SYRTE l'Observatoire de Paris | PSL

SYstèmes de Référence Temps-Espace

Gravimètres à atomes froids

S. Merlet

LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Paris, France

https://syrte.obspm.fr/spip/science/iaci/

SORBONNE UNIVERSITÉ CRÉATEURS DE FUTURS DEPUIS 1257

cnrs

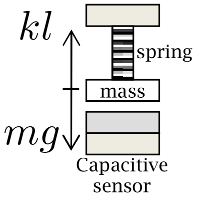
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

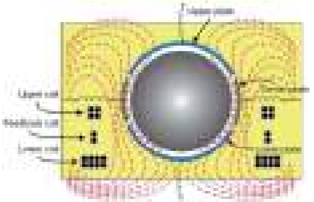
Gravimétrie - Instruments

$$\vec{g} \quad g = |\vec{g}| \qquad \mathrm{grad}\ \vec{g}$$

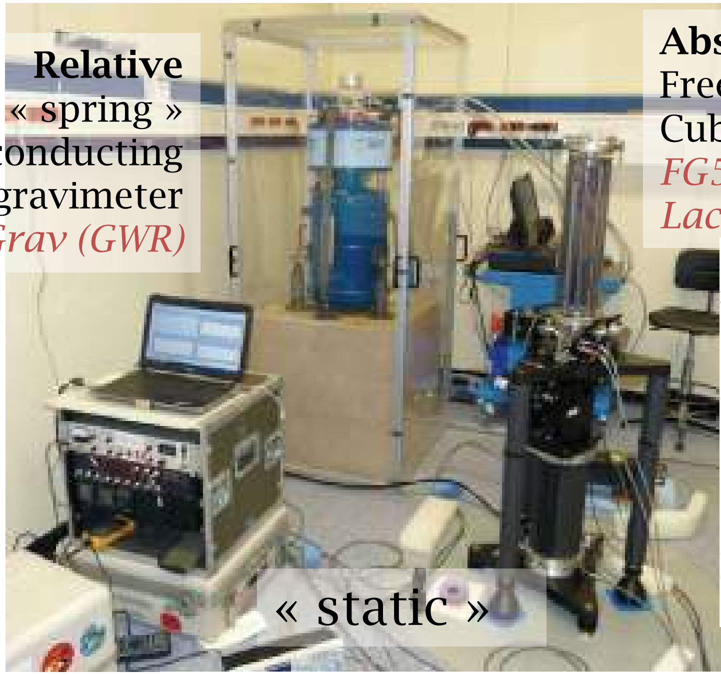
$$\begin{aligned} 1\ \mu Gal &= 10\ nm.s^{-2} \\ &\sim 10^{-9} g \end{aligned} \qquad \begin{aligned} 1\ E &= 10^{-9}\ s^{-2} \\ &= 0.1\ \mu\ Gal.m^{-1} \end{aligned}$$

Gravimeters

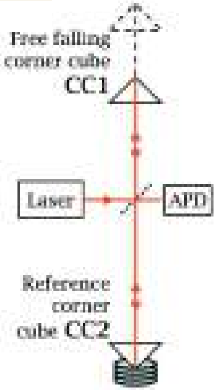




Relative
« spring »
Superconducting gravimeter
iGrav (GWR)


« static »

Absolute
Free Fall Corner Cube
FG5X (Micro-g Lacoste)



Continuous (1 Hz averaged)

$\sim 0.1\ nm.s^{-2}$ in $1\ 000\ s$

Drift (small)
Not accurate, to be calibrated

Not continuous (0.3 Hz)
dead time, #FF limited

$U \sim 20 - 30\ nm.s^{-2}$

$\sim 10\ nm.s^{-2}$ in $90\ s$

Gradiometers

Combination of accelerometers, (gyro stabilized plateform), Electrostatic, superconducting

FTG (Lockheed Martin)

EGG (ARkEX)


« onboard »

GOCE (ESA)

VK1 (UWA)

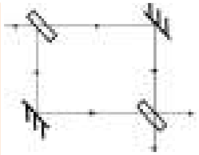
Differential measurements

$$\begin{aligned} FTG:&\ \ 20-2\ E.Hz^{-1/2} \\ SG:&\ \ 0.5\ E.Hz^{-1/2} \\ GOCE:&\ \ \sim 10\ mE.Hz^{-1/2} \end{aligned}$$

Interférométrie Atomique - Principe

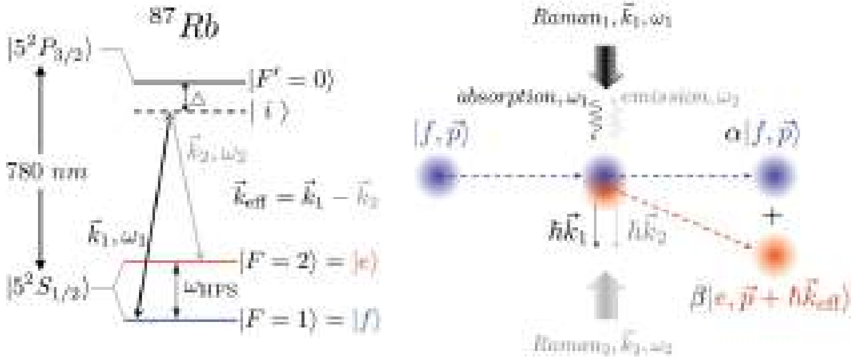
- Interférométrie atomique exploite la dualité onde-corpuscule
- Manipulation cohérente de paquets d’onde atomiques à l’aide de séparatrices laser
- Deux laser contrapropageants réalisent des lames séparatrices et un miroir

- Interféromètre analogue à un Mach Zehnder optique
- Séquence de trois impulsions lasers séparées par un temps d’évolution libre T
- La différence de phase module la population dans les ports de sortie de l’interféromètre



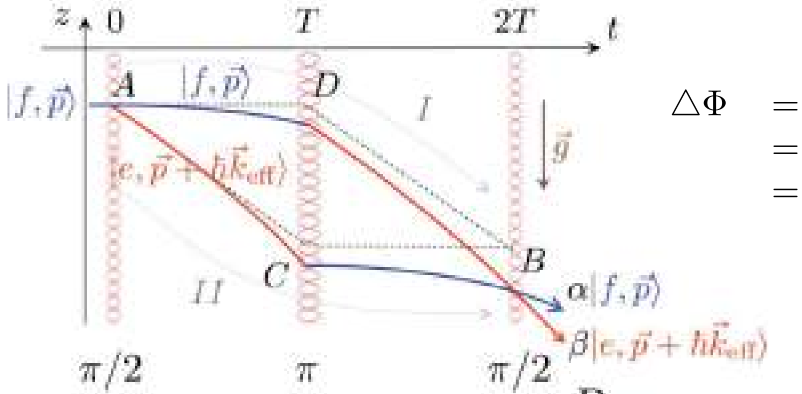
Stimulated Raman transitions

3 level atom



Two photon transition coupling $|f\rangle$ and $|e\rangle$

$$\phi(t) = \omega_{\text{eff}}t - \vec{k}_{\text{eff}}\vec{z}(t) + \varphi_{\text{eff}}(t)$$



$$\begin{aligned} \triangle\Phi &= \Phi_{II} - \Phi_I \\ &= (\phi_A - \phi_C)\text{-}(\phi_D - \phi_B) \\ &= \phi(0) - 2\phi(T) + \phi(2T) \end{aligned}$$

$$P_{|\vec{p}\rangle \to |\vec{p}+\hbar\vec{k}_{\text{eff}}\rangle} = \frac{1}{2}(1 - C\cos\Delta\Phi)$$

$$z = \frac{1}{2}gt^2$$

$$\boxed{\Delta\Phi = -\vec{k}_{\text{eff}}\vec{g}T^2} \rightarrow$$

Scales as T^2, benefits of cold atoms

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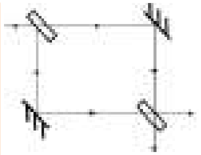

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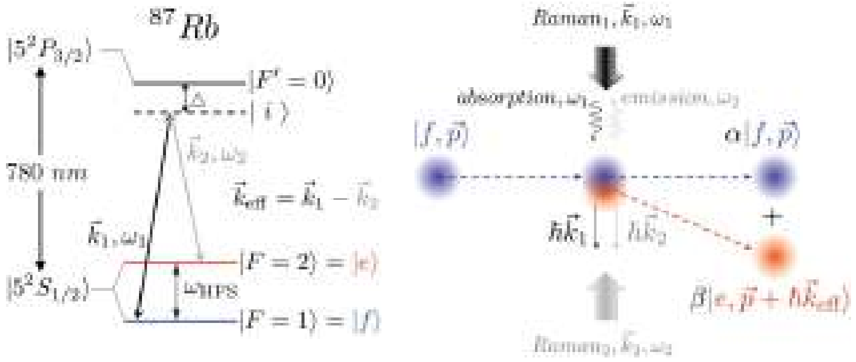

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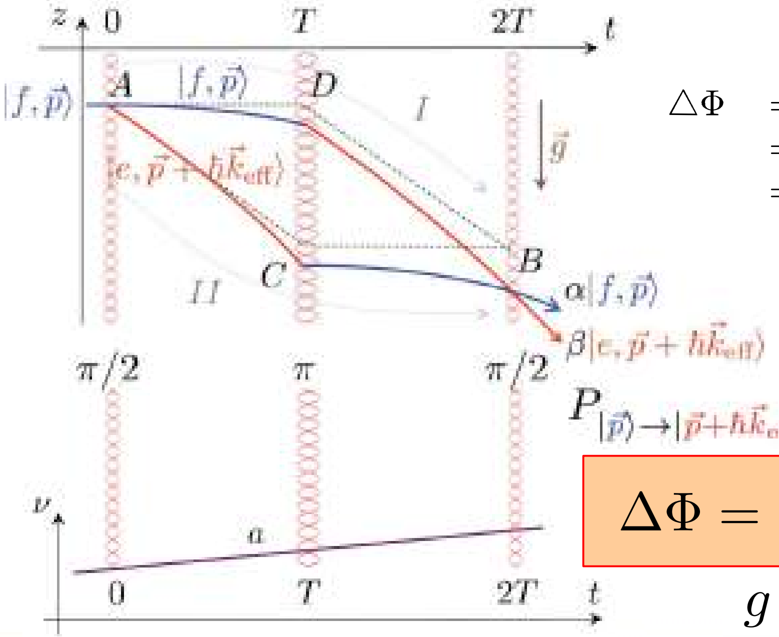

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$$\boxed{\Delta\Phi = -\vec{k}_{\text{eff}}\vec{g}T^2 + aT^2}$$

$$g = a/k_{\text{eff}}$$

Expériences pionnières : USA

VOLUME 67, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JULY 1991

Atomic Interferometry Using Stimulated Raman Transitions

Mark Kasevich and Steven Chu

Departments of Physics and Applied Physics, Stanford University, Stanford, California 94305

(Received 23 April 1991)

The mechanical effects of stimulated Raman transitions on atoms have been used to demonstrate a matter-wave interferometer with laser-cooled sodium atoms. Interference has been observed for wave packets that have been separated by as much as 2.4 mm. Using the interferometer as an inertial sensor, the acceleration of a sodium atom due to gravity has been measured with a resolution of 3×10^{-8} after 1000 sec of integration time.

PACS numbers: 32.80.Pj, 07.60.Ly, 35.80.+s, 42.50.Vk

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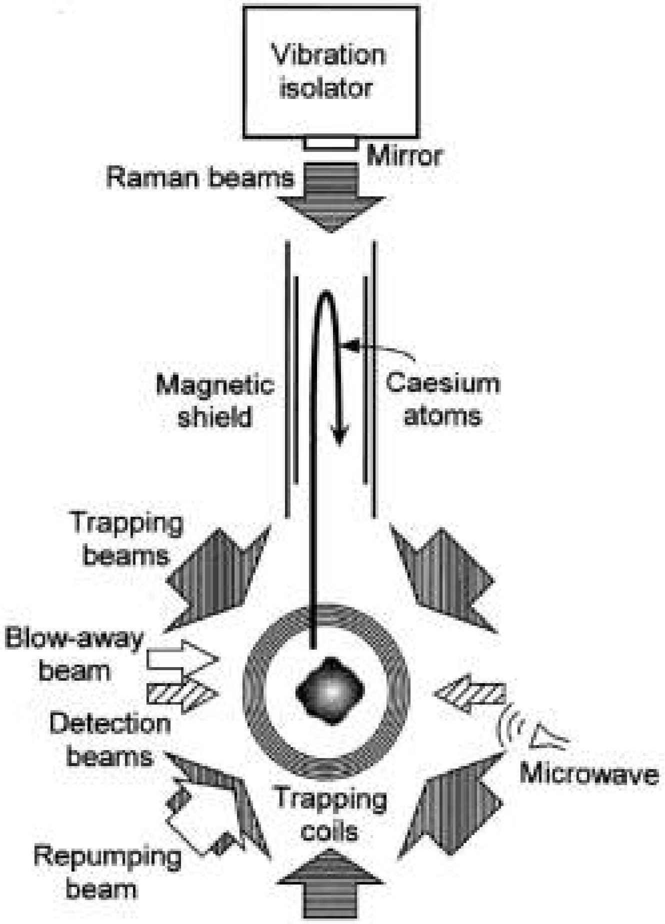
metrologia

High-precision gravity measurements using atom interferometry

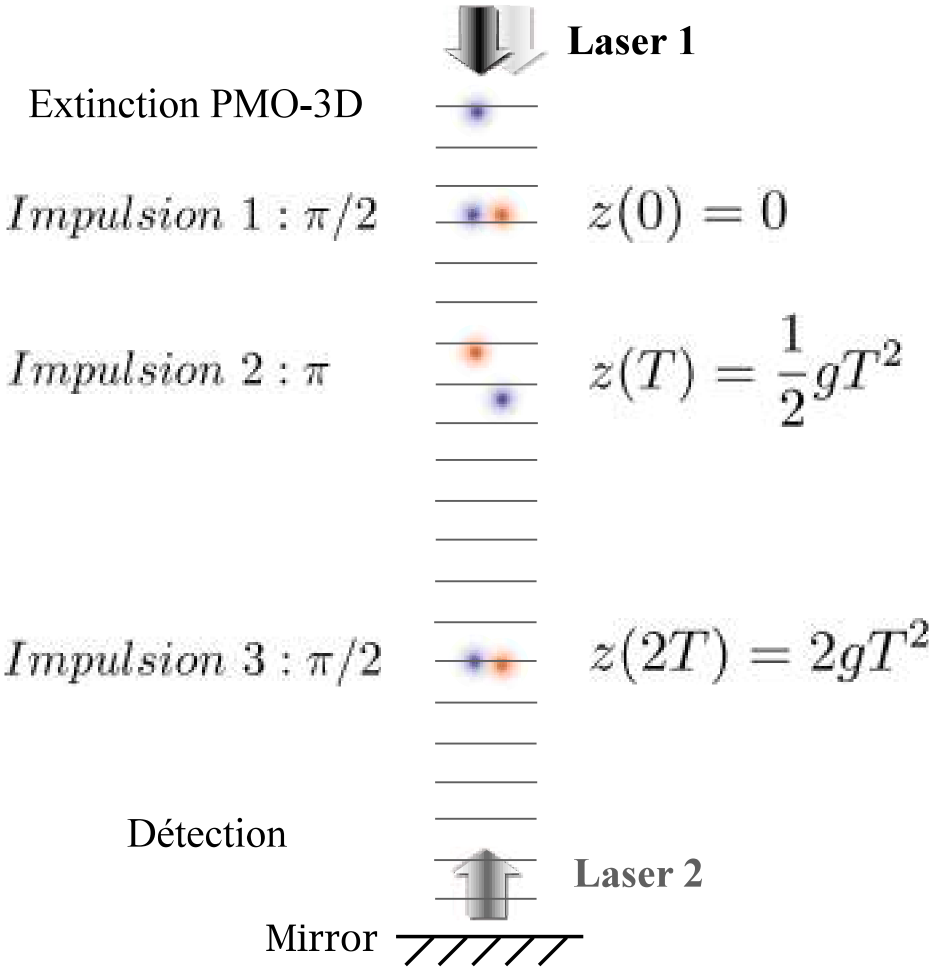
A. Peters, K. Y. Chung and S. Chu

Metrologia, 2001, **38**, 25-61

Abstract. We have built an atom interferometer that can measure g, the local acceleration due to gravity, with a resolution of $\Delta g/g = 2\times10^{-8}$ after a single 1.3 s measurement cycle, 3×10^{-9} after 1 min and 1×10^{-10} after two days of integration time. The difference between our value for g and one obtained by a falling corner-cube optical interferometer is $(7\pm7)\times10^{-9}\,g$. The atom interferometer uses velocity-selective stimulated Raman transitions and laser-cooled caesium atoms in an atomic fountain. We extend previous methods of analysing the interferometer to include the effects of a gravitational gradient. We also present detailed experimental and theoretical studies of potential systematic errors and noise sources.



