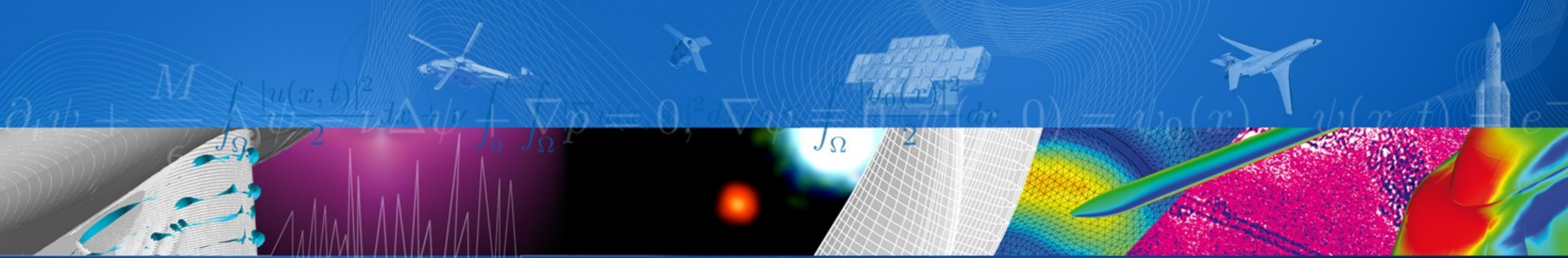

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GREMLIT
Gradiomètre électrostatique planaire et sa plateforme contrôlée dédiés pour la géodésie aérienne

CNFG2 2016, Brest, 16/11/2016

Françoise Liorzou, Bernard Foulon, Bruno Christophe
Vincent Lebat - ***vincent.lebat@onera.fr***

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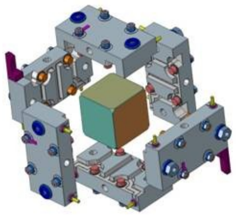
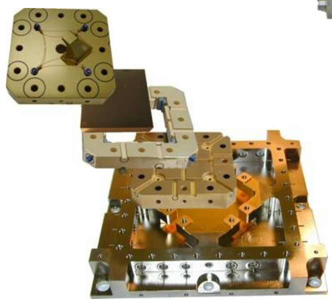
CHAMP, GRACE, GOCE, MICROSCOPE, GFO...

ONERA, world leader in ultra-sensitive space accelerometer



Future missions 2020 - 2030
Geodesy NGGM (ESA) – GRACE-2 (NASA)

Accelerometer for fundamental physic
CNES / ONERA – *Microscope – 2016 – 10^{-12} m/s²/Hz$^{1/2}$*



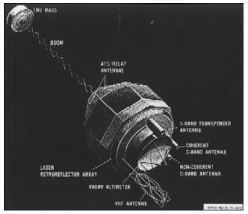
Accelerometers for geodesy
- JPL / Germany – *GRACE-FO – Launch scheduled in 2017*
- ESA – *GOCE – 2009 – 10^{-12} m/s²/Hz$^{1/2}$*
- JPL / DLR – *GRACE – 2002 – 10^{-10} m/s²/Hz$^{1/2}$*
- CNES / DLR – *CHAMP – 2000 – 10^{-9} m/s²/Hz$^{1/2}$*

Accelerometer for microgravity
- NASA – *Missions Microgravity Space Laboratory-1 – April & July 1997*
- ESA – *Mission Life and Microgravity Science – July 1996*

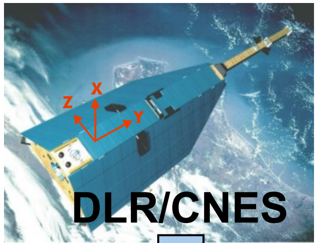
CACTUS Accelerometre – 1975– 10^{-8} m/s²/Hz$^{1/2}$

