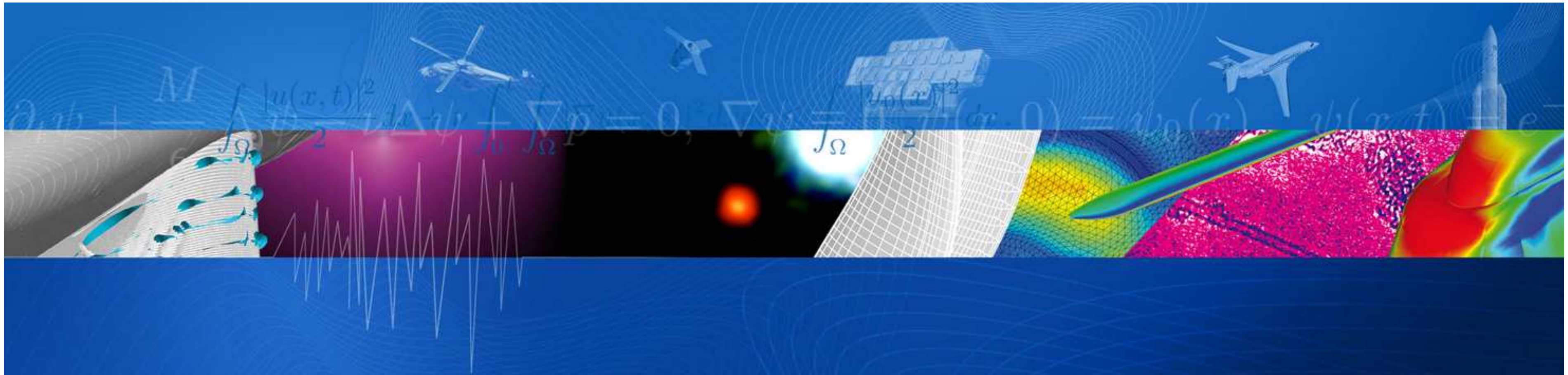


ONERA

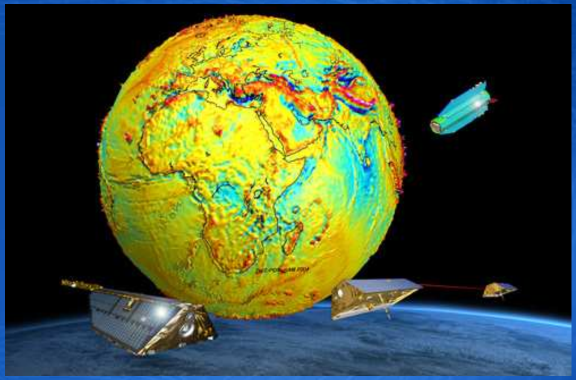
THE FRENCH AEROSPACE LAB

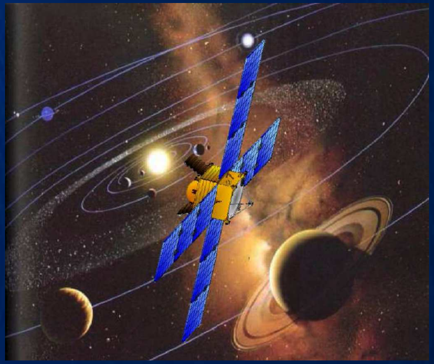
return on innovation

www.onera.fr

Mapping the Earth Gravity Field
and
Testing the Gravitation Law

Jean-Pierre MARQUE
ONERA/DMPH





ONERA
THE FRENCH AEROSPACE LAB

return on innovation

In Search of the geodesic

- The concept that a particle falling under the influence of gravity alone follow’s a geodesic in spacetime is a foundation of General Relativity (GR), our best model for gravity so far.

- Many alternative theories of gravity predict non GR geodesic motion at some level of accuracy.

- Experiments investigating the foundations of GR, like those aimed at a test of Equivalence Principle (EP) or devoted to the search of long range interactions almost invariably search for violations of the expected geodesic motion *(Precise orbit determination of planetary probes,Solar system ephemerides,non gravitational forces or acceleration).*

- Geodesic motion is also for interest to reconstruct the Gravity field of the Earth, or of other planets and moons.

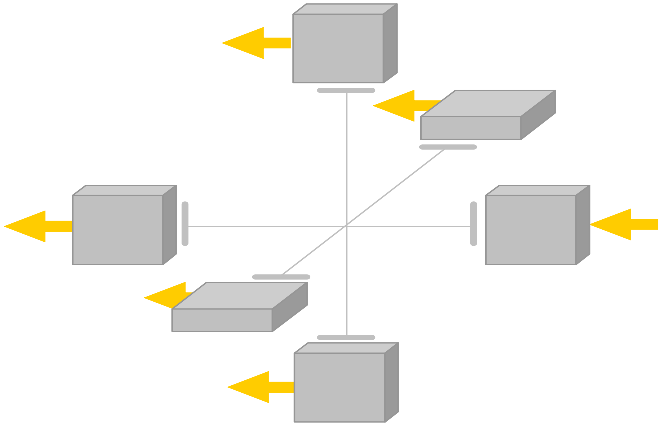
- Means used for orbit determination in these two cases are similar in terms of principle , but also in terms of final accuracy or performance.

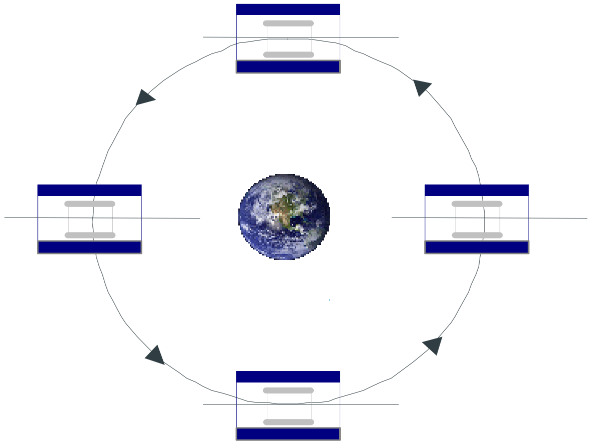
Synergy **between**

Earth Observation and Fundamental Physics

Earth Gravity Field

UFF Test : Weak equivalence principle





GOCE

6 Proof masses enslaved
to follow the free falling S/C
trajectory around Earth

MICROSCOPE

2 Proof masses enslaved
to follow the same orbit
around Earth

Measurement of differential low level acceleration

Drag Free satellites for orbits closer to geodesic

Challenge: A first Strategy, S1

Disturbing forces make test mass travelling away from their geodesic motion

2 Strategies

S1

S2

S1

- To precisely quantify these perturbations *to discriminate gravitational from non-gravitational accelerations and* to answer to these questions:
    - *Is the trajectory a geodesic one ?*
    - *Does classical explanation can be given to the residual deviation (Pioneer Anomaly)*
- To improve measurement accuracy for a resolution compatible with :
    - Non-gravitational forces and acceleration,
    - ‘non classical effects’ which might confirm a violation of GR**.**

Accelerometers are the sensors dedicated to this strategy

Challenge: A second approach, S2 or LISA Case

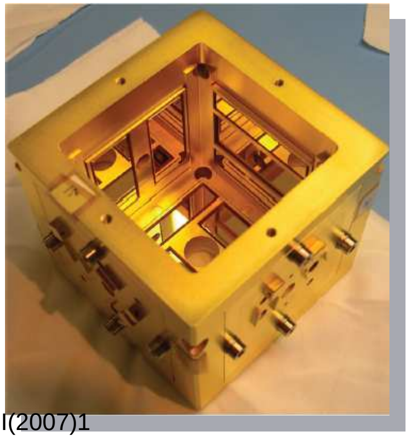
The Test mass is injected in geodesic conditions and shielded from non gravitational forces by the S/C

The S/C is Drag Free controlled and driven to follow the Test mass by relative position sensor

The inertial reference sensor CAESAR *(Capacitive and Electrostatic Sensitive Accelerometer Reference)* derived from accelerometer studies at ONERA was proposed for LISA in 1996 (*):

CAESAR sensor can be considered in two ways, both approaches compatible with a drag-free S/C::

- ❖ An inertial mass with a Capacitive Position Sensor (CPS) to provide the proof mass attitude and position with respect to the S/C - aimed resolution of 2.010^{-10} m/Hz$^{1/2}$ (4mm gap)
- ❖ An Electrostatic Positioning System (EPS) working as an accelerometer to measure and control the 6 degrees of freedom of the TM - aimed resolution for acceleration less than 10^{-14} ms^{-2}/Hz$^{1/2}$.



ESA-SCI(2007)1

Presently the GRS TM control on LISA PT is ensured by a similar electrostatic actuation system (SAU) with a resolution of 1.0 10^{-9} m/Hz$^{1/2}$

LISA
Inertial sensor (GRS)
electrode housing

The relative displacement of the 2 TM is measured by laser interferometer with picometer resolution

(*) P. Touboul,M.Rodrigues,G-M Leclerc,
ESA Symposium on Fundamental Physics in Space, London, October 1996

Endeavour in the science of precision metrology,whatever the strategy

- ❖ Theories of General Relativity shall be tested but needs unprecedented levels of refinement for measurements techniques

- ❖ To escape seismic noise and large gravity gradients effects, Space was of interest to reach:
  - ➢*Low frequency range,*
  - ➢*Increased accuracy by longer integration time*

- ❖ But, access to Space requires high technology and conditions to overcome some drawbacks

- ❖ 90’s was an active period with developements of new projects in the Earth observation domain as well as in fundamental physics

Space gravimetry with Solid Earth mission ARISTOTELES
Detection of Gravitational Waves with LISA
Tests of Equivalence Principle (EP) with STEP

which came to reality with different name or performance (except LISA) …..

