ESA Call for M4 and the GG mission proposal

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Download GG: letter of intent, 16 September 2014

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Summary

- ESA Call for medium size mission M4: key facts

GG & M4:

- Science
- Why space?
- Design of sensor
- Mission configuration
- Heritage, readiness, management and cost

ESA Call for medium size mission M4: key facts

ESA Call for medium size mission M4: key facts

- 3.5 yr definition phase after selection in March 2015 of (up to) 3 candidates, ending 2018; 6.5 yr implementation phase starting 2018 till launch in 2025
- 450 M€ cost cap to ESA (strict). Baseline: ESA covers bus, launch & mission operations; payload to be provided by national agencies (endorsement required). International collaboration possible, strictly checked
- Must rely on available technology (TRL 5-6) by end of definition phase in 2018. *"...the payload can include the development of new instruments, provided they are relying on available technologies. Some specific delta developments or verifications can still be envisaged prior to the mission adoption if they can be achieved in 2-2.5 years"*
- Vega launch preferable
- Re-entry mandatory in 25 yr maximum

GG & M4: Science

Scientific goal of GG

Test Universality of Free Fall (UFF)/Weak Equivalence Principle (WEP) to 10^{-17}

UFF/WEP: In a gravitational field all bodies must fall with the same acceleration regardless of their mass and composition. *Einstein refers to it as "the teaching of experience":*

$$\eta = \frac{\Delta a}{a} = 0 \quad .$$

General Relativity is founded on UFF/WEP (i.e $\eta = 0$):

Stated by Einstein in "The foundation of the General Theory of Relativity", § 2, 1916
Einstein quotes as experimental evidence Eötvös torsion balance tests (at $\eta \simeq 10^{-8}$)

Experimental evidence of UFF/WEP violation ⇒

either GR must be amended or a new force of nature is at play – revolution in science!
No target from theory ⇒ the more sensitive the test, the higher the chances to find new physics

Why testing GR?

- GR confirmed by experiments in weak and strong field
- Cosmology stronger than ever – experiments and theory
- Standard Model of particle physics confirmed by all experiments

... yet, only 5% of universe mass understood....
...GR and SM not reconcilable with each other
$\Downarrow$

- Big missions for in situ measurements EUCLID)
- *Question the underlying theory of gravity:*

Is GR the last word in our understanding of gravity?
Do new fundamental forces exist?
Who is wrong: Einstein or the Standard Model?

UFF/WEP tests vs measurements of gravitational redshift

Why UFF/WEP tests can be more accurate than grav redshift measurements by many orders of magnitude?

$$\eta = \frac{\Delta a}{a}$$

If TMs are coupled the experiment measures Δa directly, hence η: no experiment signal, no violation (to the level of noise); the smaller the signal (and/or the noise), the better the test.

No prediction must be made that the measured signal must be compared to in order to obtain the physical quantity of interest!

... **you must "only" beat random errors and carefully check systematics...**

A measurement of gravitational redshift is an *absolute measurement*.
GP-A result (PRL 1980) is:

$$\left(\frac{\Delta\nu}{\nu}\right)_{GP-A} = [1 + (2.5 \pm 70) \cdot 10^{-6}] \cdot \left(\frac{\varphi_s - \varphi_e}{c^2} - \frac{|\vec{v}_s - \vec{v}_e|^2}{c^2} - \frac{\vec{r}_{se} \cdot \vec{a}_e}{c^2}\right)$$

Measured freq shift to be compared to the sum of the 3 terms (gravitational potential difference, second order Doppler shift, residual of first order Doppler), whose values depend on various physical quantities, some of which to be measured during experiment.
Only after comparing theoretical prediction with measured shift the authors could establish the ratio $[1 + (2.5 \pm 70) \cdot 10^{-6}]$ yielding 1st order gravitational redshift to $\pm 7 \cdot 10^{-5}$.

... 4 years to publish the results of a 2-hr experiment!!

... more difficult as clocks improve; **2nd order still beyond reach; experimental result of space measurement very hard to interpret ($1/c^3$ terms also relevant..)**
What if a discrepancy is found? Would it question GR or simply question an inadequate physical model?

Read Am. J. Phys., 2013

UFF/WEP tests:
State of the art with rotating torsion balances

Authors	Apparatus	Source mass	Materials	$\eta \equiv \Delta a/a$
Eötvös et al. ≈1900 collected in Ann. Phys. **1922**	Torsion balance. Not rotating. No signal modulation	Earth	Many combinations	$10^{-8} \div 10^{-9}$
Roll, Krotkov & Dicke Ann. Phys. **1964**	Torsion balance. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Au	$(1.3 \pm 1) \times 10^{-11}$
Braginsky & Panov JETP **1972**	Torsion balance. 8TMs. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Pt	$(-0.3 \pm 0.9) \times 10^{-12}$
E. Fischbach et al.: "Reanalysis of the Eötvös Experiment" PRL 1986				
Eöt-Wash, PRD **1994**	Rotating torsion balance. ≈ 1hr modulation	Earth	Be – Cu	$(-1.9 \pm 2.5) \times 10^{-12}$
			Be – Al	$(-0.2 \pm 2.8) \times 10^{-12}$
Eöt-Wash, PRL 1999	Rotating torsion balance. 1hr to 36' modulation	Sun	Earthlike/ Moonlike	$\approx 10^{-12}$ (SEP 1.3×10^{-3})
Eöt-Wash, PRL **2008**	Rotating torsion balance. 20' modulation	Earth	Be – Ti	$(0.3 \pm 1.8) \times 10^{-13}$