Improvement of geoid

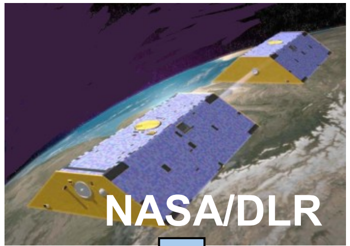
LAGEOS-GEOS3



CHAMP

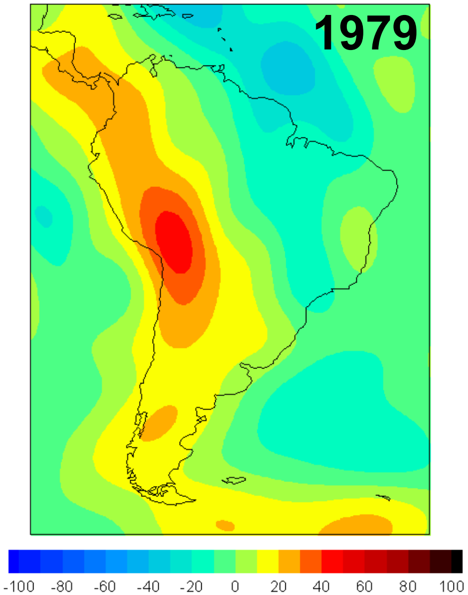


GRACE

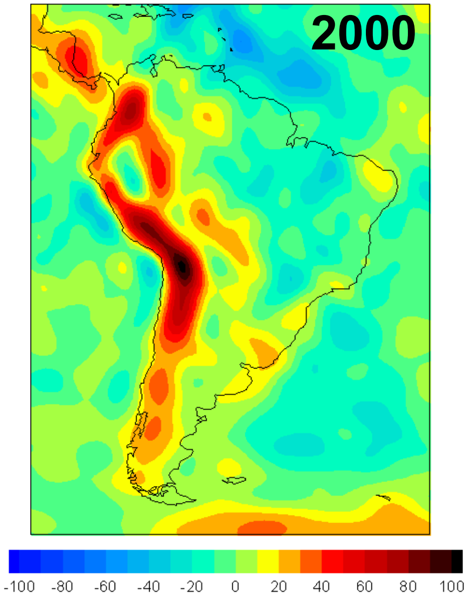


GOCE

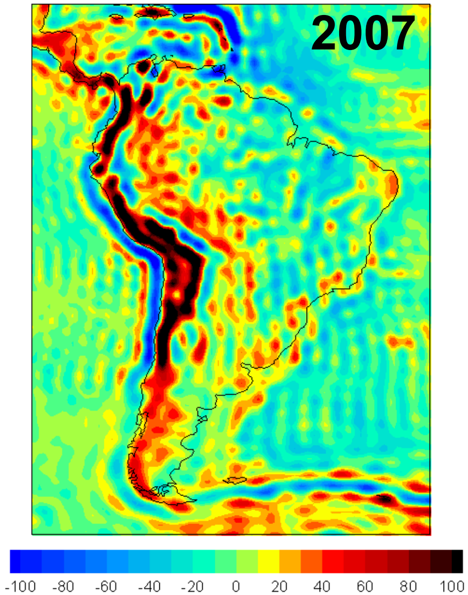
Free air gravity anomalies of South America (mGal)