Gravimètre du LNE-SYRTE



Laser 1

Extinction PMO-3D

$Impulsion\ 1 : \pi/2$ $z(0) = 0$

$Impulsion\ 2 : \pi$ $z(T) = \frac{1}{2}gT^2$

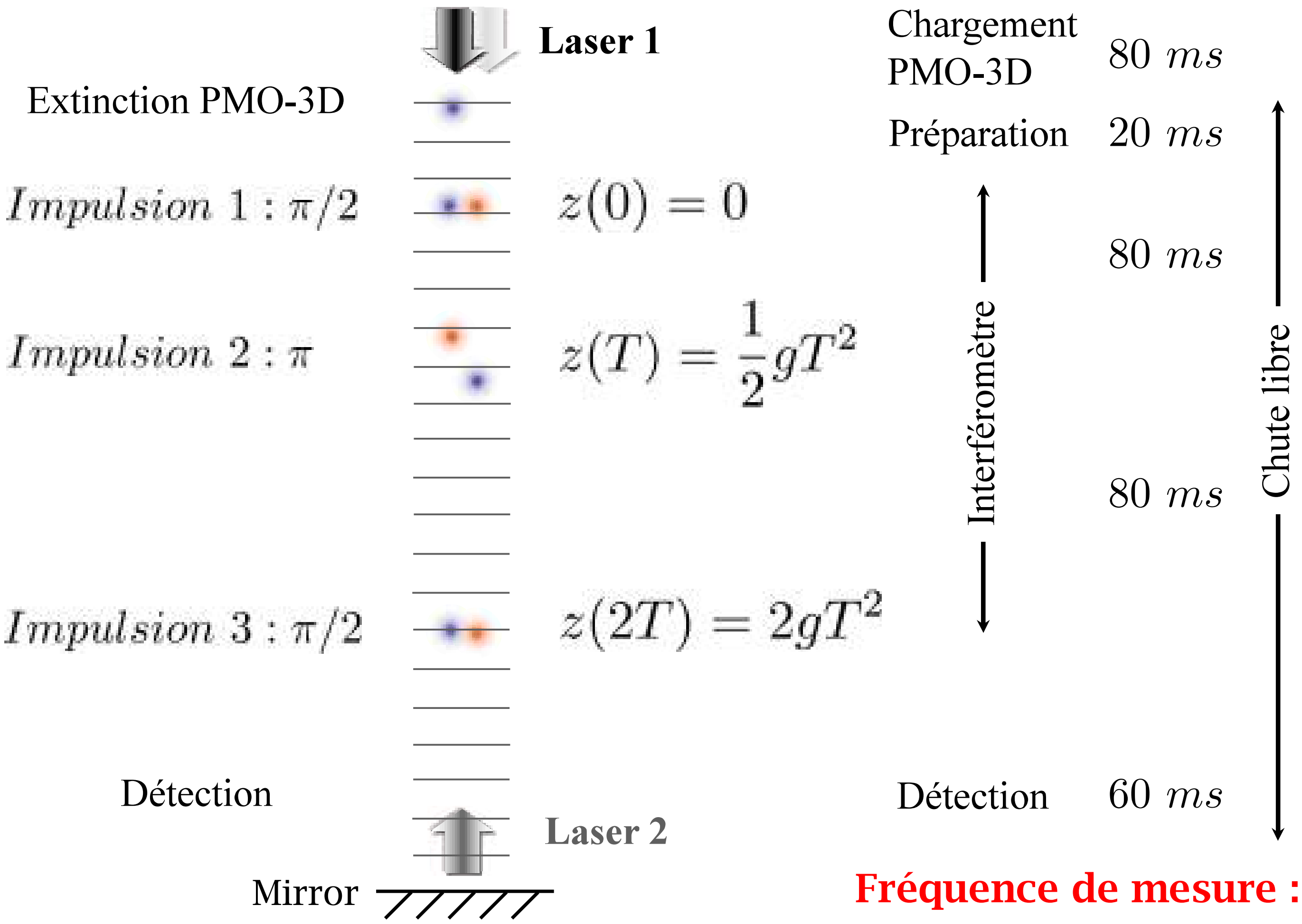
$Impulsion\ 3 : \pi/2$ $z(2T) = 2gT^2$

Détection

Laser 2

Mirror

Gravimètre du LNE-SYRTE



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Impulsion $3 : \pi/2$ $z(2T) = 2gT^2$

Détection

Laser 2

Mirror

Chargement PMO-3D $80\ ms$

Préparation $20\ ms$

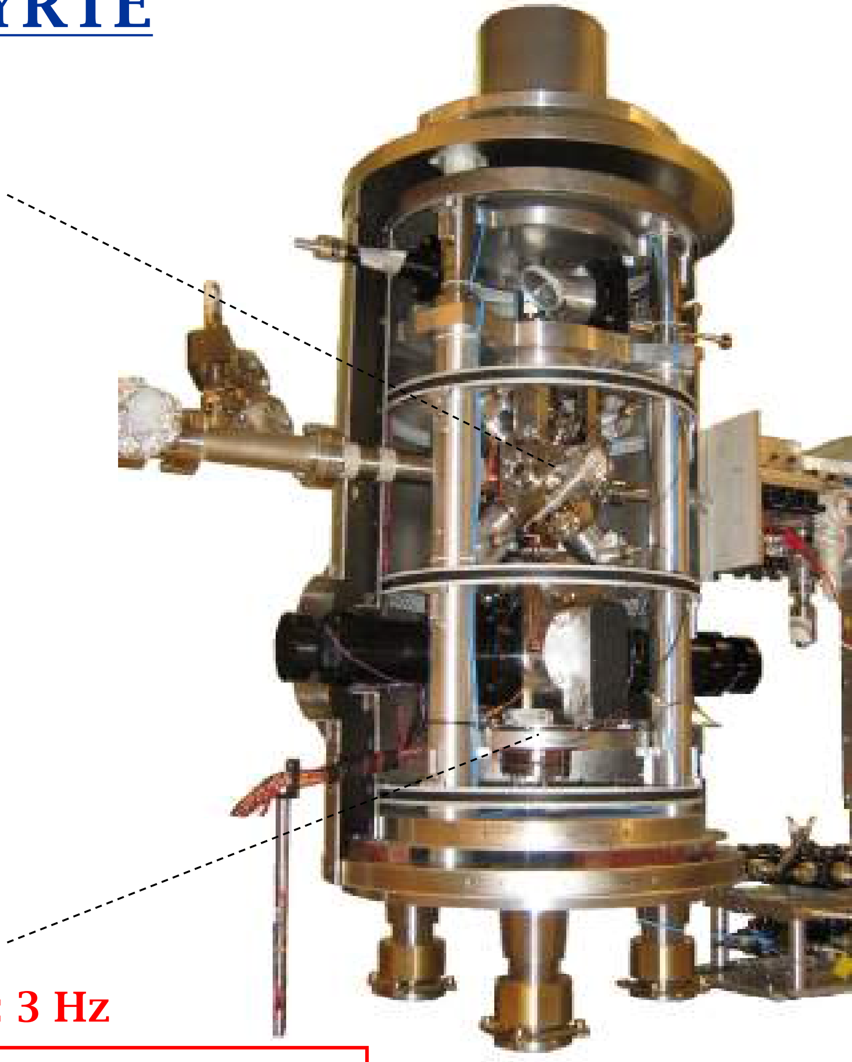
$80\ ms$

$80\ ms$

Détection $60\ ms$

Interféromètre

Chute libre

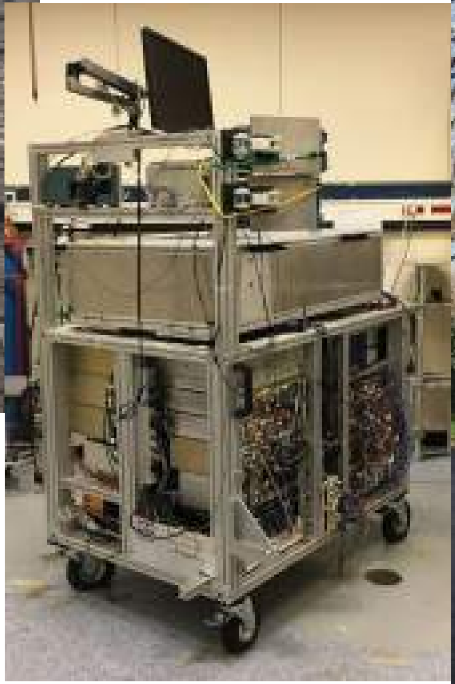


Fréquence de mesure : 3 Hz

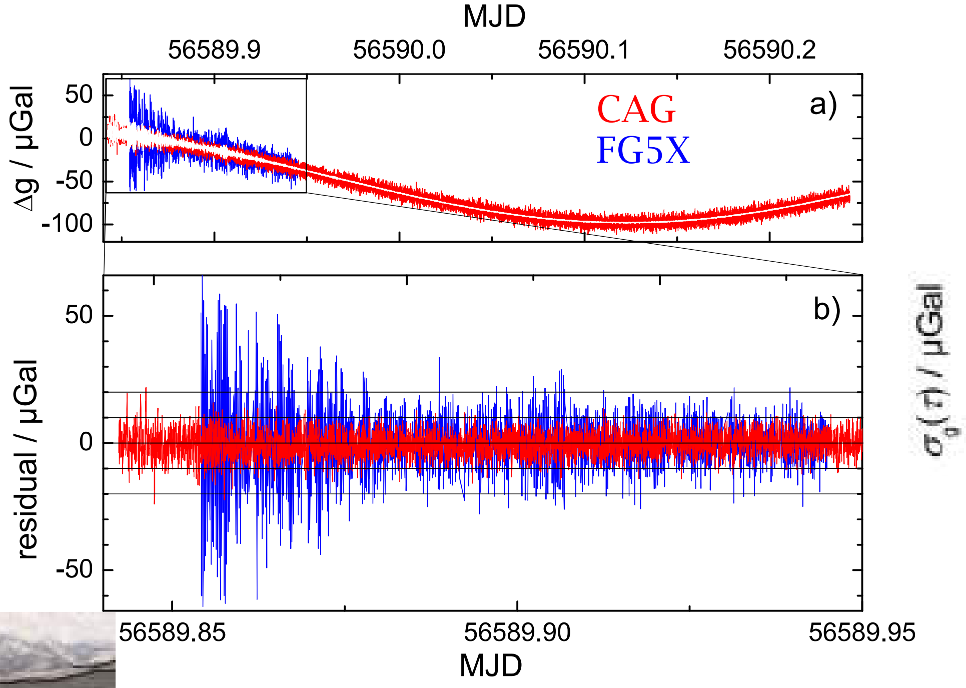
atomic measurement = measure of the relative displacement atoms/mirror

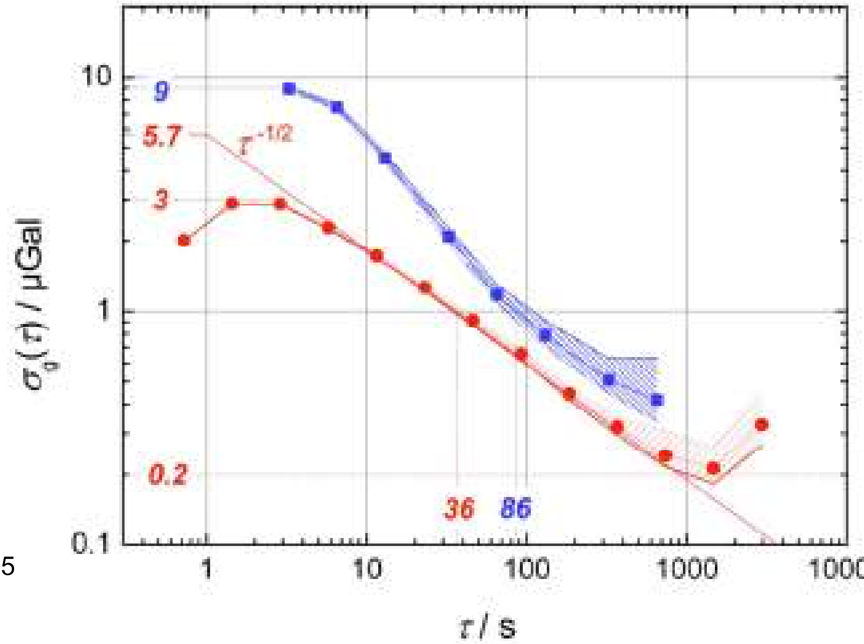
Gravimètre du LNE-SYRTE : déplaçable

OP-BIPM-LNE-Lux-LNE-LUX-LNE-LSBB-LNE-OP



Comparaison avec un gravimeter à coin de cube (FG5X)





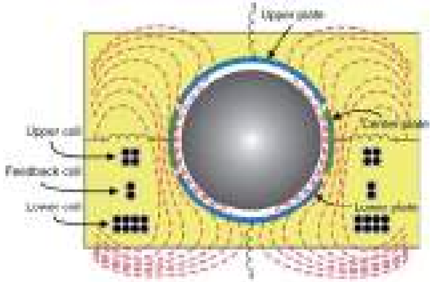
P. Gillot et al., Metrologia ***51*** *(2014)*

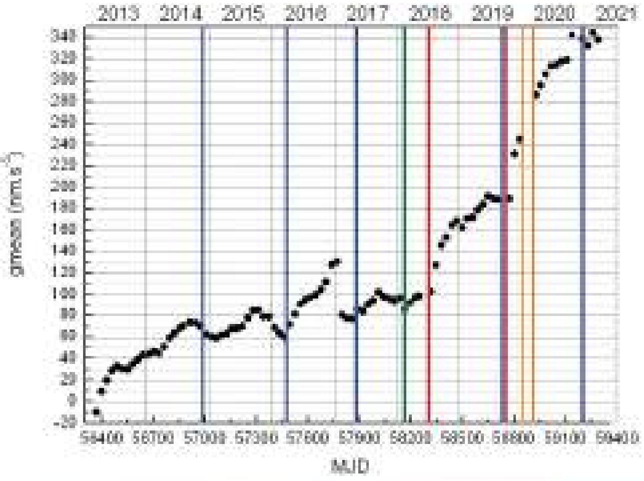
CAG : Meilleure immunité vs séismes
Mesure continue
Meilleure sensibilité: 5.7 µGal en 1 s (57 nm.s^{-2})

Long terme ?