36 yr (1972 → 2008)

14 yr (1994 → 2008)

Best result by rotating torsion balance in the field of the Earth (2008): $\eta \simeq 10^{-13}$

Mass dropping (Galileo-like) tests not competitive by orders of magnitude

Best mass dropping test with macroscopic bodies $\eta = 7.2 \cdot 10^{-10}$

Carusotto et al. PRL, 1992 Al, Cu

Best mass dropping tests with cold atoms $\eta \simeq 10^{-7}$

Fray et al. PRL 2004 Rb85, Rb87
Sclippert et al. PRL 2014 Rb87, K39
Tarallo et al. arXiv 2014 Sr87, Sr88

Major limitations:

- release errors (macroscopic masses & cold atoms) mimic violation
- huge number of drops needed to reduce single shot noise (cold atoms); should be uncorrelated but may be not..

... so far have wiped out advantage in signal strength over torsion balances by about 3 orders of magnitude

GG & M4: Why space?

Signal strength and role of space

Strength of driving signal for WEP experiments on ground and in Low Earth Orbit (in $m\,s^{-2}$)

	Earth's field		*Sun's field*	
	Ground	*LEO*	*Ground*	*LEO*
mass dropping (*Galileo – like tests*)	9.8 → (*factor 1.2 loss*)	$\simeq 8$	—	—
suspended masses (*regardless of the suspension type : mechanic, electrostatic, superconducting coils . . .*)	$\simeq 0.016$ → (***factor 500 gain!***) ; → Sun's field Ground (*factor 2.8 loss*)	$\simeq 8$	$\simeq 0.0057$	$\simeq 0.0057$

Only UFF/WEP experiments with suspended masses gain a factor 500 (in the field of Earth) by being performed in low Earth orbit (LEO)!!!

Space: two more properties to be exploited

Weightlessness:

Suspensions less stiff then on Earth by orders of magnitude $\Rightarrow$ if test masses are coupled as in a balance, coupling can be very weak i.e. high sensitivity to differential effects

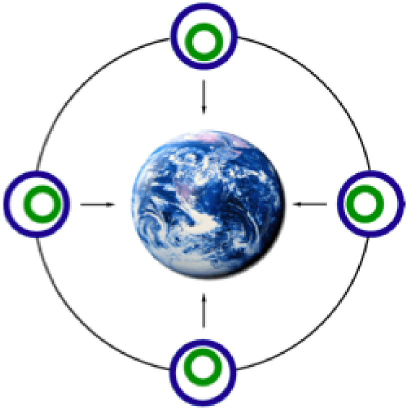
Spacecraft (laboratory) isolated in space:

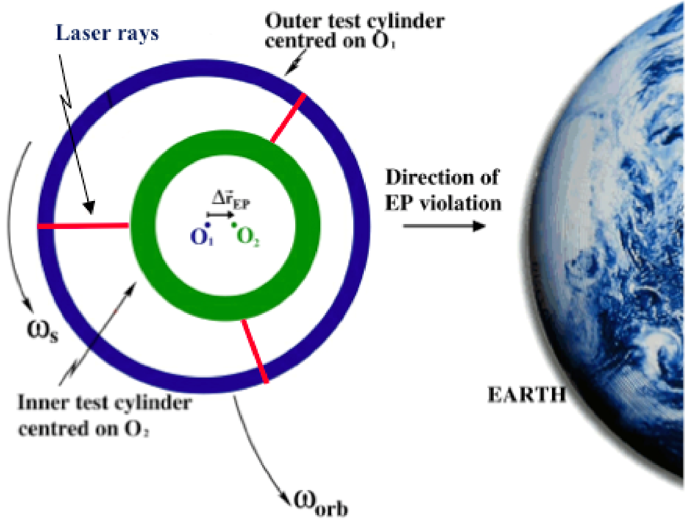
Rotation (exploited in high sensitivity UFF/WEP tests...) does not require motor/bearings if whole spacecraft rotates (angular momentum conservation)

No terrain tilts (almost..): if rotation is passive, the rotation axis remains fixed in inertial space (crucial advantage in checking target signal against systematics...)

GG & M4: The sensor

GG: signal and signal up-conversion principle



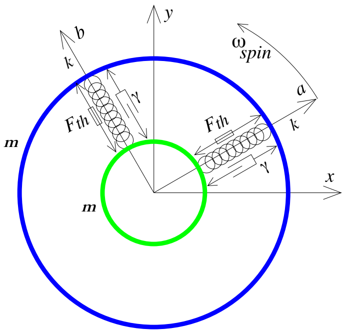


The sensitive/orbit plane of GG coupled test cylinders in case of WEP violation (when spin axis is perpendicular to orbit plane). The signal is a relative displacement vector (of constant size for zero eccentricity) pointing to the CM of the Earth as they orbit around it with $\simeq 1.7 \cdot 10^{-4}$ Hz frequency.