Recent developments

Earth Gravimetry

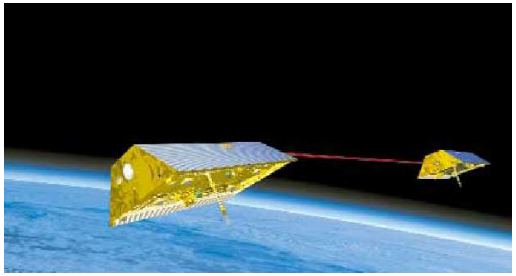
- The concept of the tri-axes electrostatic accelerometer based on the full electrostatic suspension of one unique proof mass was developped at ONERA in the 90's and shown to be very suitable for space applications requiring a very high acceleration resolution or drag-free control *(Gradio model for ARISTOTELES mission)*
- ASTRE was the first accelerometer to fly and was later on improved during the late 90's and the first 2000's years for the three space missions aiming at the recovery of the Earth gravity field:
  - *STAR for CHAMP mission with a resolution of $3.0\ 10^{-9}\ ms^{-2}/Hz^{1/2}$ (L 2000)*
  - *SuperSTAR for GRACE mission with a resolution of $10^{-10} ms^{-2}/Hz^{1/2}$ (L 2002)*
  - *GRADIO for GOCE mission with a resolution of $2.0\ 10^{-12}\ ms^{-2}/Hz^{1/2}$ (L 2009)*

Fundamental Physics

- In the 90's Several space missions for EP test were under study by the Agencies (NASA,ESA,CNES) with an objective of 10^{-17}- 10^{-18}
- Two main concepts:
  - *Magnetically suspended masses which differential motion is measured by SQUID (Mission STEP)*
  - *Servo-controlled electrostatic suspension of two masses forced to remain motionless with respect to each other*
- The second concept, based on tri-axes electrostatic accelerometers developped at ONERA came to reality in December 1999 when the CNES MICROSCOPE Mission with an accuracy goal of 10^{-15}, 2 orders of magnitude beyond the best on ground test, was selected.

Electrostatic accelerometers for Earth Gravimetry and Gradiometry (1/2)

GRACE (NASA-JPL), March 2002



Microwave K-Band
Inter satellite Ranging System
+

Electrostatic Accelerometer

The accelerometers provide the NG acceleration to correct the inter S/C range from NG contribution in order to retrieve the pure gravitational effect.

- Γ_n: $1.0 \cdot 10^{-10}$ ms^{-2} /Hz$^{1/2}$
- Γ_{max}: 510^{-5} ms^{-2}
- [$0.1 \cdot 10^{-3}$; 10^{-1}] Hz

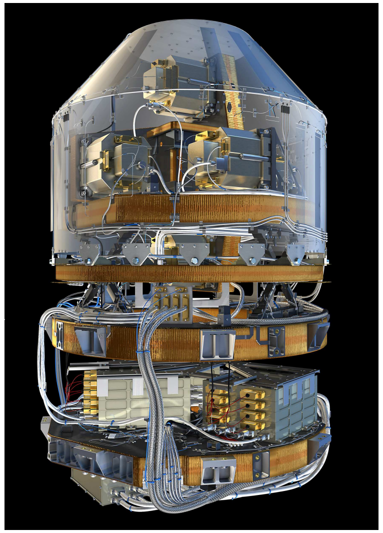
GOCE (ESA), March 2009

Drag Free System
with Electric Propulsion

\+

Gradiometer (EGG)
with 6 Accelerometers

\+



The common mode the accelerometers of each Gradio arm provides the NG acceleration to feed @10Hz the Drag Free System

Differential accelerometer measurements are used to retrieve the GGT components

- Γ_n: $2.0 \cdot 10^{-12}$ ms^{-2} /Hz$^{1/2}$
- Γ_{max}: 610^{-6} ms^{-2}
- [$5 \cdot 10^{-3}$; 10^{-1}] Hz

Electrostatic accelerometers for Earth Gravimetry and Gradiometry (2/2)

Accelerometer noise at 35–200 mHz

(10^{-10} m/s²/Hz$^{1/2}$)

Satellite	Date	Y_{ARF}	Z_{ARF}
GRACE A	**2007-01-17**	**0.6 - 1.2**	**0.5 - 1.3**
GRACE B	**2004-12-09**	**0.6 - 1.5**	**0.4 - 1.0**

J. Flury, S. Bettadpur, B.D.Tapley, Precise accelerometry on board the GRACE gravity field satellite mission, Adv. Space Res., 42, 2008.

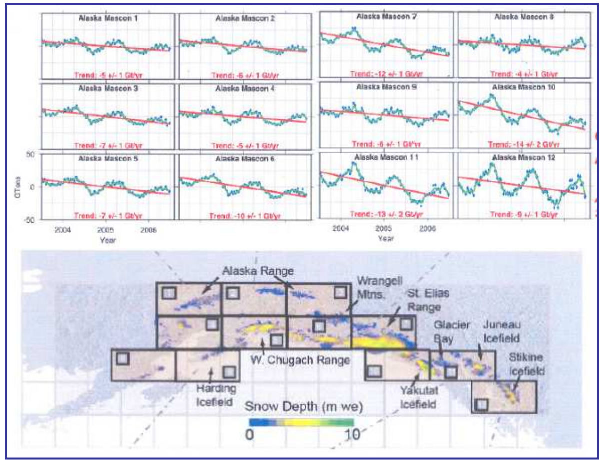
GRACE

RMS maxi error

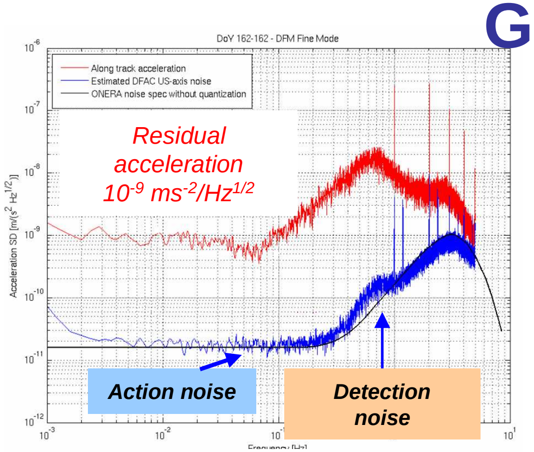
X (cross-track)	0.44 nm/s²
Y (radial)	0.50 nm/s²
Z (along-track)	0.40 nm/s²

S Bettadpur1, R. Eanes1, D. Hudson2, Z. Kang1, G. Kruizinga3 & P. Nagel1
1CSR-UT Austin, 2ONERA-DMPH, Paris, 3NASA/JPL, Pasadena

Gravity field Time variation



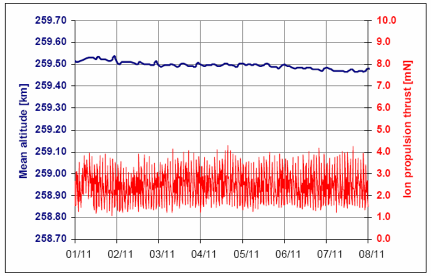
GOCE

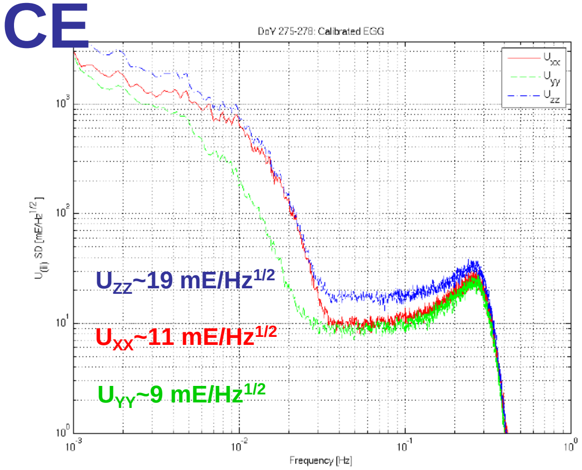


Residual acceleration 10^{-9} ms^{-2}/Hz$^{1/2}$

Action noise

Detection noise





U_{ZZ}~19 mE/Hz$^{1/2}$

U_{XX}~11 mE/Hz$^{1/2}$

U_{YY}~9 mE/Hz$^{1/2}$

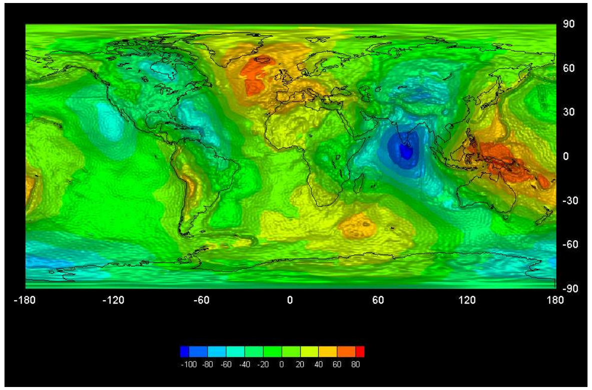
Worst case: assuming that accelerometers are the source of all the EGG noise

Accelerometer PSD in [40-100 mHz]

$ASH_{1,4}$: 3.9 10^{-12} m/s²/Hz$^{1/2}$

$ASH_{2,5}$: 3.1 10^{-12} m/s²/Hz$^{1/2}$

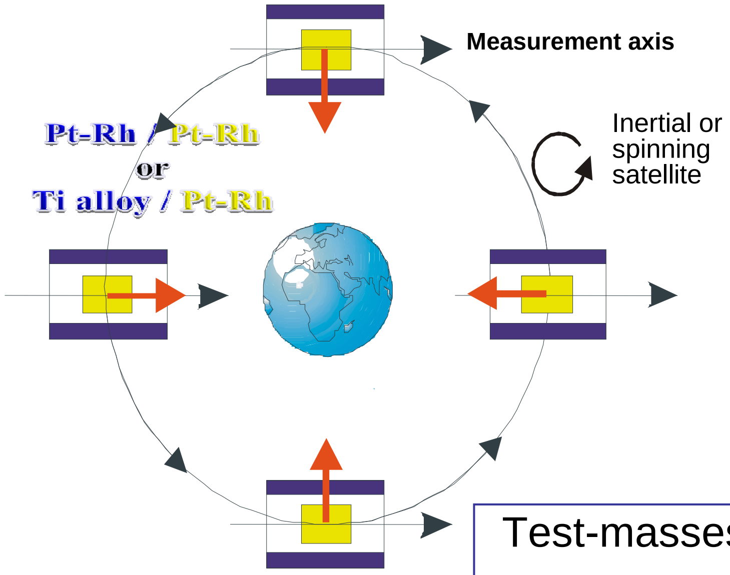
$ASH_{3,6}$: 6.7 10^{-12} m/s²/Hz$^{1/2}$

