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Géosciences pour une Terre durable
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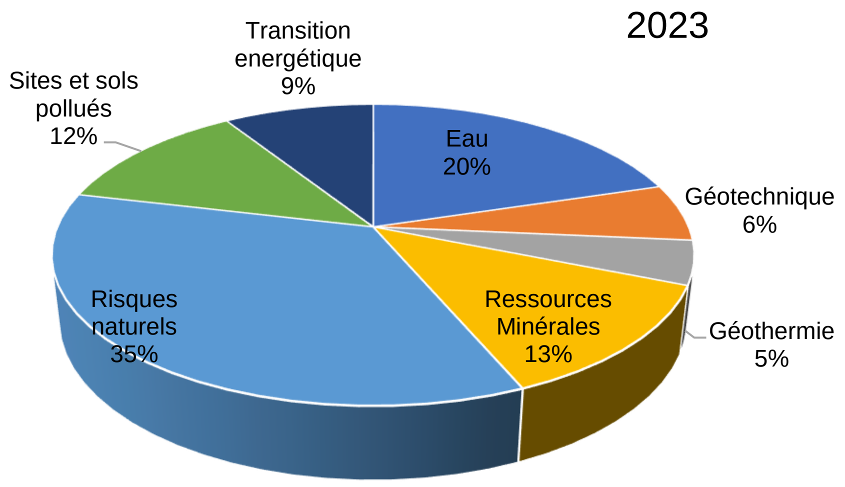
QUANTUM SENSORS IN GEOPHYSICS

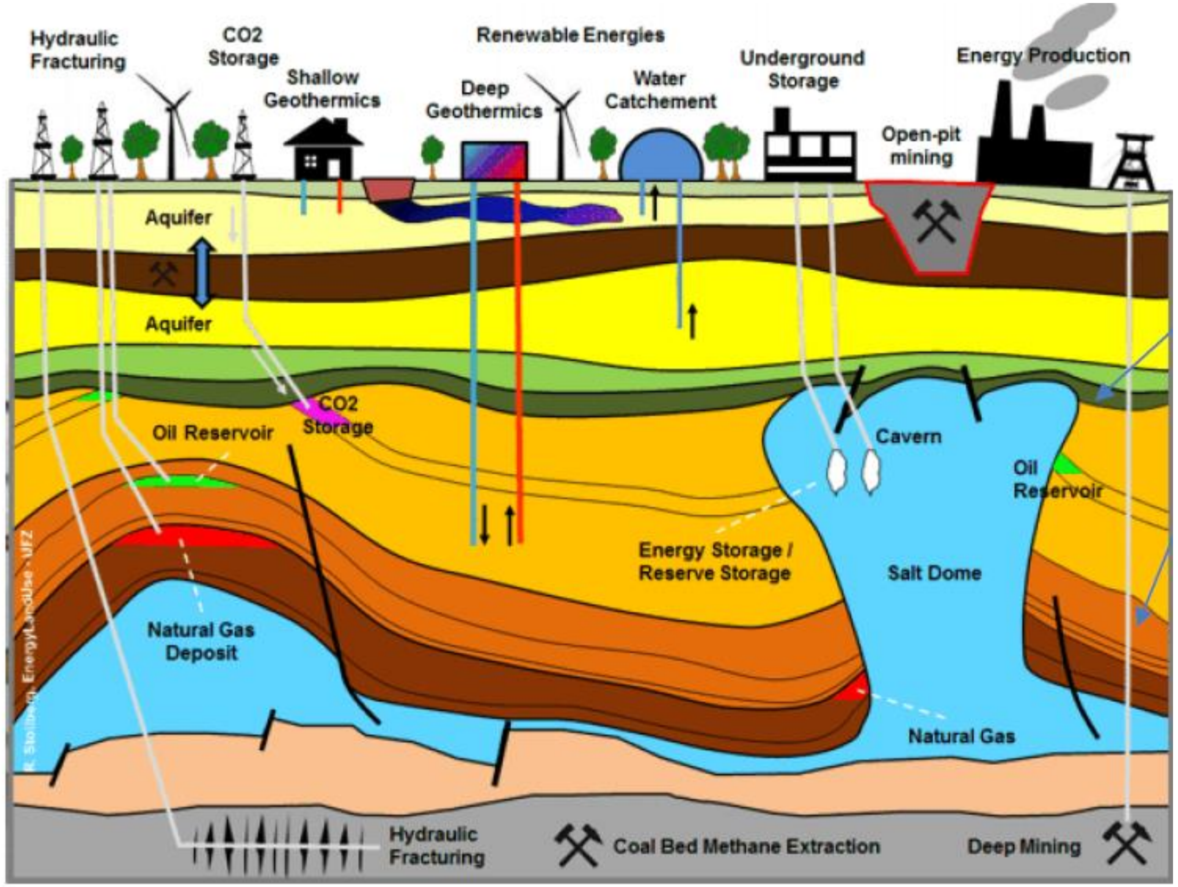
Mathieu Darnet, Thomas Jacob

14/11/2024

In BRGM, geophysics applied to…

- Water resource management
- Geothermal and CO2 exploration and monitoring
- Natural hazards : cavity, land slide, dikes, dams…
- Mining exploration and post-mining monitoring
- Pollution mapping and monitoring
- Volcanology
- UXO detection
- …





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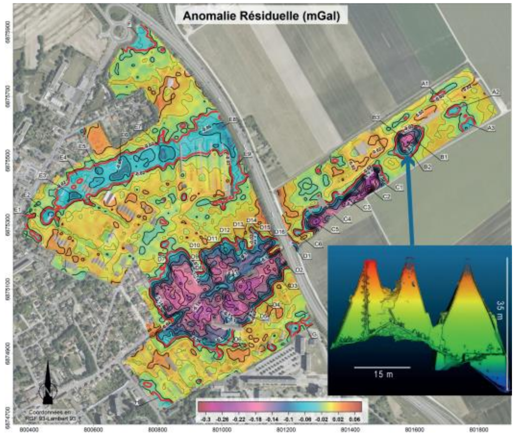
Laser Scanner + Microgravimetry for cavity detection



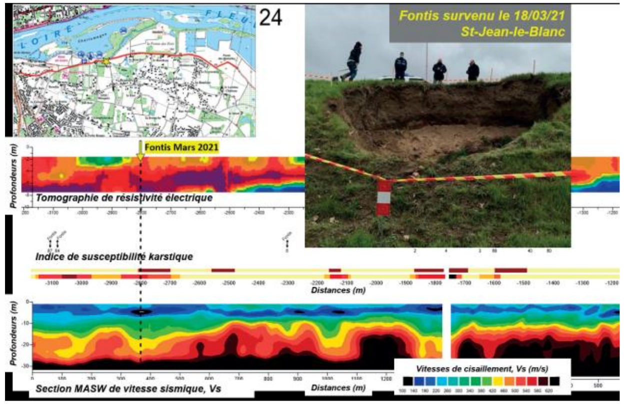
CSEM + MT

Land seismic streamer

Ground Geophysics

16 Geophysicists
3 Field Geophysicists
10 PhD, Postdoc, MSc…

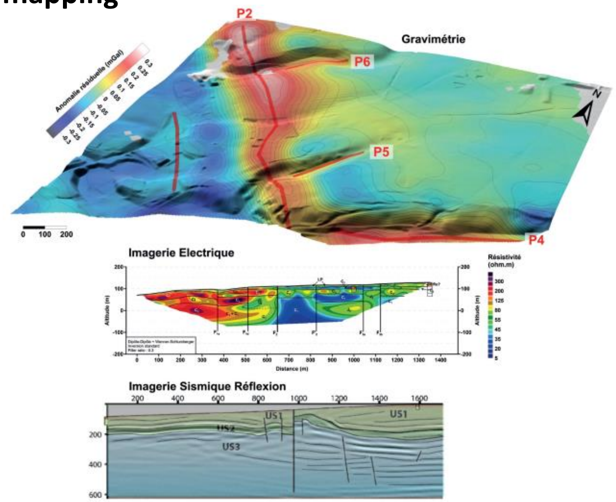
ERT + Seismic for dike mapping



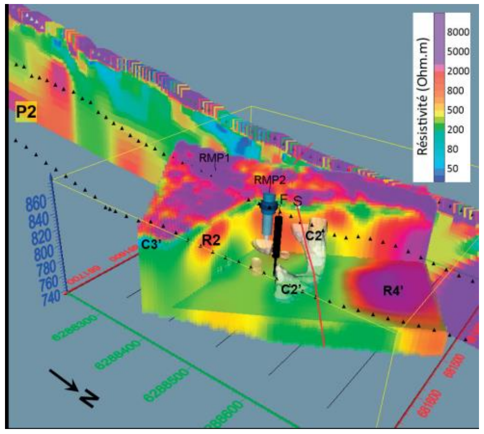
Seismic source

tTEM

Gravimetry + ERT + Seismic for structural mapping



ERT + NMR for water resource mapping



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Methods

- Electrical (ERT, IP)
- Electromagnetics (CSEM, MT, EMFI)
- Seismic (active/passive, DAS)
- Gravimetric (regional, microgravimetric)
- Logging

Acquisition / QC

- Mainly in-house (2mln€ CAPEX)
- Seismics with Smart Seismic Solutions (ex- CGG)
- New sensors: IRIS TIP/FVW, Nodes