Rotation around the symmetry axis (perpendicular to orbit plane) of test cylinders and read-out (laser interferometry gauge) up-converts the signal from $\simeq 1.7 \cdot 10^{-4}$ Hz orbital frequency to 1 Hz spin frequency.

Uniqueness of the GG differential accelerometer: a rapidly rotating mechanical oscillator in 2D

The ultimate limitation to UFF tests comes from thermal noise due to internal dissipation in the suspensions which is inversely proportional to the frequency: shown experimentally by slowly rotating torsion balances *(Adelberger et al., PPNP 2009)*



In a 2D mechanical oscillator rotating faster than its natural frequency a low frequency signal is up-converted to the rotation frequency *without attenuation* (contrary to what happens in 1D oscillators, such as torsion balances...)

In GG up-conversion of the violation signal from orbital frequency ($\nu_{orb} = 1.7 \cdot 10^{-4\,\mathrm{Hz}}$) to spin frequency ($\nu_{spin} = 1\,\mathrm{Hz}$) brings the signal to a region where the relevant thermal noise is a factor $\nu_{spin}/\nu_{orb} \simeq 5900$ smaller

Read Phys. Rev. Lett. 2011

GG integration time to reach 10^{-17}

$$< |\hat{F}_{th}(\omega_{spin})|^2 >_{tot} = \\ < |\hat{F}_{th-gas}|^2 > + < |\hat{F}_{th-id}(\omega_{spin})|^2 > + < |\hat{F}_{th-J}|^2 > \simeq \\ 3.5 \cdot 10^{-28}\,\mathrm{N}^2/\mathrm{Hz}$$

- Gas damping noise estimated with reference to Cavalleri et al., PRL 2009 and a 2 cm gap as in GG baseline with laser gauge read-out.
- Johnson noise and Eddy currents damping estimated assuming gradient of the Earth's magnetic field as large as the field itself and with a 150 reduction by μ-metal shield

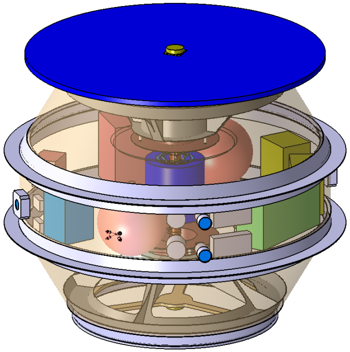
With $SNR = 2$ and a WEP target to 10^{-17} (test bodies 10 kg each); $F_{signal} \simeq 4 \cdot 10^{-16}$ N) the required integration time is:

$$t_{int} = SNR^2 \cdot \frac{< |\hat{F}_{th}(\omega_{spin})|^2 >_{tot}}{F^2_{signal}} = 4 \cdot \frac{3.5 \cdot 10^{-28}}{(4 \cdot 10^{-16})^2} \simeq 2.4\,\mathrm{h}$$

A full 10^{-17} measurement can be done in 1 d (8 t_{int} cycles, almost 15 orbits)

Nobili et al., PRD 2014

GG with low thermal noise and laser gauge read-out



GG differenatial accelerometer sensor *up-converts the signal to 1 Hz*, where thermal noise due to internal damping, -otherwise dominant- is very low (no signal attenuation)

Makes a WEP test to 10^{-17} *possible in a few hours* (0.6 pm displacement signal) $\Rightarrow$ laser gauge with $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ noise @ 1 Hz. Purely differential and linear, no dynamic range issue; 2 cm gap (not feasible with capacitance bridges) gets rid of electric patch effects and reduces gas damping (for short integration time)

Null checks: In 9-month mission and 1 WEP test to 10^{-17} per day, passive stability of GG spin axis under widely changing dynamical conditions allows the most important known sources of systematics to be identified and discriminated from signal, whose frequency and phase are known, due to their different physical signature. Is done offline; requires no sensor in addition to the one at the center of mass of the whole satellite.

$\mu SCOPE$ *integration time to reach* $\eta = 10^{-15}$

μSCOPE to fly in 2016

Thermal noise is dominated by internal damping in the gold wire connecting each test mass to its enclosure and is estimated by μSCOPE scientists to be *(Touboul Space Sci. Rev., 2009; Touboul et al. CQG, 2012)*:

$$a_{th-\mu scope} \simeq 1.4 \cdot 10^{-12}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$$

For a WEP test to 10^{-15} and $SNR = 2$:

$$a_{WEP-\mu scope} \simeq 8 \cdot 10^{-15}\,\mathrm{ms}^{-2} \quad \textit{and} \quad t_{int-\mu scope} = 4 \cdot \frac{(1.4 \cdot 10^{-12})^2}{(8 \cdot 10^{-15})^2} \simeq 1.4\,\mathrm{d}$$

which allows a reliable measurement in several days and leaves room for checks and/or improvements in 9-month mission.

Aiming at 100 times better (same target as GG) requires to increase integration time by 10^4, or reduce damping by 10^4!