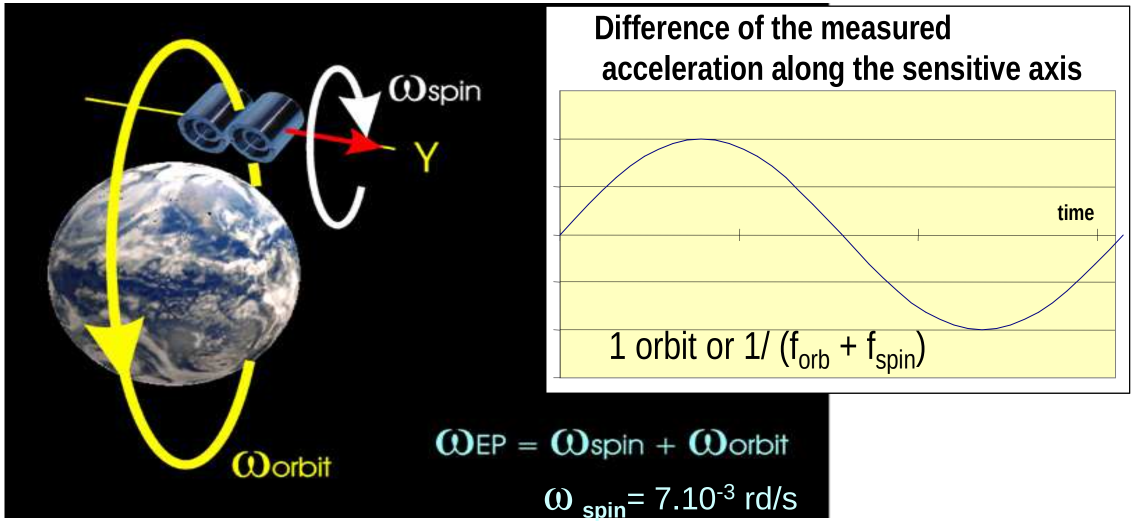


With 2 months data (Nov-Dec. 2009) very detailed gravity field signatures can be observed indicating the great potential for enhancing global gravity field modeling with GOCE Observations.

From Visser,P.N.A.M. A glimpse at the GOCE satellite gravity gradients observations. J.Adv. Res. (2010), doi:10.1016/j.asr.2010.09.015

MICROSCOPE: Testing EP in Space @10 $^{-15}$





Test-masses servo-controlled to follow at the best the same Geodesic

⬇

Operate like in an accelerometer with drag-free controlled satellite

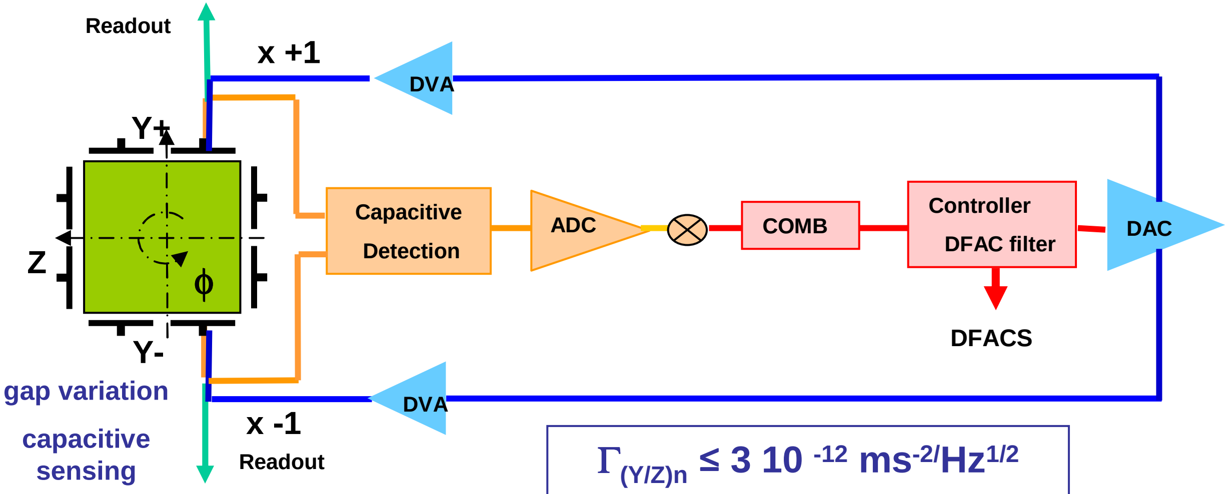
(residual acceleration of about 3 $10^{-10}ms^{-2}Hz^{-1/2}$)

The payload T-SAGE is composed of 2 differential coaxial electrostatic accelerometers

- In nominal science mode:
  - One differential accelerometers (Pt/Ti) operates in High Resolution Mode (HRM) to do the EP experiment @ fep and serves the Drag-Free and Attitude Control System (DFACS).
  - The other one is operating in Full Range Mode (FRM) and can be used for DFACS or for acceleration data process.
- The differential acceleration is composed of the EP violation signal + the Earth gravity gradient and inertia tensor terms due to the off-centering of the masses.The data are integrated over 10^5s.

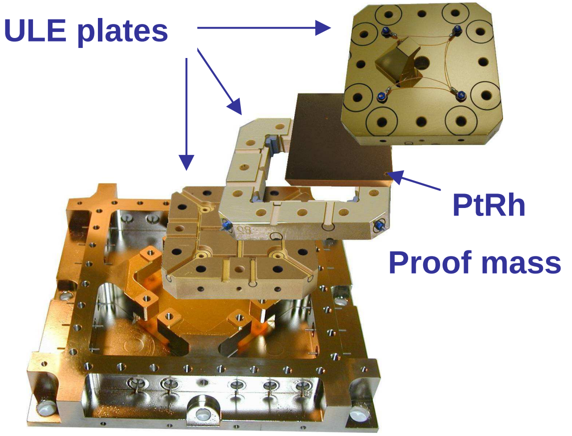
  That means an overall noise in the differential acceleration of about $8x10^{-15}$ ms^{-2} @ fep