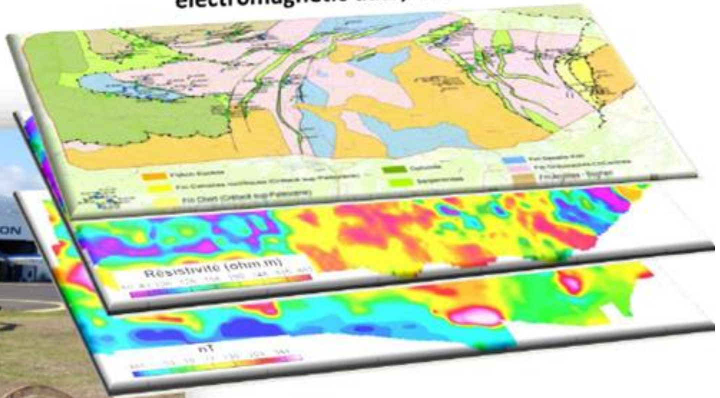
Processing

- In-house processing algorithms

In-house Modelling / Inversion

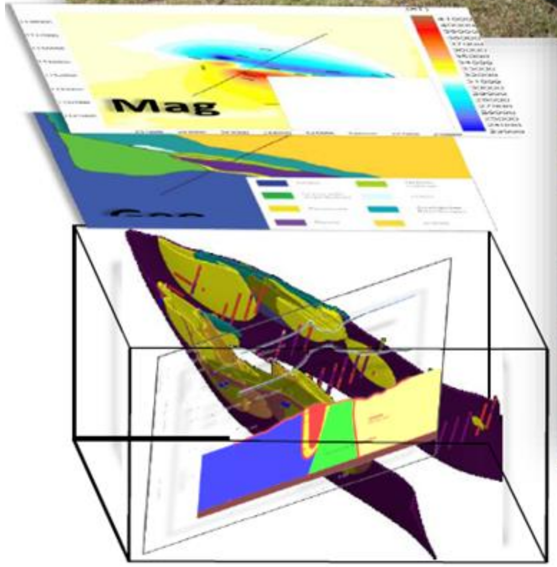
- In-house modelling & inversion algorithms
- Geophysical & Geological modelling

Geological mapping constrained by magnetic and electromagnetic data, New Caledonia



La Réunion island EM-magnetic heliborne geophysical survey

Supervision of Congo country-wide airborne geophysical survey



3D mineral targeting constrained on airborne magnetic data and boreholes, Guinea

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Airborne Geophysics

4 Geophysicists
1 PhD
2 Postdocs

Methods
- Magnetic
- Gamma-spectrometry
- Electromagnetic
- Gravimetric / gradiometry
- Satellite imagery (INSAR, hyperspectral…)

Acquisition
- Deep AEM with SkyTEM (1000m doi)
- EM sensor on drone (magnetic)

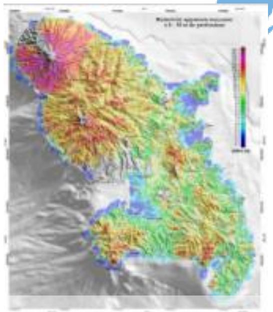
Processing
- In house TDEM processing algorithm

In-house Modelling / Inversion
- 2D TDEM inversion code under development
- Magnetic + gravity + geological modelling

Airborne geophysical mapping

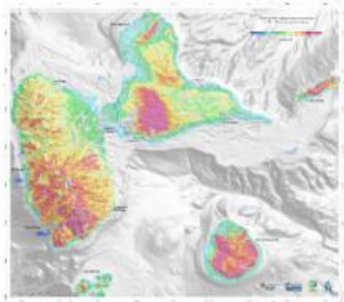
Dans des contextes sédimentaire / volcanique / socle

Massif Armoricain (1999) : Mag/Spectro
Région Centre (2009 – 43 500 kml + 3000 kml) : Mag/Spectro/EM
Bourgogne (2011 – 27500 kml)
Pays de la Loire (2010 – 39500 kml)
Chaîne des Puys (2020 – 1000 kml) : Mag/Spectro/EM
Périgord (2021 – 1500 kml) : Mag/EM
Massif central (2022 – 11 000 kml & 16 000 kml) : Mag/EM & Mag/Spectro
(2023 – 4 500 kml & 40 000 kml) : Mag/EM & Mag/Spectro
(& 2024…)
Besançon (2023 – 760 kml) : Mag/EM



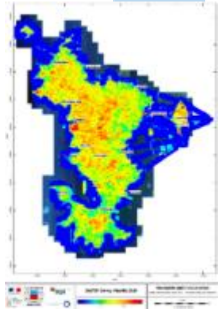
Martinique (2013 – 3700 kml)

Dans un contexte volcanique

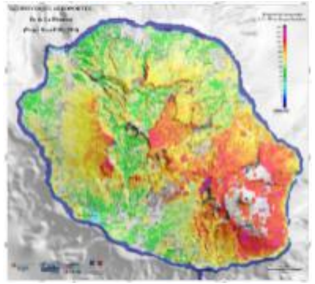


Guadeloupe (2013 – 5400 kml)

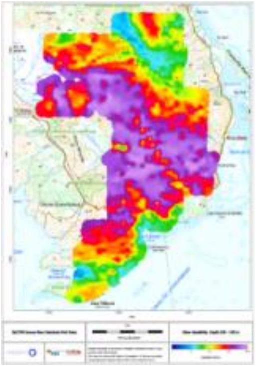
Mayotte (2010 – 3000 kml)



La Réunion (2014 – 10 400 kml)
La Plaine des Fougères (2021 – 600 kml)



Dans des contextes métamorphique et plutonique



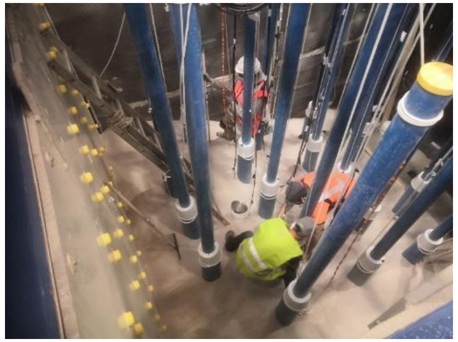
Nouvelle Calédonie (2015 – 800 kml
2020 – 15 000 kml)

Collaborative Research Platforms

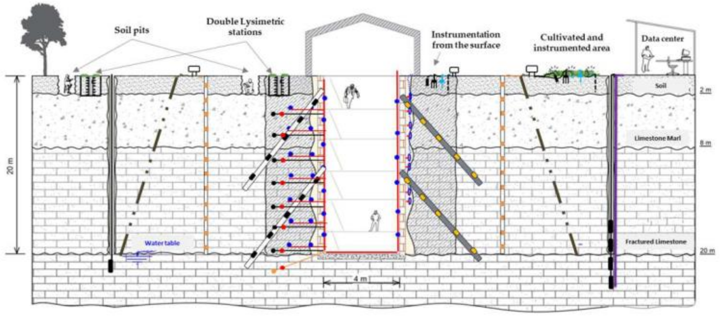
- Hydrogeophysics: Unsaturated zone (O-ZNS), Pluri-metric Platform (PPM)
- Geothermal: Rhine Graben EGS, Paris Basin
- CCUS: Pilotstrategy in Paris Basin
- Mining: Mineral Resource Inventory
- Natural hazards: DAS karst project
- Volcanology: MARMOR/REVOSIMA

