Cold Atom Interferometry: from Ground to Space

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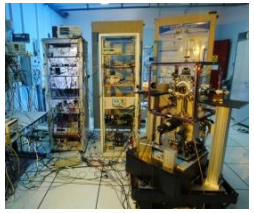
G2-2018
13/11/2018 - Montpellier

ONERA's Cold Atom sensor projects

• Cold Atom Gravimeters:

GIRAFON (2003)

Lab gravimeter



GIRAFE (2007)

Transportable gravimeter

DGA

GIRAFE 2 (2013)

Onboard gravimeter

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2011 : First gravity measurements in a moving **elevator** (12 floors)

2011: First inertial measurements in an **aircraft** (ZERO-G plane/ICE project)

cnes

l'Observatoire de Paris SYRTE

INSTITUT d'OPTIQUE GRADUATE SCHOOL

2015/2016: First gravity meas. compaigns on a **boat** (Atlantic)

SHOM

DGA

2017: First gravity meas. compaign on an **aircraft** (Iceland)

DTU

esa European Space Agency

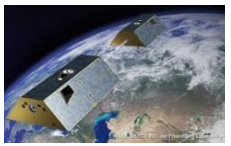
2018: **Long term** continuous gravity meas. (6 months) on a boat (Atlantic)

• Futur Space Missions with Atom Interferometers

- Hybrid Atomic-Electrostatic accelerometer for geodesy missions

TUM

esa European Space Agency

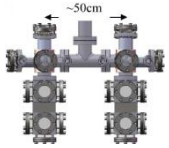


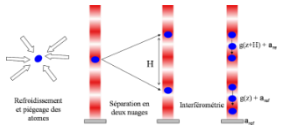
• Multispecies Cold Atom Sensors:

- Universality of Free Fall
- Towards new generation of instruments with increased meas. range, sensitivity, no deadtime

• Development of a cold atom gradiometer/IMU :

- Realization under progress
- Bloch oscillations for atomic clouds separation





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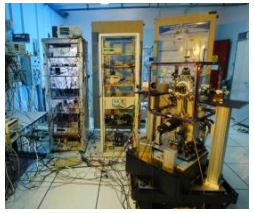

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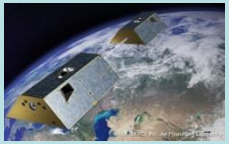

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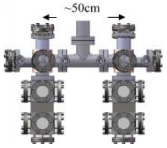
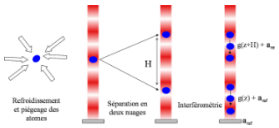
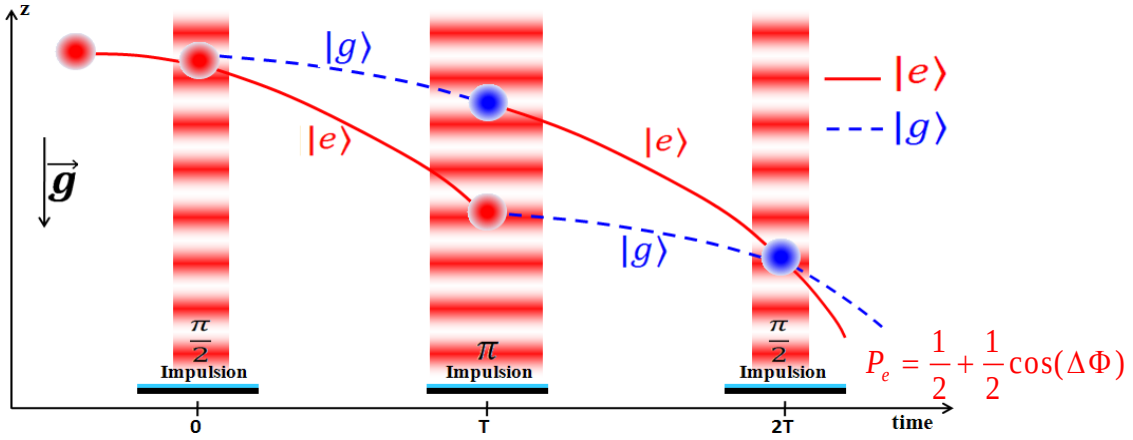




Cold Atom Accelerometer : Basic Principles

Principle: Acceleration measurement of free falling cold atoms relative to a mirror
→ Measurement through Atom Interferometry

Typically:
~ 10^7 atoms free falling in Vacuum
Cloud size ~ 1 mm
Atomic temperature ~ 1 µK



Output signal: $P = \frac{1}{2} + \frac{1}{2} Cos(\Delta\Phi)$ with $\Delta\Phi = k_{laser} T^2 a(t)$

Scale factor $k_{laser}T^2$ and biases very well known
Intrinsically excellent in terms of accuracy and long term drift

No classical absolute gravimeter for dynamic measurements
High potential of onboard cold atom gravimeters

Cold Atom Accelerometer : limitations for dynamic measurements

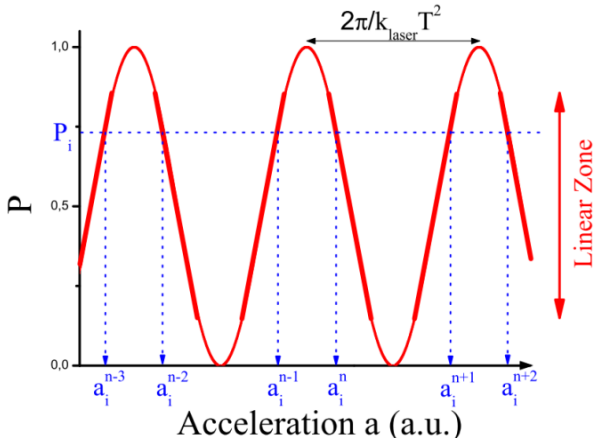
• Measurement range :

The output signal: $P_i = \frac{1}{2} + \frac{1}{2} Cos(\Delta\Phi_i)$

with $\Delta\Phi_i = k_{laser} T^2 a_i(t)$

→ Ambiguity on the determination of the acceleration

→ limited measurement range (100µg for T=20ms)



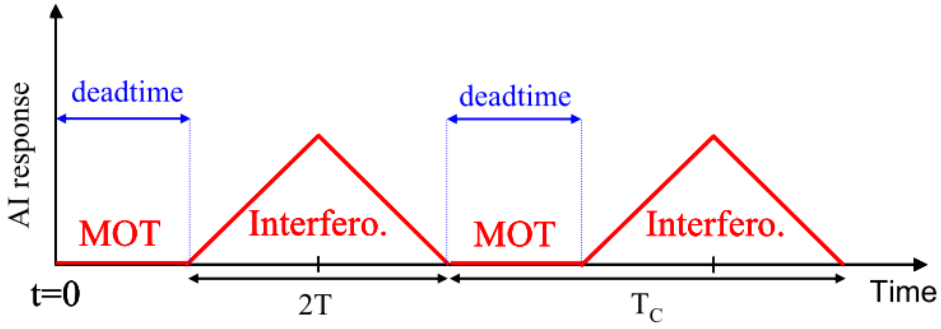
• Deadtime measurements:

Acceleration meas. only during the interferometer phase

→ Deadtimes

→ Aliasing effects

(typically 2T=40ms and Tc=100 ms)



For onboard applications (high vibration noise) need to increase the measurement range and remove aliasing effect due to deadtimes

⇒ hybridization with a classical accelerometer

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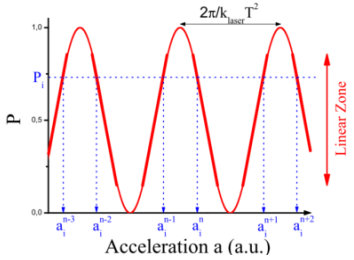
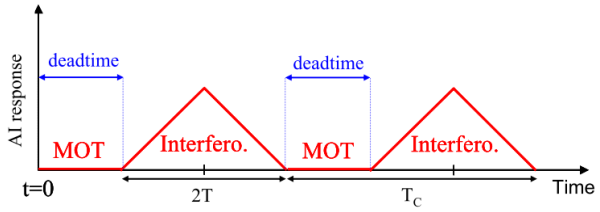
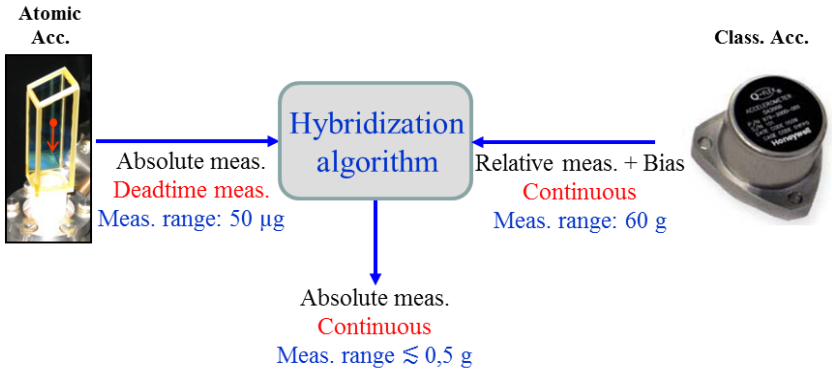
GIRAFE 2 (2013): Dynamic mode / hybridization