GOCE and MICROSCOPE



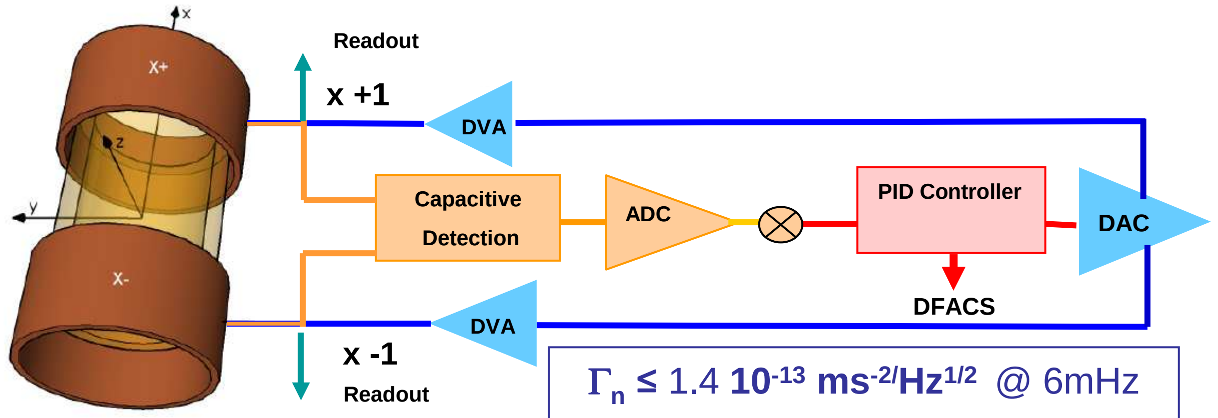
gap variation

capacitive sensing



$\Gamma_{(Y/Z)n} \leq 3\ 10^{-12}\ \mathrm{ms^{-2}/Hz^{1/2}}$

$X_n = 0.24\ 10^{-11}\ \mathrm{m/Hz^{1/2}}$



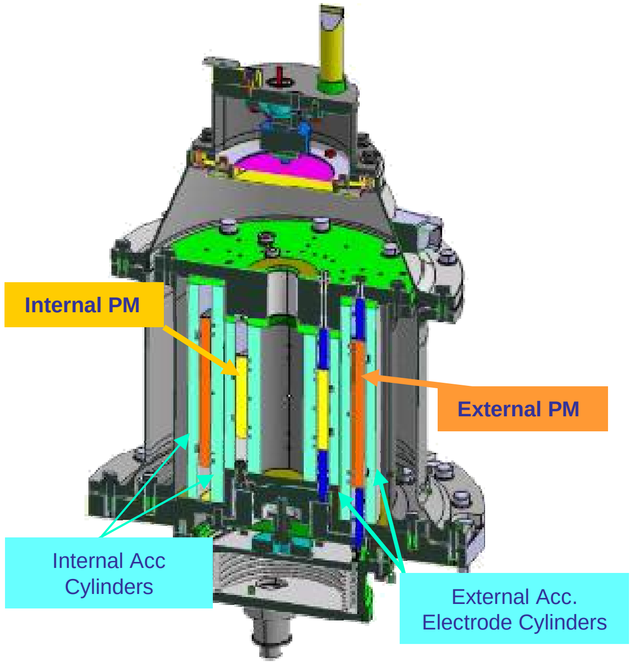
Surface variation

capacitive sensing

$\Gamma_n \leq 1.4\ 10^{-13}\ \mathrm{ms^{-2}/Hz^{1/2}}$ @ 6mHz

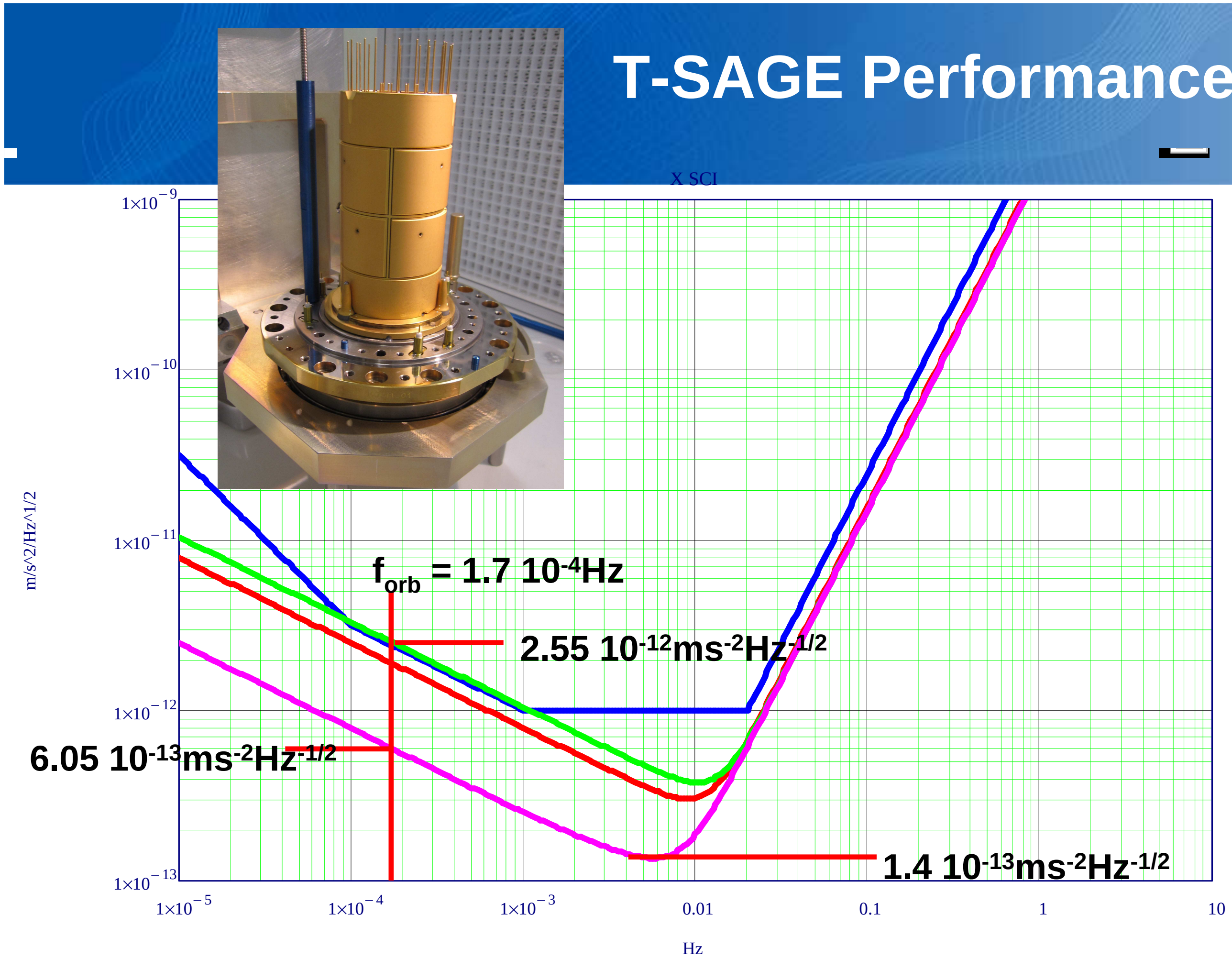
$(Y/Z)_n = 1.9\ 10^{-11}\ \mathrm{m/Hz^{1/2}}$

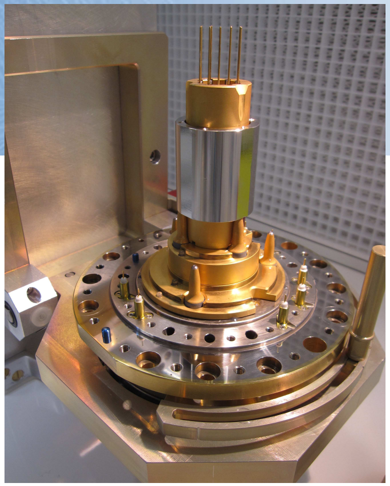
$0.7\ 10^{-12}$ m @fep

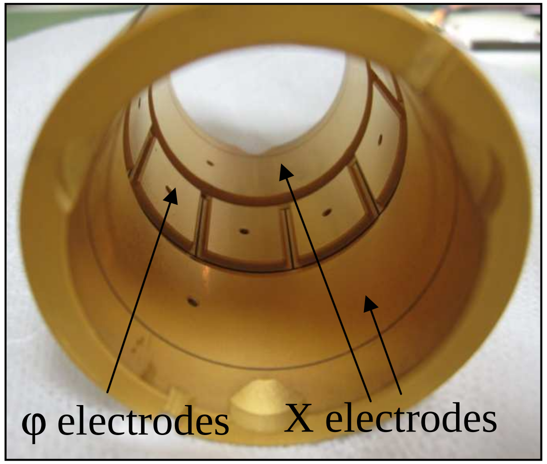


Blocking System

T-SAGE Performance



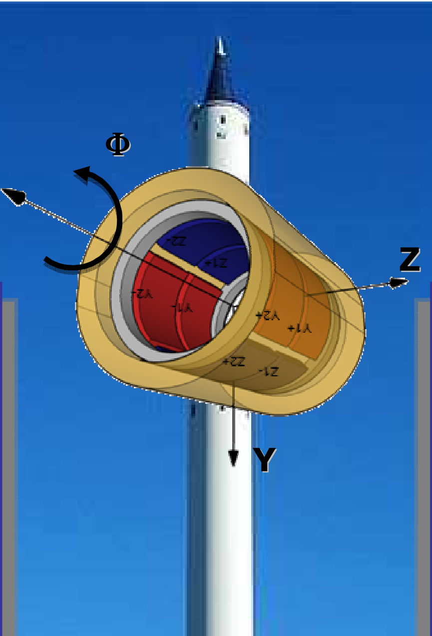




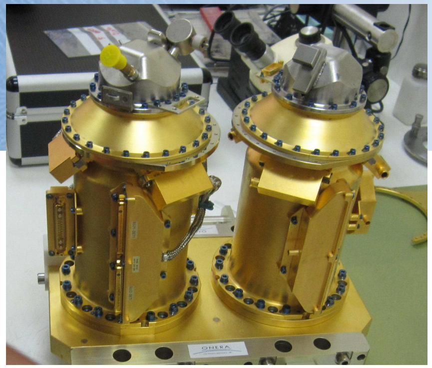
$1.4\ 10^{-13}\ ms^{-2}Hz^{-1/2}$ @ $f = 6\ 10^{-3}$ Hz for external mass PtRh
$6.05\ 10^{-13}\ ms^{-2}Hz^{-1/2}$ @ $f_{orb} = 1.7\ 10^{-4}$ Hz for external mass PtRh
$2.55\ 10^{-12}\ ms^{-2}Hz^{-1/2}$ @ $f_{orb} = 1.7\ 10^{-4}$ Hz for external mass TA6V

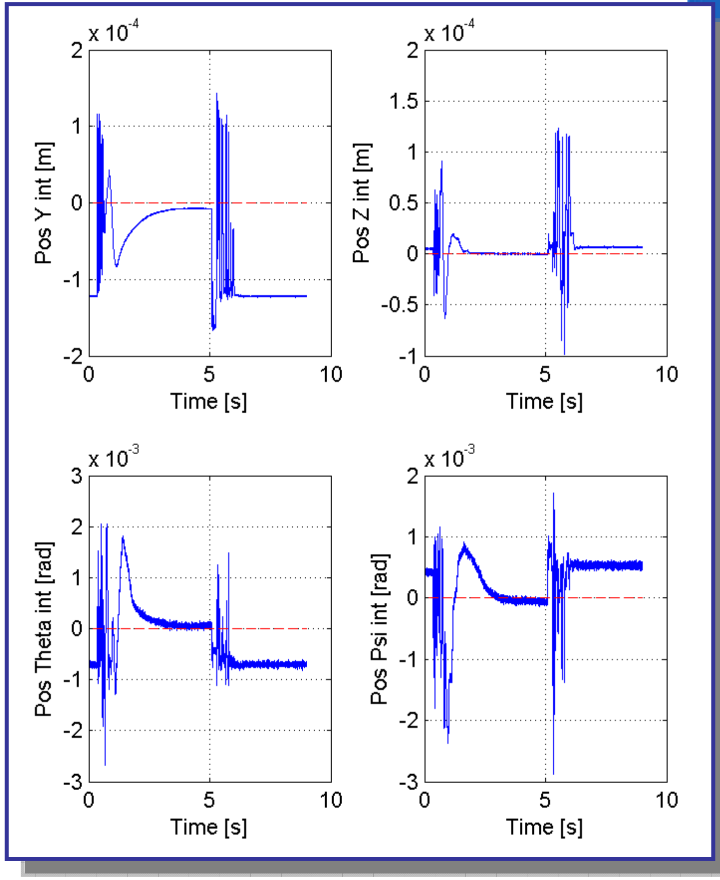
$4.4\ 10^{-11}\ rads^{-2}Hz^{-1/2}$ à $f = 2\ 10^{-2}$ Hz for external mass PtRh
$4.0\ 10^{-10}\ rads^{-2}Hz^{-1/2}$ à $f_{orb} = 1.7\ 10^{-4}$ Hz for external mass PtRh