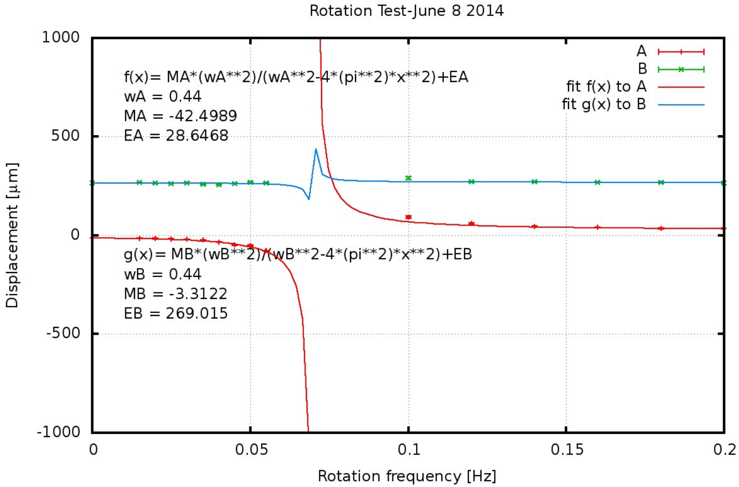
What if μSCOPE result will be, even marginally, compatible with violation? Pressure to check it will be enormous...

How physics allows rapid rotation in 2D

The centers of mass of the tests bodies cannot be perfectly concentric. The offset vector $\vec{\varepsilon}$ (fixed with the rotating masses) is not zero but in 2D it is reduced by the factor $\omega_{diff}^2/\omega_{spin}^2$. The solution (in the non rotating frame) is:

$$\vec{r}(t) \simeq -\varepsilon \left(\frac{\omega_{diff}^2}{\omega_{spin}^2 - \omega_{diff}^2} \right) \begin{pmatrix} \cos(\omega_{spin} t + \varphi) \\ \sin(\omega_{spin} t + \varphi) \end{pmatrix} \simeq -\varepsilon \left(\frac{\omega_{diff}^2}{\omega_{spin}^2} \right) \begin{pmatrix} \cos(\omega_{spin} t + \varphi) \\ \sin(\omega_{spin} t + \varphi) \end{pmatrix}$$

Proof masses are centered on one another by physics.



Experimental data from the GGG accelerometer agree with the theoretical curves in both directions $\alpha\,,\beta$ of the rotating plane and allow the mechanical unbalance to be separated out from the electrical one (so as to be reduced, hence improving self-centering):

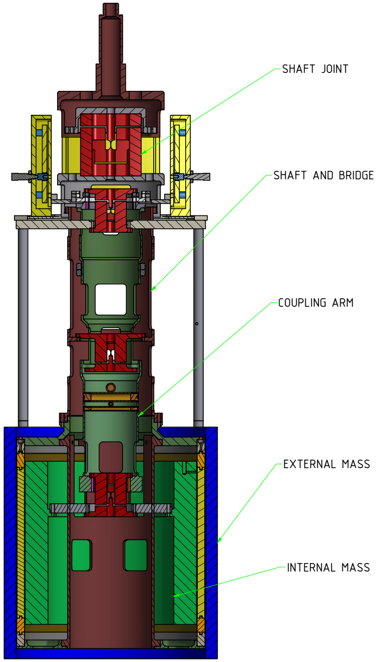
$$r_{\alpha,\beta}(\nu_{spin}) = \varepsilon_{\alpha,\beta} \cdot \frac{\nu_{\alpha,\beta}^2}{\nu_{\alpha,\beta}^2 - \nu_{spin}^2}$$

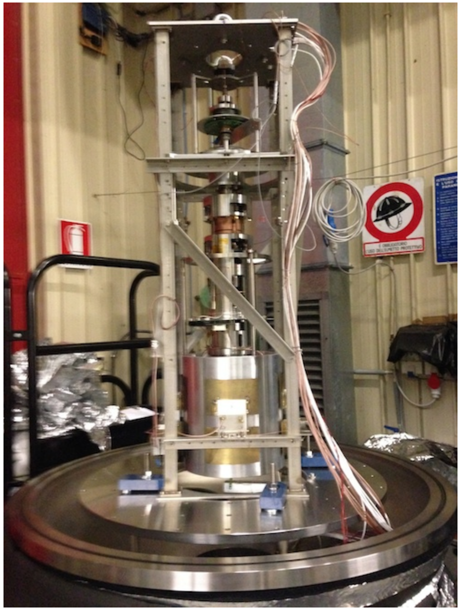
GG on Ground (GGG)

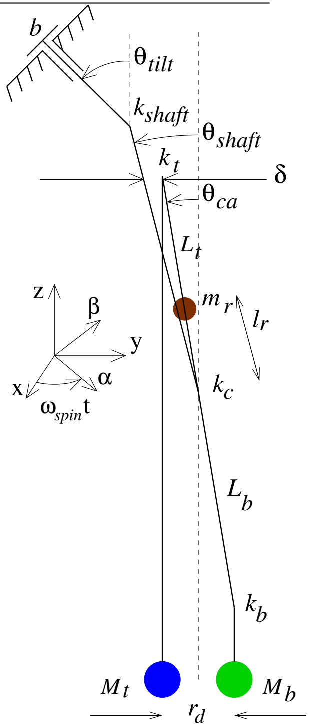
Possible because the GG sensor has 2 DOF: use spin/symmetry axis to suspend it, sensitive in the horizontal plane of lab (same number of DOF as in space), full scale, rotation in supercritical regime...