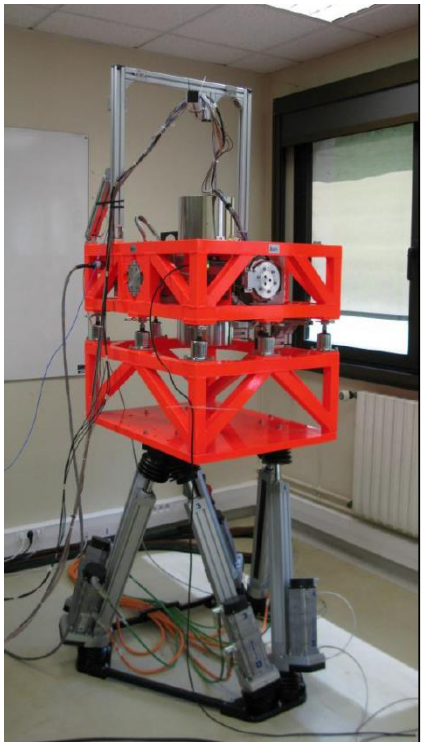
Hybridization with classical sensors: Linear accelerometers (+ angular acc.)





Implementation of a robust hybridization algorithm:





Cold atomic sensor integrated into a 2-axis gyrostabilized platform (IMAR)

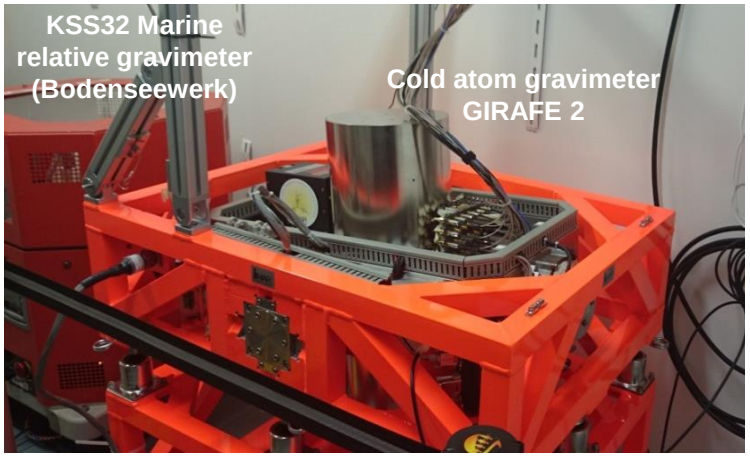
- keep verticality (< 100 µrad)
- Gimbaled platform
- IMU + GPS

Validation of dynamic mode in the lab
on an excitation platform (PZT actuators) and on an Hexapod

GIRAFE 2: Marine survey (2015-2016)

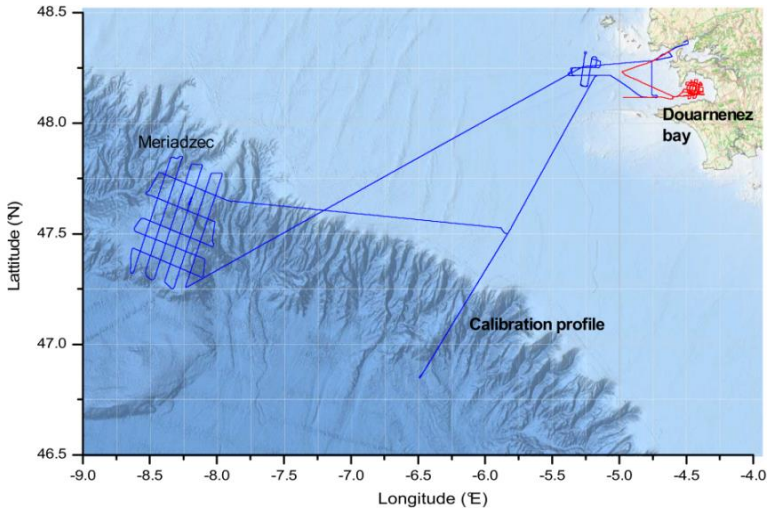
2 shipborne gravity campaigns (~ 10 days) in Oct. 2015 and Jan. 2016
on the BHO Beautemps-Beaupré french ship (SHOM)

85 m long ship BHO



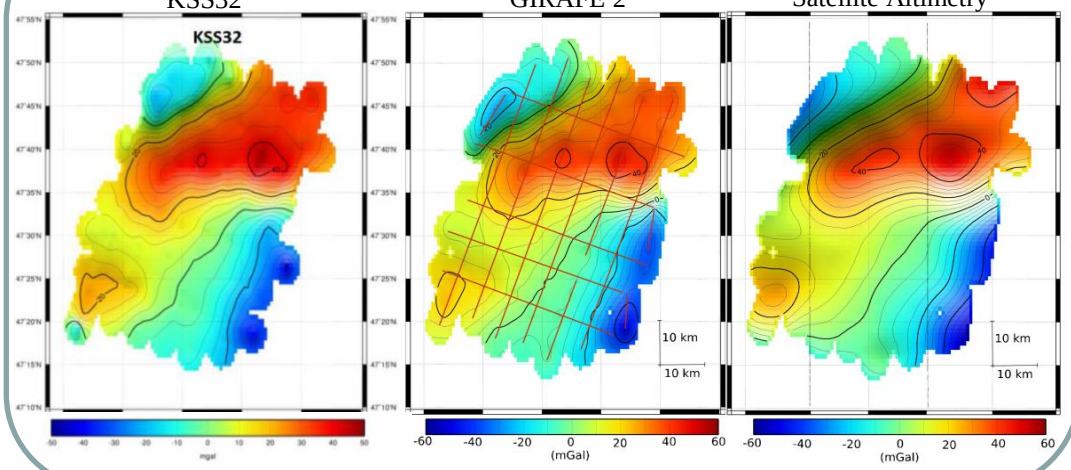
Measurements: GIRAFE 2 and KSS32 comparison

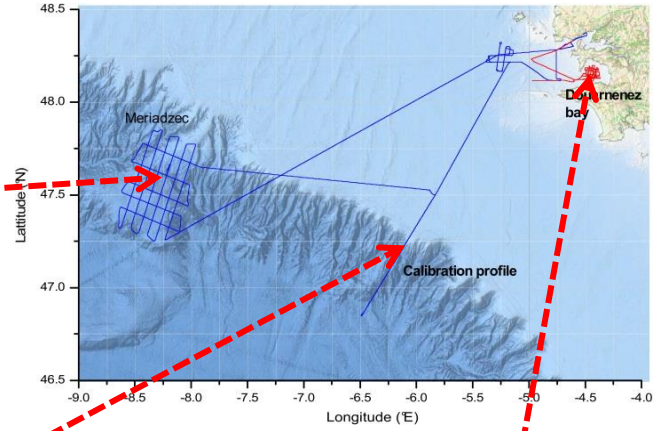
Harsh environment:
Sea state 4-6, Atlantic Ocean (off West French Brittany coast)
Wave heights: 2-5 m, angles ±20° / ±32°, acc. ~ 0.5 g



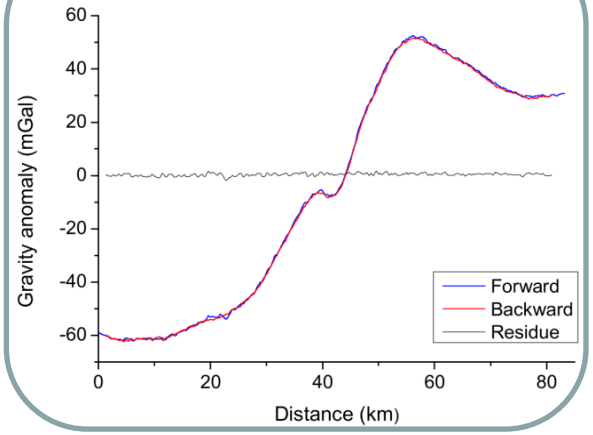
GIRAFE 2: Marine survey (2015-2016)- results

Gravity anomaly map of Meriadzec

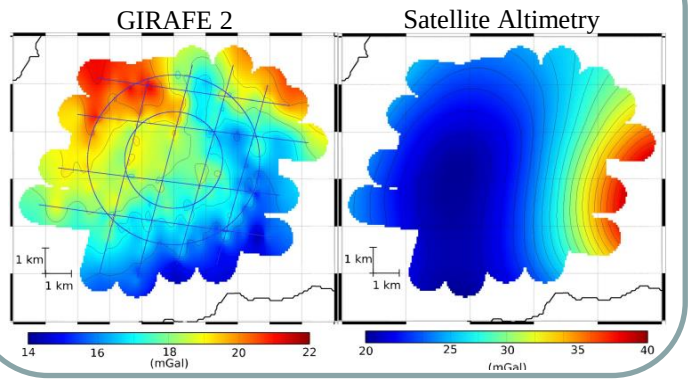




Calibration profile (GIRAFE 2)