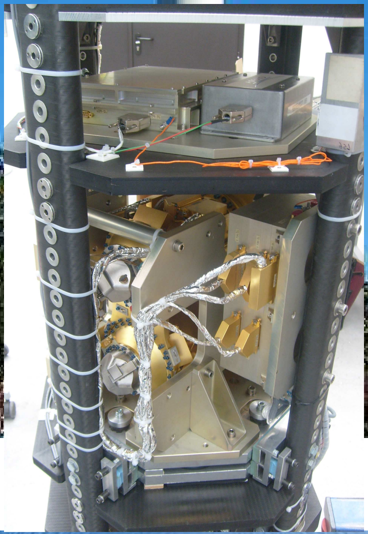
Free Fall Test of the Qualification model of the T-SAGE Instrument

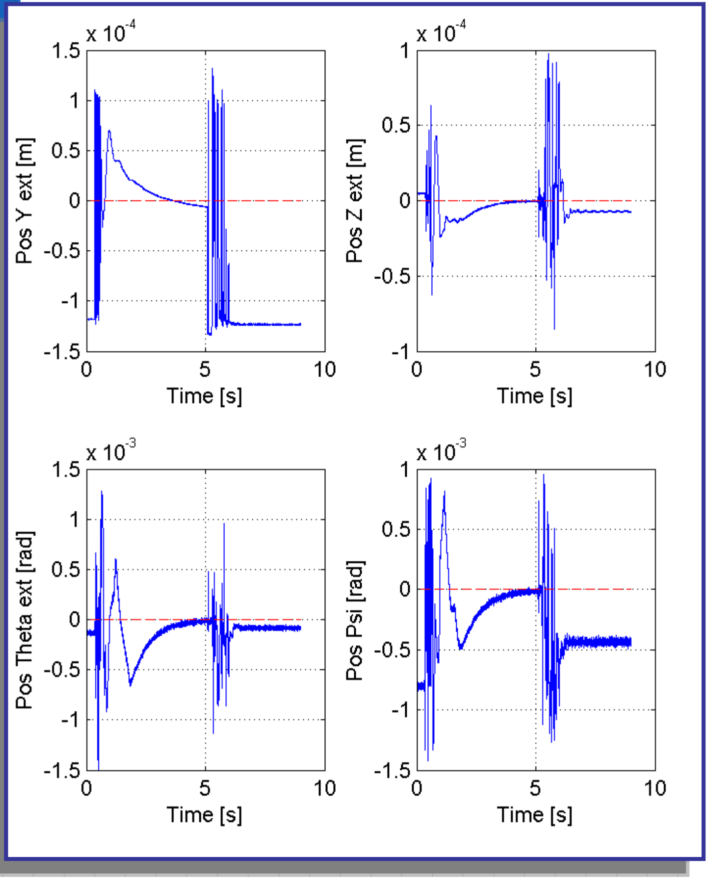


Fall duration









Acquisition and control of the two **proof-masses (int/ext)**

FUTURE

The progress in electrostatic accelerometers have continuously accompagned the progress in Space Geodesy and Fundamental physics .

They remain good candidates for future mission as technological leaders in this metrology field allowing accelerometry and displacement resolution at levels of $pms^{-2}/Hz^{1/2}$ or tens of $pm/Hz^{1/2}$.

Gravity Field Observation: Next Generation Gravity Mission

- *Under studies (ESA,NASA CNES (Micromega))*
- *L around 2020 – 2025 (except e.motion proposal to ESA EE8 if agreed)*
- *Based on S/C in formation and electrostatic accelerometers*

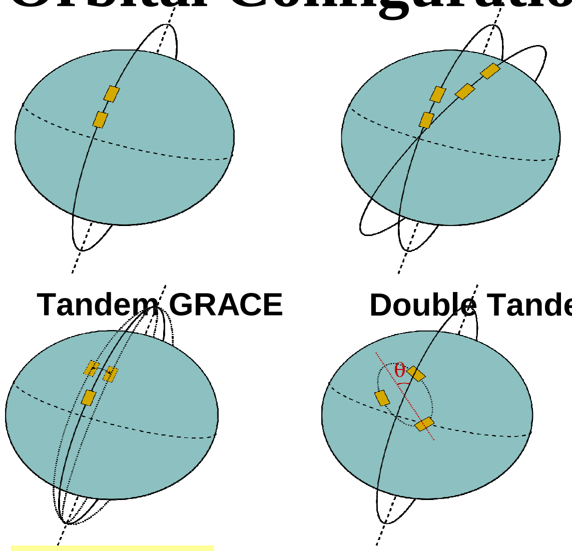
Fundamental Physics: Large Scale Test of Gravitation Mission

- *Two projects under development (EJSM-JGO and OSS)*
- *L around 2020 – 2025*
- *Based on MicroSTAR electrostatic accelerometer*
- *Associated to Geophysics studies of the visited planets and moons*

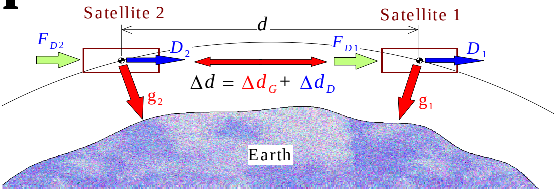
Next Generation Gravity Mission

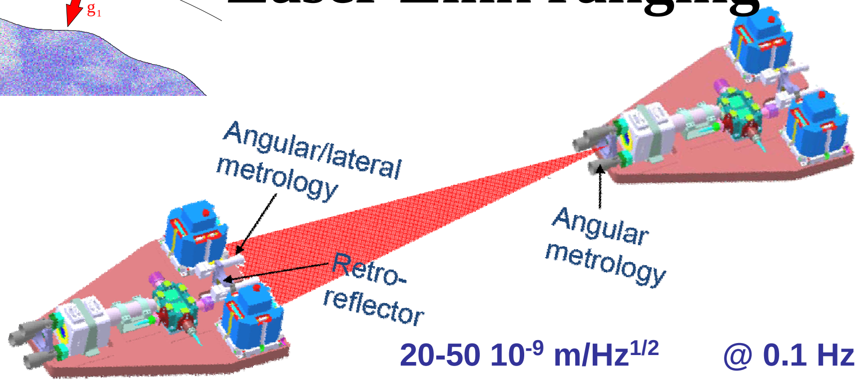
“a system de satellite capable of global determination of changes in the Earth's gravity field from global down to regional spatial scales and on time scales of two weeks or shorter”.

Orbital Configuration



inter-satellite Laser Link ranging





20-50 10^{-9} m/Hz$^{1/2}$ @ 0.1 Hz

750- 2000 10^{-9} m/Hz$^{1/2}$ @ 10^{-4} Hz

Need of fine attitude control of the satellite

Interest of accurate angular acceleration measurements

- ➢By combination of linear accelerations → GOCE like config.
- ➢Cubic proof-mass accelerometer

Satellite architecture

Low orbit, Low thrust propulsion

Low drag shaped satellite

or

Drag-Free satellites (along track only ?)

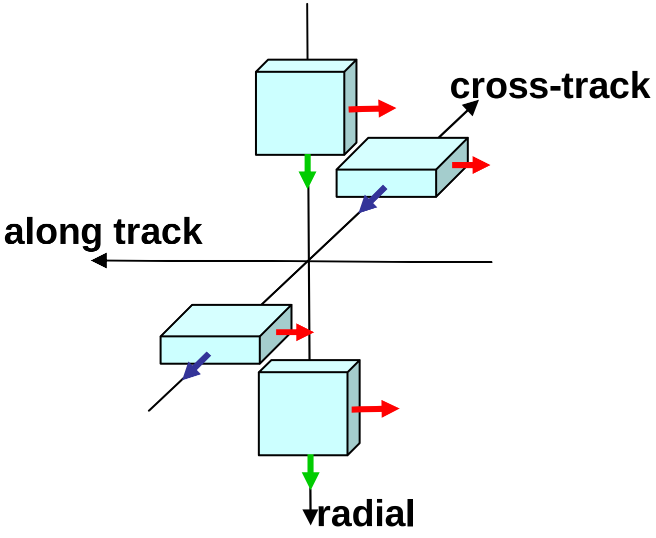
Critical item:

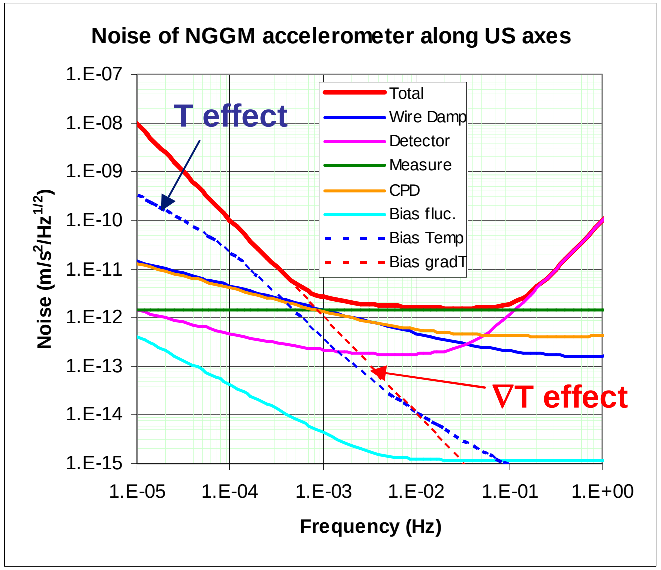
- ☐ Accelerometer at Center of mass
- ☐ Thermal stability