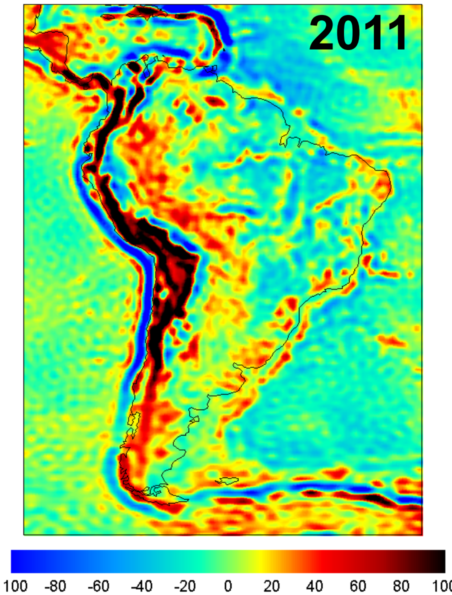
GEM9
Lerch FJ et al. 1979



GRIM 5s
Biancale R et al., 2000

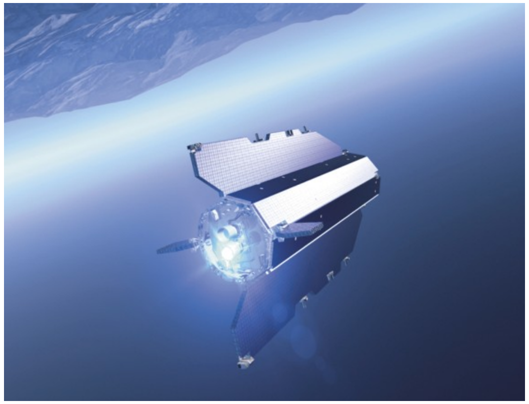


GGM03s
Tapley et al 2007

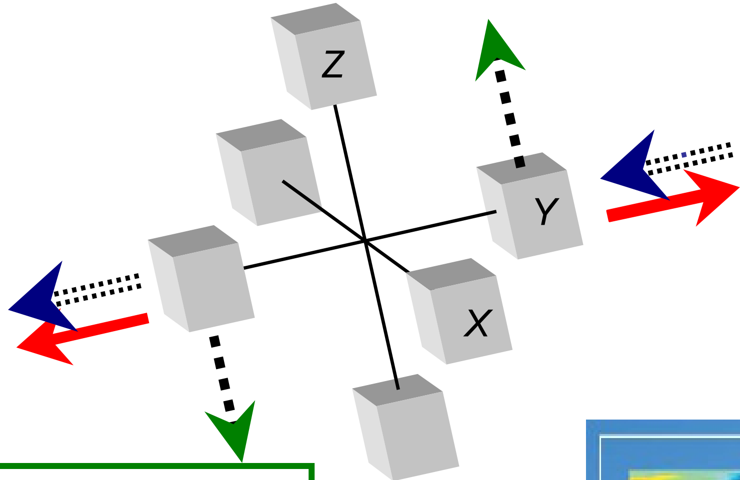


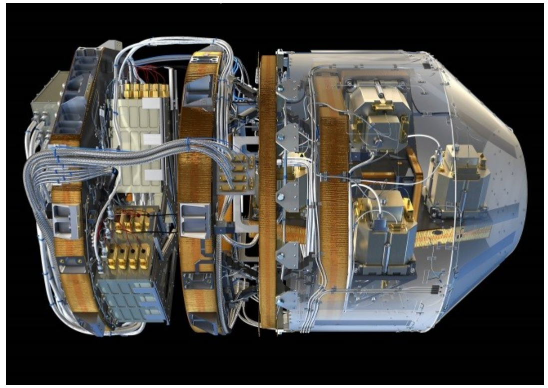
GOCE TIM4
Pail et al 2011

GRADIO inheritage : drag compensation + gradiometer



GOCE - Gradiometer (EGG) with 6 Accelerometers



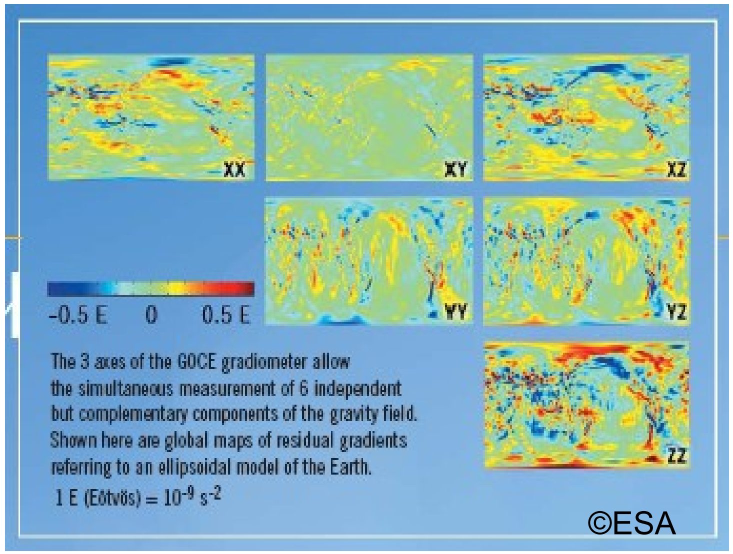


$$V_{\alpha\beta} = \frac{\partial}{\partial \beta} g^{U}_{\alpha} = \frac{\partial^{2}}{\partial \alpha\beta} U$$

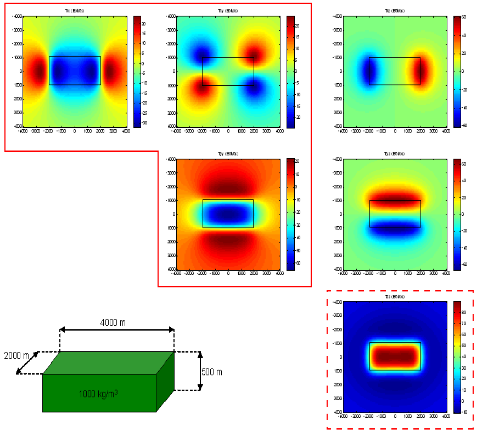
Transvers differential acceleration
⇒ Angular acceleration
⇒Angular speed (by integrated)

Commun mode acceleration "In line"
⇒ externe integration at CoG

<u>Differential acceleration</u> "In line"
⇒Measurement of Gravity Gradient
(after removing of angular acceleration)

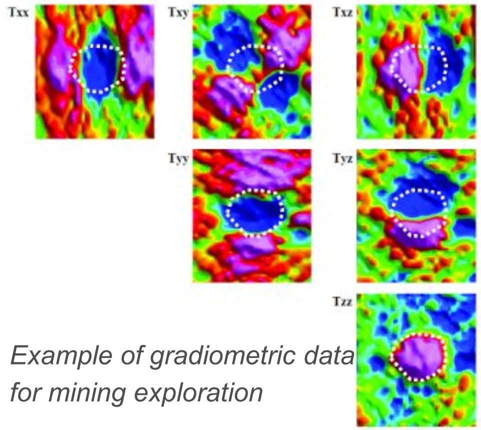


Motivation : Airborne gradiometry



Gradiometer versus Gravimeter ?

- Increase in spatial resolution
- High resolution data
- Prospecting and imaging where seismic methods are difficult to operate

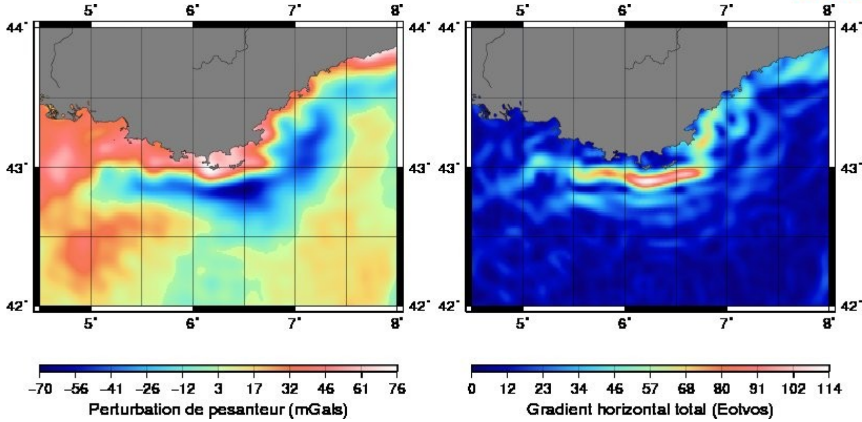


Example of gradiometric data for mining exploration

Needs for coastal areas ?

Knowledge of the gravity field and geoid in coastal areas is necessary for :

- current circulation from altimetry
- exploitation of natural resources
- passive navigation



Gravity measurements vs gradiometry measurements

GREMLIT (« GRadiomètre Electrostatique pour Mesures en zone LITtorale »)

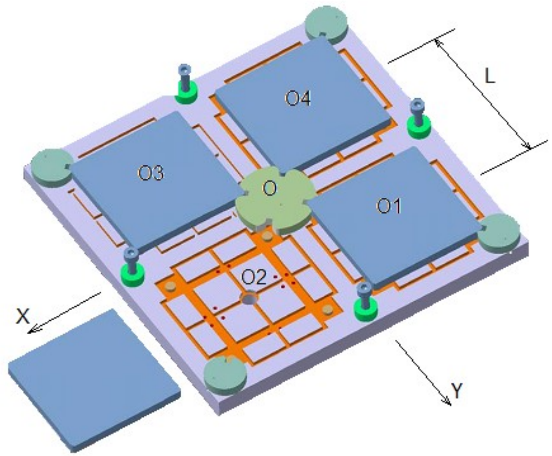
→ Airborne gravity gradiometer instrument to cover land/sea transition areas with uniform precision, and suitable spatial resolution (10 km scale)