... remember: **it is the prototype of a sensor designed and optimized for space. At $1\,g$ torsion balances are better (thin fiber yields high torsional sensitivity..)**

The GGG prototype



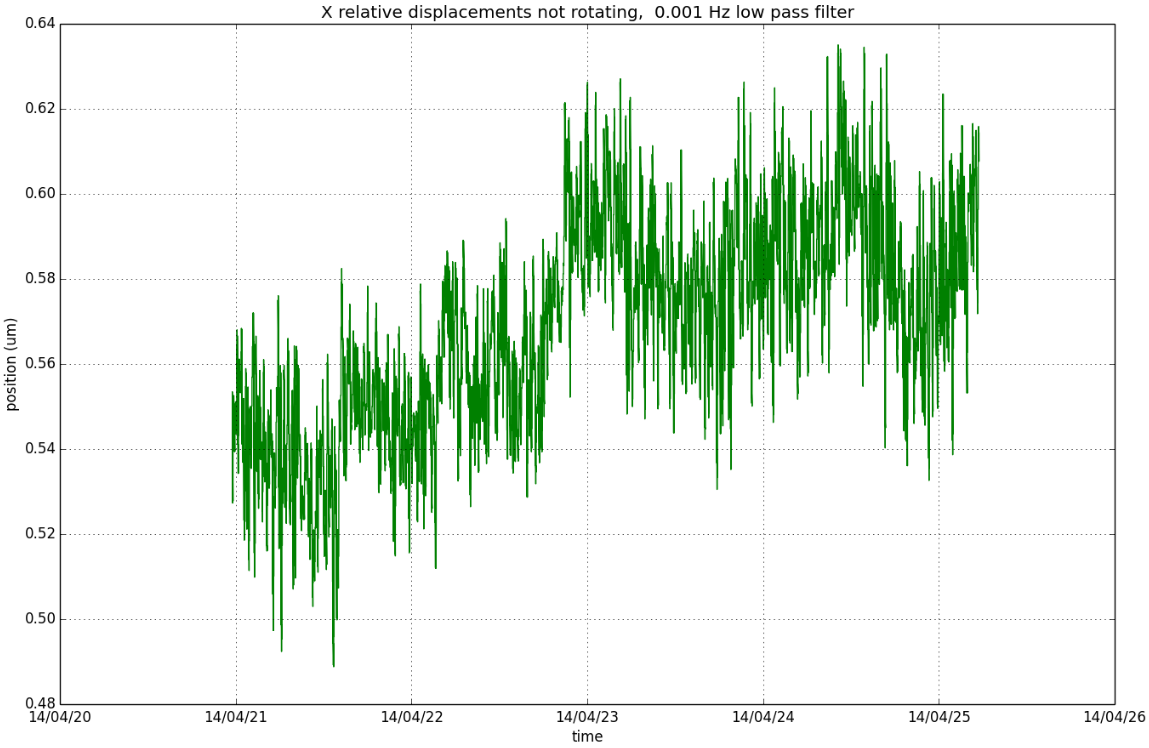




GG in space needs no motor no bearings, has no "terrain" tilts, has weaker coupling and higher sensitivity by 3 orders of magnitude; the driving signal from Earth is 500 times stronger ...yet the key features are the same as in GGG

Monolithic rotating 2D joint provides attenuation of low frequency terrain microseismicity (much better than active control in closed loop on conventional tiltmeter...)

The GGG prototype: current sensitivity (I)

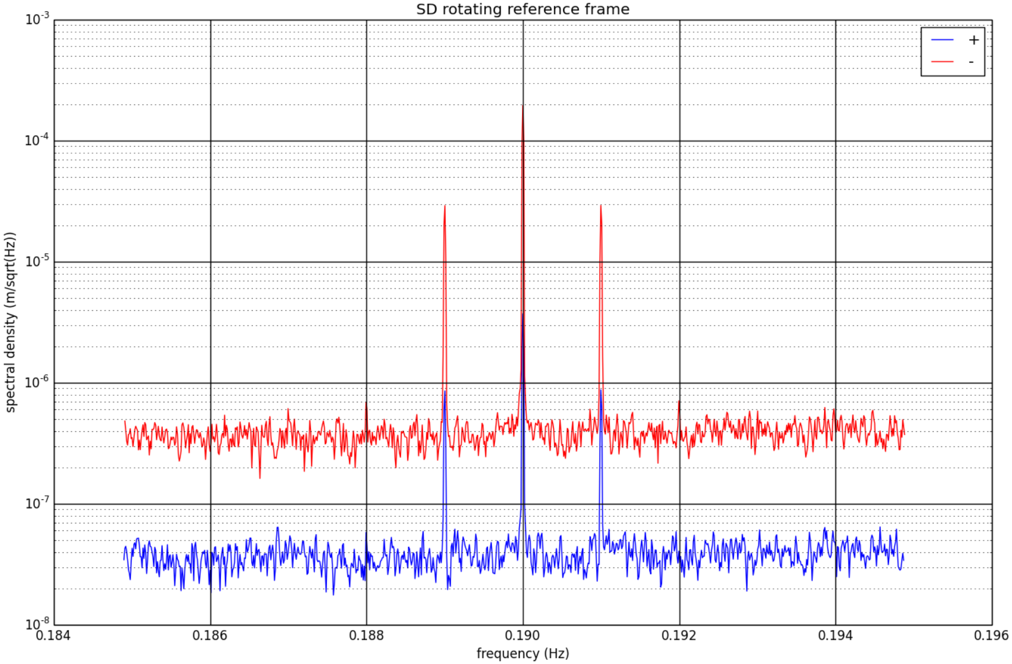


Time series (low frequencies) of the relative displacements of the test cylinders in one direction of the horizontal plane of the lab (non rotating frame).