…

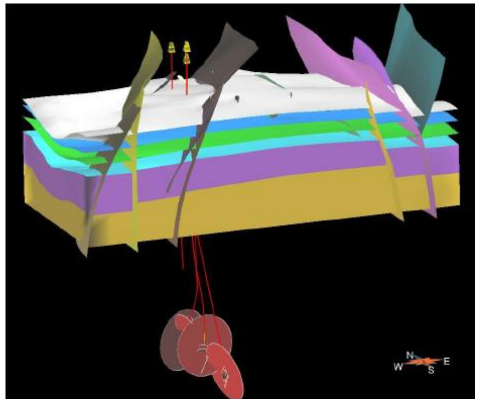
PPM Lab



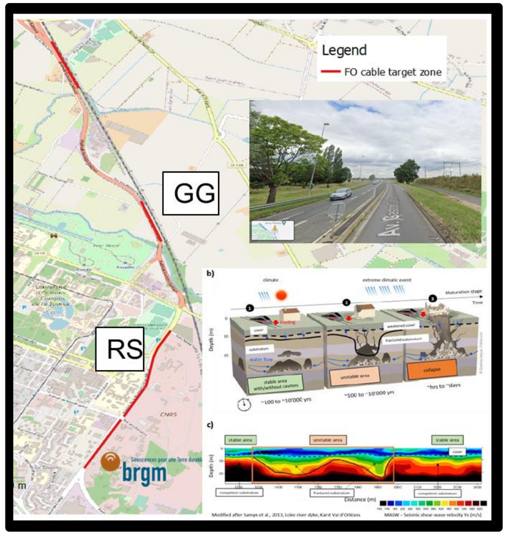
O-ZNS Platofrom



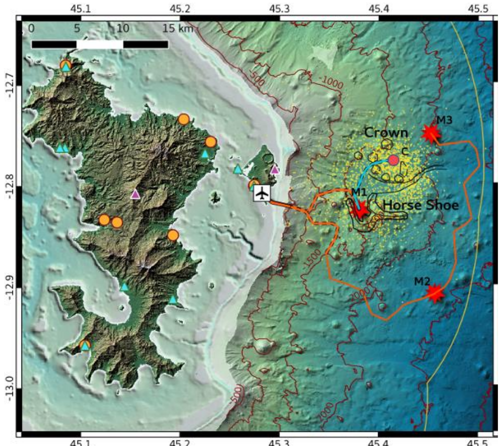
Soultz EGS project



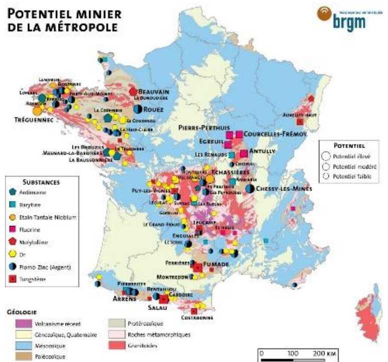
DAS karst project



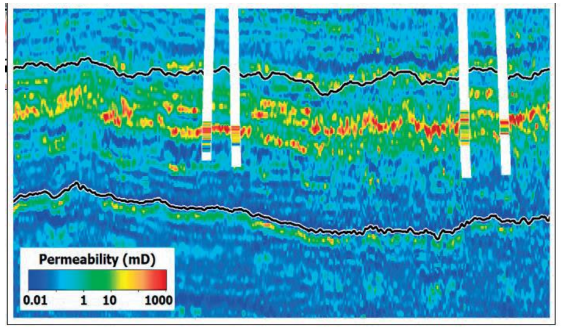
Mayotte Offshore MT/DAS Obs



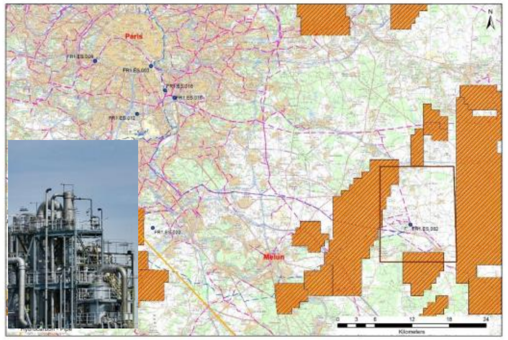
Mineral Resource Inventory



Geothermal exploration in Paris Basin



CO2 seismic site characterization



Current main geophysical research topics in geophysics

- **Acquisition:**
  - ✓ New physics: broadband EM (100 kHz – 100 MHz), muography, electrostatics, NMR
  - ✓ New sensors: DAS FO, distributed sensors ("3D"), multi-physics sensors (ERT-IP/EM/seismic)
  - ✓ New carriers: towed, airborne, semi-airborne, borehole
  - ✓ Monitoring: cost-effective 4D (CSEM, MT, ERT, seismic, FO…)

Quantum sensors?

- **Processing/Imaging:**
  - ✓ 3D EM modelling/inversion (CSEM, MT, ERT-IP, AEM…)
  - ✓ Seismic FWI (crosswell, surface waves)
  - ✓ Passive seismic Interferometry
  - ✓ Multi-physics modelling/inversion (grav+mag+EM, seismic+EM, seismic+ERT, grav+laser…)

- **Integration/interpretation**
  - ✓ Petrophysics (seismic+EM+grav, upscaling issue…)
  - ✓ Multi-physics structural imaging (seismic+EM, EM+grav…)
  - ✓ Multi-physics quantitative interpretation (deterministic, stochastic, AI, clustering inversions…)
  - ✓ Coupled geophysical & geological modelling (inverse problem?)

And more…!

Trends in geophysical acquisition systems

- **Better signal to noise ratio:**
  - ✓ Lower sensor noise level for natural field methods: gravity, magnetics, passive electromagnetics, passive seismics
  - ✓ Higher S/N for active methods (electromagnetics and seismics): stronger sources + lower sensor noise level
  - ✓ …

- **Higher efficiency of deployment:**
  - ✓ Better sampling of the earth: faster deployment (airborne, drone, towed…), higher spatial density (1 mln channel 3D seismics, fiber optics…)
  - ✓ Faster acquisitions: higher sampling rates
  - ✓ Multi-physics sensors: "all in one" approach
  - ✓ Remote sensing (volcanoes, borehole, deepwater…)
  - ✓ …

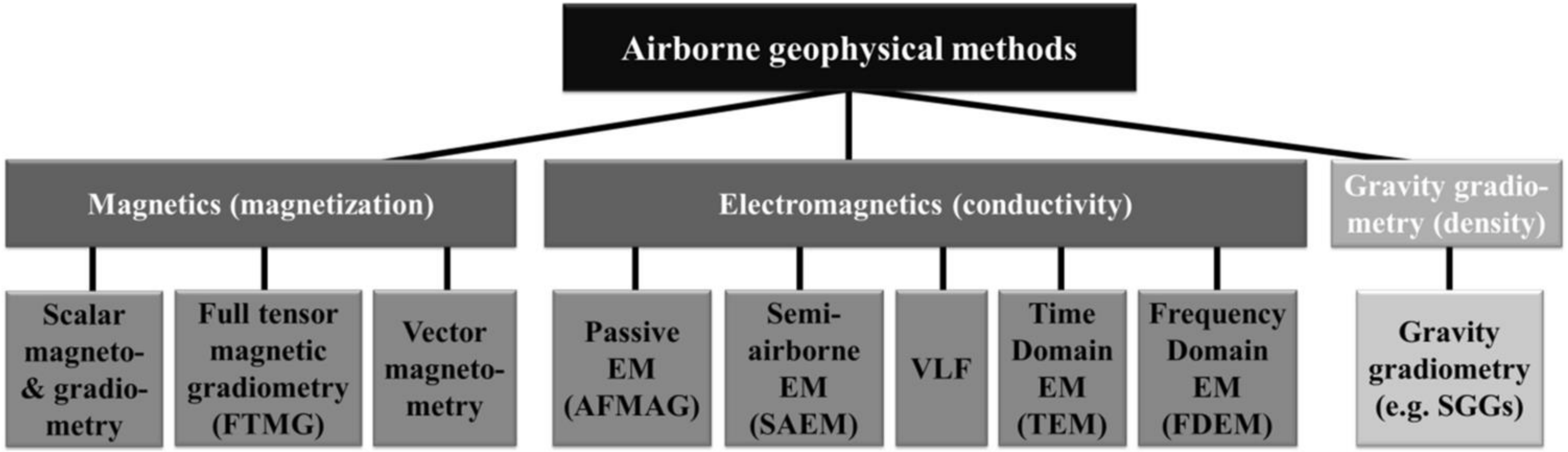
And obviously lower cost …!

Quantum sensors in geophysics … so far!

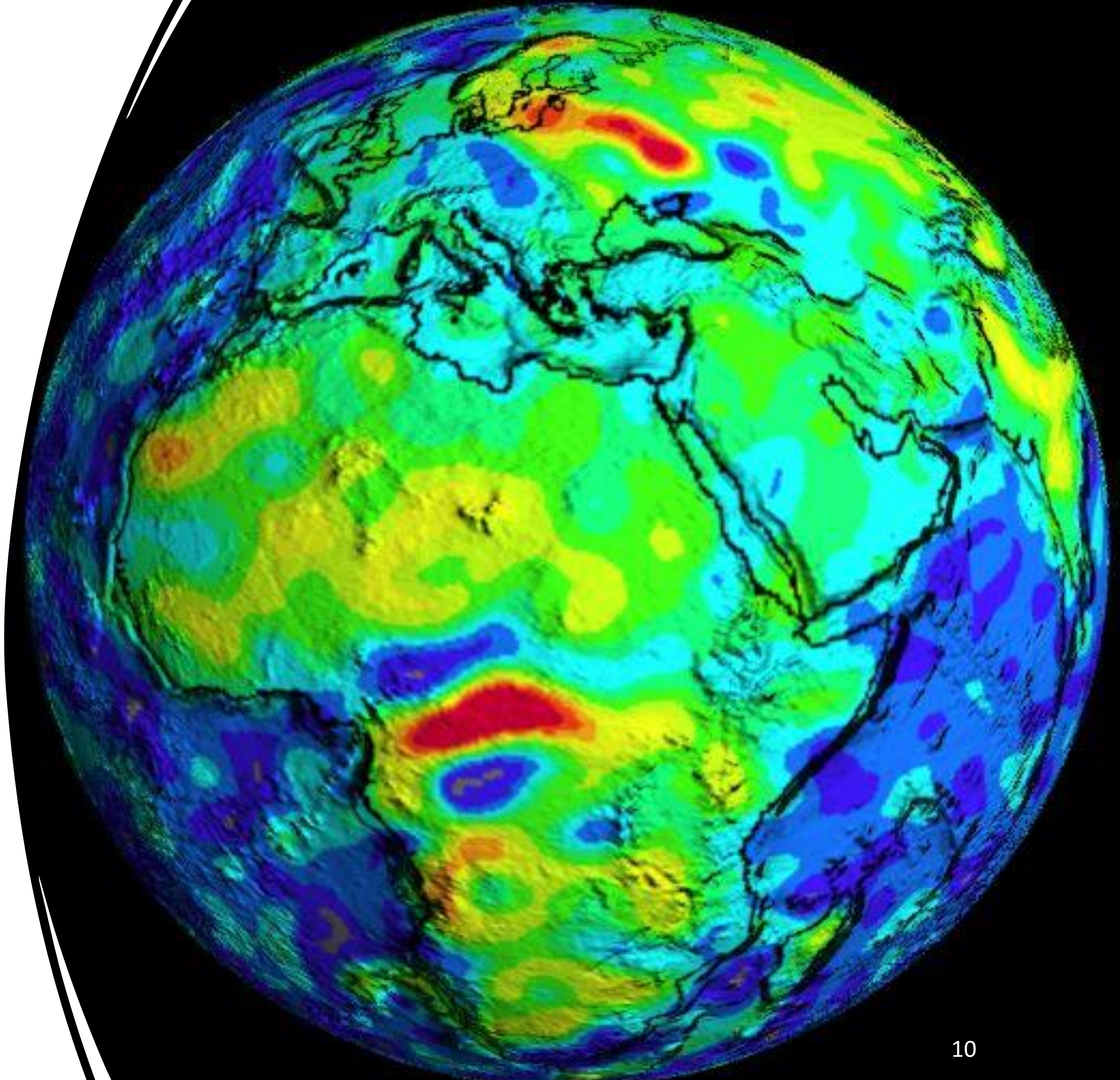
❑ **Magnetometers:**
- ✓ Proton Magnetometers
- ✓ Overhauser Magnetometers
- ✓ Optically Pumped Magnetometers Helium 4
- ✓ Cesium/Potassium Magnetometer
- ✓ Magnetometer
- ✓ Superconducting QUantum Interference Device (SQUID)
- ✓ Nitrogen vacancy diamonds
- ✓ …

❑ **Gravity :**
- ✓ Cold atoms
- ✓ …

And …?