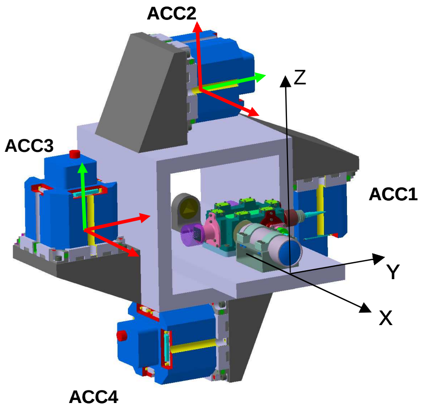
Accelerometer

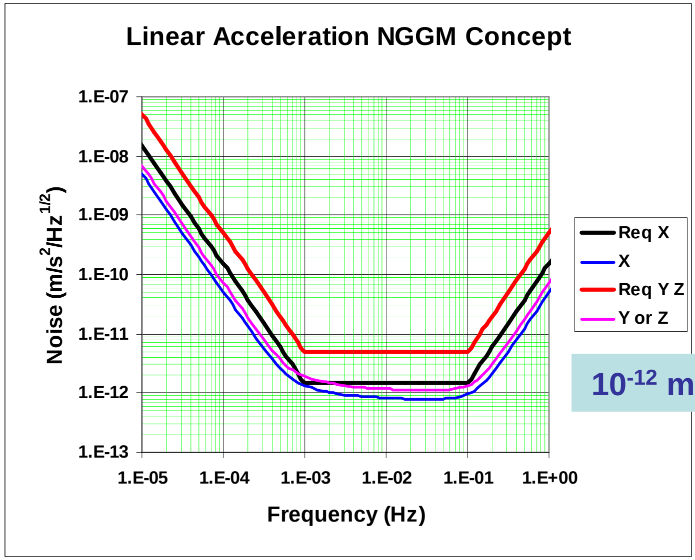
- **10^{-11} – 10^{-12} ms^{-2}/Hz$^{1/2}$**, 2 or 3 axes ? - MBW [10^{-4} – 0.1 Hz]
- LF Performance ► ultimate Performance
- Optical detection of the PM position
- Accomodation and Implementation: CoG, Gradiometer ?

ONE POSSIBLE CONCEPT: 10^{-12} m/s²/Hz$^{1/2}$ and 5 10^{-10} rad/s²/Hz$^{1/2}$

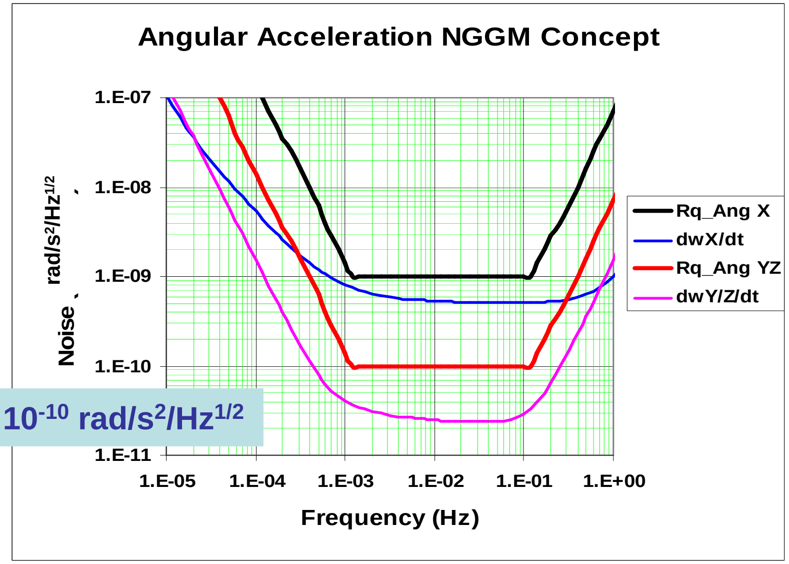








10^{-12} m/s²/Hz$^{1/2}$



5 10^{-10} rad/s²/Hz$^{1/2}$

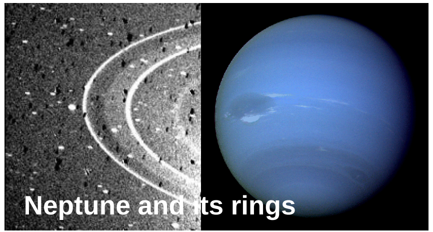
Large Scale Test of Gravitation

- EJSM - JGO
(Cosmic Vision L1 candidate)

GAP Instrument for Fundamental Physics and Planetary objectives:

- Scale dependance test of Gravitation
- Ganymede gravity field and atmosphere

- OSS (ex ODYSSEY)


Neptune and its rings


Triton

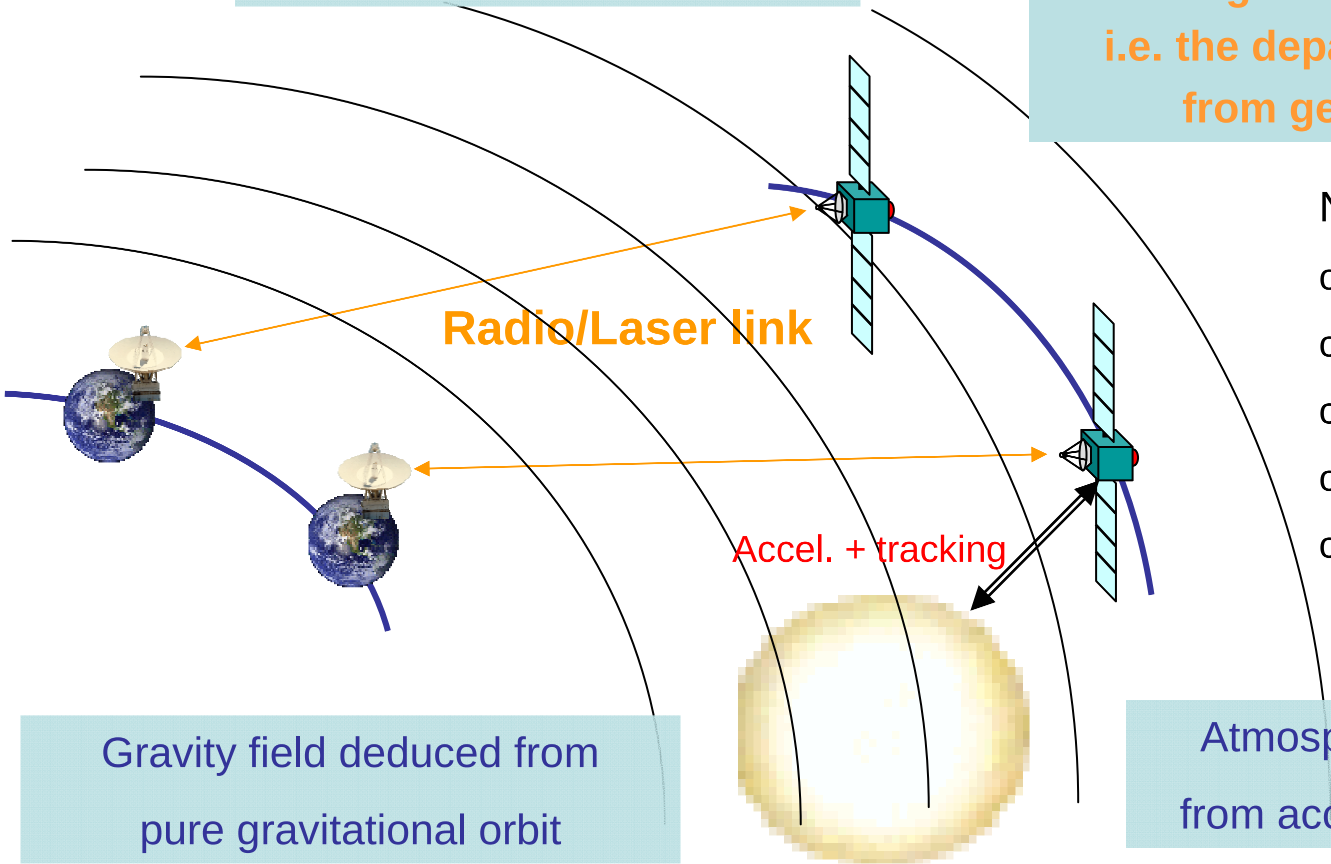
a Deep Space Gravity Explorer towards Neptune and Triton with Fundamental Physics and Planetary objectives:

- Deep Space Gravity
- Neptune/Triton gravity field and atmosphere
- Cosmic Vision M class mission
- L = 2022

ONERA, Chatillon, France ,
Laboratoire Kastler Brossel, ENS Paris, Observatoire de la Côte d'Azur, Grasse
DLR, Institute for Planetary Research, Institute of Space System, Bremen, Germany
ZARM, University of Bremen, Germany

LSTG combined with planetary science objectives

total acceleration – non-gravitational acceleration = geodesic motion



Probe with an accelerometer
with high bias knowledge and stability

The accelerometer measures the non-gravitational acceleration, i.e. the departure of the probe from geodesic motion.

