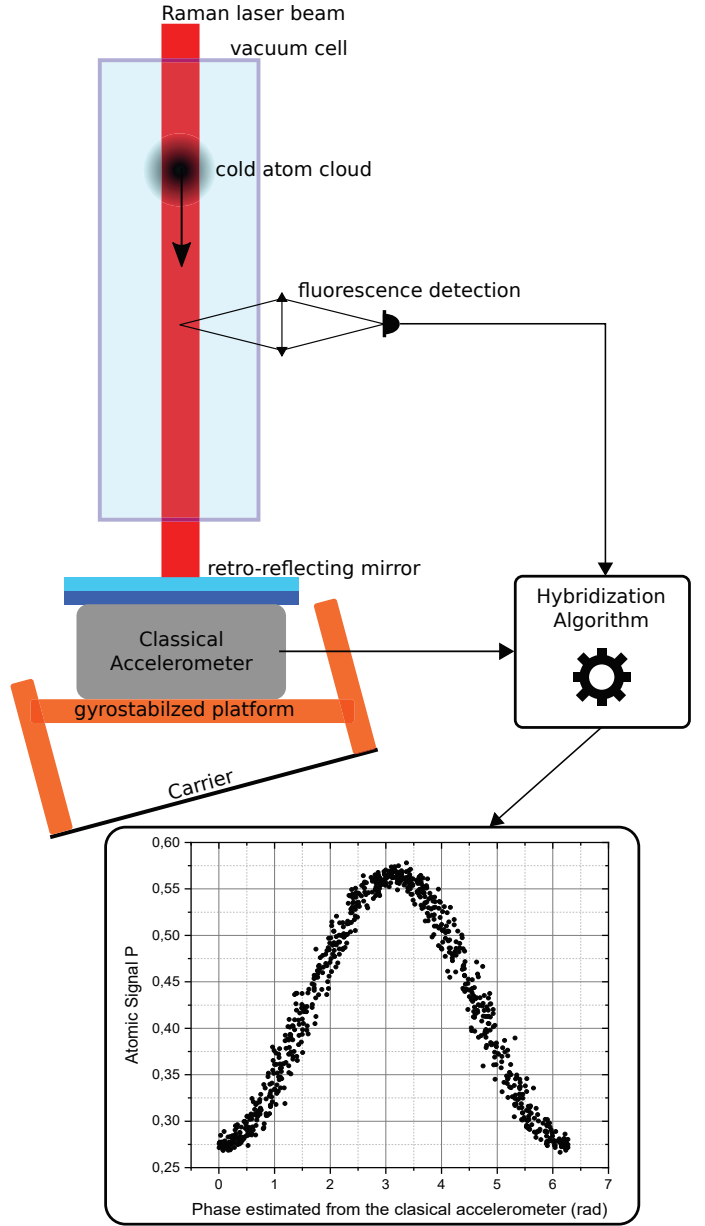


Fig. 1. Simplified scheme of the global principle of the sensor. The main key components are displayed: the mechanical components as the vacuum cell, the optics, the retro-reflecting mirror, the accelerometer are rigidly bound/linked inside the sensor head. The final gravity measurement relies on the hybridization between the atom accelerometer and the high performance classical accelerometer. A typical correlation fringe between the two accelerometric signals is displayed.

be found in [1]. In conclusion it allows to combine the advantages of both technologies: namely the accuracy and long-term stability of the atomic sensor with the high bandwidth and high dynamic range of the force balanced sensor.

The atom gravimeter is implemented in a compact housing consisting of a cylinder of 22 cm diameter and 52 cm height placed into the gyro-stabilized platform. It contains the vacuum chamber, magnetic coils, optics, three classical accelerometers. It is magnetically shielded by two layers of

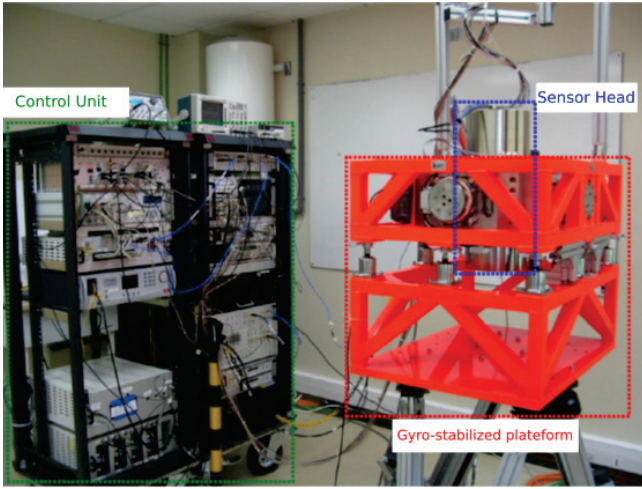


Fig. 2. Picture of the gravimeter system.

mu-metal. The frequency doubled telecom laser system, electronics, power supply and control system are assembled in transportable racks of 38 U and connected to the sensor head through 5 m long wires and optical fibers (see Fig. 2).