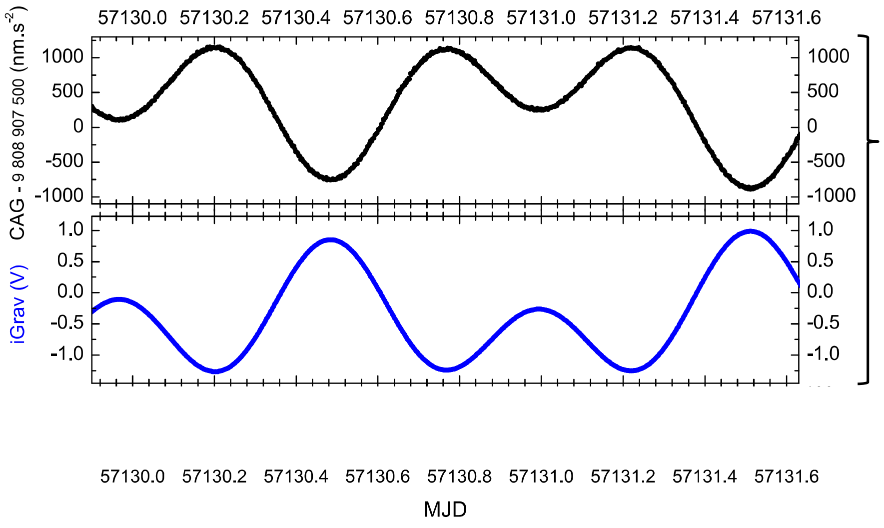
Comparaison avec un gravimeter supraconducteur, étalonnage

Relative gravimeter
iGrav005 SG
since 2013
http://doi.org/10.5880/igets.tr.l1.001
(12Hz „averaged“) 1 gravity point / s
Continuous





1.7 d de mesure en vue commune CAG vs iGrav



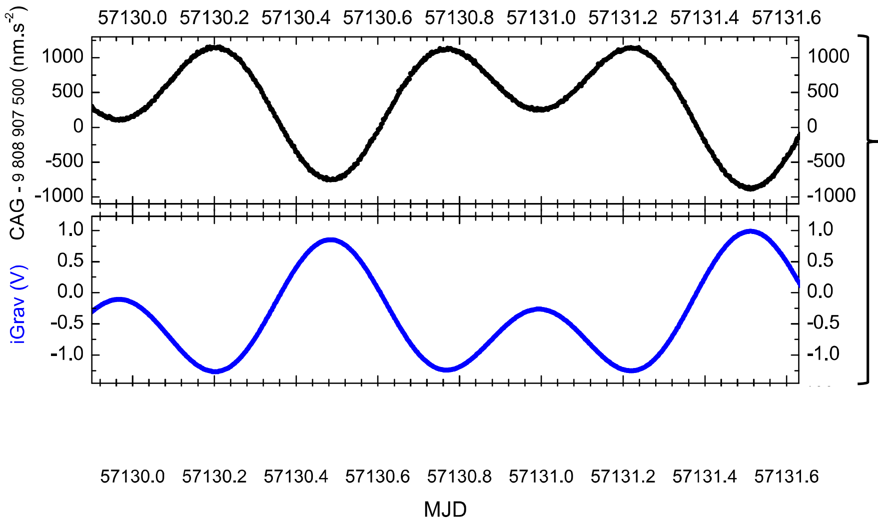
$$\mathrm{AG} = \mathrm{CF} \times \mathrm{SG} + \mathrm{Offset}$$

No drift in the fit.

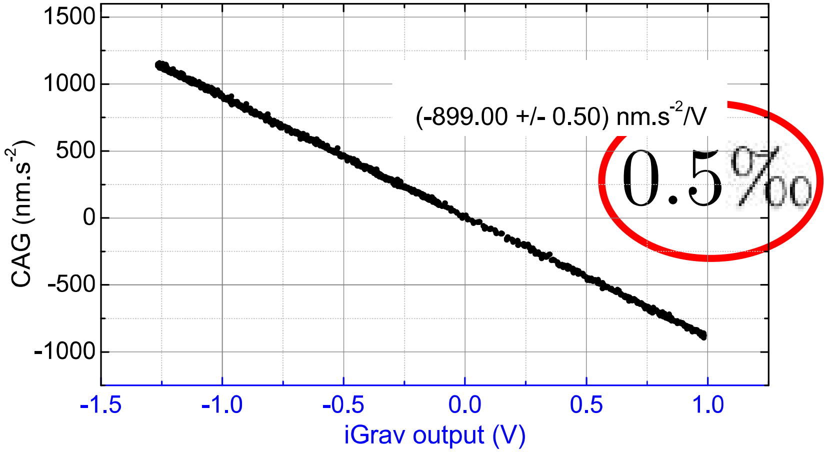
SG is dedrifted based on long term measurement

Take into account a drift possibility in the fit would modify our CAG data and improve the long term sensitivity (which is what we investigate).

1.7 d de mesure en vue commune CAG vs iGrav



$$AG = CF\times SG+Offset$$



No drift in the fit.

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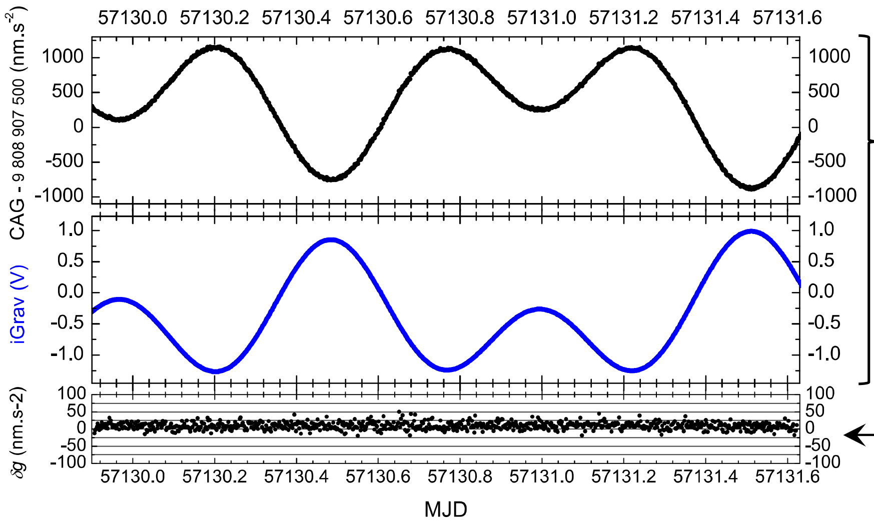
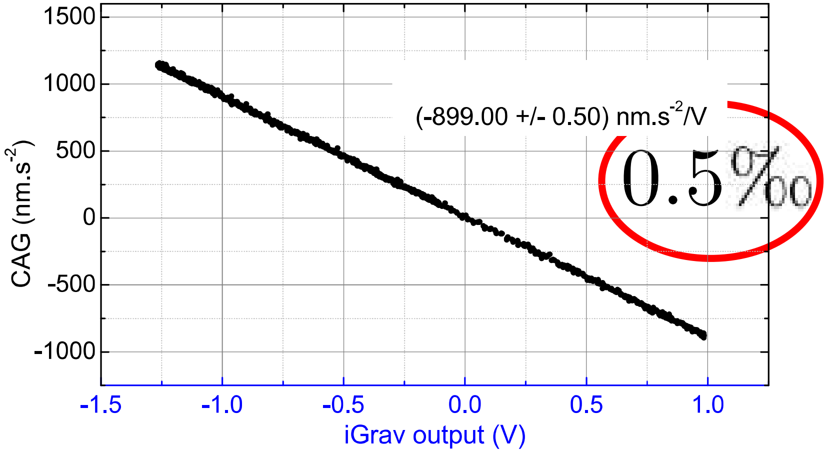
1.7 d de mesure en vue commune CAG vs iGrav



$$\mathrm{AG} = \mathrm{CF}\times\mathrm{SG}+\mathrm{Offset}$$

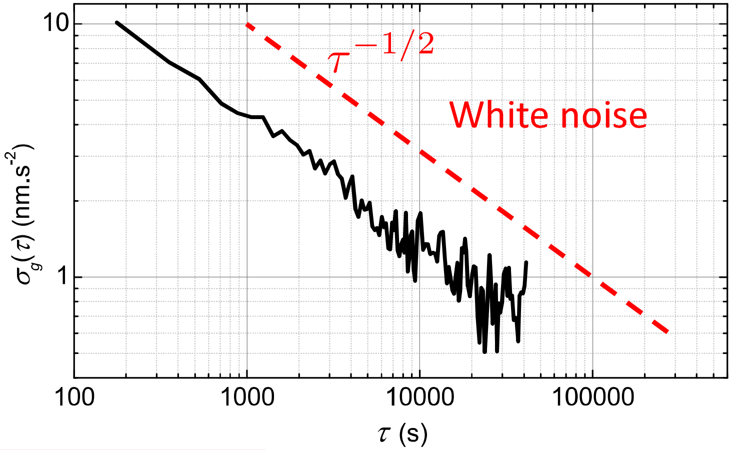
residual

Allan Std Dev analyse



(-899.00 +/- 0.50) nm.s^{-2}/V

$0.5‰$



White noise

No drift in the fit.

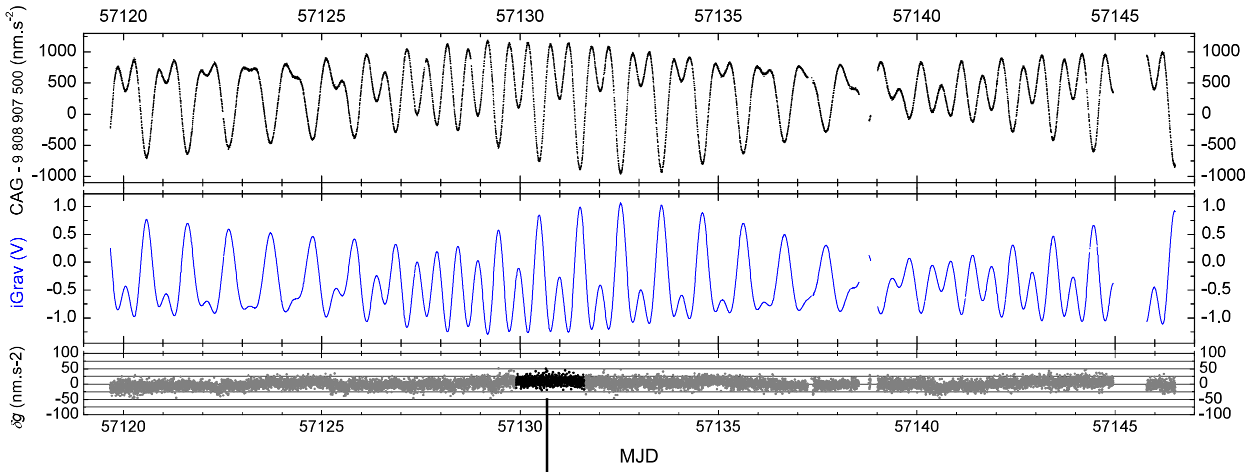
SG is dedrifted based on long term measurement

Take into account a drift possibility in the fit would modify our CAG data and improve the long term sensitivity (which is what we investigate).

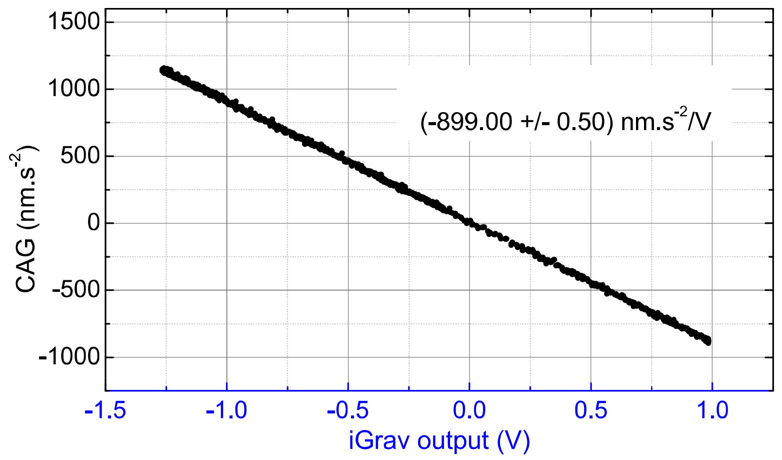
$0.5 - 0.6\ \mathrm{nm.s}^{-2}$ in 20 – 30 000 s, moreover CF at $0.5‰$ in less than 2d.

Study finished.