NG acceleration due to:

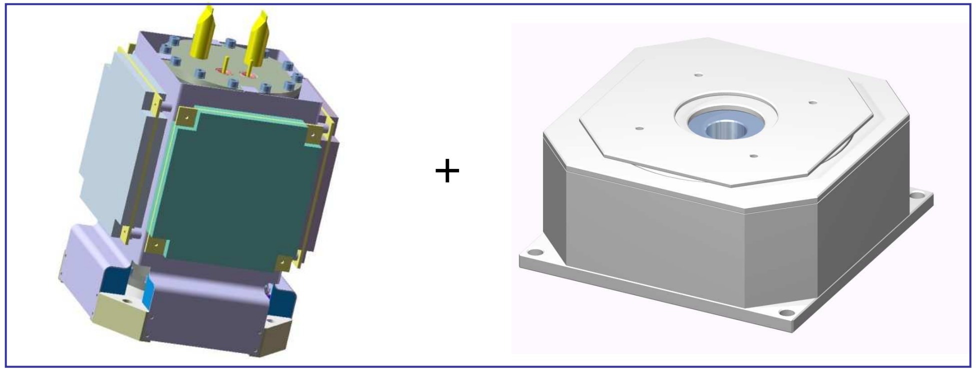
- o Solar radiation pressure
- o Thermal radiation
- o Atmospheric density (flyby)
- o Planet albedo
- o Others

Gravity field deduced from pure gravitational orbit

Atmospheric density deduced from acceleration measurement

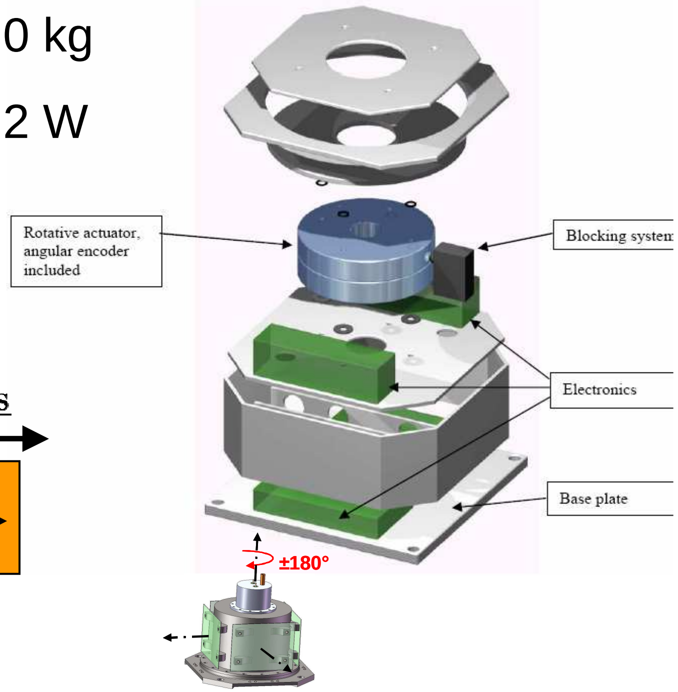
GAP: Gravity Advanced Package

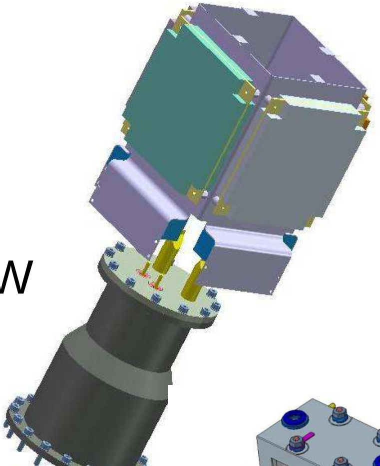
MicroSTAR Accelerometer + Bias Rejection System



1.0 kg

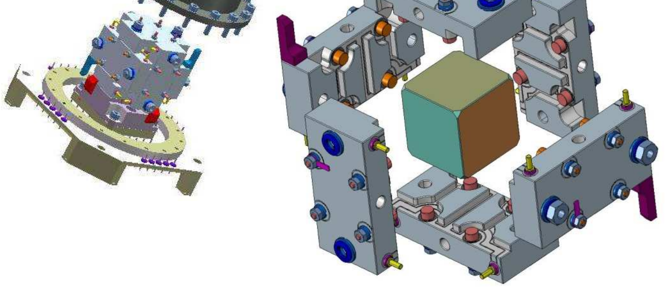
0.2 W



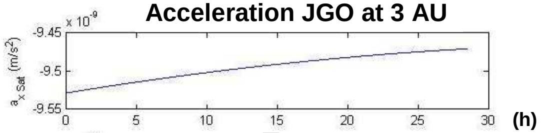


1 kg

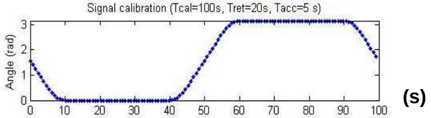
1.4 W



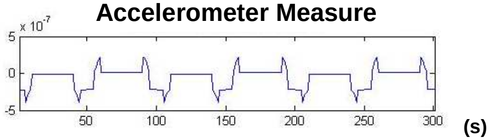
Acceleration JGO at 3 AU



Modulation

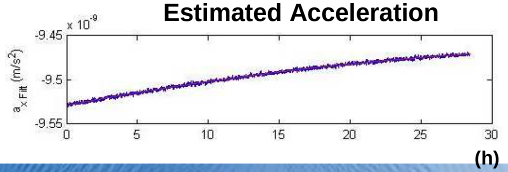


Accelerometer Measure

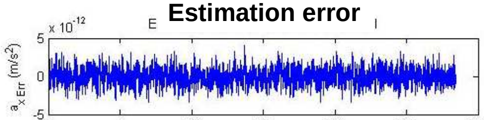


Ground processing

Estimated Acceleration



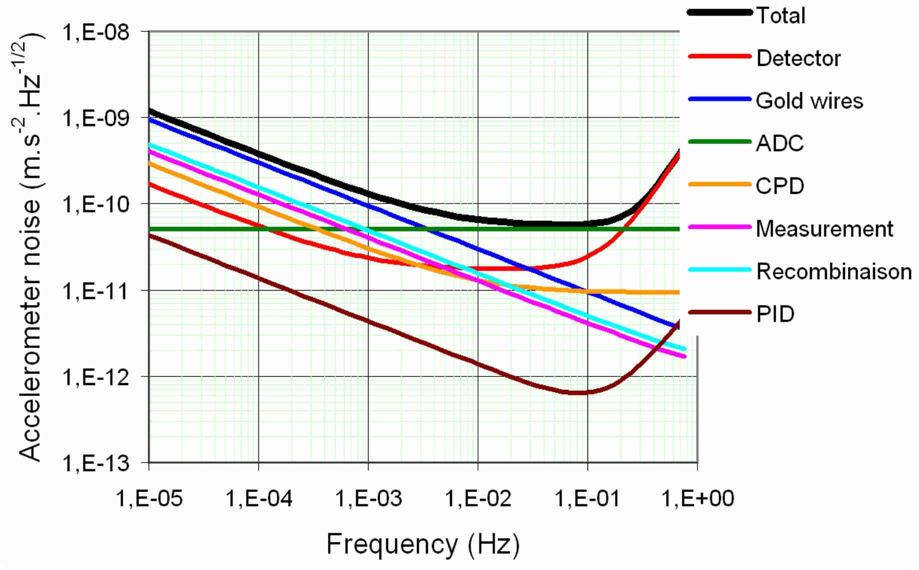
Estimation error



Error < 5 pm/s2

EJSM-JGO : Performance of the payload

MicroSTAR noise figure



With Bias Rejection system (*)

Modulation period = 10 min

Integration time = 5 h

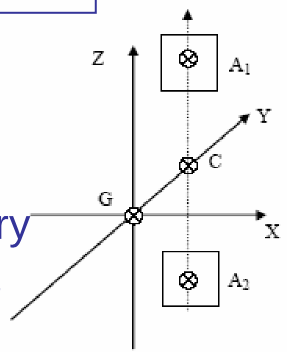
Acceleration uncertainty = 1 pm.s^{-2}

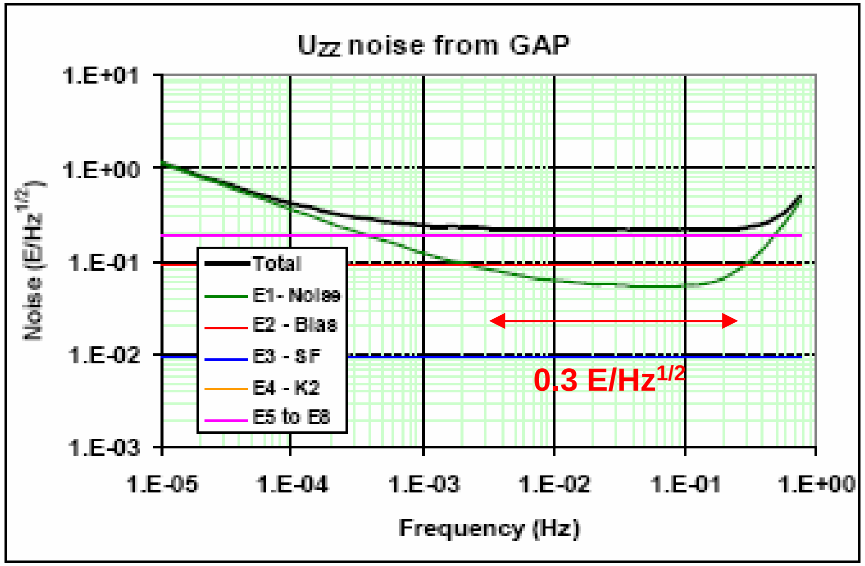
As one axis Gradiometer (**)

2 (Microstar + BSR) units

one axis gradiometer

Ganymede Gravity field recovery with atmospheric density data from S/C acceleration.





Uzz noise < 1 E/Hz$^{1/2}$ = 10^{-9} s^{-2}/Hz$^{1/2}$

over (10^{-5} – 10^{-1} Hz)

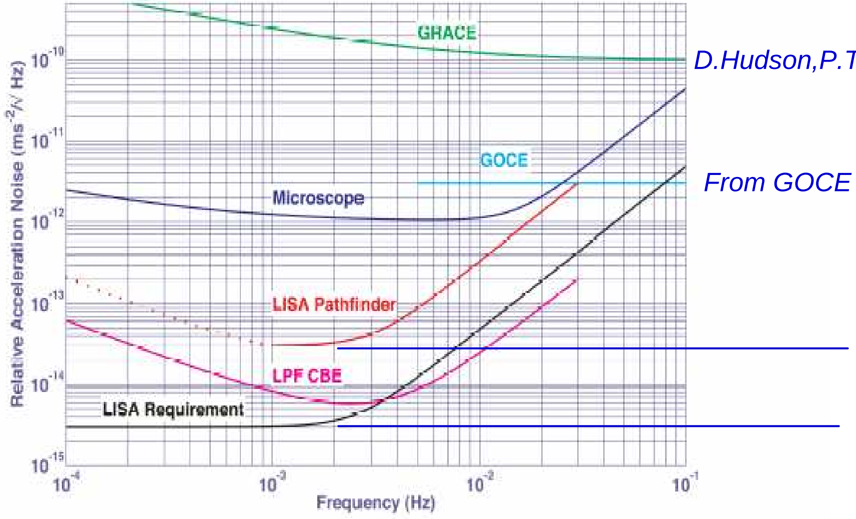
(*) *B.Lenoir et al. Submitted to Planetary and Space Science*

(**) Configuration proposed for EJSM-JGO with 1.5 m baseline

Future Electrostatic Accelerometers: Improvements tracks

Modification	Improvement	Drawback
Heavier proof-mass (size & density)	Possible resolution until 10^{-13} ms^{-2}/Hz$^{1/2}$	Blocking mechanism if > 350 g (Microscope experience)
No gold wire	No damping at low frequency → possible resolution better than 10^{-13} ms^{-2}/Hz$^{1/2}$	Need of a charge control system as in GP-B or LISA PM acquisition and sensing more complex
Cryogenic temperature	Gain of a factor 10 on thermodynamic noise : 10^{-14} ms^{-2}/Hz$^{1/2}$	Liquid helium Dewar → limited time life
Flat proof-mass area variation capacitive sensing	Intrinsic linearity *(position sensing and actuation)*	Only 2 ultra sensitive axes limited range → drag free conf.
Cubic proof-mass	3 ultra sensitive axes and 3 angular accelerations	No more on-ground levitation *(only free fall tests)*

reference: LISA-LPF-RP-0002
date: 30/3/2009
issue 1 : revision 1



Comparison of the performance of several missions. The line labeled *LPF CBE* is the current best estimate of the expected performance of LPF, the line labeled *LISA Pathfinder* is the LPF science requirement.