Gravity anomaly map of Douarnenez



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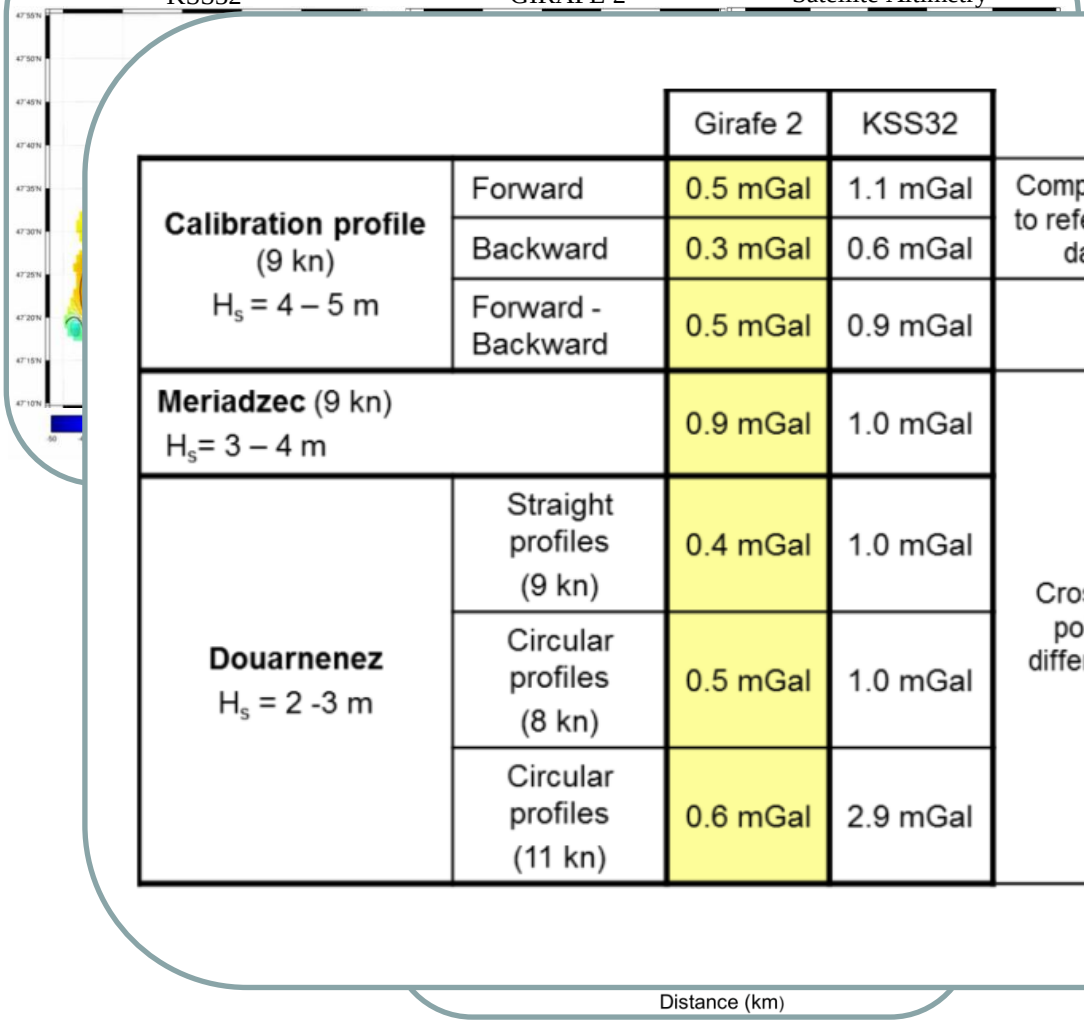
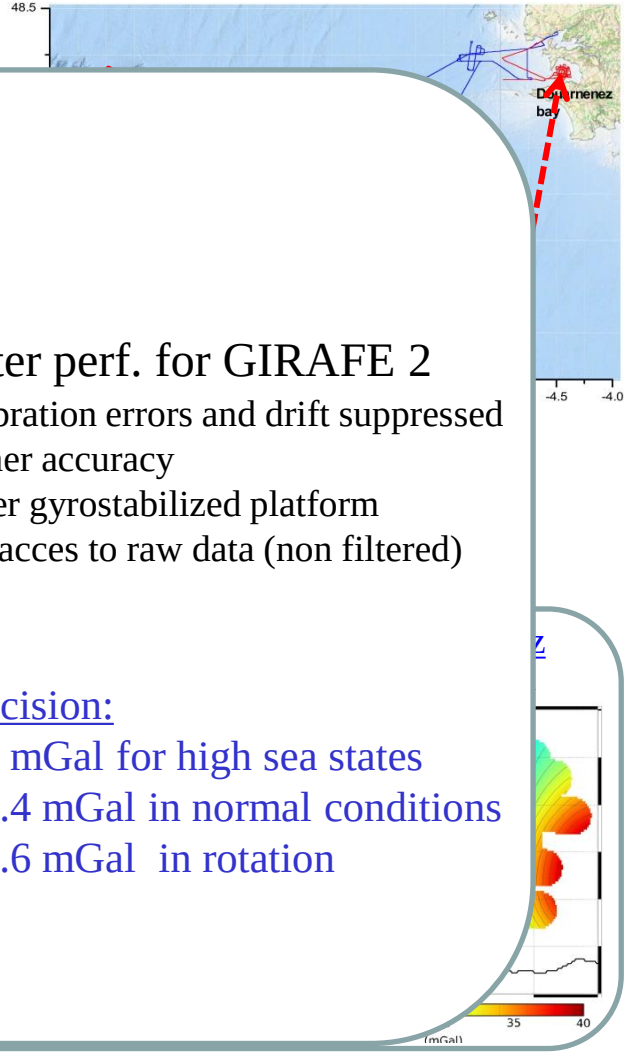
Gravity anomaly map of Meriadzec

KSS32 GIRAFE 2 Satellite Altimetry





		Girafe 2	KSS32	
Calibration profile (9 kn) H_s = 4 – 5 m	Forward	0.5 mGal	1.1 mGal	Comparison to reference data
	Backward	0.3 mGal	0.6 mGal	
	Forward - Backward	0.5 mGal	0.9 mGal	
Meriadzec (9 kn) H_s= 3 – 4 m		0.9 mGal	1.0 mGal	Crossing points difference
Douarnenez H_s = 2 -3 m	Straight profiles (9 kn)	0.4 mGal	1.0 mGal	
	Circular profiles (8 kn)	0.5 mGal	1.0 mGal	
	Circular profiles (11 kn)	0.6 mGal	2.9 mGal	

Better perf. for GIRAFE 2

Calibration errors and drift suppressed
Higher accuracy
Better gyrostabilized platform
Full acces to raw data (non filtered)

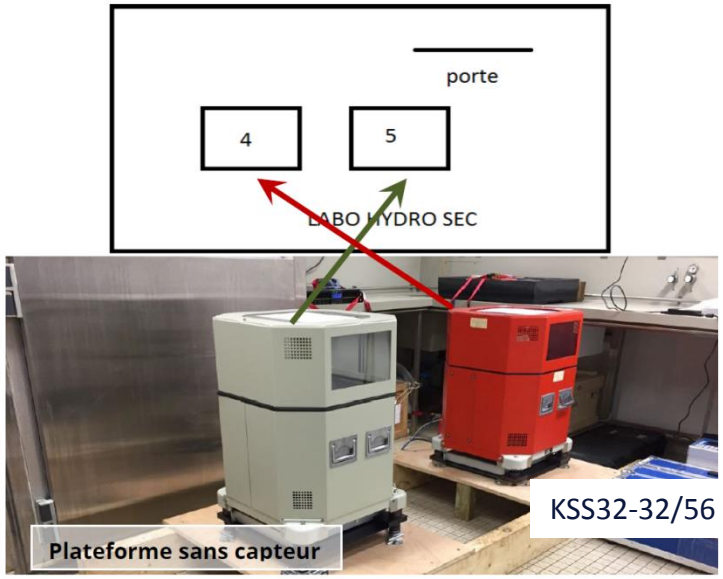
Precision:
< 1 mGal for high sea states
< 0.4 mGal in normal conditions
< 0.6 mGal in rotation