→ **Onera internal Project founding**

Main principle of the GREMLIT instrument

- 4 planar accelerometers on a square configuration
  - **Vertical axis levitation (max acc 10 m/s² ± 10)**
    Planar configuration especially well suited to sustain the proof-mass levitation in the Earth's gravity field
  - **Horizontal axes linearity – sensitive axes (max acc 10^{-4} m/s²)**
    intrinsic linearity of position sensing and electrostatic actuation, which minimizes the aliasing due to high frequency vibrations or motions generated outside the measurement bandwidth
  - **Compactness**
    Design with reduced level arms ensures excellent dimensional stability, good thermal homogeneity

The GREMLIT instrument is taking advantage of GOCE return of experience and of technologies, formerly developed by ONERA for the GRACE and GOCE space instruments

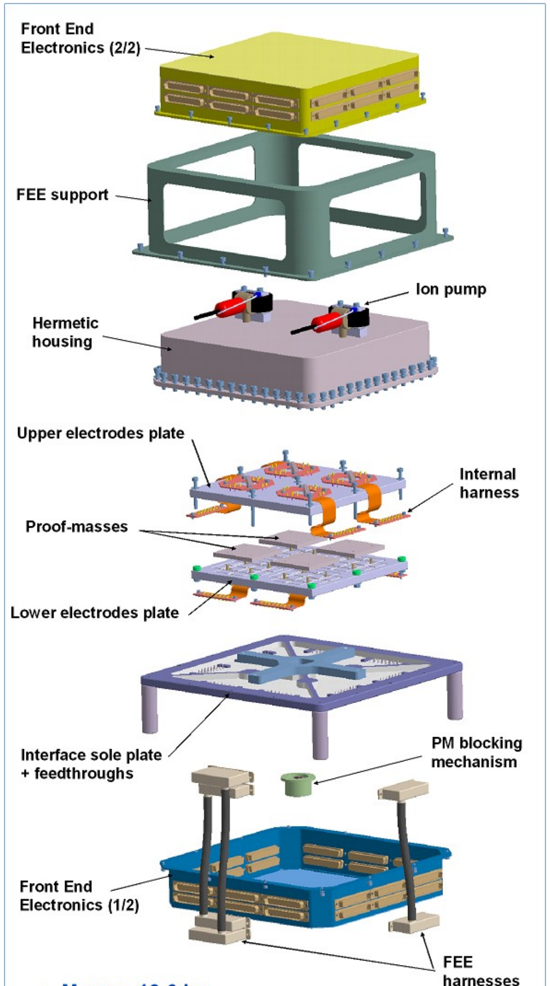


$$\Gamma_{xx}(O) = \frac{1}{2}\cdot\left(\frac{a_x(O_3) - a_x(O_4)}{L} + \frac{a_x(O_2) - a_x(O_1)}{L}\right)$$

$$\Gamma_{yy}(O) = \frac{1}{2}\cdot\left(\frac{a_y(O_1) - a_y(O_4)}{L} + \frac{a_y(O_2) - a_y(O_3)}{L}\right)$$

$$\Gamma_{xy}(O) = \frac{1}{2}\cdot\left(\frac{a_y(O_3) - a_y(O_4)}{L} + \frac{a_y(O_2) - a_y(O_1)}{L}\right)$$

$$\Gamma_{yx}(O) = \frac{1}{2}\cdot\left(\frac{a_x(O_1) - a_x(O_4)}{L} + \frac{a_x(O_2) - a_x(O_3)}{L}\right)$$



- Mass : 13.6 kg
- Volume : 355 × 355 × 238 mm
- Power : 15 W

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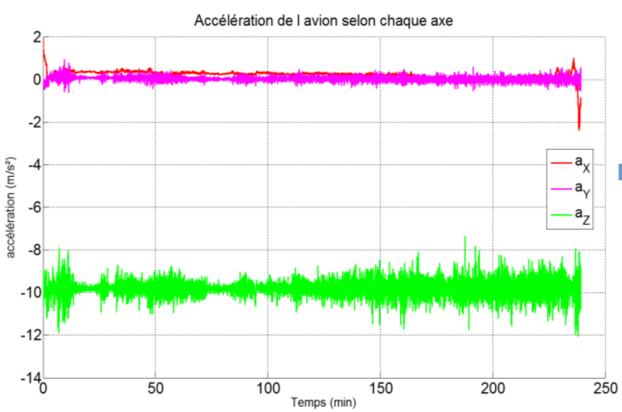
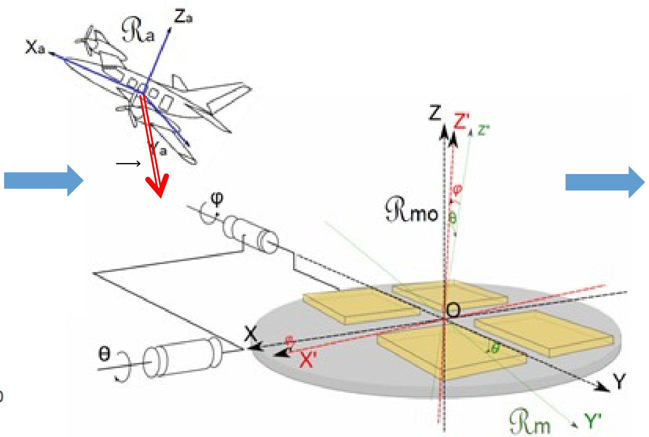
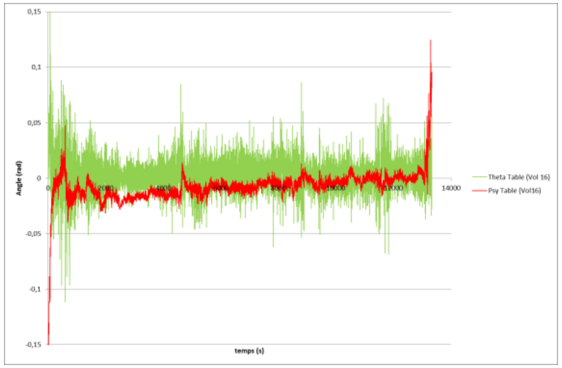
Stabilized platform is necessary