The cylinders spin at 0.19 Hz (with 0.07 Hz natural differential frequency).

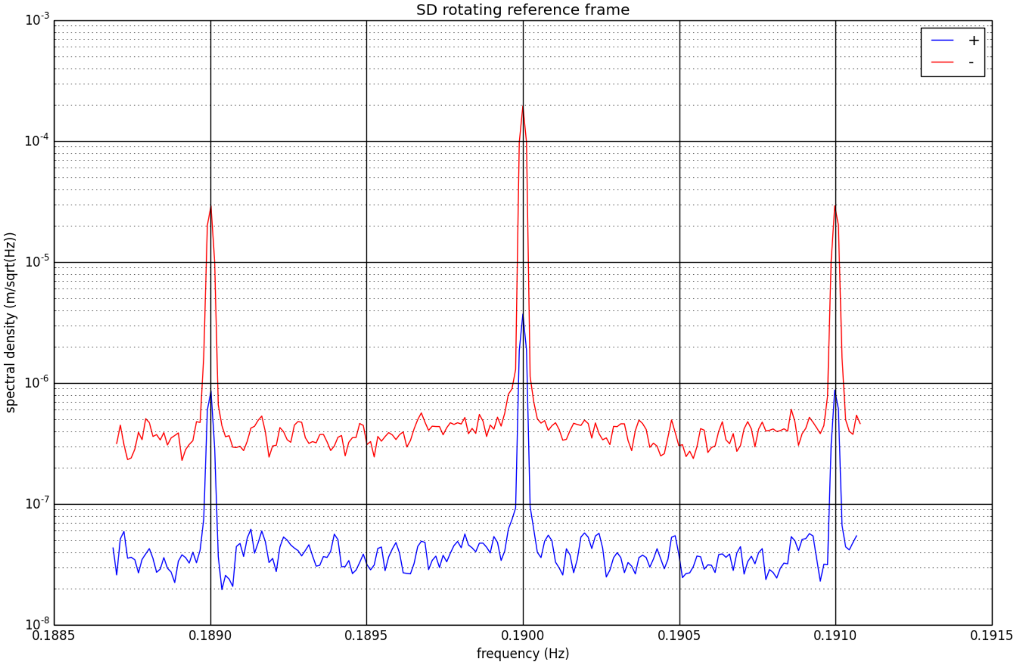
Their centers of mass stay 0.14 μm away from each other other all the time (low frequencies)

The GGG prototype: current sensitivity (II)



Spectral Density (SD) in complex form (+ and -). Calibration signal applied at 1mHz along fixed direction in lab plane to mimic low frequency terrain tilt (absent in space): should not appear in SD+ curve. In reality it is rejected, and so is rotation noise (NOT possible in 1D)

The GGG prototype: current sensitivity (III)



The GG signal is at $\nu_{GG} = 1.7 \cdot 10^{-4}\,\mathrm{Hz}$, hence it is seen by the rotating sensors this close to the spin frequency (here at 0.1902 Hz or 0.1898): the lowest level of noise we get is $\simeq 4 \cdot 10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$

The GGG prototype: current sensitivity (IV)

@ GG frequency:

- Lowest displacement/root(Hz) noise: $\simeq 4 \cdot 10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ (with $T_{res} = 86400\,\mathrm{s}$)
- Lowest displacement noise (20 days): $\simeq 3.7 \cdot 10^{-11}\,\mathrm{m}$
- Lowest differential acceleration noise/root(Hz) (0.07 Hz natural differential frequency):
  $\simeq 4 \cdot 10^{-8} \cdot (2\pi \cdot 0.07)^2\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}} \simeq 7.74 \cdot 10^{-9}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$
- Lowest differential acceleration noise (20 days): $\simeq 7.2 \cdot 10^{-12}\,\mathrm{m/s}^2$
  $\Longrightarrow \;\; \eta_{GG} \simeq \frac{7.2 \cdot 10^{-12}}{8} \simeq 9 \cdot 10^{-13}$

GGG: where does it stand as a prototype of GG?

$$\eta_{GGG_{\oplus} prototype @ 1.7\cdot 10^{-4}\mathrm{Hz}} \simeq \frac{7.2\cdot 10^{-12}\,\mathrm{m/s^2}}{8\,\mathrm{m/s^2}} \simeq 9 \cdot 10^{-13}$$

$$\eta_{GG_{\oplus} target @ 1.7\cdot 10^{-4}\mathrm{Hz}} = 10^{-17}$$

$$\frac{\eta_{GGG_{\oplus} prototype @ 1.7\cdot 10^{-4}\mathrm{Hz}}}{\eta_{GG_{\oplus} target @ 1.7\cdot 10^{-4}\mathrm{Hz}}} = 9 \cdot 10^{4}$$