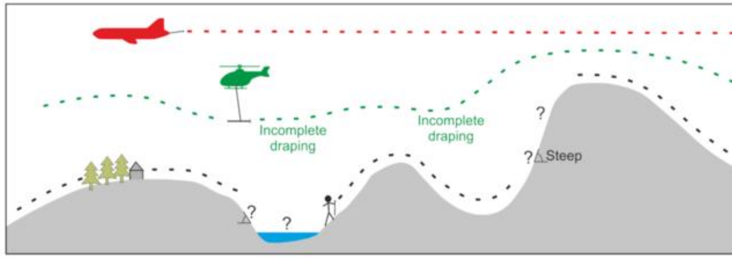


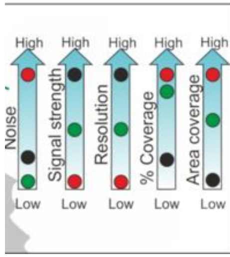
Magnetic sensors



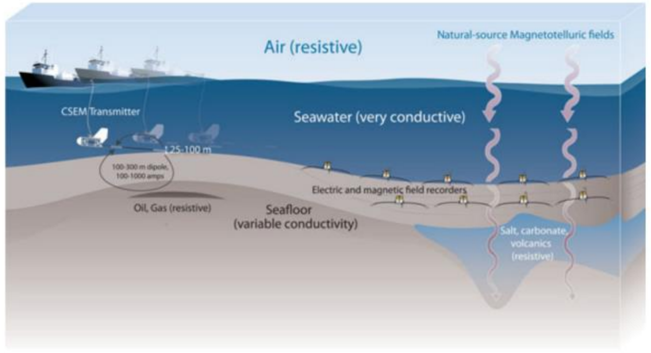
Magnetometers in geophysics

- **“Passive” methods = measure the Earth magnetic field**
  - ✓ **Total field measurements**
  - ✓ **Scalar/Vector measurements**
  - ✓ **Sampling rate up to 1 kHz**
  - ✓ **Mapping Earth magnetic (induced and remnant susceptibility) and electrical (conductivity) properties for geological mapping (tectonics, volcanology…), resource mapping (minerals, geothermal, O&G…)**
  - ✓ **Carriers: hand-held, towed, drone, airborne, satellite…**
  - ✓ **Nick names: Magnetics, Magneto-Tellurics, DRONEMAG, AFMAG, AMT…**





- **“Active” methods = measure the magnetic field induced by an electromagnetic transmitter**
  - ✓ **Relative field measurements (no need for DC)**
  - ✓ **Scalar/Vector measurements**
  - ✓ **Sampling rate up to 1 GHz**
  - ✓ **Mapping Earth electrical (conductivity, permittivity) for geological mapping (tectonics, volcanology…), resource mapping (minerals, geothermal, O&G…)**
  - ✓ **Carriers: hand-held, towed, drone, airborne, satellite…**
  - ✓ **Nick names: Controlled-Source Electromagnetics, Georadar, SAR…**



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Magnetometers in geophysics

- A wealth of sensors…
  - ✓ Induction coils
  - ✓ Fluxgates
  - ✓ SQUID
  - ✓ OPM
  - ✓ …

Development of the MONARCH fixed wing Gradiometer was based on GEM's re-designed, Ultra Light Weight Potassium technology sensors. Now, GEM's DRONEmag™ sensors have become standard across all UAV magnetometer platforms.

Eagle Geophysics' Multi sensor Gradiometer, measures 10 vertical G horizontal gradients.

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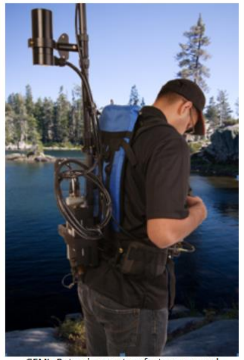


GEM's Potassium system features a novel backpack-mounted solution with sensors, electronics and cabling all self-contained. System is designed for "hands-free" operation to save time and effort.

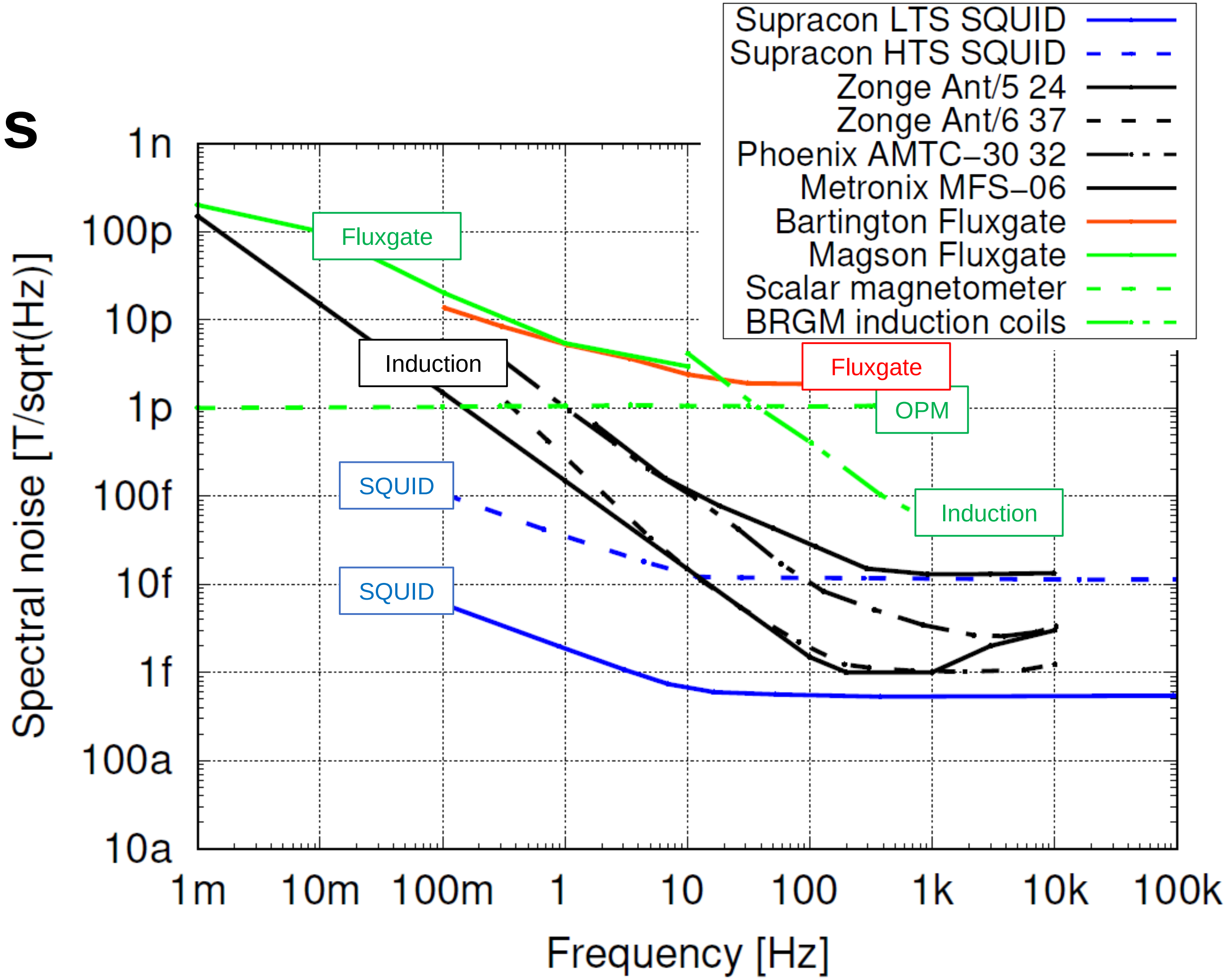


Figure 4: Spectral noise levels (the lower the better the measurement quality) versus signal frequency of various magnetic field sensors employed in surface measurements where sensor size is not a concern (SQUIDs - blue solid and dashed lines, induction coils - black solid and dashed lines, fluxgate - red) and sensors developed by consortium members and intended to be used in new borehole magnetometer system (Magson fluxgate - green solid line, scalar (optically pumped) magnetometer - green dashed line, BRGM induction coils - green dashed and dotted line. Whereas the BRGM induction coils are inferior to induction coils used in surface measurements, they are still better than induction coil sensors for borehole measurements developed by competitors. Note that the constant spectral noise level of the optically pumped sensor will allow to improve the magnetic fields measured by Magson's fluxgate and BRGM's induction coils for frequencies of up to roughly 40 Hz.