- Stabilized platform is essential
  - To not sature the sensitive axes of the instrument (10^{-4} m/s²) due to the flight perturbation
  → orientation of the vector acceleration normal to the vertical axis of the instrument (10 m/s²)
  - To achieve the global performance
  → High accuracy of the equipment on the platform(Gyro, instrument orientation wrt IMU), necessary for the global measurement



σ_{acc_x}= 0,1 >>10^{-4} m.s^{-2}





σ_θ= 0,02 rad σ_φ= 0,005 rad

$$\underline{\underline{\Gamma}} = \underline{\underline{V}} - \dot{\underline{\underline{\Omega}}} - \underline{\underline{\Omega}}.\underline{\underline{\Omega}}$$

$$V_{xx} =$$

$$V_{yy} =$$

$$V_{xy} = V_{yx} = \frac{1}{2}.(\quad + 2. $$

- GREMLIT Measurement
- Gyrometer on the platform
- V_{zz} is not measured but deducted from the null trace property of the gradient gravity tensor
- The orientation of the platform is controlled with the common mode of GREMLIT (1rst order of magnitude) $= \quad = 0$ m.s^{-2}

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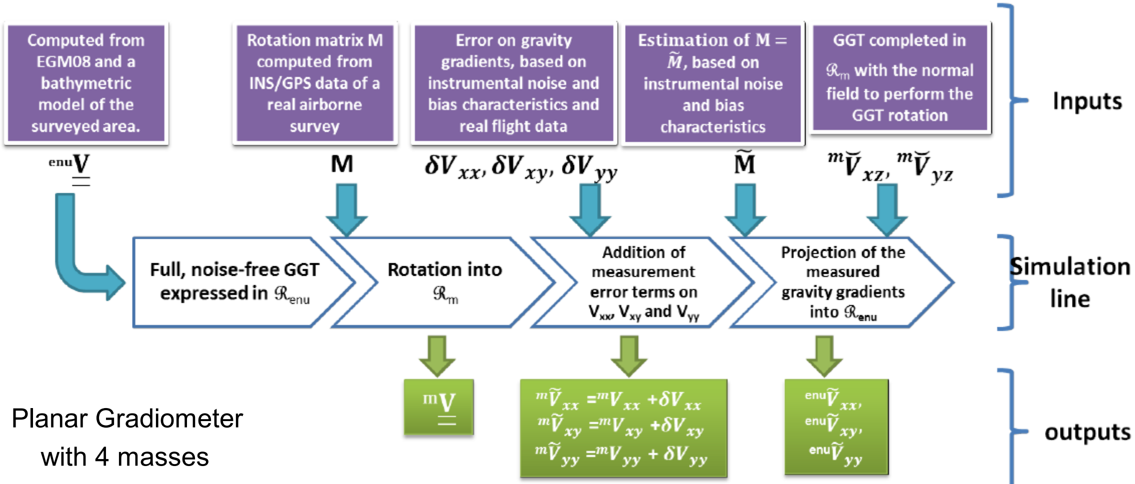
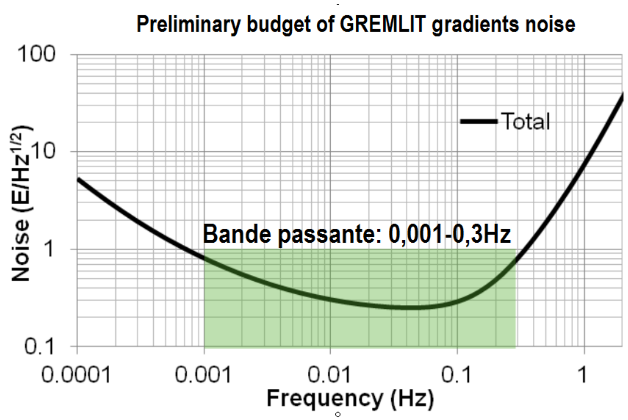
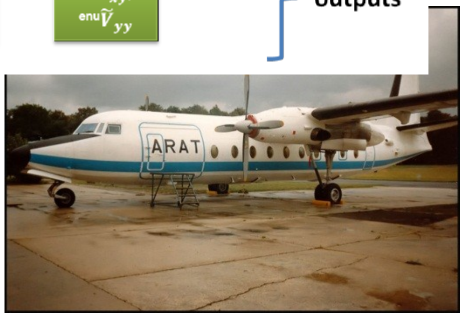
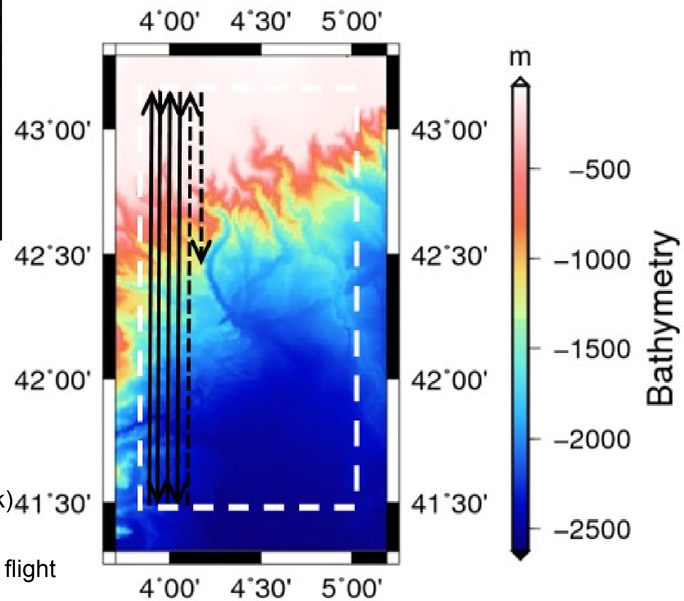
Performance evaluation : simulation principle