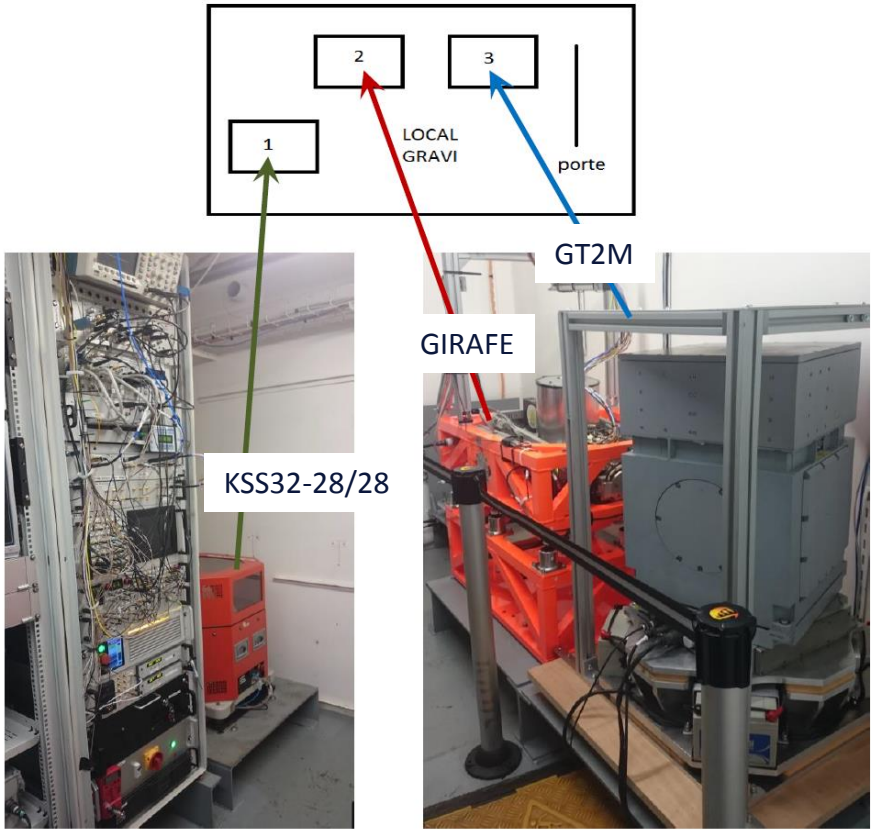
1ER RÉSULTATS DES MESURES LONG TERME SUR BHO *BEAUTEMPS-BEAUPRÉ*

AVRIL-OCTOBRE 2018

4 gravimètres à bord du BHO Beautemps-Beaupré à partir du 30 mars 2018 :

- Le gravimètre relatif KSS32-28/28 opérationnel
- Le gravimètre relatif KSS32-32/56 dans le cadre de la recette de la plateforme SN032
- Le gravimètre relatif GT2M (CMG) dans le cadre de l'évaluation de nouveau systèmes
- Le gravimètre absolu GIRAFE dans le cadre des tests long terme





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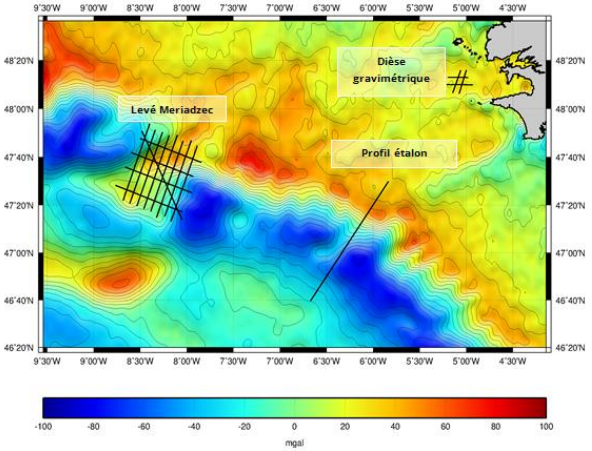
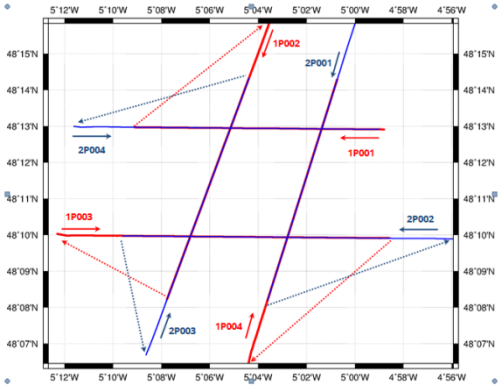
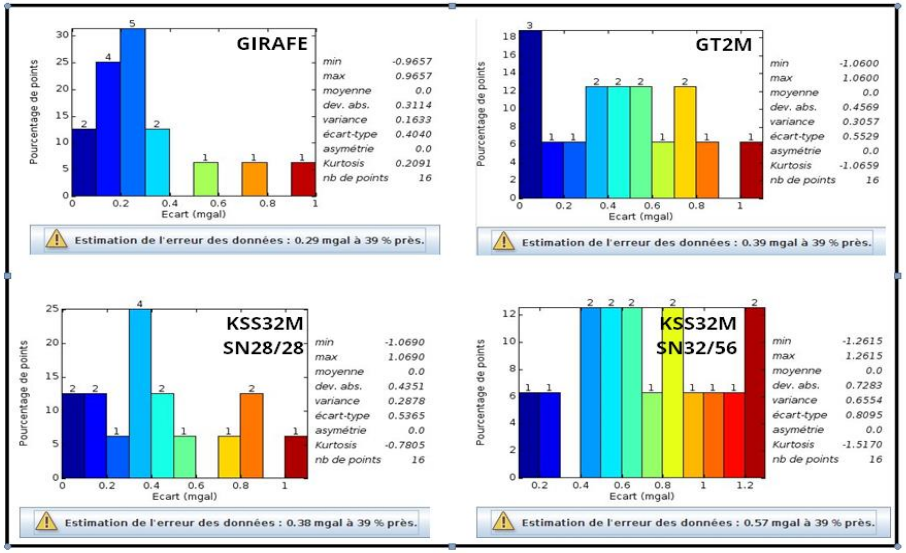
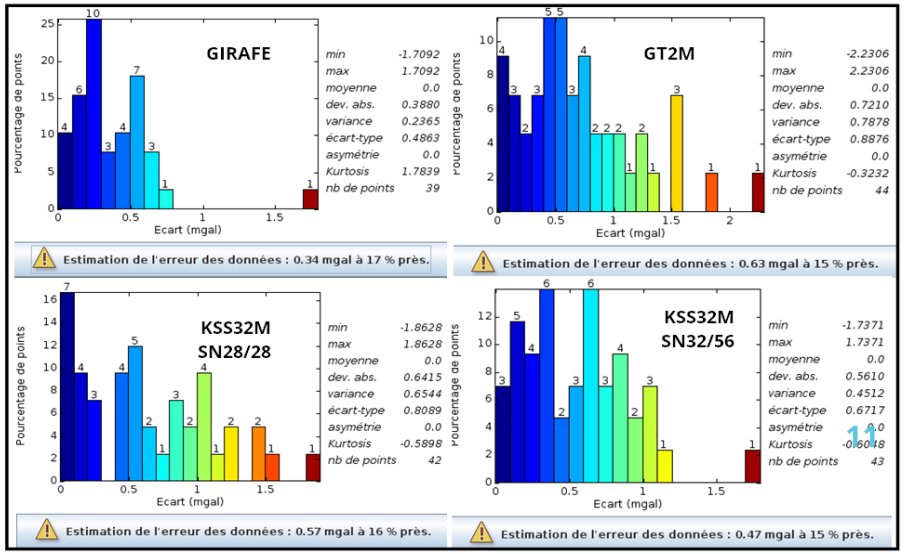