Pas 1.7 d mais 27 d de mesure en vue commune CAG vs iGrav



1.7 d previously analysed

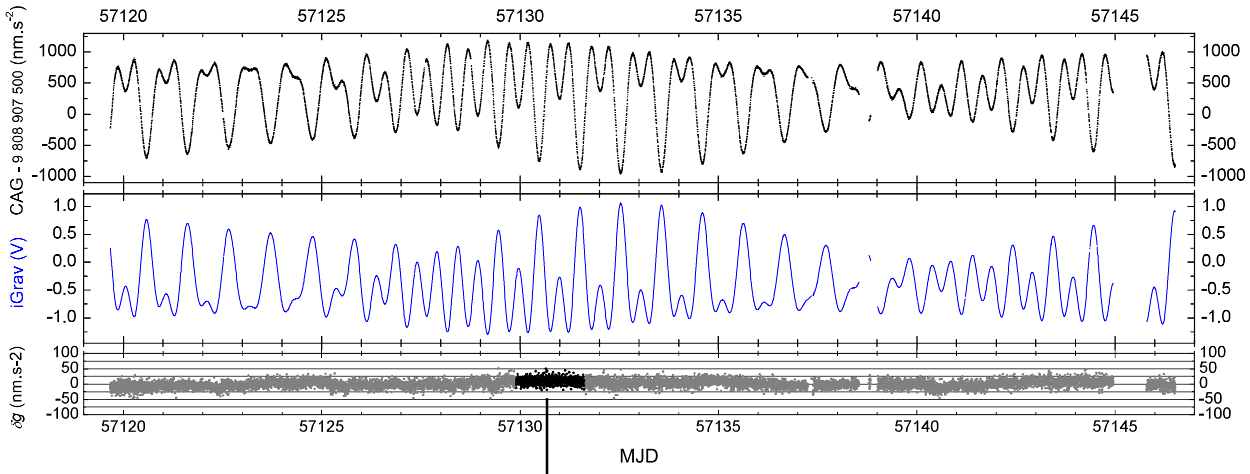


No drift in the fit. $\mathrm{AG} = \mathrm{CF}\times\mathrm{SG}+\mathrm{Offset}$

Repeat the treatment for the long measurement

27 jours de mesures continues
Inaccessible aux gravimètres coin de cube (usure), mais OK pour supra
Opération concurrente de deux instruments : CAG et iGrav

Pas 1.7 d mais 27 d de mesure en vue commune CAG vs iGrav



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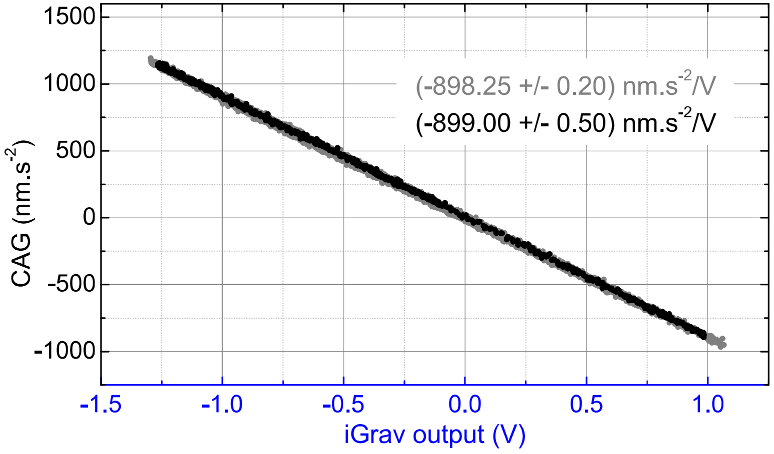
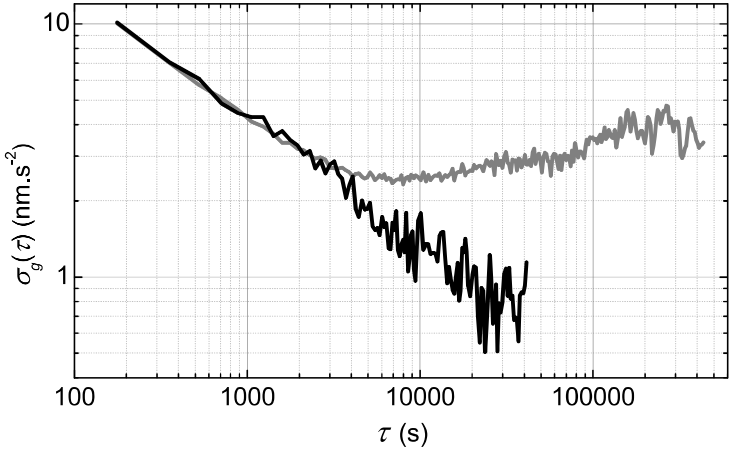




No drift in the fit. $\mathrm{AG} = \mathrm{CF} \times \mathrm{SG} + \mathrm{Offset}$

Repeat the treatment for the long measurement

CF ? Agreement.

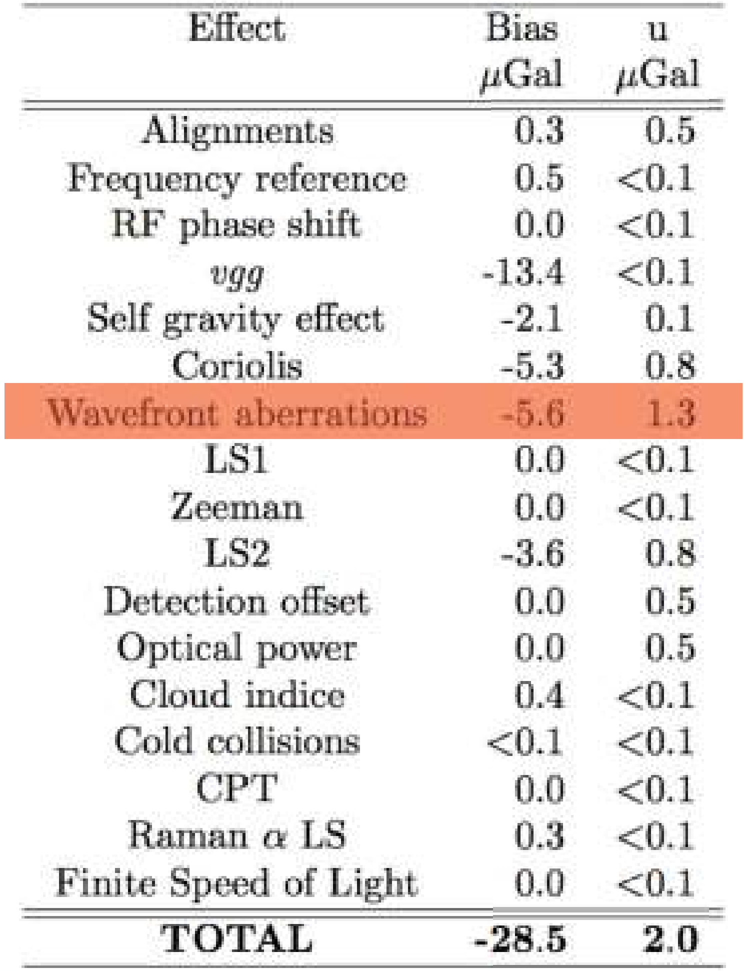
Level ? $0.2‰$?

Long term stability ?

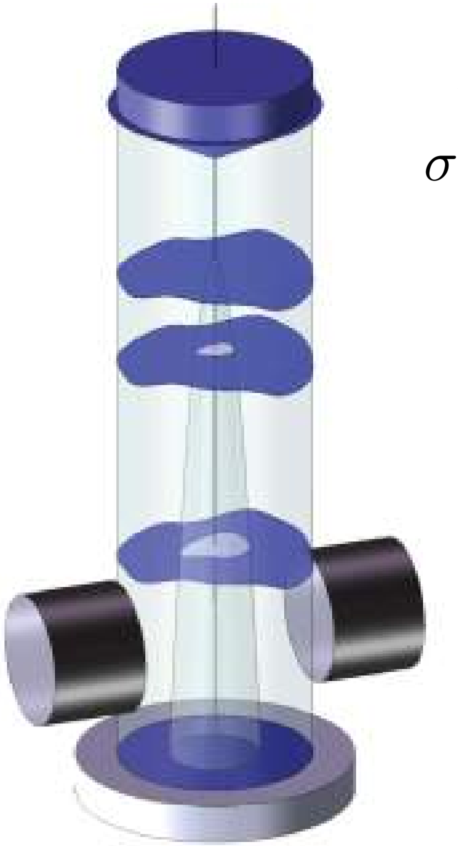
Not White noise, so 0.20/898.25 not possible

S. Merlet et al., J Geod 95, 62 (2021)

Exactitude



Effect	Bias μGal	u μGal
Alignments	0.3	0.5
Frequency reference	0.5	<0.1
RF phase shift	0.0	<0.1
vgg	-13.4	<0.1
Self gravity effect	-2.1	0.1
Coriolis	-5.3	0.8
Wavefront aberrations	-5.6	1.3
LS1	0.0	<0.1
Zeeman	0.0	<0.1
LS2	-3.6	0.8
Detection offset	0.0	0.5
Optical power	0.0	0.5
Cloud indice	0.4	<0.1
Cold collisions	<0.1	<0.1
CPT	0.0	<0.1
Raman α LS	0.3	<0.1
Finite Speed of Light	0.0	<0.1
TOTAL	**-28.5**	**2.0**

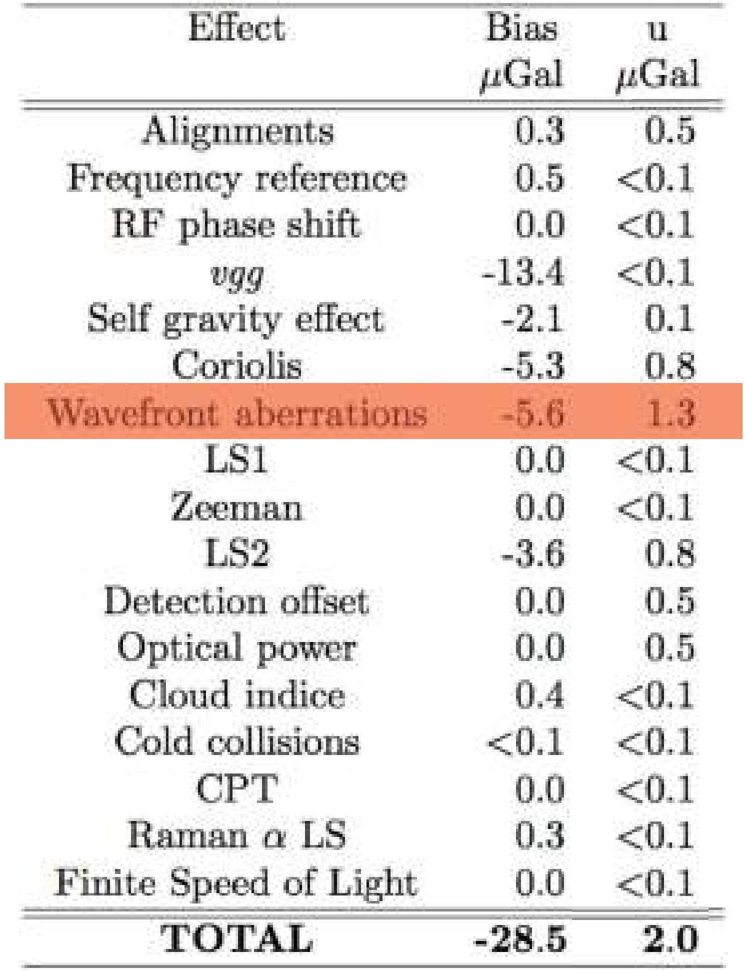


Atomes froids

$$T_{emp} \sim 2\mu K$$

$$\sigma_v \sim 14\ mm.s^{-1}$$

Exactitude



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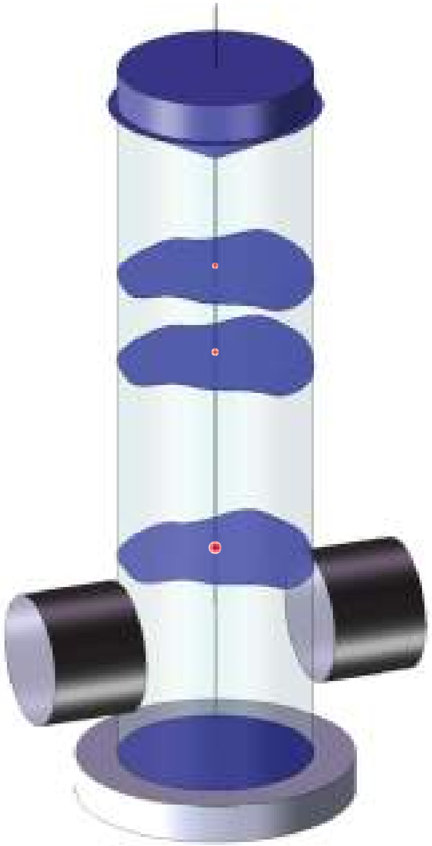
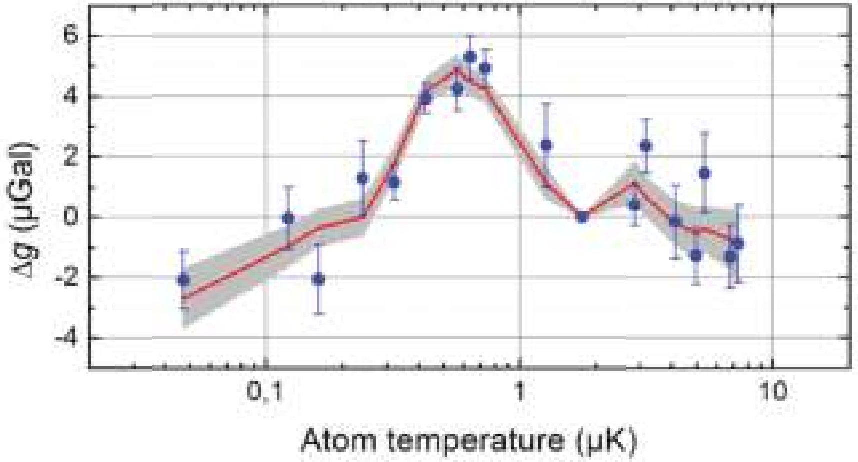


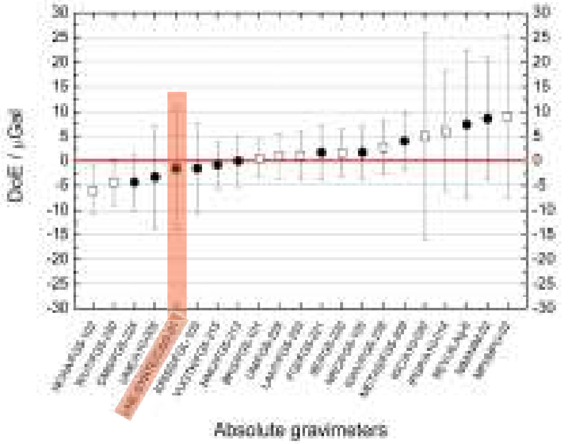
Atomes ultra
froids dans un
piège dipolaire
(refroidissement
évaporatif)
50 nK à 7 μK



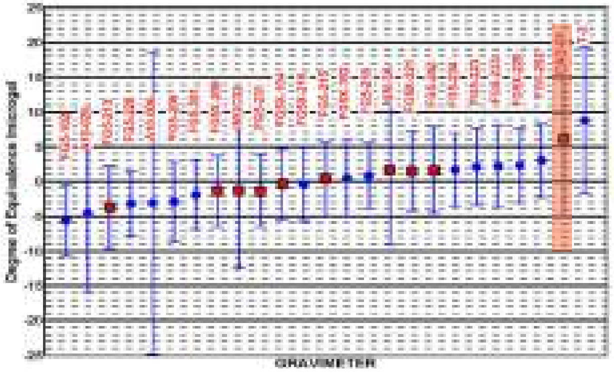
R. Karcher et al New J. Phys. 20 (2018)