Quantum magnetometers in geophysics

Quant Technology	Scalar/Vector	Bandwidth	Sensitivity	Deployment	Maturity	Provider
Proton	Scalar	Up to 2 Hz (GEM GSM-25)	0.15 nT @ 1 Hz (GEM GSM-25)	Ground	Commercial	GEM …
Overhauser	Scalar	Up to 5 Hz (GEM GSM-19)	0.022 nT @ 1 Hz (GEM GSM-19)	Ground	Commecial	GEM …
Ce/K OPM	Scalar	Up to 20 Hz (GEM GSMP)	0.0002 nT @ 1Hz (GEM GSMP)	Ground	Commercial	GEM …
4He OPM	Scalar or Vector	DC to 1 kHz	Down to 100 fT/√Hz	Ground/airborne	Research?	CEA-LETI
SQUID	Scalar or Vector	flat frequency response from dc up to 10 kHz	better than 50 fT/√Hz, 1/f cutoff frequency less than 10 Hz	Ground Towed Airborne	Commercial	Supercon Magnicon DIAS (QAMT) Crone Geophysics …
NV Diamond	? Scalar	? Up to 100 Hz	? <10 pT/sqrt(Hz)	Ground/Airborne	Close to commercial	SB Quantum Zurich Instrument

Development of the MONARCH fixed wing Gradiometer was based on GEM's re-designed, Ultra Light Weight Potassium technology sensors. Now, GEM's DRONEmag™ sensors have become standard across all UAV magnetometer platforms.

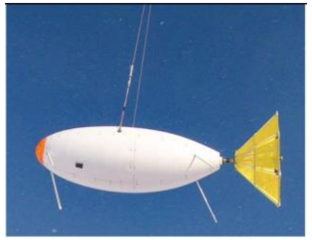
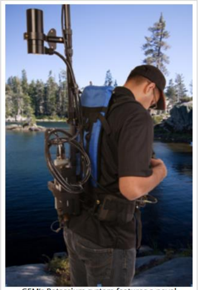


Figure 2: Towed bird with high drag tail.

A Hexacopter UAV platform with suspended DRONEmag™ from GEM Systems for High Resolution surveying at 15 m line spacing: more than 3 times denser than conventional airborne surveys. DRONEmag™'s high sensitivity is ideal for aerial platforms due to its ability to resolve even subtle signals at standard 100-foot drone magnetometer flying heights. Photo courtesy of MWH Geo-Surveys Ltd.

Eagle Geophysics' Multi sensor Gradiometer, measures 10 vertical G horizontal gradients.



GEM's Potassium system features a novel backpack-mounted solution with sensors, electronics and cabling all self-contained. System is designed for "hands-free"

Lower noise level is not necessarily better…

- **The Earth magnetic field is "red" at low frequencies, as well as induced magnetic fields**
  - ✓ **S/N at low frequencies?**
  - ✓ **Bandwidth of sensors?**

➔ **Careful selection of sensors…**

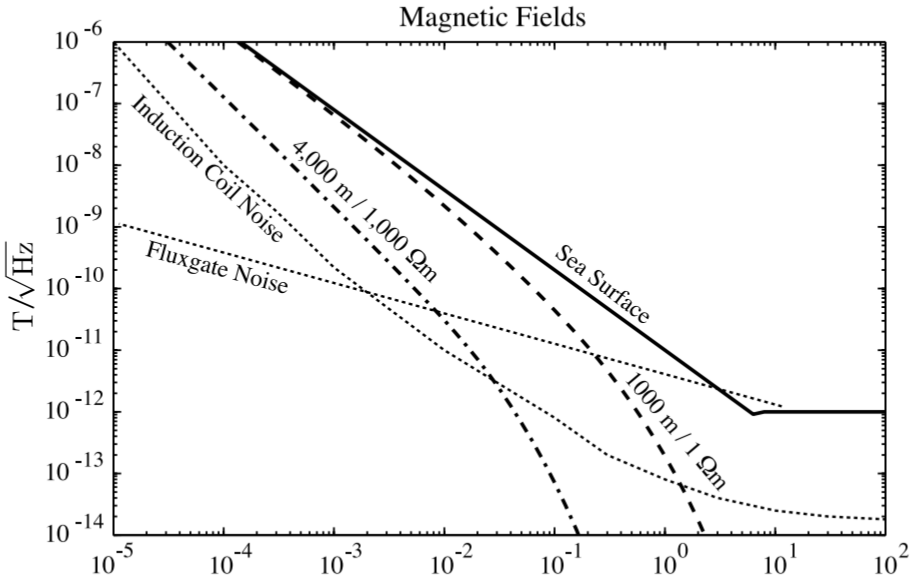
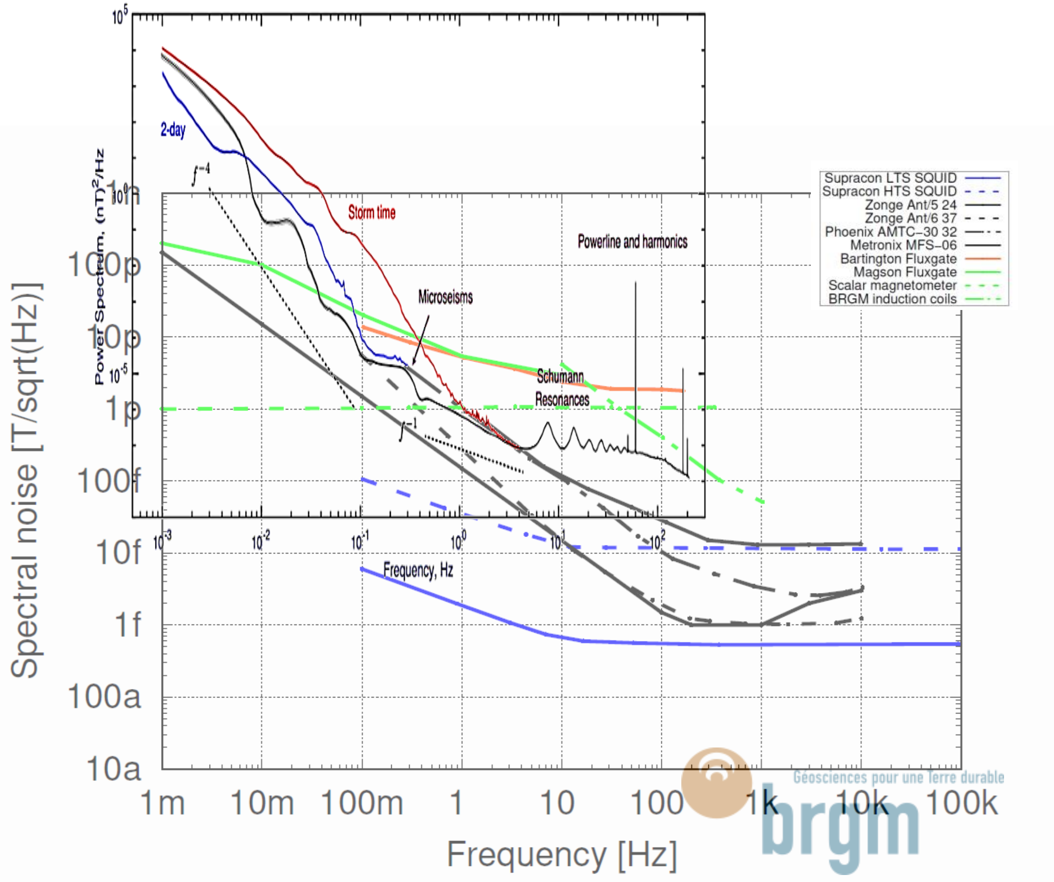


Figure 2 Magnetic fields at the sea-surface and downward continued 1 km to the sedimented sea-floor on the continental shelf and 4 km to the volcanic sea-floor in the deep ocean, along with the corresponding induced electric fields (sea-surface electric fields are for the continental shelf model). Noise floors are shown for a BF-4 induction coil magnetometer from EMI, Inc., a low-noise ring-core fluxgate based on data from Ripka (1992) and the electric field instrument noise shown in Fig. 6.