$\frac{sensitivity@zero-g}{sensitivity@one-g} = (0.07\,\mathrm{Hz}/1.85 \cdot 10^{-3}\,\mathrm{Hz})^2 = 1430$ *no way to bridge this gap at 1-g!*

$\Downarrow$

The only factor that GGG can still gain (by reducing rotation noise and terrain tilt noise, absent in space and possibly improving read-out) is: $\frac{9\cdot 10^4}{1430} = 63$

(... read-out in space with $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ @ $1\,\mathrm{Hz}$ noise level: laser gauge..)

GGG: where does it stand compared to others?

Best GGG result at diurnal frequency in CQG, 2012 (long run required; ambient thermal stress very high in lab....)

$$\eta_{GGG_\odot @ 1.16 \cdot 10^{-5}\mathrm{Hz}} \simeq \frac{3.4 \cdot 10^{-10}\,\mathrm{m/s^2}}{a_{\odot - Pisa}} \simeq \frac{3.4 \cdot 10^{-10}\,\mathrm{m/s^2}}{0.0057\,\mathrm{m/s^2}} \simeq 6 \cdot 10^{-8}$$

Sensitivity to differential accelerations @ low frequencies:

i) $6 \cdot 10^4$ *times* **worse** *than torsion balances (they cannot fly)*
Braginsky & Panov, JEPT 1972 (Univ. Moscow)
Baessler et al., PRL 1999 (UW Seattle, USA)

ii) $2.9 \cdot 10^3$ *times* **better** *than* ^{85}Rb, ^{87}Rb test
Fray et al., PRL 2004 (Max Planck, DE), also ***Schlippert et al., PRL 2014*** using K, ^{87}Rb

iii) 202 *times* **better** *than* Cs, SiO_2 test
Peters et al., Nature 1999 (Stanford, USA)

iv) 124 *times* **better** *than* ^{87}Rb, SiO_2 test
Merlet et al., Metrologia 2010 (LNE-SYRTE, Paris, FR)

v) 20 *times* **better** *than* Al, Cu test
Carusotto, Polacco et al., PRL 1992 (CERN)

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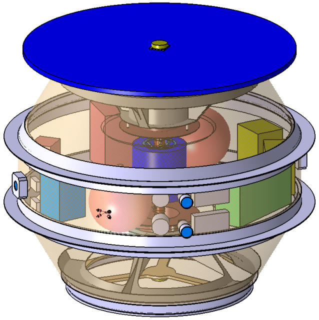
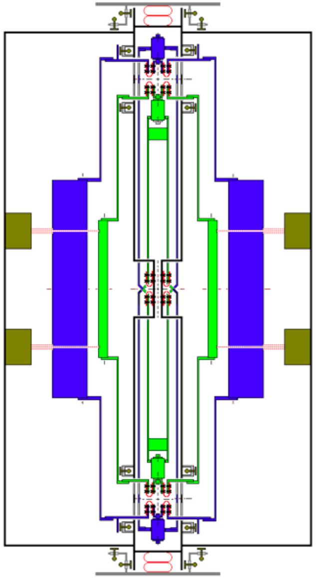
GG & M4: Mission configuration

Overview (I)

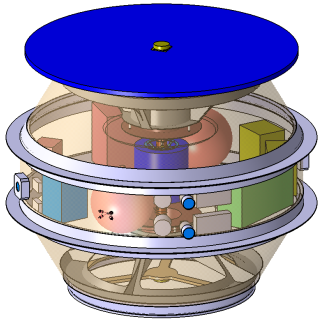


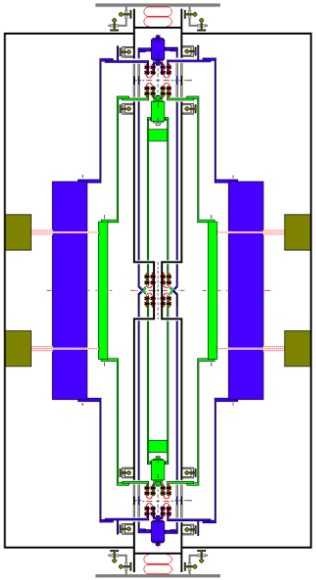
400 kg total mass, 1.4 m width, 1.2 m height
Passively stabilized by 1-axis rotation
Outer skin weakly coupled to PGB, enclosing in its turn the GG sensor (nested configuration)
Drag-free at ν_{orb} with PGB as test mass, cap bridges as sensors and cold gas thrusters as actuators (180 times less demanding than μSCOPE and 6000 times less demanding than LISA-PF)
GG differential acceleration sensor located at the center of mass (outer test cylinder visible in blu). → see section along spin axis to the right..



Section of GG balance along symmetry/rotation axis. Inner and outer test cylinder (green and blue) are suspended at their centers of mass from the PGB (an intermediate suspension stage sketched with a rectangular section) which encloses the sensor, screens it from various disturbances and mounts instrumentation (here the read-out laser gauge is shown)

Overview (II)





Cylindrical symmetry. Attitude stabilization by rotation around symmetry axis.