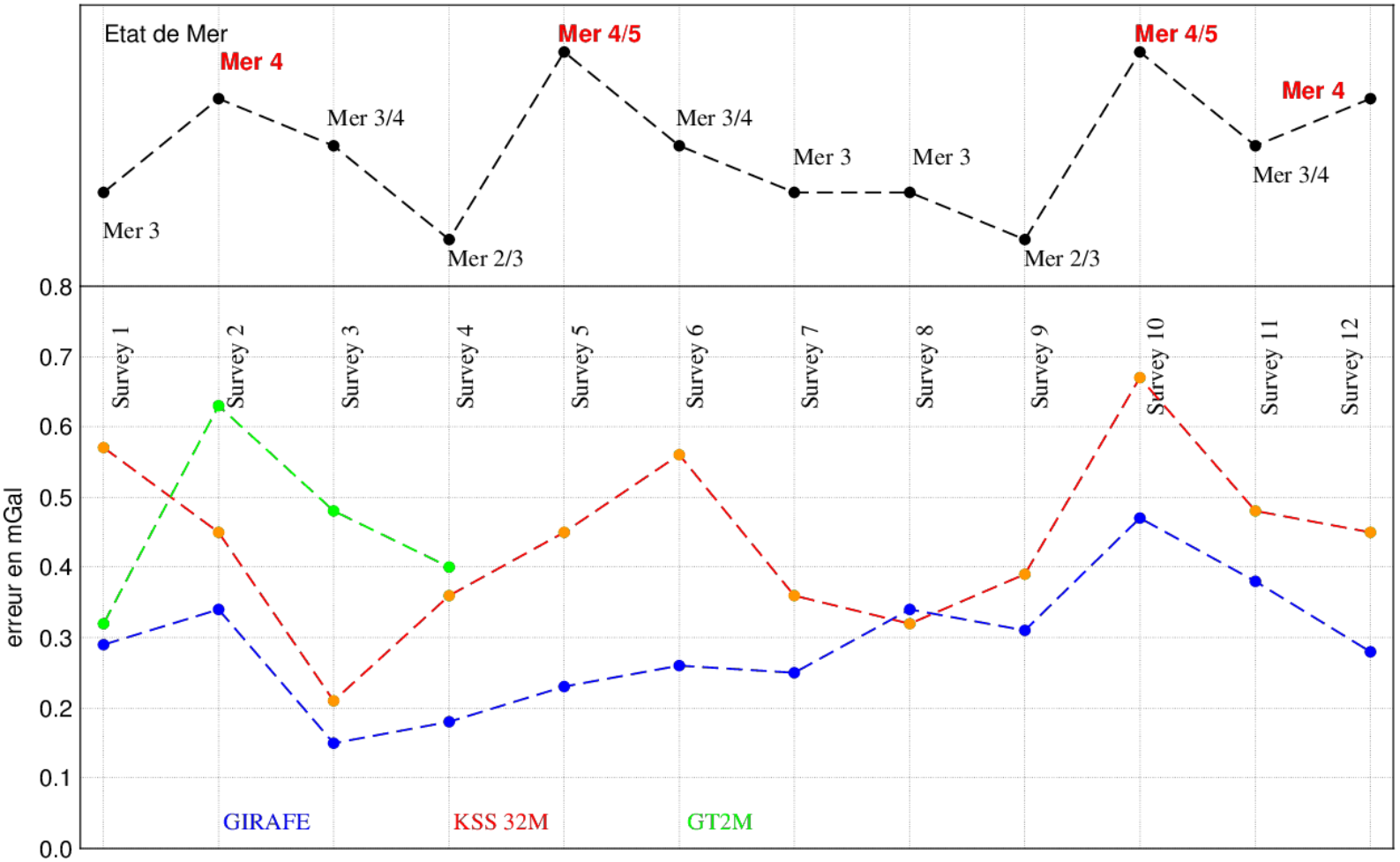
Erreurs sur le dièse : GIRAFE : **0.3 mGal**
KSS32 SN28 : 0.4 mGal
KSS32 SN56 : 0.6 mGal
GT2M : 0.4 mGal

Erreurs sur Meriadzec : GIRAFE : **0.3 mGal**
KSS32 SN28 : 0.6 mGal
KSS32 SN56 : 0.5 mGal
GT2M : 0.6 mGal





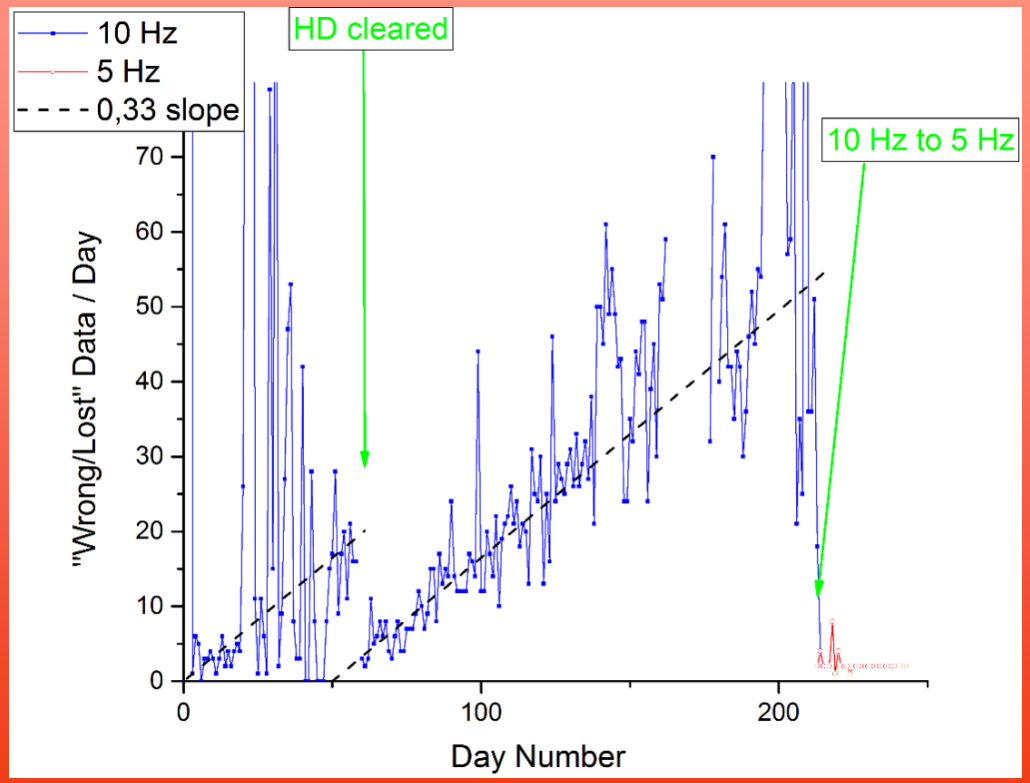
Résultats sur la période 1er avril au 10 octobre 2018



Résultats sur la période 1er avril au 10 octobre 2018

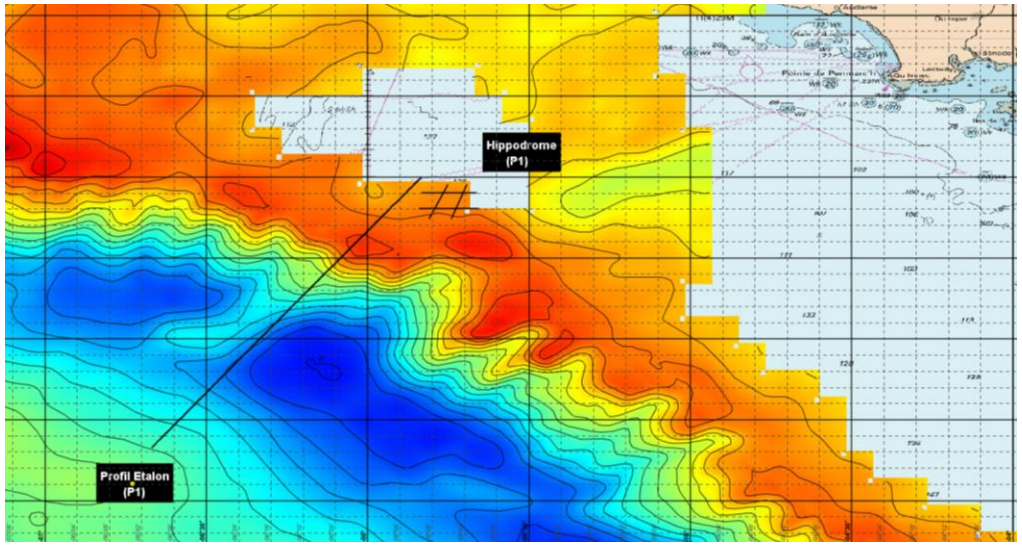
Augmentation du nbr de "pts faux" dans le temps

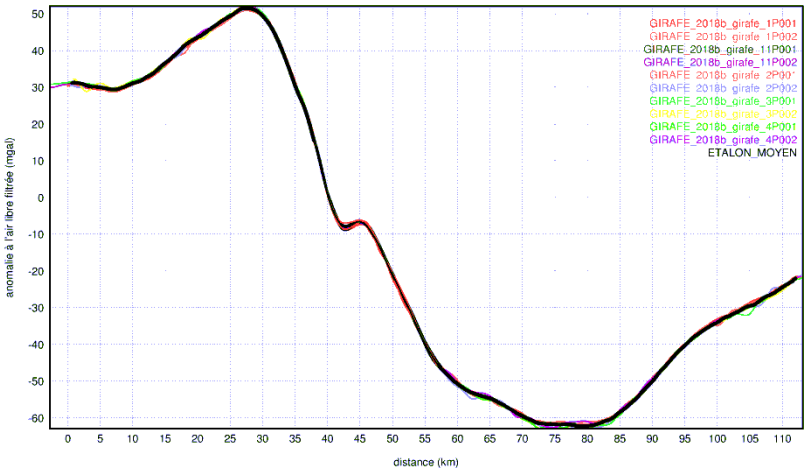
Augmentation de l'erreur dans le temps



Nouvelle zone de calibration des gravimètres à partir des mesures GIRAFE

- Détermination d'un dièse de référence obtenu à partir de 4 passages réalisés en aller/retour
- Nouveau profil étalon de référence calculé à partir de la moyenne des différents passages réalisé uniquement avec le gravimètre GIRAFE (precision ≈ 0.1 mGal)