Fig. 7. Adaptive multi-taper spectrum of 2 h of induction coil data sampled at 500 Hz collected near Borrego Springs, California (black line) and for 2 days of data re-sampled at 5 Hz (blue line). Also shown is the spectrum of 12 h data collected at 50 Hz in South Australia during a 200 nT magnetic storm on May 4, 1998 (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

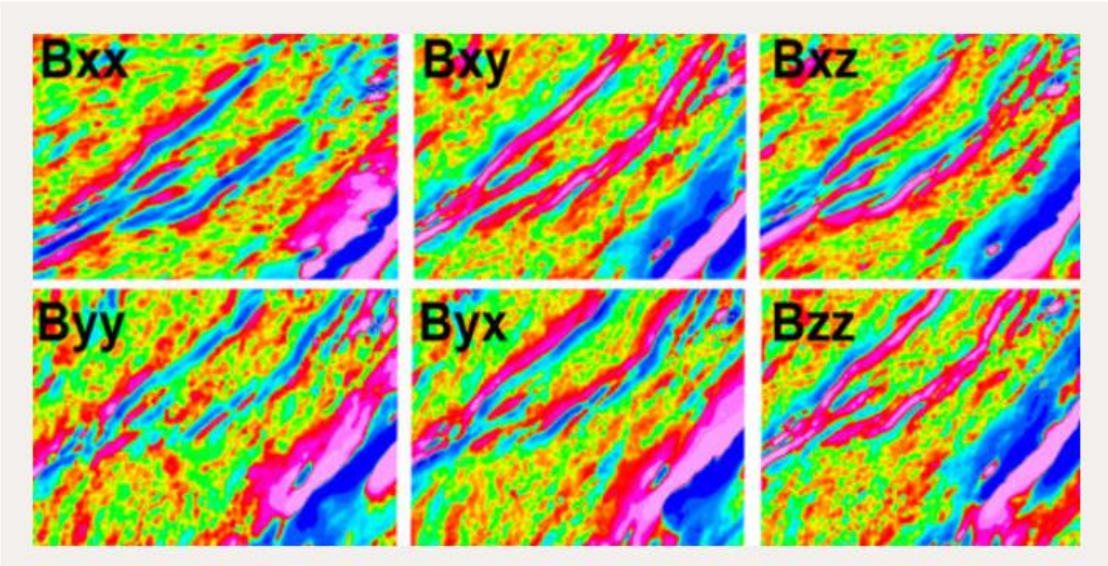


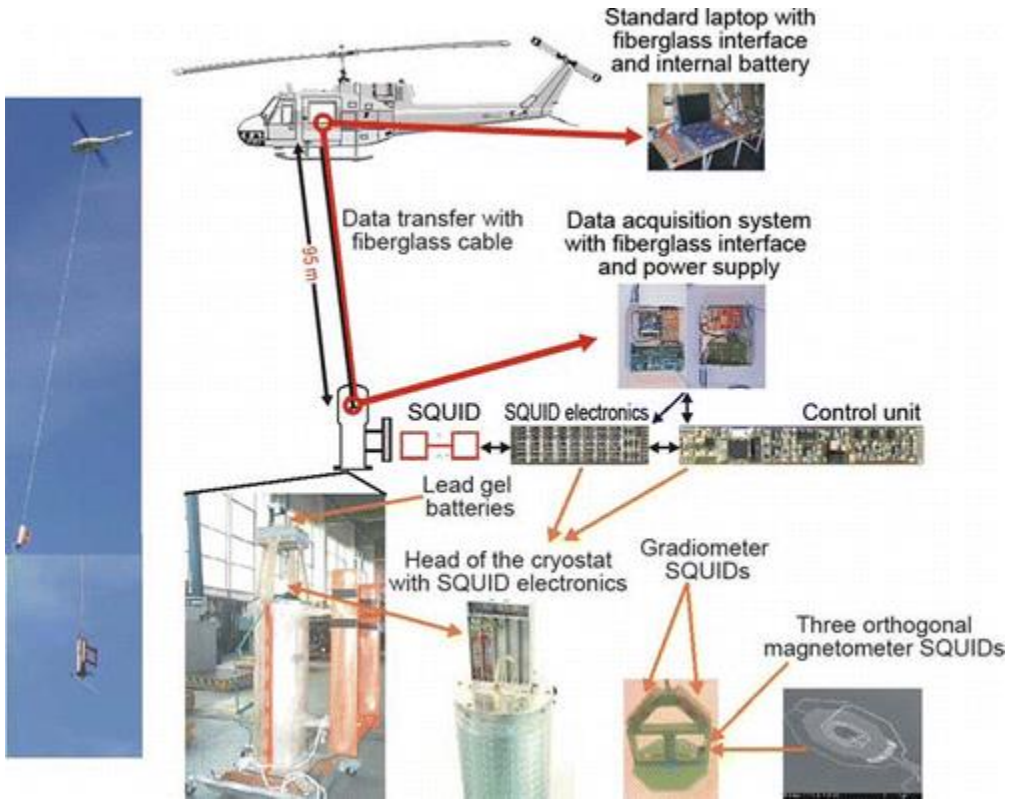
DIAS GROUND & AIRBORNE GEOPHYSICAL SURVEYS

Airborne Full-Tensor Magnetic Gradiometry

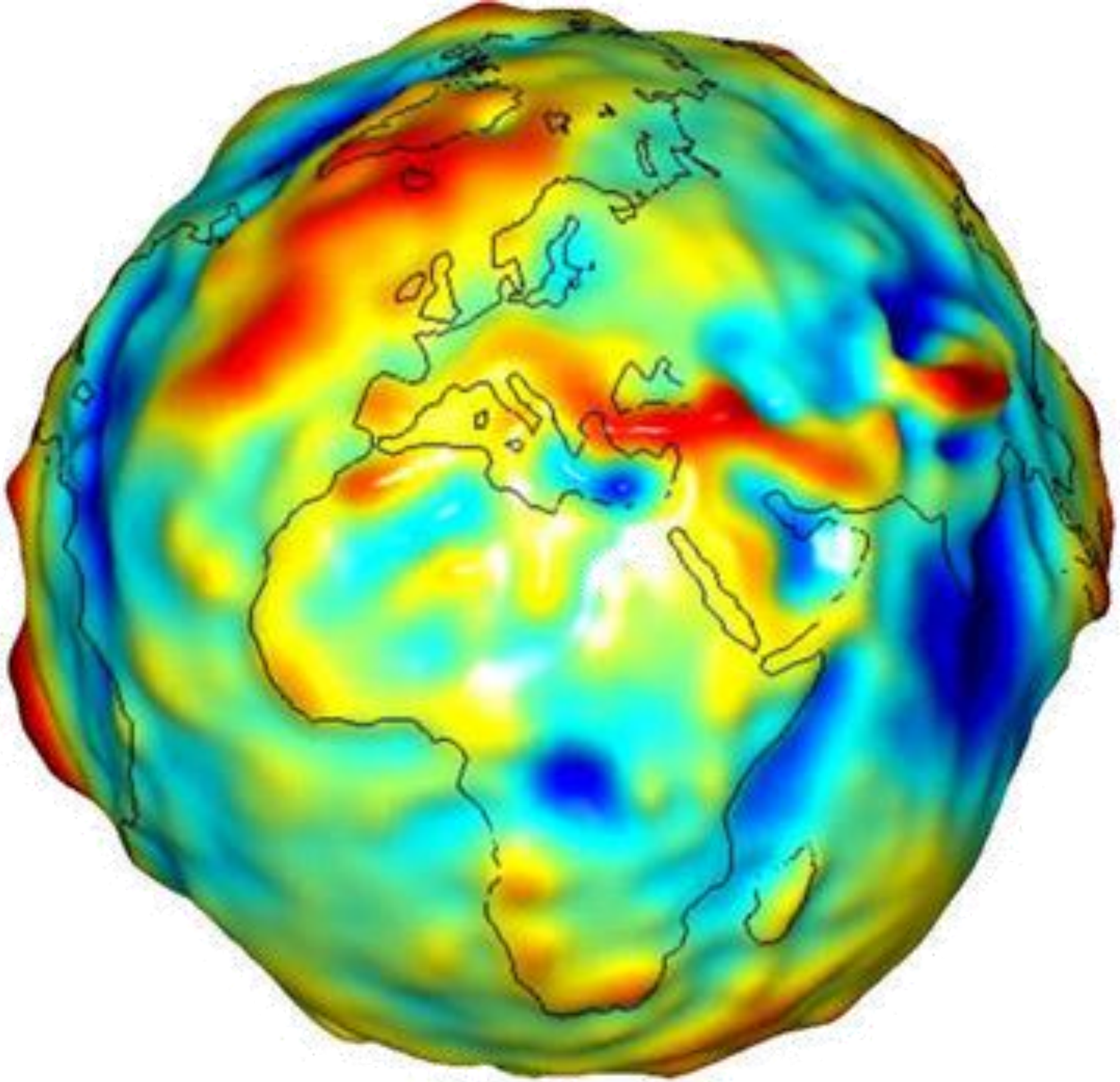
❑ QMAGT Specifications

- ✓ SQUID sensor: 6-channel first-order planar gradiometers
- ✓ Intrinsic gradient noise: <100 fT / (m√Hz)
- ✓ Magnetometer: 4-channels of magnetometers
- ✓ Intrinsic noise: 2 pT / √Hz
- ✓ SQUID electronic bandwidth: > 3 MHz
- ✓ Sampling Rate: 10,000 samples per second
- ✓ Operating temperature range: -10°C to +40°C
- ✓ Cryostat operation: 2.5 days per refill
- ✓ Data acquisition: 20 channels of 24 bit ADCs
- ✓ IMU system: 3 fibre optic gyros, 3 accelerometer sensors



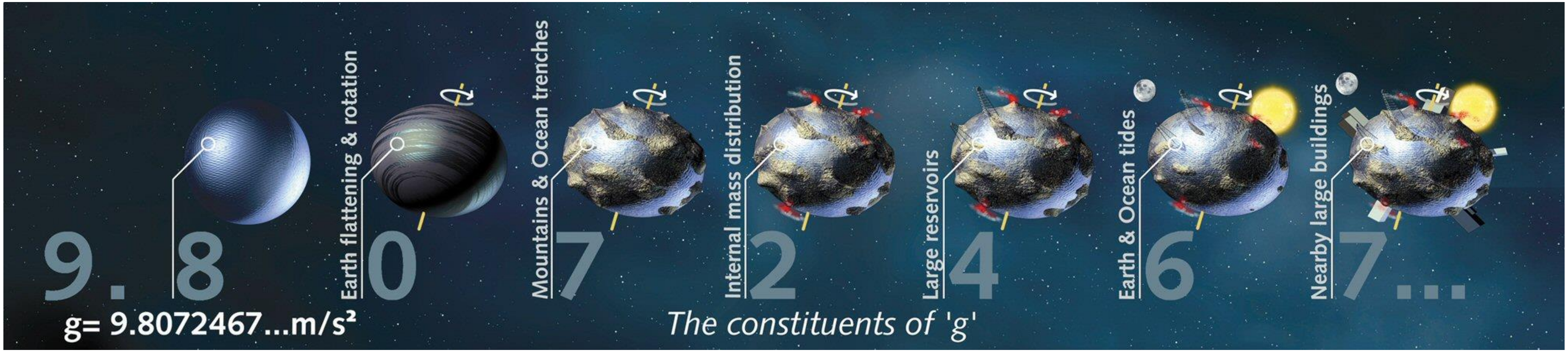


Gravity sensors



Why measure gravity in geophysics ?