III. STATIC MEASUREMENTS

The performance of the atom gravimeter has been characterized in static condition. The Allan standard deviation after a typical static measurement for few hours is displayed in Fig. 3. The short term sensitivity is about $0.75 \times 10^{-5} \text{ m.s}^{-2} \cdot \text{Hz}^{-1/2}$ and is limited by the sensitivity of the forced balanced accelerometer. After correcting the measurement from gravimetric tides at the gravimeter location, a long term stability of about $\sim 10 \times 10^{-8} \text{ m.s}^{-2}$ is reached for an integration time of about 10^4 s .

The strength of atomic sensors is that they can provide very accurate and stable measurements. In static operation, as the retro-reflecting mirror does not move compared to the ground and as the atoms are in perfect free fall inside the vacuum chamber, the interferometer output phase is simply $\Delta\Phi = (k_{\text{eff}}T^2) \times g$ (cf. equation (1)), if \vec{k}_{eff} and \vec{g} are perfectly aligned, and where \vec{g} is the local gravity vector at the atoms mean position. The scale factor of the atom sensor ($k_{\text{eff}}T^2$) is accurately known as the laser wavelength $\lambda = \frac{4\pi}{|k_{\text{eff}}|}$ is referenced to an atomic transition of ^{87}Rb and as the time base and frequencies are referenced to an rubidium-disciplined crystal clock locked on the PPS signal from GPS when available. Thus the true and accurate value of g can be directly derived from the interferometric phase in the SI system. In practice there exist systematic effects that need to be carefully estimated in order to correct for the biases. The main systematic effects are listed in table I for the different interrogation times are more detailed in the methods section of [1]. Note that in static operation a longer interrogation time $T = 39.5 \text{ ms}$ is also accessible using a longer falling distance and a lower fluorescence imaging system. For $T = 20 \text{ ms}$, the main uncertainties on the systematic effects are due to

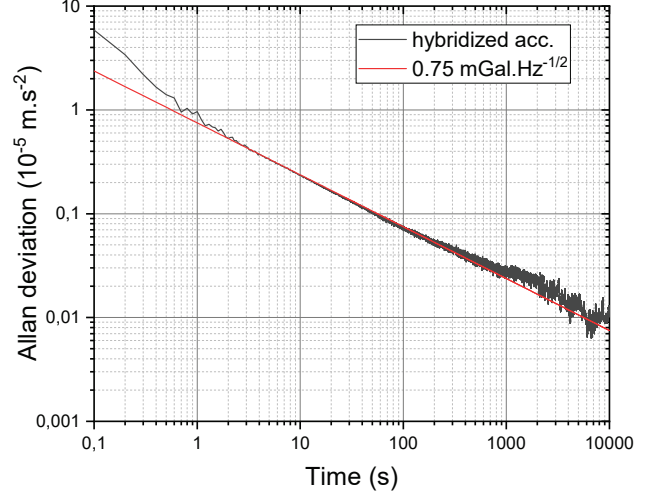


Fig. 3. Allan standard deviation of the atom gravimeter in static mode in units of $1 \times 10^{-5} \text{ m.s}^{-2}$ for $T = 20 \text{ ms}$. The measurement is corrected from the gravimetric tides at the gravimeter location. The sensitivity is $0.75 \times 10^{-5} \text{ m.s}^{-2} \cdot \text{Hz}^{-1/2}$ and the long term stability reaches here $\sim 10 \times 10^{-8} \text{ m.s}^{-2}$.

the additional laser lines (coming from the phase modulation scheme the Raman laser) and to the Raman laser frequency. The total estimated accuracy is about $0.076 \times 10^{-5} \text{ m.s}^{-2}$. In order to confirm this level of accuracy, the measurement of the atomic sensor was compared to an absolute reference gravity value in our lab and a final discrepancy of $0.1 \times 10^{-5} \text{ m.s}^{-2}$ was obtained. Despite these systematics, the biases are well understood and controlled and remains stable over time as proved by Fig. 3. This ensures a stable and accurate gravity measurement at the $0.1 \times 10^{-5} \text{ m.s}^{-2}$ level.