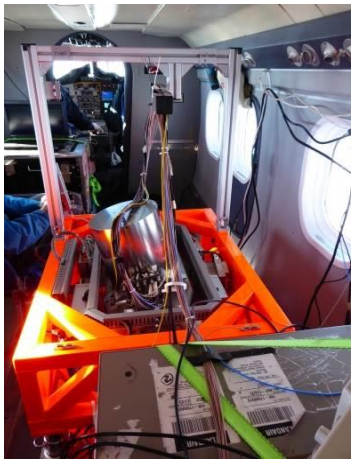
First Airborne gravity survey with a cold atom gravimeter

- In the frame of ESA-CryoVex campaigns aiming to record sea-ice/ice cap thickness to validate ESA's CryoSat-2 mission

- Idea to assess the potential of a new technology for airborne gravity measurements

- Collaboration with DTU-Space (Technical University of Denmark)

- Airborne campaigns (Twin Otter DHC-6) in april 2017 over Iceland



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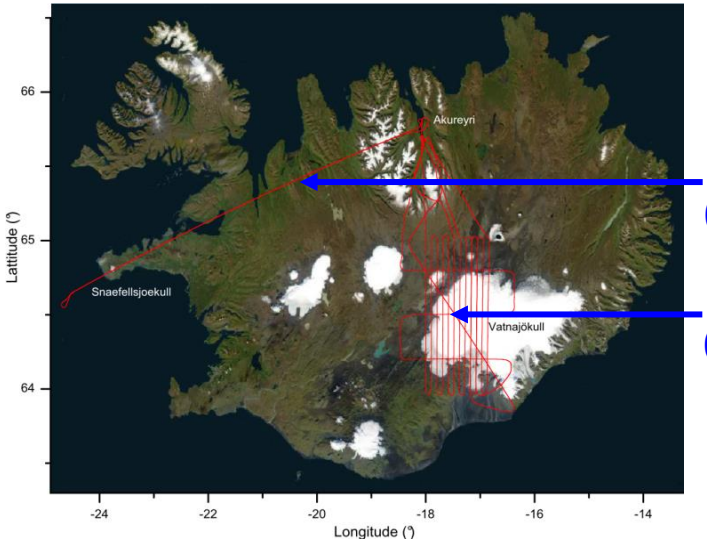


Round trip (Snaefellsjokull)

Gravity map (Vatnajökull)

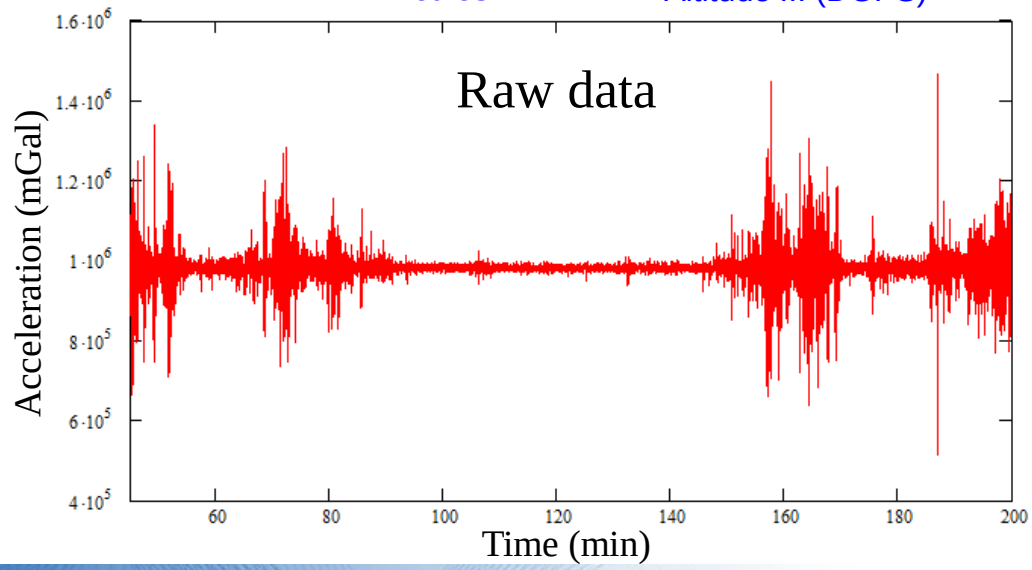
$$g_{mes} = g_{normal} + \underbrace{2\,\overrightarrow{\Omega_{Terre}} \times \overrightarrow{v_{plane}} + \frac{v_{plane}^2}{R_{Terre}}}_{\text{Eötvös !!}} + \underbrace{\Gamma_{zz}.H + \ddot{H}}_{\text{Altitude !!! (DGPS)}} + \Delta g$$

$v_{boat} \sim 5\ m/s$
$v_{plane} \sim 70\ m/s$

Results:

Round trip (Snaefellsjokull)

Raw data
peak-to-peak acc. variation ~ 0.7 g



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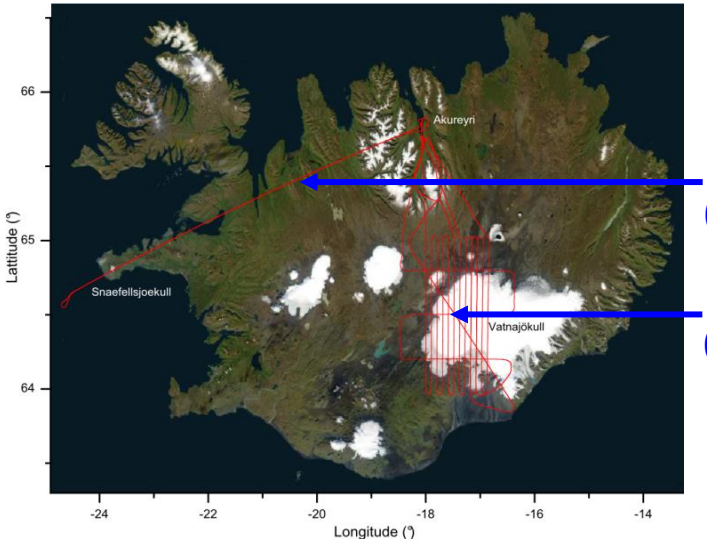

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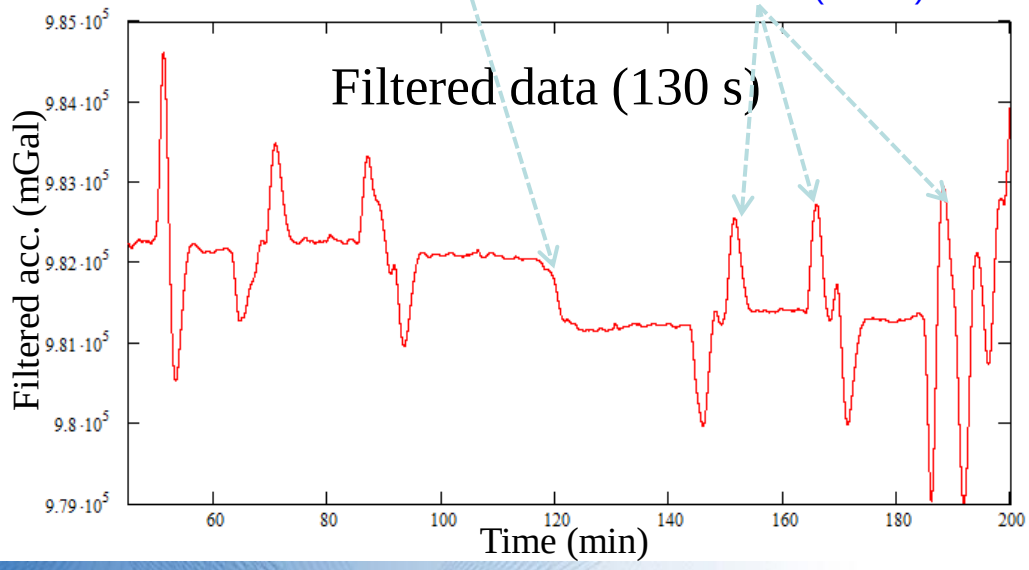
$v_{boat} \sim 5\ m/s$
$v_{plane} \sim 70\ m/s$

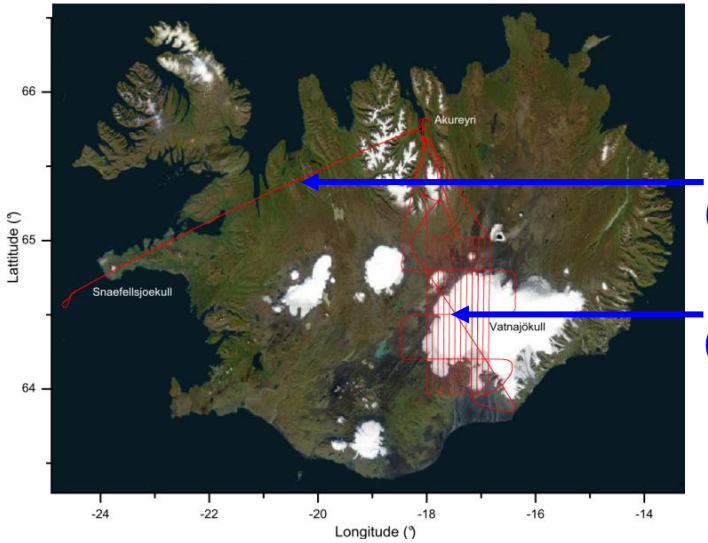
Results:

Round trip (Snaefellsjokull)

Filtered data (130 s ~ 10 km)
peak-to-peak acc. variation ~ 4 mg



First Airborne gravity survey with a cold atom gravimeter



Round trip (Snaefellsjokull)

Gravity map (Vatnajökull)

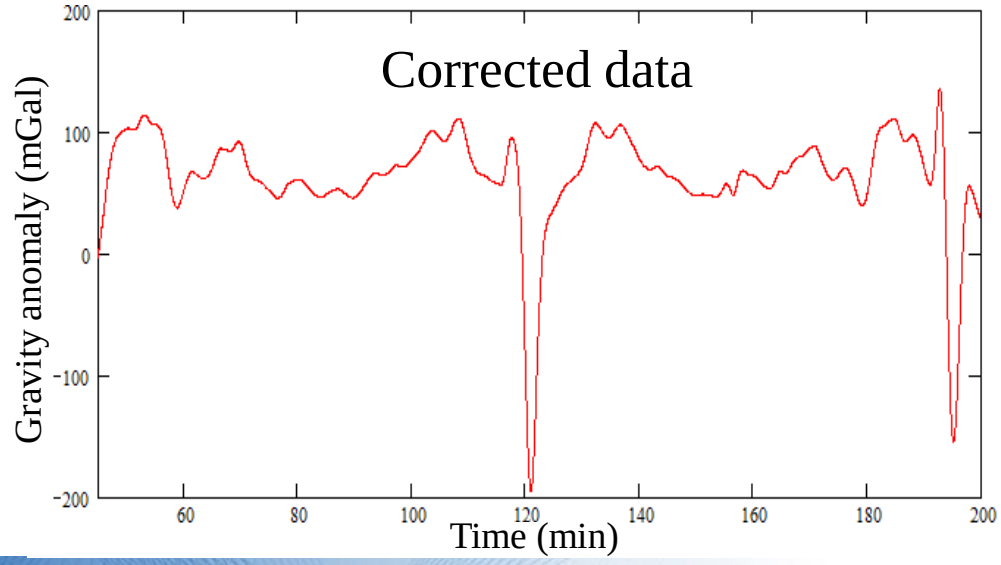
$$g_{mes} = g_{normal} + \underbrace{2\,\overrightarrow{\Omega_{Terre}} \times \overrightarrow{v_{plane}} + \frac{v_{plane}^2}{R_{Terre}}}_{\text{Eötvös !!}} + \underbrace{\Gamma_{zz}.H + \ddot{H}}_{\text{Altitude !!! (DGPS)}} + \Delta g$$

$v_{boat} \sim 5\ m/s$
$v_{plane} \sim 70\ m/s$

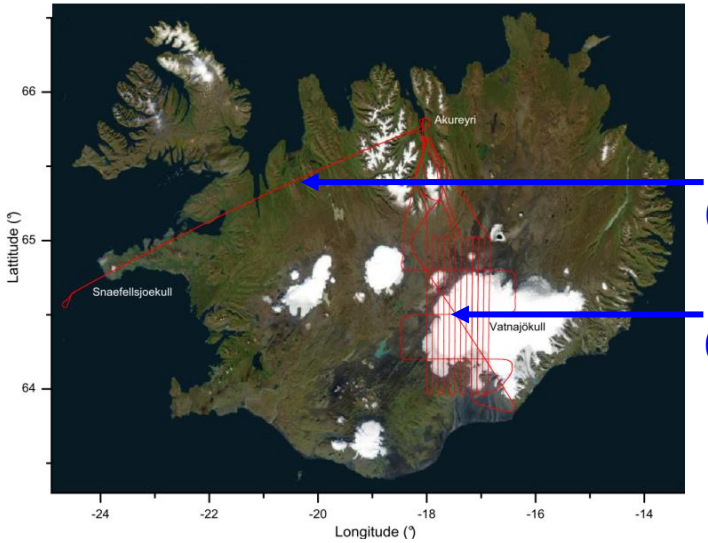
Preliminary results:

Round trip (Snaefellsjokull)

Corrected data
(- Eötvös - Altitude - g_{norm})



First Airborne gravity survey with a cold atom gravimeter



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$v_{boat} \sim 5\ m/s$

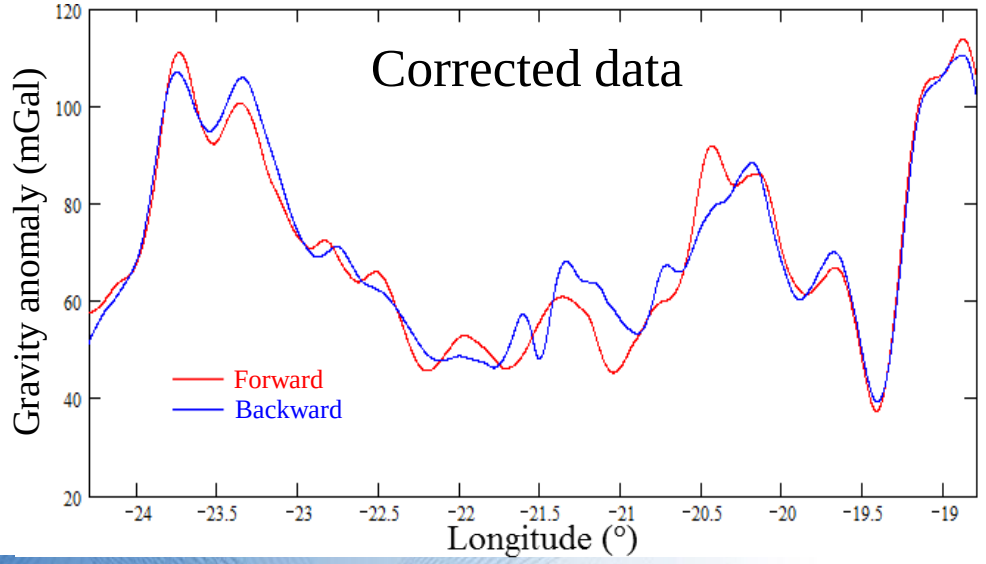
$v_{plane} \sim 70\ m/s$

Results:

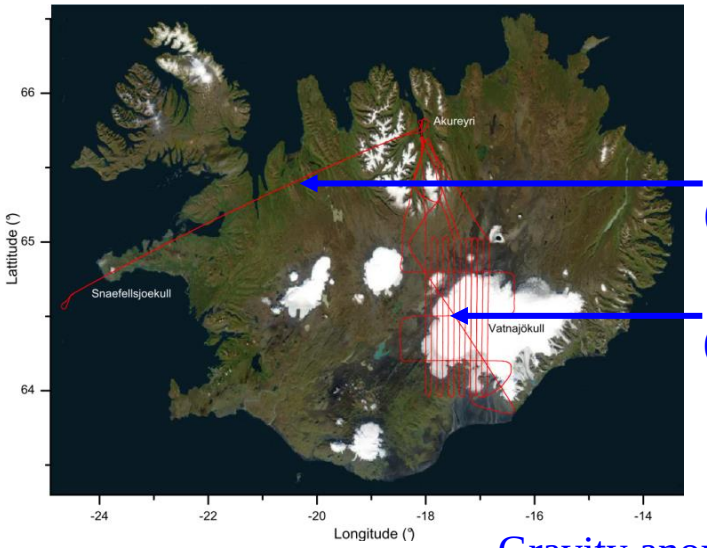
Round trip (Snaefellsjokull)

Corrected data
(- Eötvös - Altitude - g_{norm})

Residual: Std = 4.5 mGal
Mean = 0.62 mGal



First Airborne gravity survey with a cold atom gravimeter

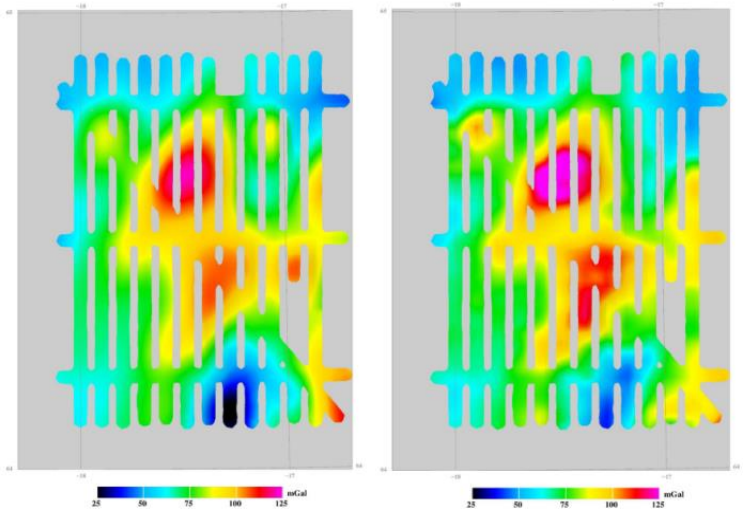


Round trip
(Snaefellsjokull)