Comparaisons Internationales et Nationales

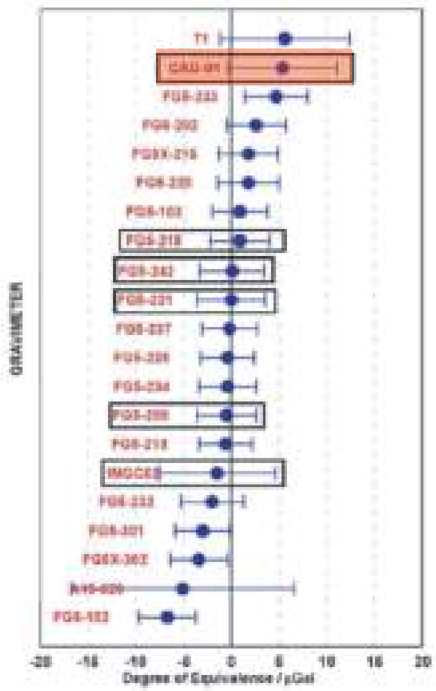
ICAG'09 (BIPM) : CCM.G-K1



CCM.G-K2 (2013, LUX)



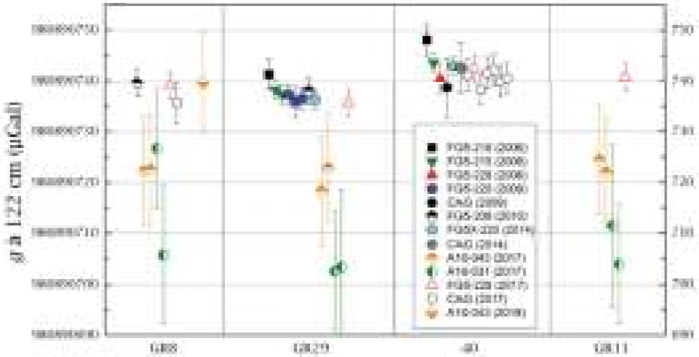
ECAG (2011, LUX)



Résultats du CAG

Date	Différence $g_{CAG}-g_{REF}$ (µGal)
2009	- 1.6 (7.8)
2011	+ 5.4 (5.7)
2013	+ 6.2 (5.5)

Deux comparaisons « clés » 2009 & 2013
CAG : 1er gravimètre atomique à participer
Autres instruments : gravimètres à coin de cube



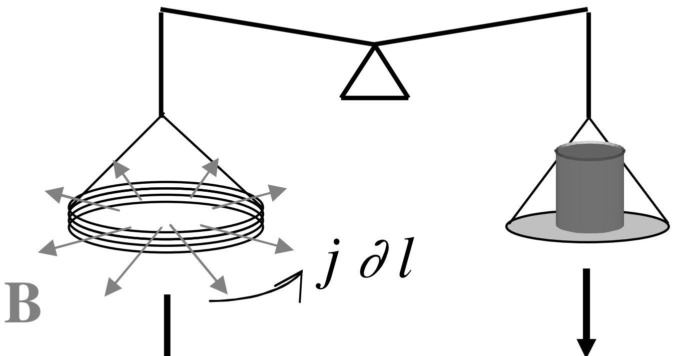
Résumé applications avec le CAG et futur

- Référence nationale, missions métrologie LNE
- Participations au CIPM KC
- Amélioration de la référence (U<10nm.s^{-2}, stalibilté long terme 1 nm.s^{-2}, fiabilisation et fonctionnement en « *mode opérationnel* »)
- Support aux utilisateurs (FFCC et AI)
- Transfert industriel
- Participation au SNO Gravimétrie
- Etalonnage de l'iGrav#005, études sur le facteur d'échelle
- *Détermination de g pour la mise en pratique de la définition du kg, précédemment détermination de la constante de Planck et participation à la révision du SI*

Cf, 36$^{\text{ième}}$ réunion de la Commission « GeoPos » du CNIG, 17/10/2019

Balance du watt ou de Kibble

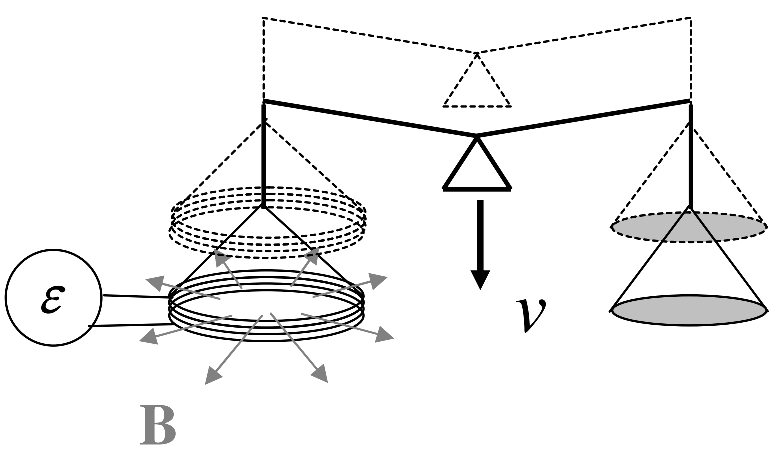
Etape statique



$\mathbf{F}_{\mathbf{Laplace}} = B \cdot l \cdot I$ $\quad \mathbf{F}_{\mathbf{g}} = m \cdot g$

$$\boxed{F_z = mg = Bli}$$

Etape dynamique



$$\boxed{\epsilon = -Blv}$$

$$mgv = \epsilon i = \epsilon V/R$$

$$mgv = \frac{A}{K_{\mathrm{J}}^2 R_{\mathrm{K}}}$$

$$A = \frac{n_1 f_1 n_2 f_2 i}{k}$$

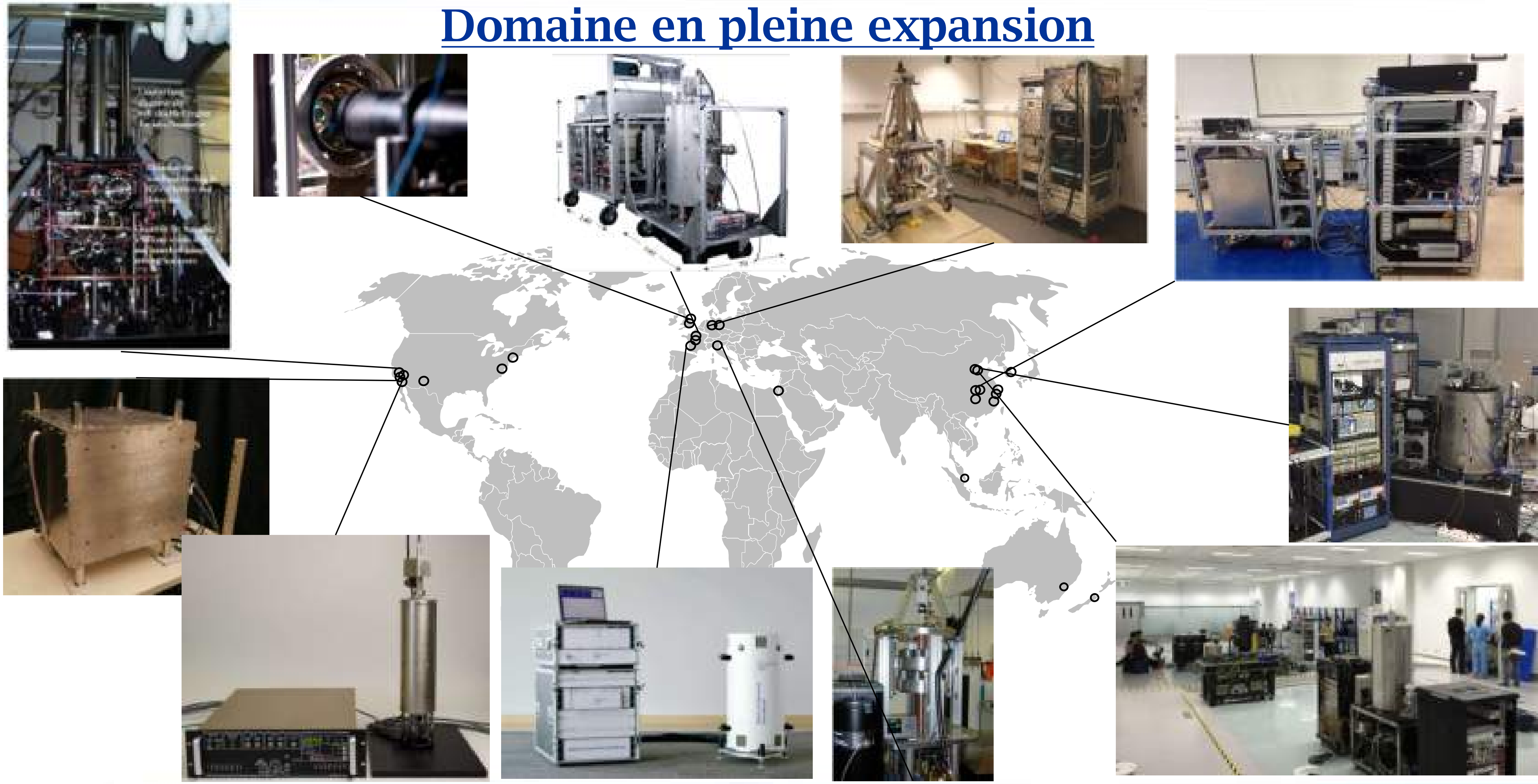
1962: Josephson effect
$V = nf/K_J \qquad K_J = 2e/h$

1980: Quantum Hall effect
$R_H(i) = R_K/i \quad R_K = h/e^2$

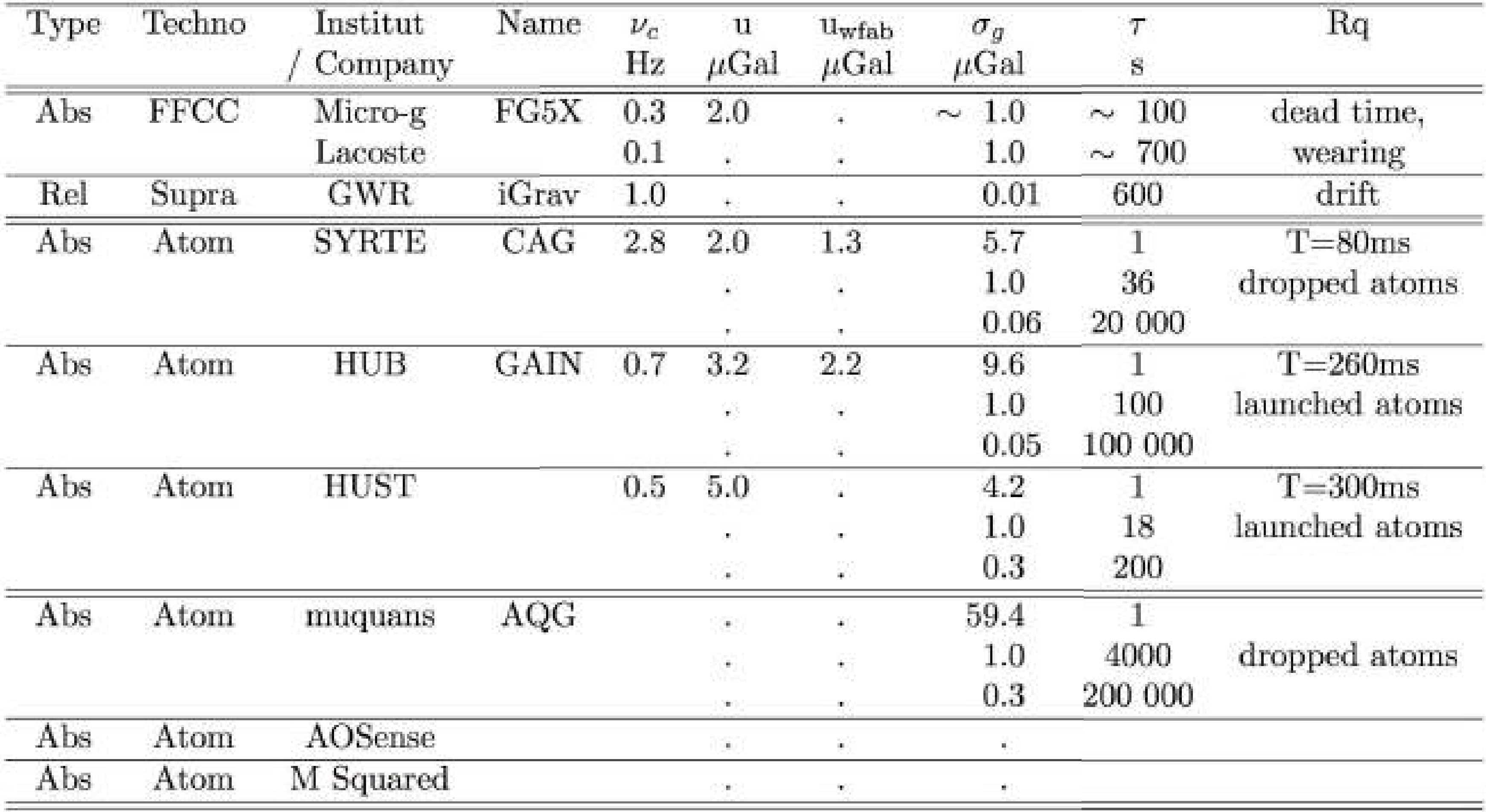
$$\boxed{\frac{m}{h} = \frac{A}{4gv}}$$

Besoin d'une mesure de g, ***exacte***

Domaine en pleine expansion



Etat de l'art



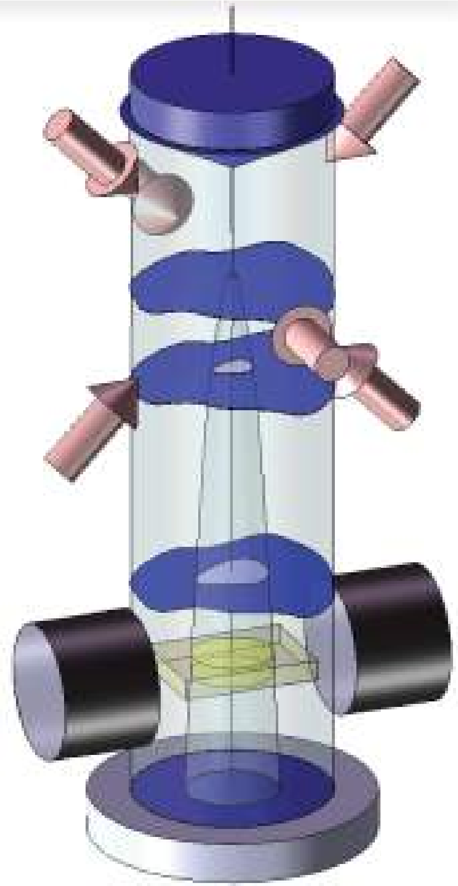
Type	Techno	Institut / Company	Name	ν_c Hz	u μGal	u_{wfab} μGal	σ_g μGal	τ s	Rq
Abs	FFCC	Micro-g	FG5X	0.3	2.0	.	~ 1.0	~ 100	dead time,
		Lacoste		0.1	.	.	1.0	~ 700	wearing
Rel	Supra	GWR	iGrav	1.0	.	.	0.01	600	drift
Abs	Atom	SYRTE	CAG	2.8	2.0	1.3	5.7	1	T=80ms
					.	.	1.0	36	dropped atoms
					.	.	0.06	20 000	
Abs	Atom	HUB	GAIN	0.7	3.2	2.2	9.6	1	T=260ms
					.	.	1.0	100	launched atoms
					.	.	0.05	100 000	
Abs	Atom	HUST		0.5	5.0	.	4.2	1	T=300ms
					.	.	1.0	18	launched atoms
					.	.	0.3	200	
Abs	Atom	muquans	AQG		.	.	59.4	1	
					.	.	1.0	4000	dropped atoms
					.	.	0.3	200 000	
Abs	Atom	AOSense			.	.	.		
Abs	Atom	M Squared			.	.	.		