Standard near circular, low altitude ($\simeq$ 600 km) sun-synchronous orbit for a 9-month mission duration.

Standard VEGA launch using a fraction of its capability.

Uncontrolled re-entry in 25 years by atmospheric drag possible (cheap).

Well designed measurement sessions and procedure in order to discriminate signal from systematic errors.

The sensor is in essence a beam balance with 2 concentric cylinders rotating around its beam coupled by weak U-shape CuBe flexures (relative displacements read by low noise laser interferometry gauge).

Each arm has 2 parts and they are all adjustable (with capacitors as sensors and PZT as actuators) for common mode rejection.

Laser beam launchers, sensor electronics, thermal insulation etc..

all located on enclosing PGB

GG design and flexibility

GG as a whole (payload + bus) is designed *as a single experimental apparatus* optimized to detect UFF/WEP violation in the field of Earth

Definition of bus and payload is flexible and can be adjusted. Current strategy is to put most of the burden on the bus (ESA cost) and less on the payload (ASI cost)

GG & M4: Heritage, readiness, management and cost

Heritage (I)

- GG industrial studies by TAS-I Torino funded by ASI since 1996
  Latest Phase A2 study in 2009 (delta study on cold gas thrusters in 2011) based on expertise gained by TAS-I as prime contractor of GOCE. Includes realization of spin rate sensor at INRIM with $\Delta\nu_{spin}/\nu_{spin} \simeq 10^{-4}$
  Results of Phase A2 study made available by ASI to JPL (President decision) and 2.5 month study of GG at JPL in 2010
- Key heritage from GOCE: control tools in very low noise environment (fully successful)
- Cold gas thrusters qualified for GAIA (flying); will fly on LISA-PF in 2015 and in μSCOPE in 2016: should modifications/improvements be necessary, they will be available for GG

Heritage (II)

- GGG lab prototype funded by INFN and ASI. Feasibility of GG sensor demonstrated; sensitivity close to best possible at 1-g achieved

  Same number of degrees of freedom & full scale. GG sensor is not exactly the same as GGG (cannot be..) but relies on technologies available from GGG (test cylinders coupling with low dissipation suspensions, dissipation measurements, capacitance bridges - needed in GG as ancillary sensors and actuators - whirl damping, calibration and centering, data analysis)

  Only laser gauge read-out not tested in GGG

Readiness

All items must have TRL 5-6; 2-2.5 years development allowed

TRL 5: Component and/or breadboard critical function verification in a relevant environment	Critical functions of the element are identified and the associated relevant environment is defined. Breadboards not full-scale are built for verifying the performance through testing in the relevant environment, subject to scaling effects.	Preliminary definition of performance requirements and of the relevant environment. Identification and analysis of the element critical functions. Preliminary design of the element, supported by appropriate models for the critical functions verification. Critical function test plan. Analysis of scaling effects. Breadboard definition for the critical function verification. Breadboard test reports.

TRL 5 to be achieved for GG laser gauge read-out: $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at $1\,\mathrm{Hz}$ required
Design of laser gauge realized by M. Shao at JPL preferable
M. Shao available for collaboration
ITI program of ESA-ESTEC now open, deadline December 2014, Laser division of ESTEC favorable to initial funding of LIG (Laser Interferometry Gauge) proposal, discussion initiated in 2013

Management and cost (I)

- TAS-I Torino has good chances to win ESA bid for GG.
  Bus to include outer skin and PGB (PGB serves as test mass for drag free control; weak coupling between outer skin and PGB provides nutation damping for spin-axis passive stabilization)
  Laser gauge on PGB hence part of bus, to be funded by ESA. We must provide credible design and development route within credible institution. INRIM + collaboration of Mike Shao strong assets

Management and cost (II)

Payload (to be funded nationally) includes:

- Test cylinders with fine polished spots and holes for laser reflection
- Coupling arms
- U-shape low CuBe flexures (6 for cylinders suspension at the center of the shaft - rigid with PGB - and 6 for coupling the cylinders through arms)
- Launch locks for both cylinders and arms to PGB (in turn launch locked to outer skin)
- Small capacitance bridges between arms and PGB shaft for whirl damping with inchworms at 45° to be used during lock-unlock at zero g
- PZTs (inchworms) on arms for adjustments (balancing of GG balance)
  Note: no device on payload (capacitance bridges, inchworms) will be ON during science measurements

INRIM is the most natural and best choice in Italy for the GG payload (+ very good high precision small companies in the Torino area)

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Management and cost (III)

- Total cost of GG: solid estimate available from previous industrial studies, formally accepted by ESA during debriefing on S1 proposal in 2012
  Read GG debriefing summary with ESA Science Directorate, December 2012

  Though this estimate is likely to be revised upwards (it was based on launch as Vega piggy-back, small team, short timeframe) GG is for sure a small mission, with small team, concentrated activity, Vega launcher $\Rightarrow$ cost far below ESA cost cap.

  Important to reduce cost to ASI, make GG appealing (moneywise) & because it can involve small high precision mechanical companies and attract ESA funds to Italy (Torino...)