IV. ON-BOARD MEASUREMENTS

This sensor was also used to carry out in-field marine [1] and airborne [2] gravity surveys since 2015. In such dynamical environments the gravimeter also measured the kinematic acceleration of the carrier and the acceleration resulting from the coupling between the Earth rotation and the horizontal velocity of the vehicle (Eötvös Effect). The acceleration actually measured by the gravimeter is then given by:

$$a_{\text{meas}} = g + \ddot{h} + a_{\text{Eot}} \quad (2)$$

where \ddot{h} is the time second derivative of the ellipsoidal height (vertical kinematic acceleration of the carrier) and a_{Eot} is the Eötvös acceleration (see [2] for more details).

On a ship and in an airplane, the Eötvös acceleration is estimated and corrected using GNSS and navigation data. On a ship the vertical kinematic acceleration, resulting from the ocean swell and waves, is not corrected but simply filtered out with typically 4th or 5th order Bessel filter with cut off frequencies of about $\frac{1}{100\text{s}}$. These parameters depend on the sea state and result from a compromise between targeted precision

TABLE I
SYSTEMATIC EFFECTS IN UNIT OF $1 \times 10^{-5} \text{ m.s}^{-2}$

T	2.5 ms	5 ms	10 ms	20 ms	39.5 ms
Systematic Effect					
Light Shifts	12.3 ± 1.2	3.97 ± 0.49	1.44 ± 0.15	0.42 ± 0.02	0.12 ± 0.01
Additional Laser lines	-0.823 ± 0.041	-0.822 ± 0.053	-0.66 ± 0.074	-0.548 ± 0.045	0.700 ± 0.048
Microwave Frequency	0 ± 0.005	0 ± 0.005	0 ± 0.005	0 ± 0.005	0 ± 0.005
Coriolis Effect	0 ± 0.03	0 ± 0.03	0 ± 0.03	0 ± 0.03	0 ± 0.03
Wavefront Curvature.	0 ± 0.026	0 ± 0.026	0 ± 0.026	0 ± 0.026	0 ± 0.026
Microwave Power	0 ± 0.136	0 ± 0.068	0 ± 0.034	0 ± 0.017	0 ± 0.009
Magnetic Field	0 ± 0.01	0 ± 0.01	0 ± 0.01	0 ± 0.01	0 ± 0.01
Raman Laser Frequency	0 ± 2.368	0 ± 0.592	0 ± 0.148	0 ± 0.037	0 ± 0.009
Total	11.477 ± 2.659	3.148 ± 0.774	0.780 ± 0.230	-0.128 ± 0.076	0.820 ± 0.065

and spatial resolution. The vertical accelerations encountered in an aircraft are usually larger in amplitudes and broader in spectrum. Thus, the \dot{h} term needs here to be precisely estimated and corrected using differential and post-processed GNSS data. All the data are also filtered out using Bessel or Gaussian filters with cut off frequencies of about $\frac{1}{100s}$. The demonstrated stability and repeatability reached typically few $0.1 \times 10^{-5} \text{ m.s}^{-2}$ in a marine campaign [1] and few $1 \times 10^{-5} \text{ m.s}^{-2}$ in an airborne survey [2].

V. CONCLUSION

We have presented an absolute cold atom gravimeter used to realize marine and airborne gravity mapping surveys. The final performance in terms of stability and repeatability compares favorably to existing relative commercial gravimeters. These results exhibit the versatility of such sensors to address various vehicles and prove their potential robustness and reliability on long timescales.

To push forward the performance, mainly for airborne applications, the atom gravimeter could be hybridized with a complete inertial unit and would strongly benefit from improvements regarding acquisition and post-processing of GNSS data.

On a more fundamental level, multi-species atom interferometry [14] appears as a promising technique to improve the performance of cold atom gravimeters. For instance, by handling three different atomic species in a single sensor, one could realize an acceleration measurement without dead-times by performing interleaved interferometers [15] with limited cross-talks: indeed the different atomic species require different laser frequencies for preparation, interrogation and detection. Such a configuration would also allow to increase the repetition rate of the measurement, to average faster the vibration noise and to reduce the impact of the classical accelerometer sensitivity on the global short term sensitivity of the sensor.

ACKNOWLEDGMENT

The development of the GIRAFE atom gravimeter was funded by the French Defense Agency (DGA). The marine campaign was done in collaboration with the French Naval

Hydrographic and Oceanographic Service (SHOM). The Iceland airborne campaign was carried out with support from ESA (Cryovex), ONERA and DTU Space.

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