$$\Delta\Phi = -\vec{k}_{\text{eff}}\vec{g}T^2$$

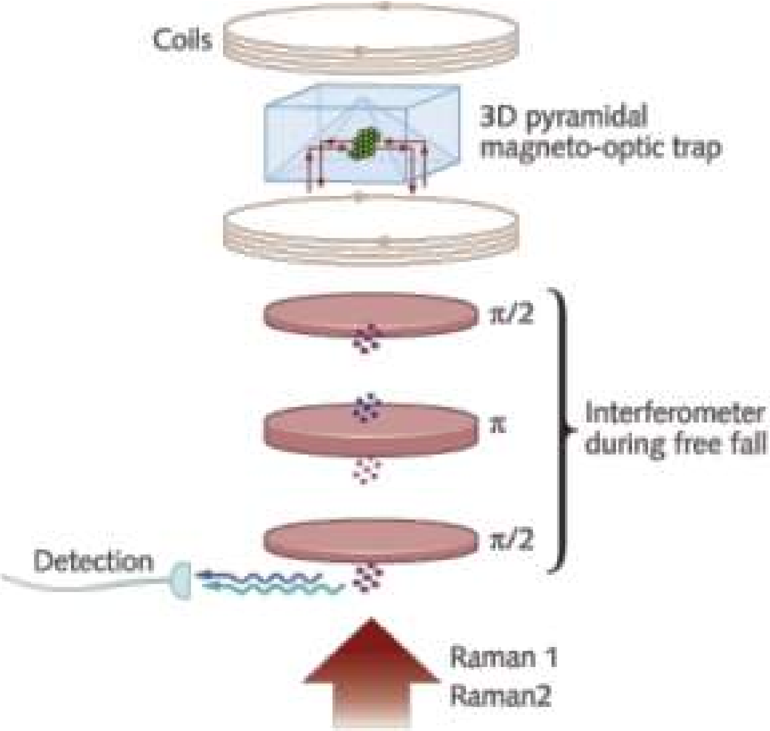
Différences de 2T pas nécessairement corrélées avec les performances

Motivation pour le développement de gravimètres compacts (2T ≈ 100 ms, h ≈ 5 cm)

Simplification, fige les fonctions



15 fibres



1 seule fibre

1 seul faisceau pour réaliser :
- la source,
- l'interféromètre,
- détecter

APPLIED PHYSICS LETTERS 96, 134101 (2010)

A cold atom pyramidal gravimeter with a single laser beam

Q. Bodart,[1] S. Merlet,[1] N. Malossi,[1] F. Pereira Dos Santos,[1] P. Bouyer,[2] and A. Landragin[1,a)]
[1]*LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 61 avenue de l'Observatoire, 75014 Paris, France*
[2]*Laboratoire Charles Fabry de l'Institut d'Optique, CNRS et Univ Paris Sud, Campus Polytechnique, RD 128, 91127 Palaiseau Cedex, France*

(Received 17 December 2009; accepted 5 March 2010; published online 29 March 2010)

Suppression de la plateforme d'isolation

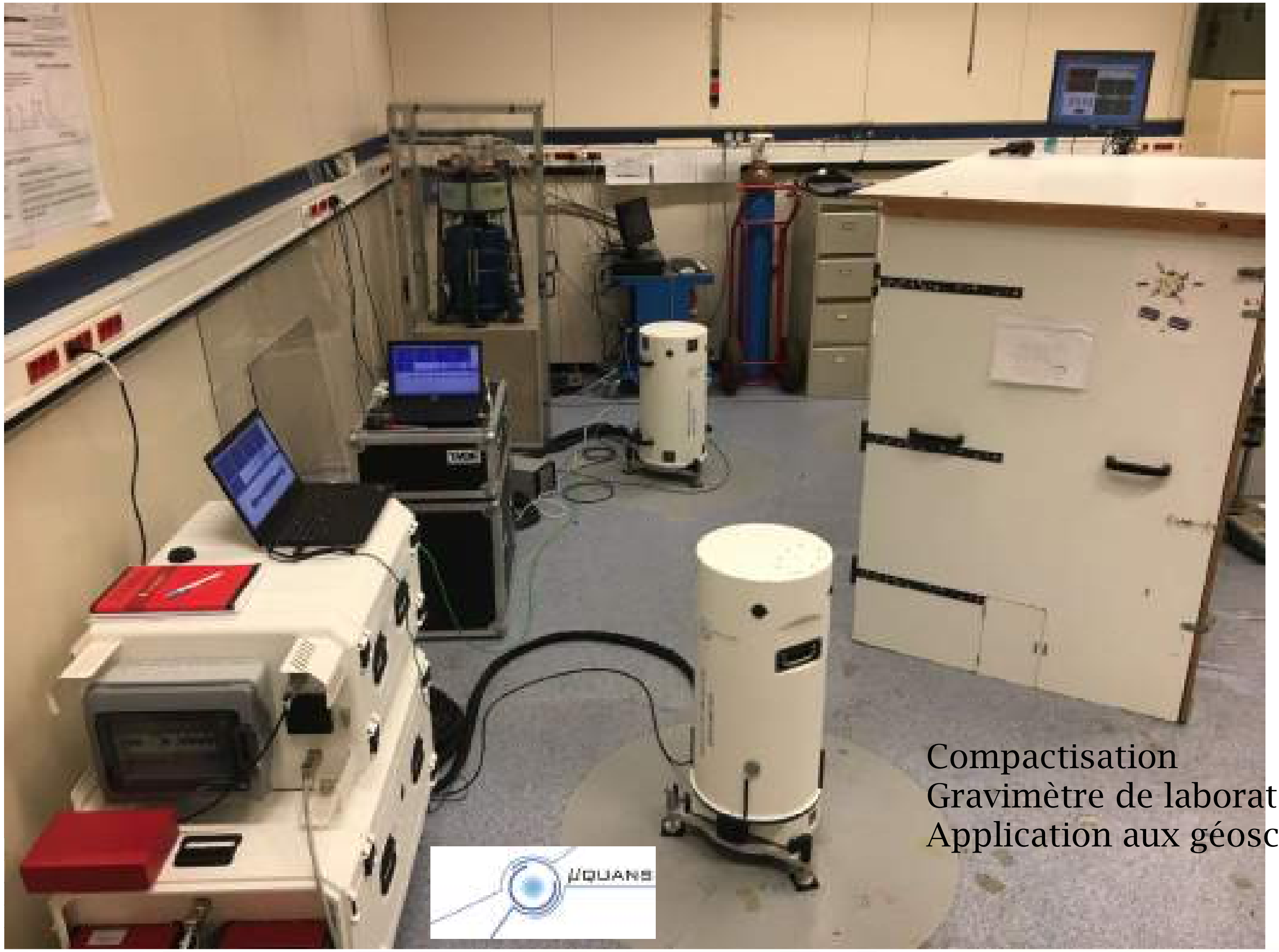
APPLIED PHYSICS LETTERS 105, 144102 (2014)

Hybridizing matter-wave and classical accelerometers

J. Lautier, L. Volodimer, T. Hardin, S. Merlet, M. Lours, F. Pereira Dos Santos, and A. Landragin[a)]
LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 61 avenue de l'Observatoire, 75014 Paris, France

(Received 29 August 2014; accepted 24 September 2014; published online 6 October 2014)

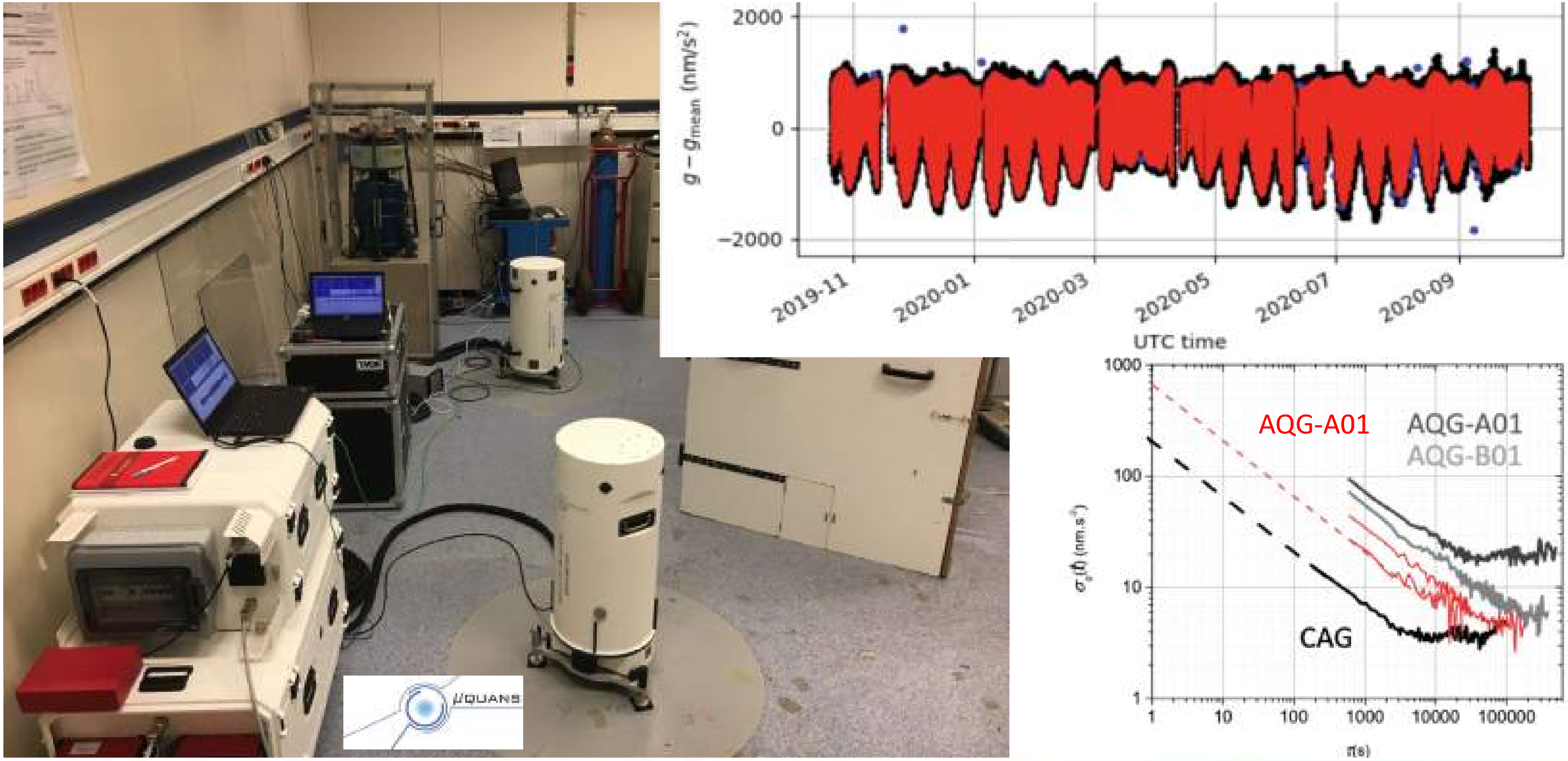
Gravimètres commerciaux



Compactisation
Gravimètre de laboratoire et de terrain
Application aux géosciences

Gravimètres commerciaux

1 an de mesure

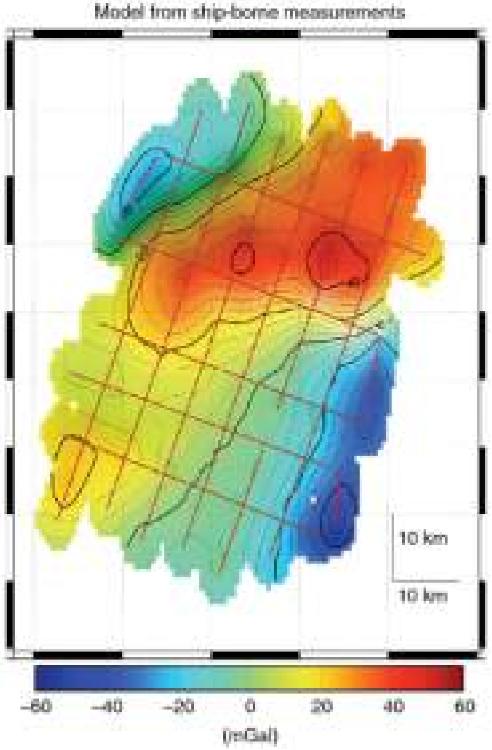


Mesures embarquées

Développement par l'ONERA d'un gravimètre compact pour gravimétrie marine
Campagnes de mesures sur Beautemps-Beaupré (Marine Nationale)

KSS32 relative Marine Gravimeter (Bodenseewerk)

Cold Atom Gravimeter (Onera)


Model from ship-borne measurements

→ **Meilleure performance pour le gravimètre absolu Girafe 2**

- Suppression des erreurs de calibration initiale et des corrections de dérive du gravimètre relatif

Y. Bidel et al Nat Commun. 9, 627 (2018)

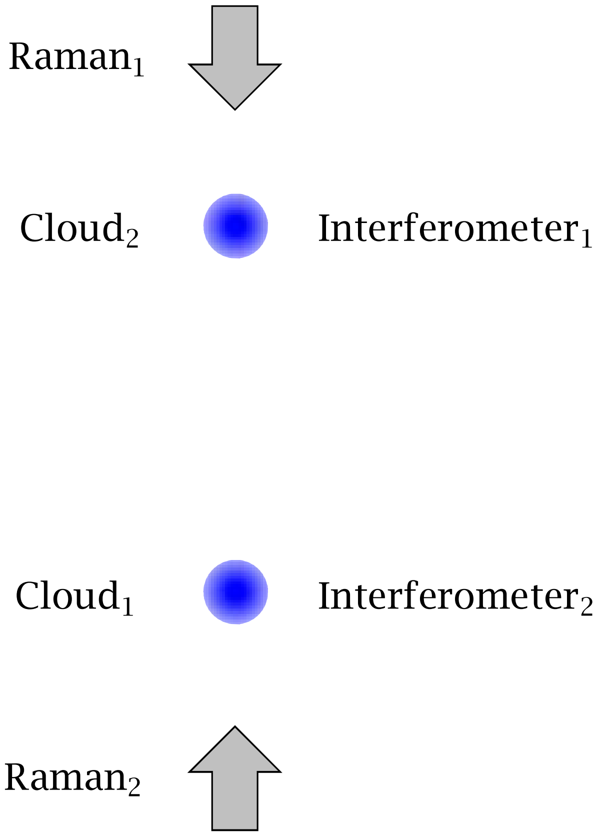
→ Gain d'un facteur 2-3 sur l'incertitude des mesures