- Gravimetry is the science of measuring « small g »
- Measuring g provides information on the **density (mass) distribution below ground**
- The better the resolution, the smaller the mass you can detect



source: ESA

Units : 1.10^{-8} m/s^2 $= 1$ µGal $= 10$ nm/s^2

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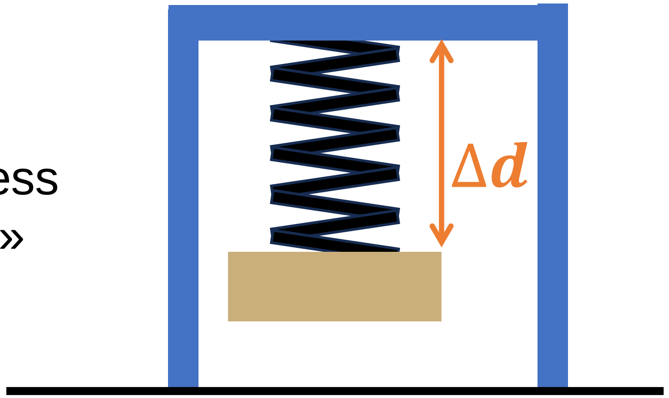
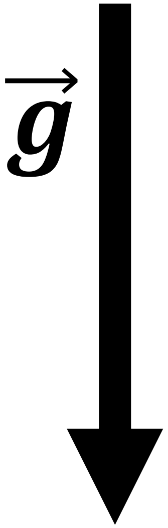
Types of gravimeters

Relative gravimeters

- Compact
- Drift
- No trueness
- « cheap »

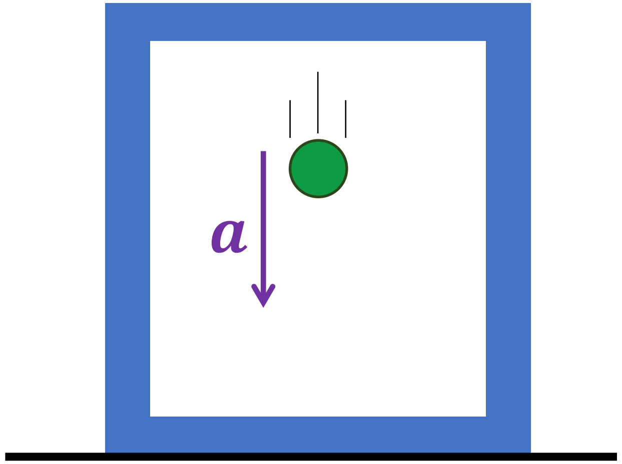


$$\Delta g = K \Delta d$$



Absolute gravimeters

- Fairly large
- Stable and true
- Expensive



$$g = a$$

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Gravity measurements

Types of gravimeters

Relative gravimeters

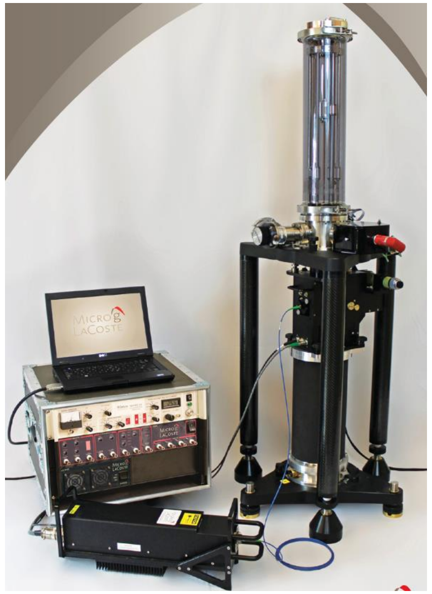
- Compact
- Drift
- No trueness
- « cheap »

Scintrex CG-6

$$\Delta g = K \Delta d$$

$$\vec{g}$$

Absolute gravimeters



Microg Lacoste FG5-X

Exail AQG-B

- Fairly large
- Stable and true
- Expensive

$$g = a$$

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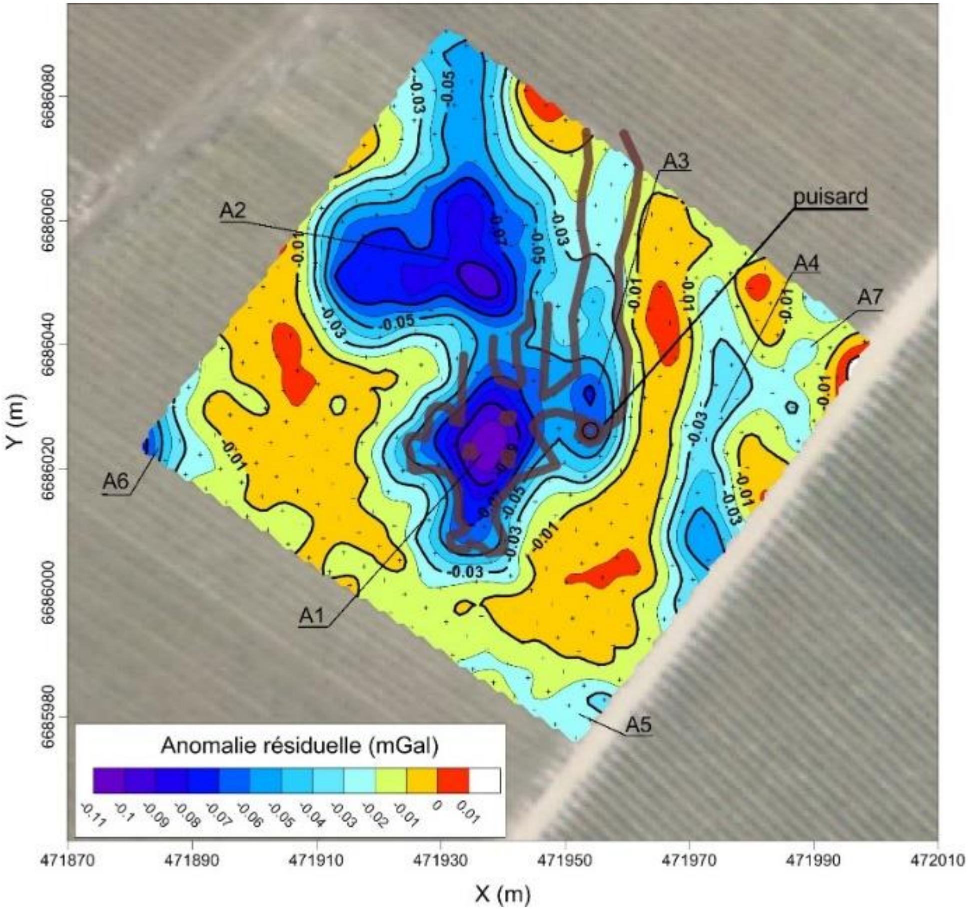
Types of Surveys