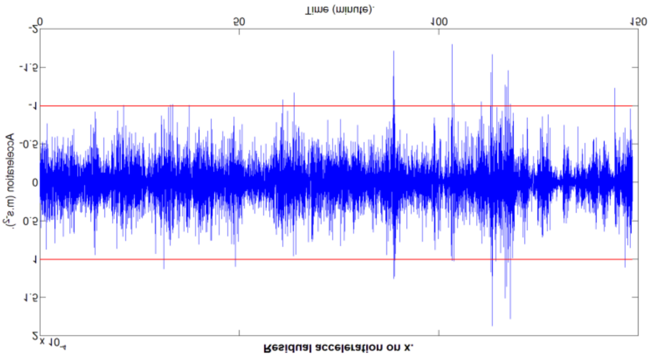


Planar Gradiometer
with 4 masses
Noise < 1 Eötvös in [0.001-0.3 Hz] MBW
Gyros with 0.003°/s bias
and white noise of 0.02°/h/$Hz^{1/2}$
Platform orientation wrt carrier IMU
with bias of 0.05°
and white noise of 0.1°/$Hz^{1/2}$



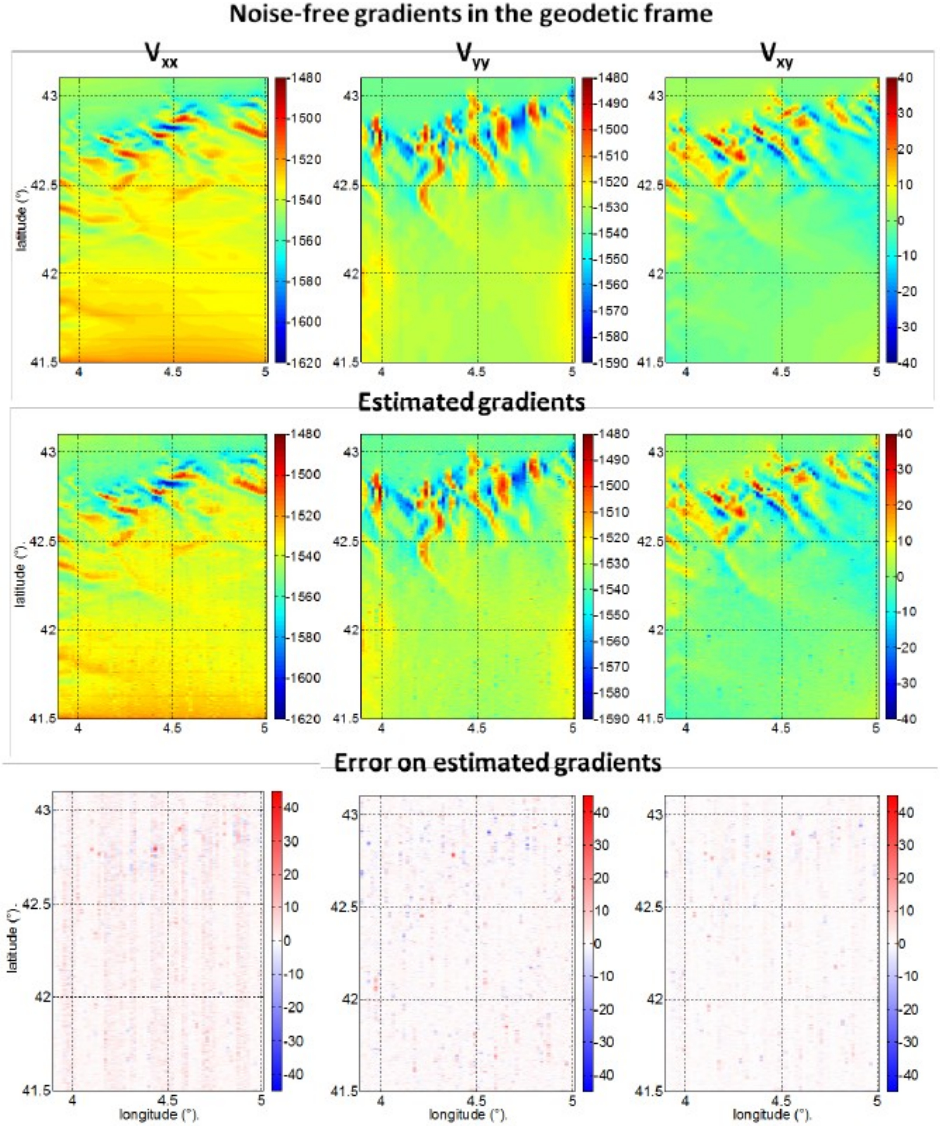






<u>Carrier</u> : Fokker 27 from IGN flying
at 500 m altitude and at 300 km speed
<u>Area</u> : Golf du Lion
0.25 Hz sampling frequency (333 m along track)
61 N-S lines with 2 km spacing
534 x 61 grid = 32574 points during 36 hours of flight

Performance evaluation : simulation results



Error of the horizontal gravitational gradients after gyro biases calibration by an ordinary least squares regression over the full time series

in instrumental frame

	std (E)	max‖.‖ (E)
δV_{xx}	1.103	16.9
δV_{xy}	0.84	14.2
δV_{yy}	1.86	26
δV_{zz}	2.28	30.6

in geodetic frame

	std (E)	max‖.‖ (E)
ΔV_{xx}	2.7	41.3
ΔV_{xy}	1.9	34.6
ΔV_{yy}	2.57	41.3
ΔV_{zz}	3.8	44