\+ Campagne aéroportée *Y. Bidel et al J. Geod. 94, 20 (2020)*

ICE : Expérience pionnière
Pour accélérométrie embarquée

Gravimètre embarqué:
Problème des vibrations

Gradiométrie



$g_1,\ g_2,\ g_1 - g_2$

- ○ Simultaneous interferometers on two cold atom clouds with common Raman lasers
- ○ Differential measurement allows for extracting the acceleration difference (and thus the Earth gravity gradient)
- ○ **Suppression of common mode noise**, and in particular of the vibration noise
- ○ Adapted for onboard measurements
- ○ g and Δg: resolve ambiguities in determination of mass and position

How to increase the sensitivity ?

$$\triangle\Phi = \vec{k}_{\mathrm{eff}}\vec{g}T^2$$

Increase the scale factor

New tools

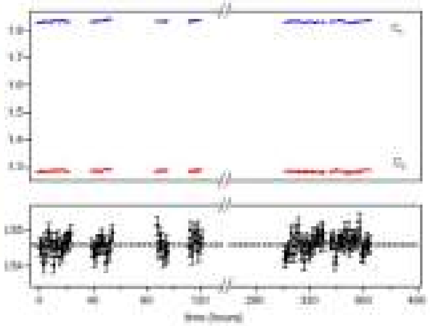
- ➢ High order Bragg diffraction LMBS with up to N photons
- ➢ Ultracold atoms Fast generation on atom chip

Applications

- Mesure de G

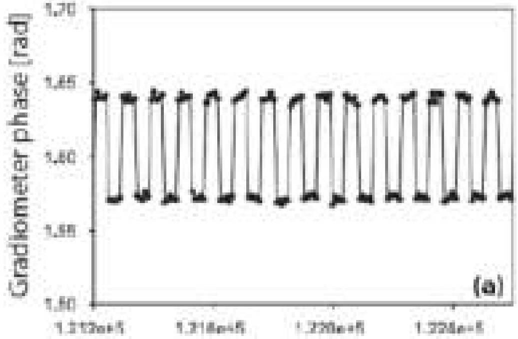
Florence (G. Tino)

Incertitude relative : 1.5 10^{-4}

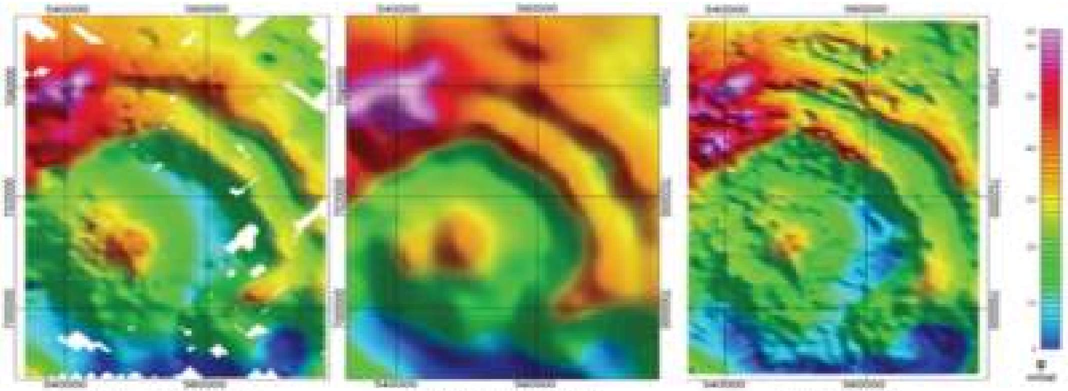


- Mesure de G

Stanford (M. Kasevich)



- Mesures embarquées (aéroportées)



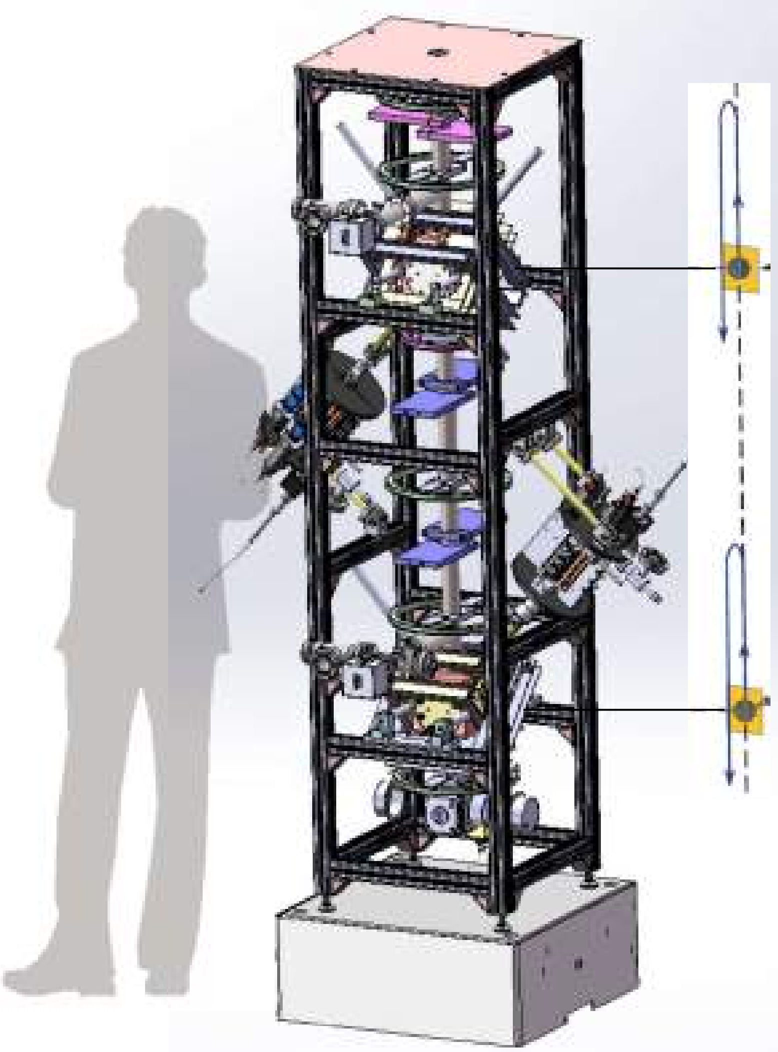
Ground Gravimetry
500m to 5km Stations
Difficult Access

Airborne Gravimeter
4km Line Spacing
~ 7km Filter

FALCON AGG
1km Line Spacing
150m Resolution

- Génie civil
  Détection infrastructures souterraines, réseaux de tuyaux …
  Projet Gravity Pioneer (UK)

Quantum dual gravi-gradio meter



- → 2 ultracold Rb clouds obtained on 2 chips
- → 2 clouds launched with elevator
- → 2 Interferometers drived by LMTB

Targeted parameters

$$T_c = 2s \quad N_{\text{atoms}} = 5.10^5$$

$$T_{emp} = 10 - 100nK$$

$$p = 100\hbar k \quad 2T = 0.5s$$

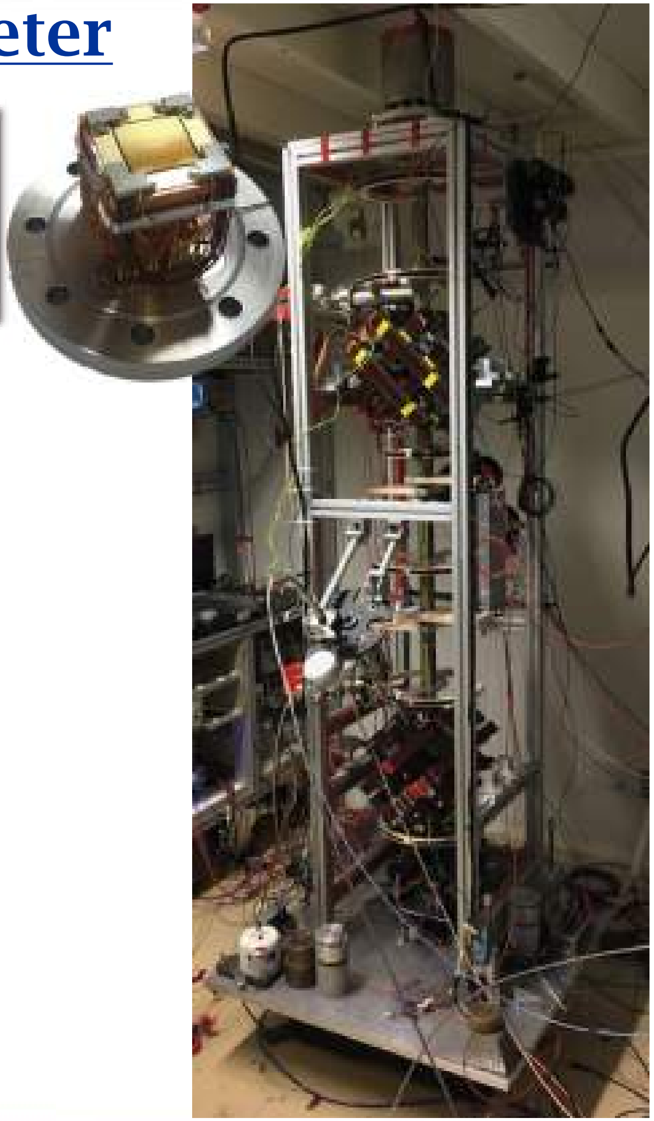
$$\sigma_{\text{g}}^1 = 9 \times 10^{-11} m.s^{-2}.Hz^{-1/2}$$

If limitated by QNP

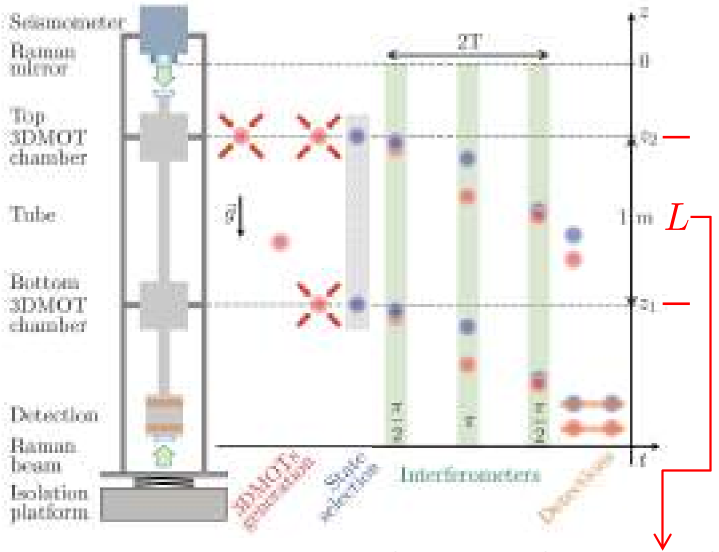
$$\Delta z = 1m$$

$$\sigma_{\text{grad}g} = 126\ mE\ @1s$$

More than one order of magnitude better than state of the art

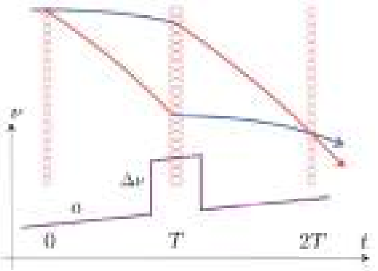


Premiers résultats



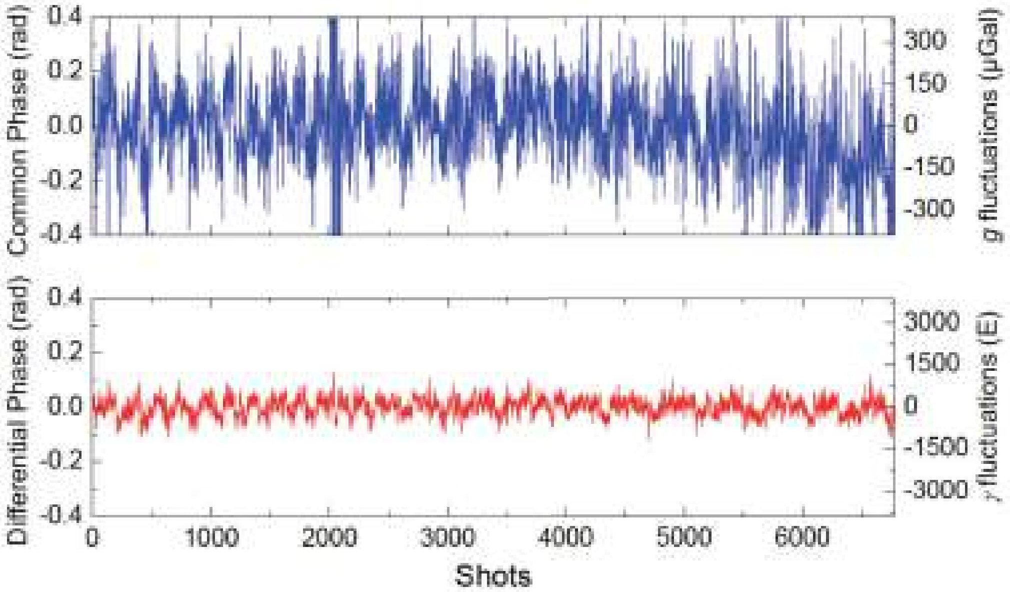
$$\Delta\Phi = \Phi_2 - \Phi_1 = kg_2T^2 - kg_1T^2 = k\gamma \boxed{L} T^2$$

$$\Phi_i = kg_iT^2 + aT^2 + K_i\Delta\nu \begin{cases} \Delta\Phi_i^{\mathrm{FC}} = aT^2 \\ \Delta\Phi_i^{\mathrm{FJ}} = K_i\Delta\nu \end{cases}$$



$$\begin{cases} \Delta\nu = \dfrac{k(g_1 - g_2)T^2}{K_2 - K_1} \\ a_s = -k\left(\dfrac{K_2g_1 - K_1g_2}{K_2 - K_1}\right) = -kg_s \end{cases} \xrightarrow[g_i = g_0 + \gamma z_i]{K_i = 8\pi z_i/c} \boxed{\begin{cases} \Delta\nu_\gamma = -\gamma \dfrac{kT^2c}{8\pi} \\ g_s = g_0 \end{cases}}$$