Gravity map
(Vatnajökull)

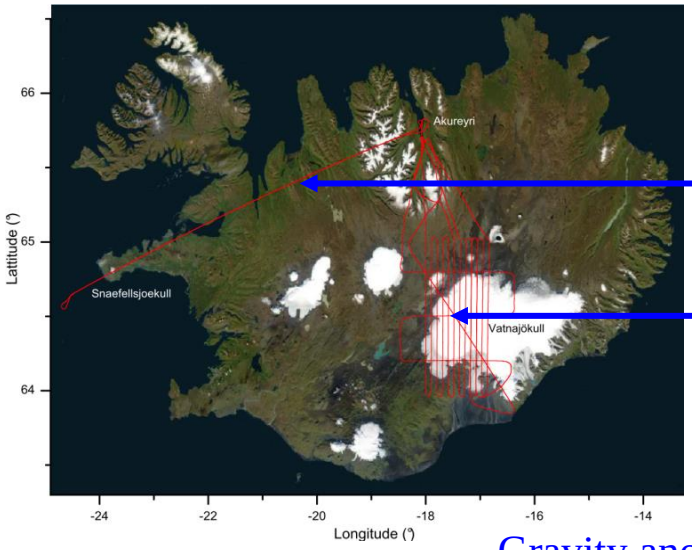
Gravity anomaly map of Vatnajökull (glacier/volcano)

GIRAFE 2 | Ground truth (DTU)



Precision < 3 mGal
(Crossing points StD
& Ground truth deviation)

First Airborne gravity survey with a cold atom gravimeter



Round trip
(Snaefellsjokull)

Gravity map
(Vatnajökull)

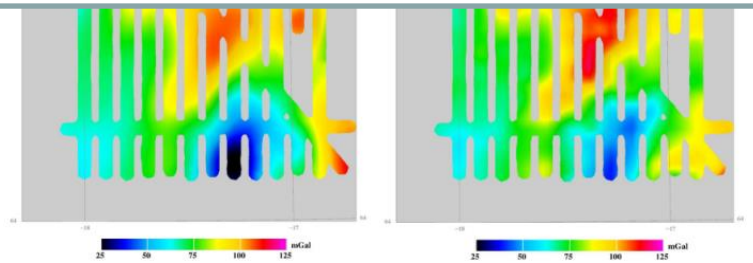
Gravity anomaly map of Vatnajökull (glacier/volcano)

Next Flight in April 2019 with SAFIRE

SAFIRE
the French facility for airborne research

Precision

cnes · GET · IRD · SHOM · DTU · ONERA THE FRENCH AEROSPACE LAB · ...



ONERA THE FRENCH AEROSPACE LAB

Hybrid Electrostatic-Atomic accelerometer for space missions

Study with ESA of an Hybrid Atom-Electrostatic System for Satellite Geodesy

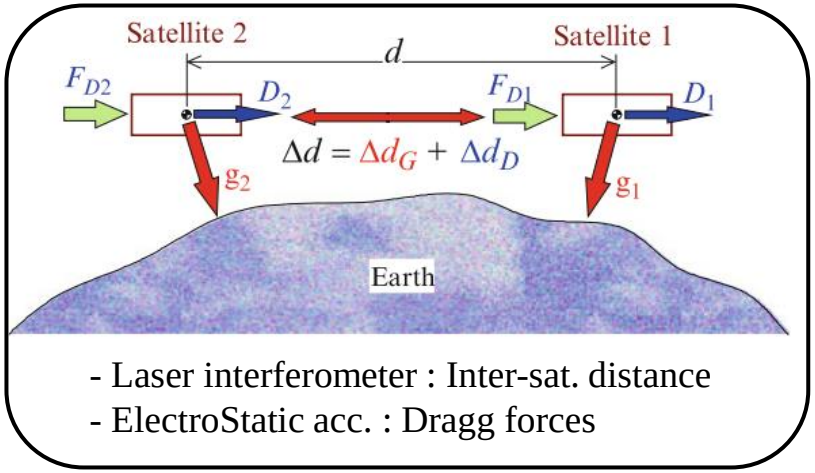
For future geodesy space missions → Need of highly sensitive accelerometers

State-of-the-Art: Electrostatic Acc.
(CHAMP, GRACE, GOCE, GRACE FO)
+ : Short term sensitivity, maturity, cont. meas.
- : Long term stability, accuracy

New generation of sensors: Atom Interferometers

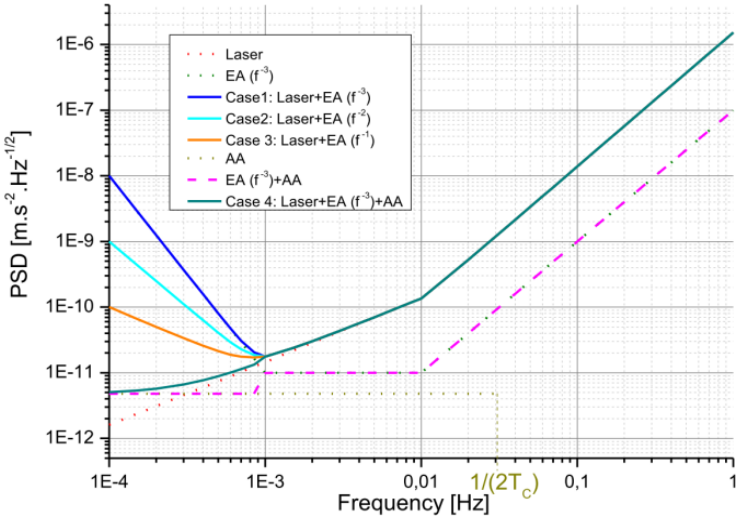
+ : Long term stability, accuracy, sensitivity
- : Low meas. rate, dead-times, low meas. range

Low-Low Satellite-to-Satellite Tracking scenario mission



- Laser interferometer : Inter-sat. distance
- ElectroStatic acc. : Dragg forces

Instrument limited at low frequency
by the ES acc.

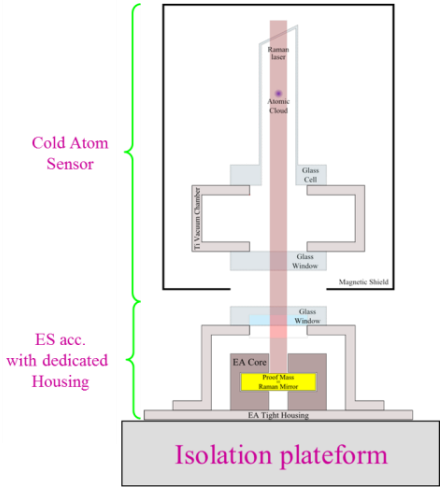


Idea of adding an Atom acc. to the instrument payload to correct the drift of the ES acc.

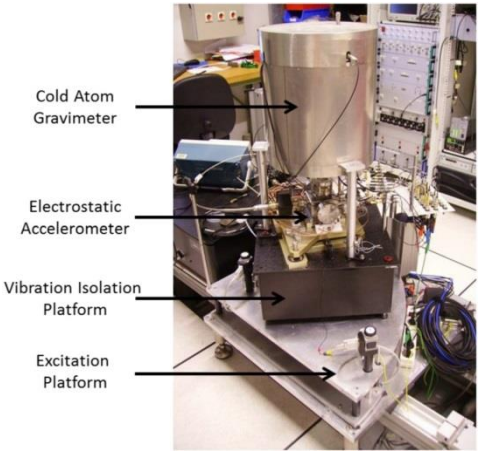
Hybrid project

Developement of a Lab. prototype

Dedicated ES accelerometer operating under gravity



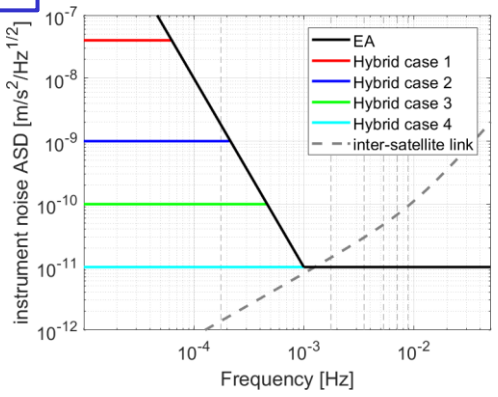
Cold atom gravimeter



Numerical gravity performance simulation

Simulation parameters:

- AI White noise level
- Low frequency corner
- Low frequency slope



Modelisation of the hybrid acc. in orbit