Correlation matrix of the errors of the 3 gradients

in instrumental frame

	δV_{xx}	δV_{xy}	δV_{yy}
δV_{xx}	1		
δV_{xy}	-0.013	1	
δV_{yy}	0.126	0.154	1

in geodetic frame

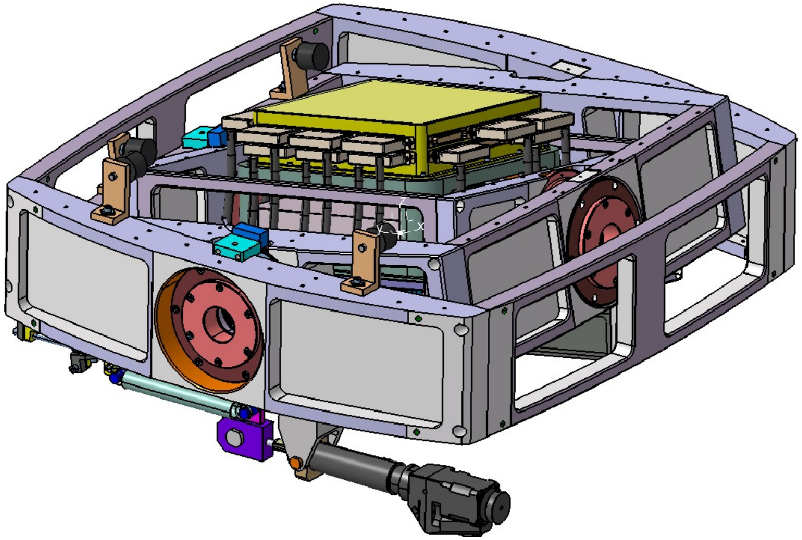
	ΔV_{xx}	ΔV_{xy}	ΔV_{yy}
ΔV_{xx}	1		
ΔV_{xy}	0.067	1	
ΔV_{yy}	0.043	0.1	1

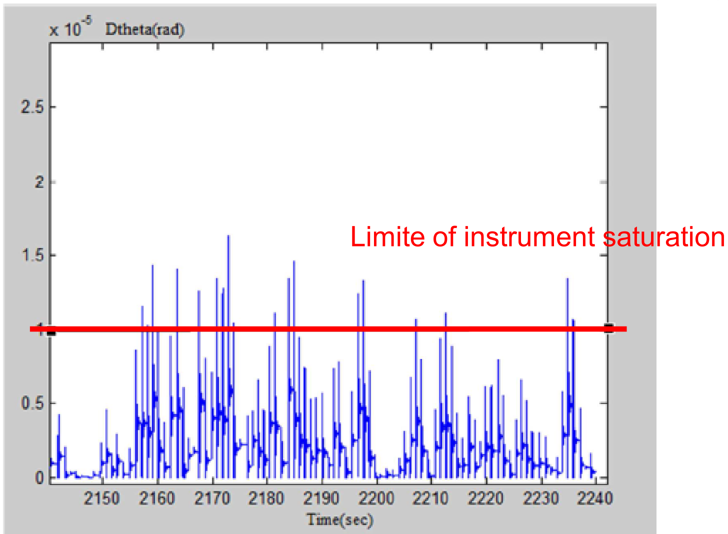
Design of the stabilized platform

- Rotation controlled with high resolution linear actuator (0,1 µm) with handle, to reach the target resolution for the angle of 10^{-6} rad ($<10^{-5}$ rad are needed in regard of the max acc 10^{-4} m/s²)
- High resolution bearing
- Specific design to suppress clearance in the mechanic connections
- 3 gyrometers $< 10^{-5}$ rad.s^{-1}
- The orientation of the platform is controlled directly with the common mode of GREMLIT

  Thermomechanical stability of the platform is not a blocking point

  Nominal effort of the actuator is over of the needs, to not be limited by mechanical frictions (hysteresis)
- Measurement of the orientation of the platform with interferometer directly on the instrument (position between GREMLIT and IMU)
- First simple controlled laws simulated show the nice behavior of the platform

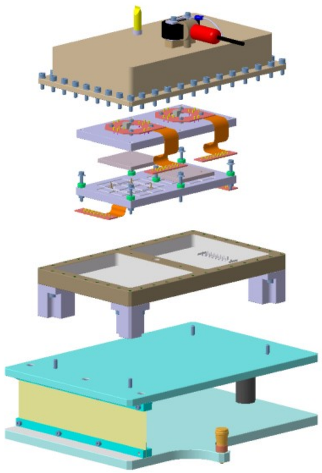


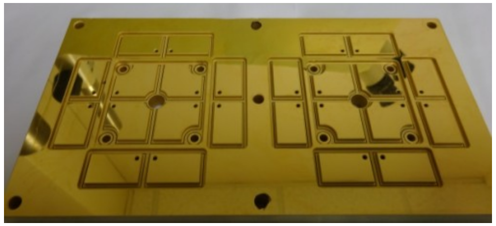


Simulation - Real angle of the platform

Progress of the Gradiometer development 1/2

- 1rst Internal Project founding from 2012 to 2015
  - **Confirmation of the feasibility and performance of the planar gradiometer**
    - PhD grant from ONERA (2015)
  - **Development of a single axis gradiometer**
    - To demonstrate the viability of the measurement
    - All parts are manufactured, the integration is scheduled in October 2016
    - First tests are scheduled before the end of 2016 (initially scheduled in 2015, but delayed due to the availability of internal specific manufacturing bench)
  - **Study of the feasibility of the stabilized platform, essential to achieve the performance**
    - Confirmation of the feasibility to achieve the performance of the gradiometer