Accurate determinations of **both** the gravity acceleration (at the mirror position) and the gravity gradient, **independent from the baseline**



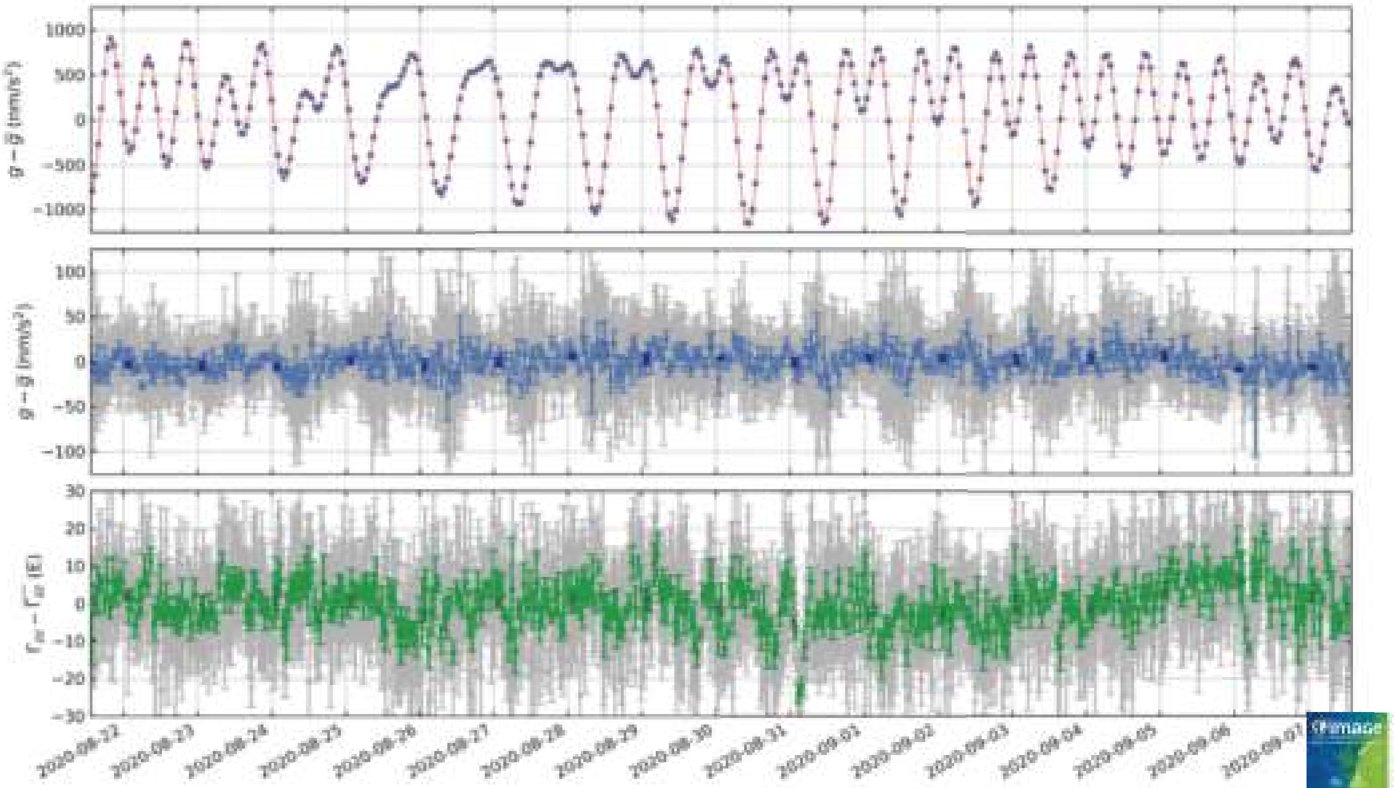
R. Caldani et al., Phys. Rev. A ***99*** *033601 (2019)*

Collaboration GRADIOM, ANR GRADUS

RAPID (**R**égime d'**AP**pui à l'**I**nnovation **D**uale) DGA avec muquans et Alphanov. Nouveau (suite) projet ANR Gradus

Mesures continues de *g* et *dg* (vertical) avec un instrument compact et facilement transportable

Differential Quantum Gravimeter (DQG)



50 E/$\sqrt{\tau}$ et 360nm/s²/$\sqrt{\tau}$ (au 2ème étage !)
Long terme: 0.1E et > 5nm/s²

C. Janvier et al., Recent advances in quantum gravity sensors, *(2021)*, https://doi.org/10.1190/segam2021-3580909.1

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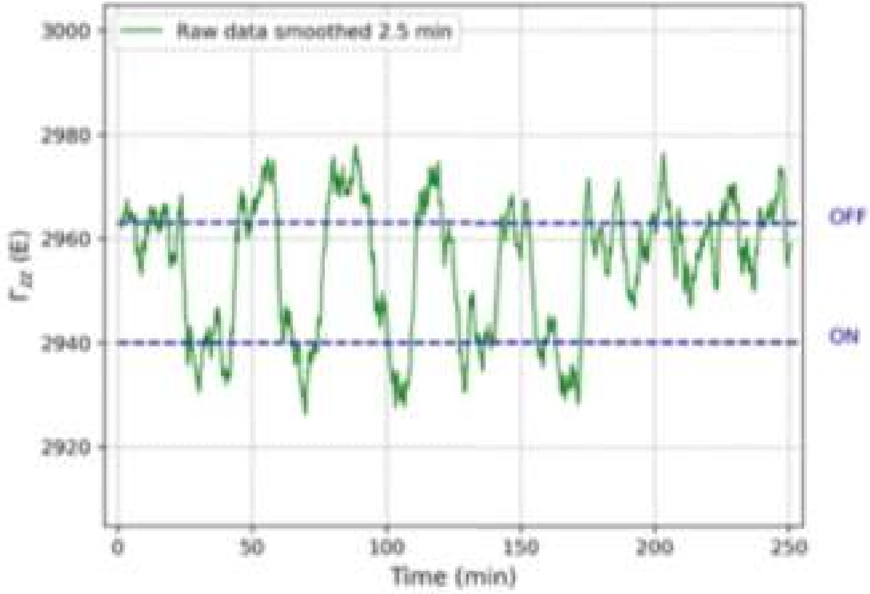
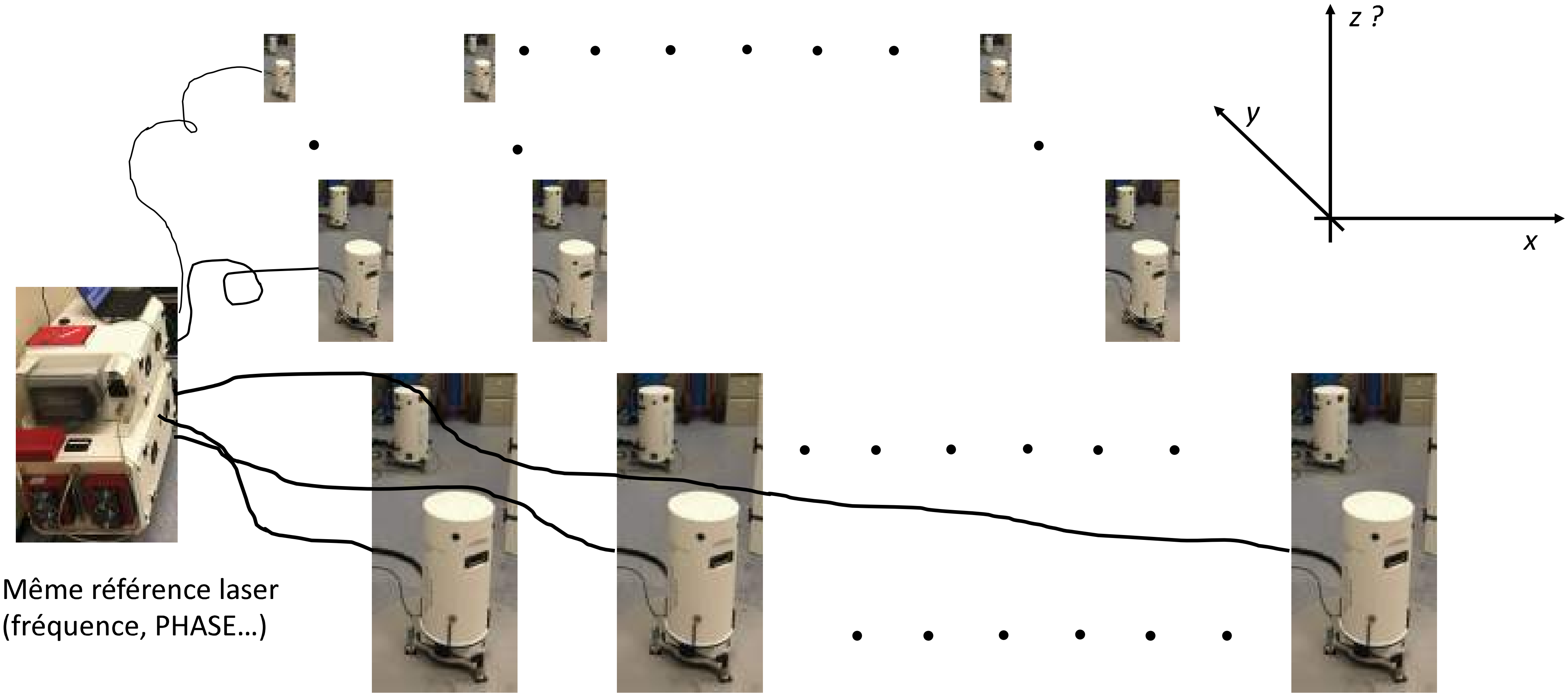


Déplacement d'une masse de 100 kg à proximitédu DQG

C. Janvier et al., Recent advances in quantum gravity sensors, *(2021)*, https://doi.org/10.1190/segam2021-3580909.1

Réseaux

Réseaux de gravimètres et/ou gradiomètres, échelles ?



Même référence laser
(fréquence, PHASE…)

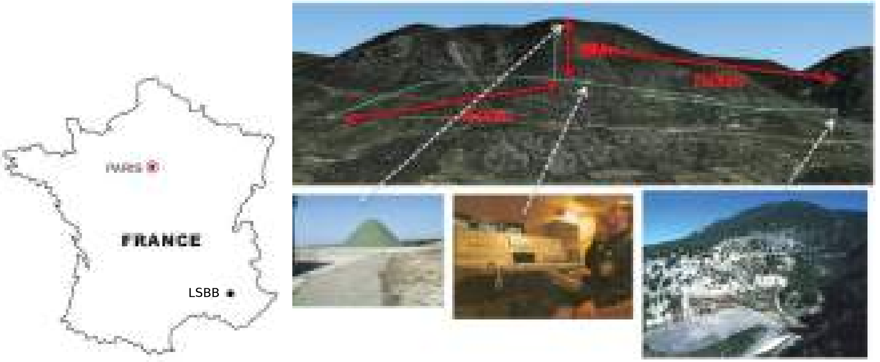
MIGA : Gravitation et Géophysique avec des capteurs atomiques

Equipex porté par LP2N, consortium de 15 laboratoires

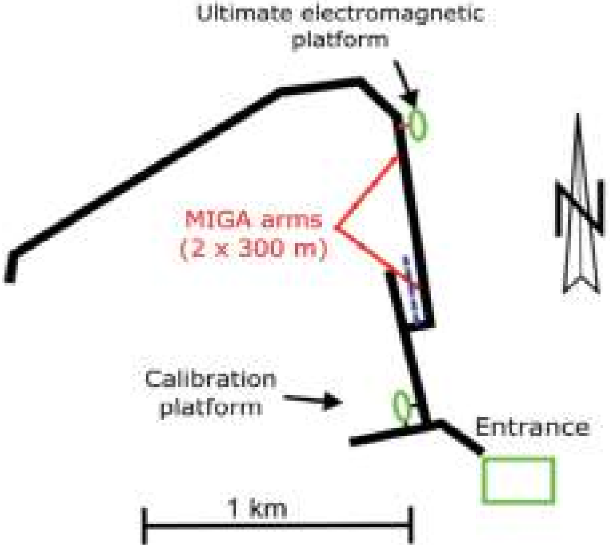
Gradiométrie à très longue ligne de base avec 3 interféromètres séparés de 150 m

B. Canuel et al., « Exploring gravity with the MIGA large scale atom interferometer », arxiv. 1703.02490.

- Surveillance des distributions de masses souterraines
  Applications: géophysique, hydrologie
- Détection d'ondes gravitationnelles



LSBB
Laboratoire Souterrain à Bas Bruit



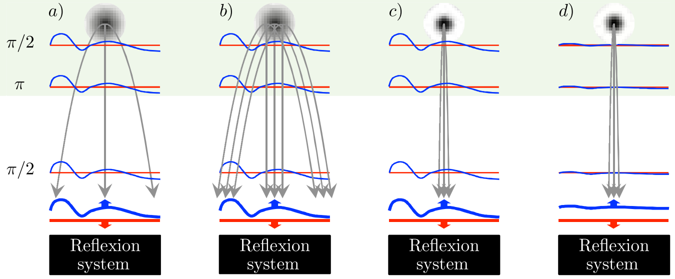
T. Farah et al., Gyr & Nav 5, (2014).

Inauguration projet LSBB 2020, 22/10/2021

Conclusion

https://syrte.obspm.fr/spip/science/iaci/
https://syrte.obspm.fr/spip/science/iaci/publications/

- ➢ Techniques AI: matures pour développement de gravimètres et de capteurs inertiels
- ➢ Performances rivalisent ou dépassent les technologies « classiques »



Efforts pour rendre plus compacts, plus robustes les sous systèmes clefs

Transfert industriel, commercialisation

- ➢ Limites pas encore atteintes, perspectives d'amélioration des performances (sources ultra-froides et transitions multiphotoniques…)

Diversité des applications : physique fondamentale, géophysique, géodésie, surveillance des réservoirs, génie civil, navigation…

- ➢ Projets spatiaux: Gradiométrie Atomique spatiale

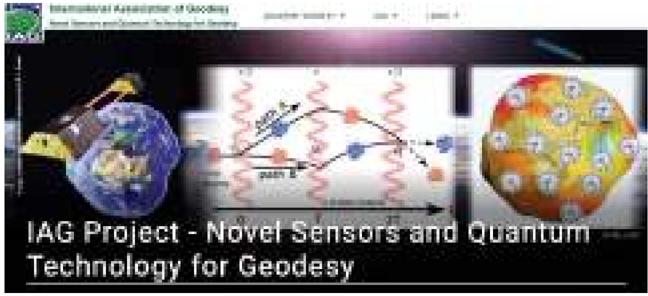
CAI

CARIOQA

European Commission
Quantum technologies for space gravimetry
TOPIC ID: HORIZON-CL4-2021-SPACE-01-62

https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl4-2021-space-01-62

QuGe



IAG Project - Novel Sensors and Quantum Technology for Geodesy

https://syrte.obspm.fr/spip/science/iaci/
https://syrte.obspm.fr/spip/science/iaci/publications/

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union