D.Hudson,P.Touboul,M.Rodrigues, 9th ICATPP Conf. (2005)

From GOCE specification of 2 10-12 @ f> 5 mHz

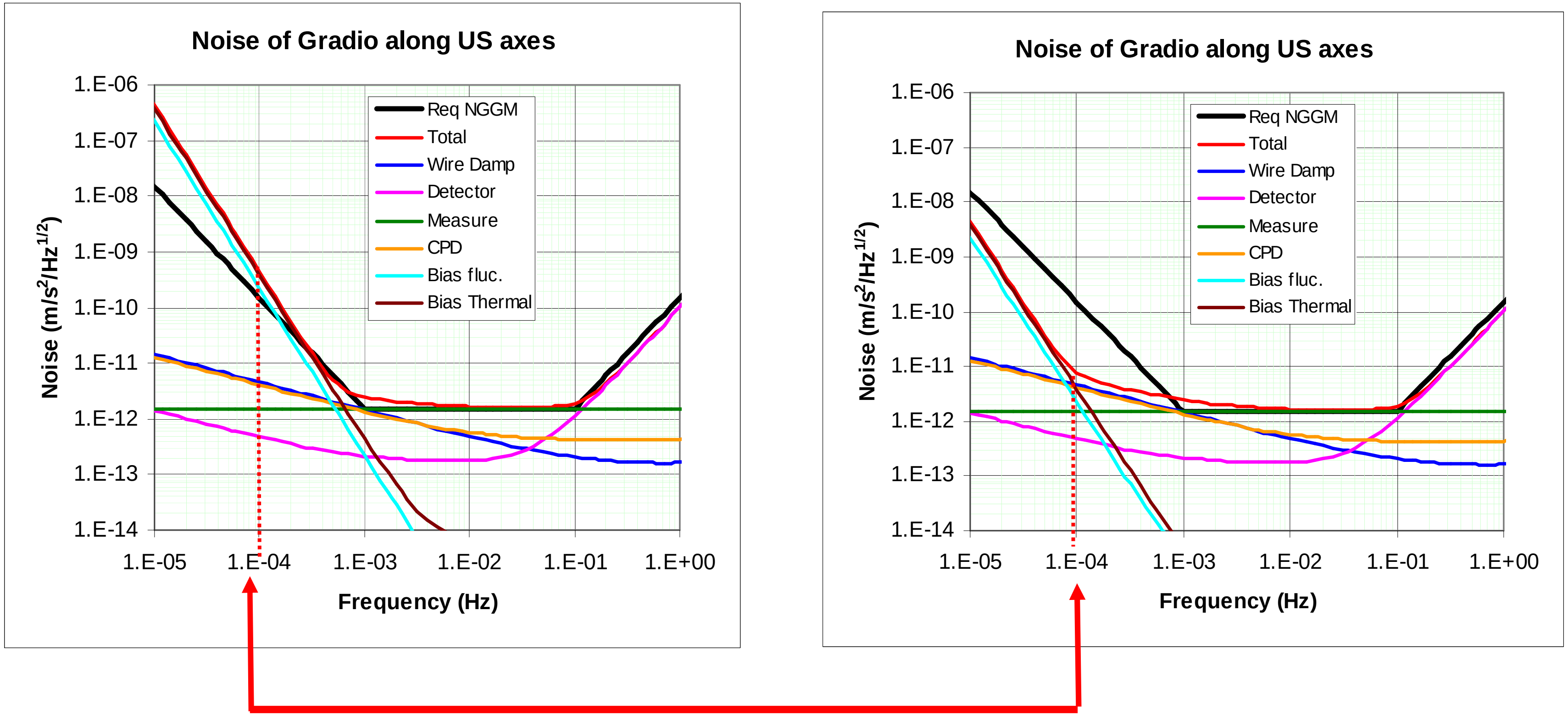
x 1/100

x 1/500

3.0 10^{-14} ms^{-2}/Hz$^{1/2}$

4.0 10^{-15} ms^{-2}/Hz$^{1/2}$

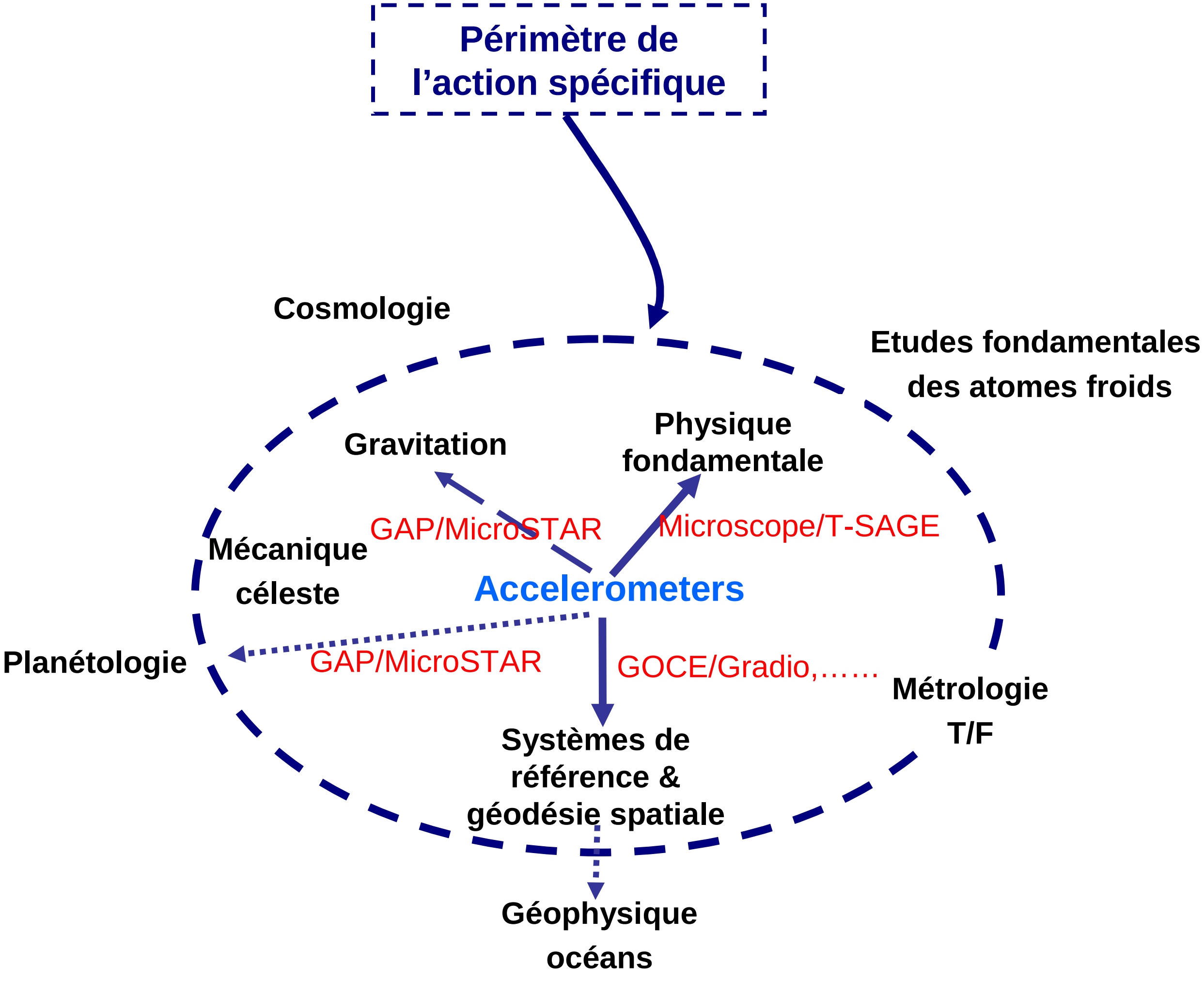
Effect of improving thermal stability



A factor 50 @ 10^{-4} Hz

GRADIO accelerometer noise with the temperature fluctuation divided by 100 with respect to the GOCE environment (1/f core temperature stability -12 mK/$Hz^{1/2}$ @ 1 mHz - in flight data)

CONCLUSION



Périmètre de l'action spécifique

Cosmologie

Etudes fondamentales des atomes froids

Gravitation

Physique fondamentale

Mécanique céleste

GAP/MicroSTAR

Microscope/T-SAGE

Accelerometers

Planétologie

GAP/MicroSTAR

GOCE/Gradio,……

Métrologie T/F

Systèmes de référence & géodésie spatiale

Géophysique océans

ONERA

THE FRENCH AEROSPACE LAB

retour sur innovation

Thank you for your attention

www.onera.fr