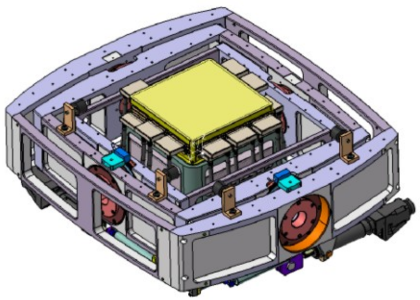


1 axis gradiometer

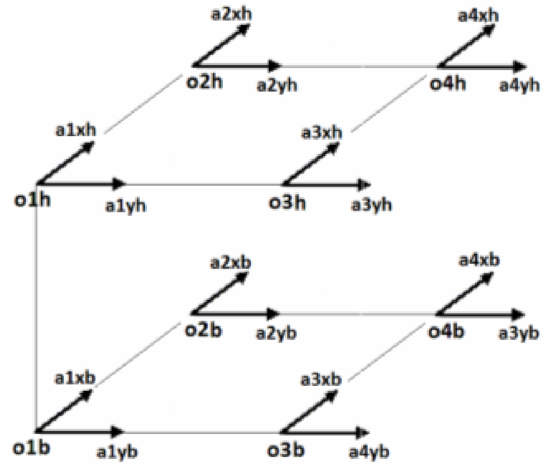
Simple 1 axis platform

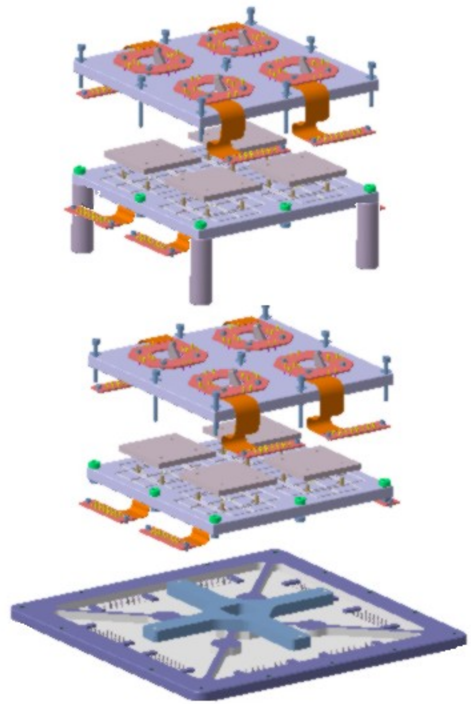
Progress of the Gradiometer development 2/2

- **2nd Internal Project founding from 2016 to 2018**
  - **→ Development of the complete gradiometer 2 axes**
  - **Definition of the architecture of the stabilized platform (in progress)**
    - Design (mechanical, electronics) (done)
    - Control laws
    - Validation of the performance
  - **Manufacturing and integration of the stabilized platform**
  - **Test of the platform with 1 axis gradiometer (axis per axis)**
    - Using of an internal bench to simulate the real flight (hexapod)
    - Confirmation of the global concept and the performance of the assembly
  - **Manufacturing of the 2 axis gradiometer**
  - **Test of the complete configuration of the gradiometer 2 axes**
    - Using of an internal bench to simulate the real flight (hexapod)
    - Confirmation of the global concept and the performance of the assembly
    - Real flight to realized first measurements



Future possibility evolution 1/2
Full tensor Gradiometer





$$
\begin{pmatrix}
\frac{\partial a_x}{\partial x} & \frac{\partial a_x}{\partial y} & \frac{\partial a_x}{\partial z} \\
\frac{\partial a_y}{\partial x} & \frac{\partial a_y}{\partial y} & \frac{\partial a_y}{\partial z} \\
\frac{\partial a_z}{\partial x} & \frac{\partial a_z}{\partial y} & \frac{\partial a_z}{\partial z}
\end{pmatrix}
=
\begin{pmatrix}
\frac{\partial^2 V}{\partial x^2} & \frac{\partial^2 V}{\partial x \partial y} & \frac{\partial^2 V}{\partial x \partial z} \\
\frac{\partial^2 V}{\partial y \partial x} & \frac{\partial^2 V}{\partial y^2} & \frac{\partial^2 V}{\partial y \partial z} \\
\frac{\partial^2 V}{\partial z \partial x} & \frac{\partial^2 V}{\partial z \partial y} & \frac{\partial^2 V}{\partial z^2}
\end{pmatrix}
-
\begin{pmatrix}
0 & -\dot{\omega}_z & \dot{\omega}_y \\
\dot{\omega}_z & 0 & -\dot{\omega}_x \\
-\dot{\omega}_y & \dot{\omega}_x & 0
\end{pmatrix}
$$

$$
-\begin{pmatrix}
-\omega_y^2 - \omega_z^2 & \omega_x.\omega_y & \omega_x.\omega_z \\
\omega_y.\omega_x & -\omega_x^2 - \omega_z^2 & \omega_y.\omega_z \\
\omega_z.\omega_x & \omega_z.\omega_y & -\omega_x^2 - \omega_y^2
\end{pmatrix}
$$

6 acceleration gradients

+ 2 angular rate components

+ null trace property

Future possibility evolution 2/2
Cold atoms / electrostatic hybridization

Coupling Cold Atoms Interferometry GIBON Gradiometer along the vertical axis

→ providing Vzz gravity gradient and Gz absolute gravity magnitude

With Electrostatic GREMLIT Gradiometer along the horizontal axes

→ providing Full Tensor gravity gradiometer

Could permit to combine very high resolution electrostatic instrument measurements with very stable and absolute cold atoms interferometer measurement

Merci pour votre attention

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