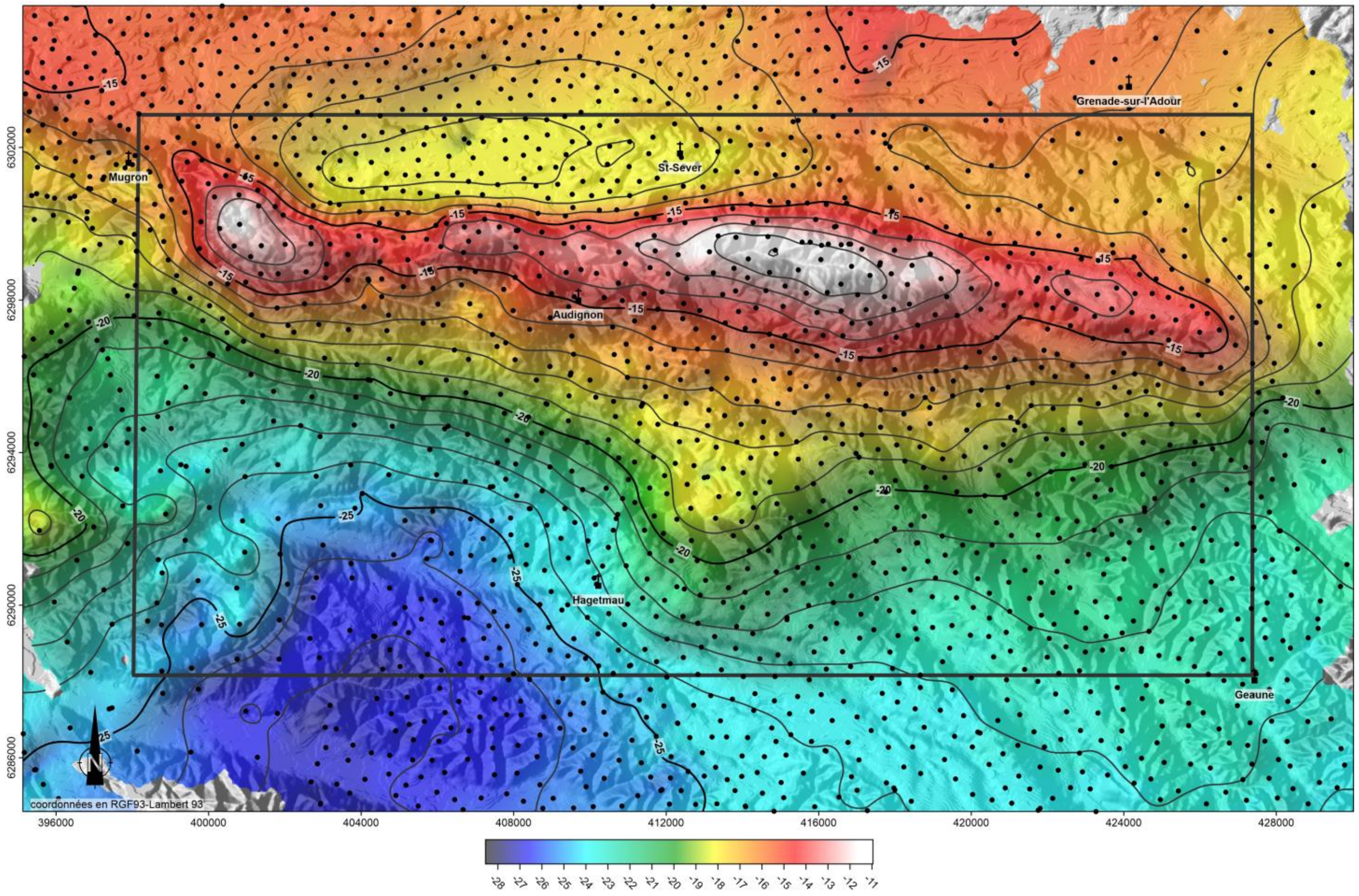
Type	Spatially resolved : gravity mapping
Goal	Image the density distribution below ground in a given area
Scale	A few 10m² to 10000km²
Instrumental requirements	Low setup time, ease of manipulation, high sensitivity, field compatibility, good stability
Typical applications	Cavity detection, geological mapping, exploration (mining, oil&gas)
Vector	Ground, (ship- and air-borne*, satellite)

* See ONERA presentation this afternoon

Gravity mapping examples



Residual anomaly map (mGal) over an underground quarry (partially mapped), France



Bouguer Anomaly map (mGal) over the Audignon anticline structure, France

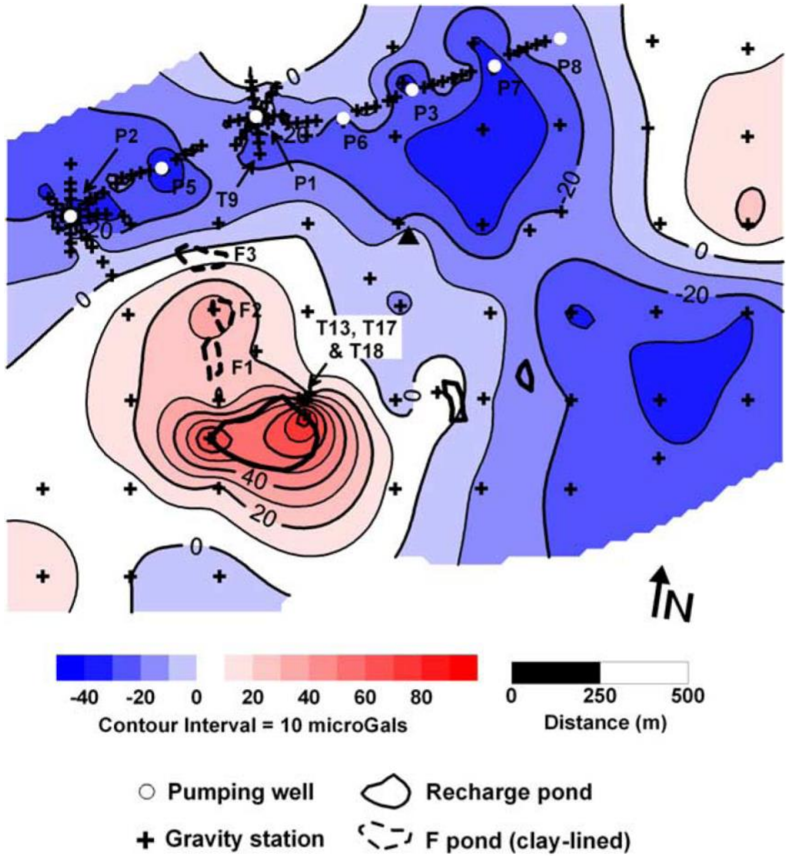
Géosciences pour une Terre durable
brgm

Types of Surveys

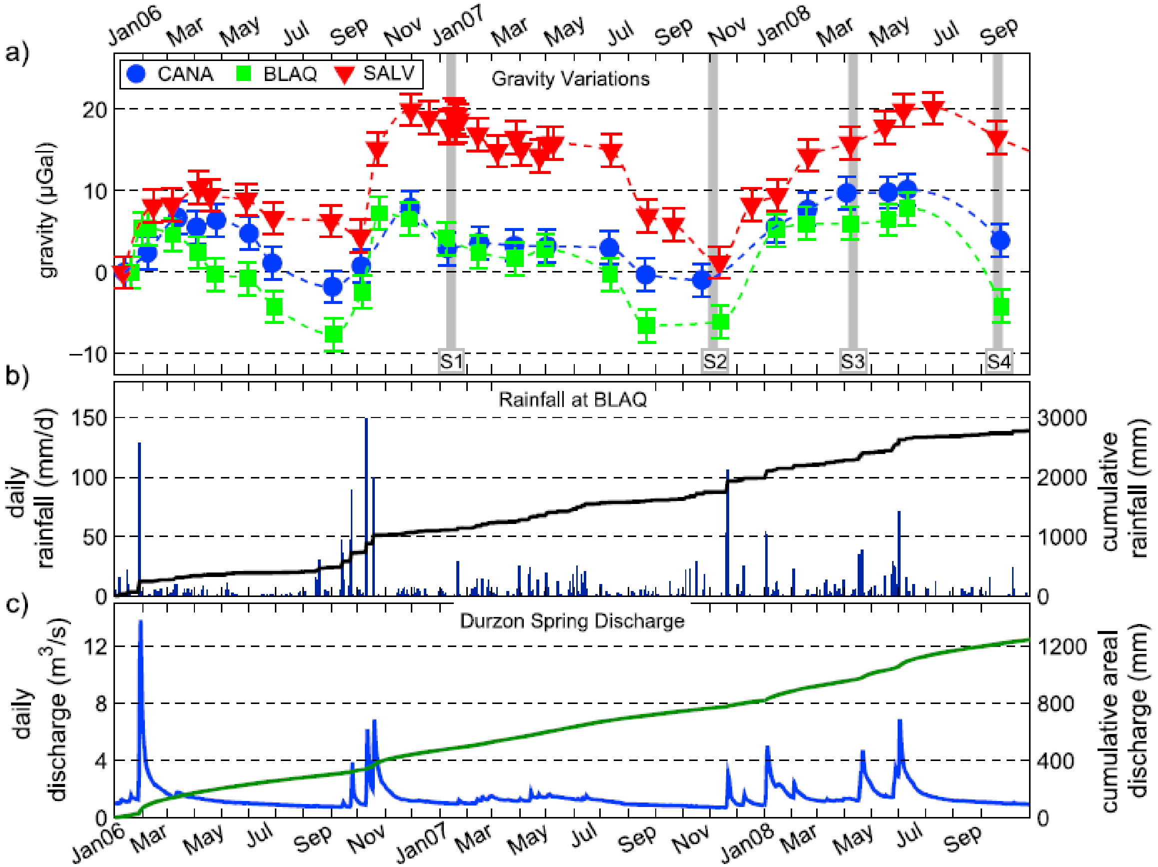
Type	Time resolved : gravity monitoring
Goal	Monitor mass change below ground
Scale	A few hours to a few decades, continuous or time-lapse measurements
Instrumental requirements	Extreme stability, repeatability, trueness, low power consumption, low maintenance
Typical applications	Hydrology, volcanology*, glaciology, reservoir monitoring (CO_2, EOR, geothermal)
Vector	Ground, (satellite)

* See Exail presentation this afternoon

Gravity monitoring examples



Gravity change over aquifer pumping and recharge areas, after Gehman, WRR 2009

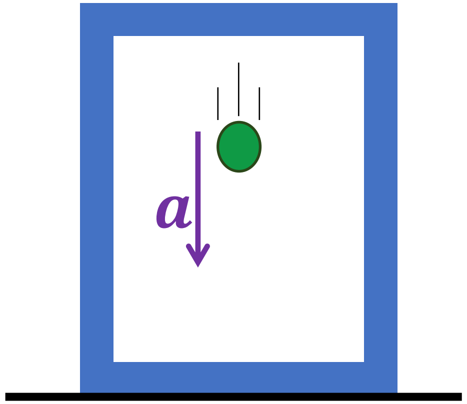


Gravity change at 3 stations over a karst aquifer, after Jacob, JGR 2010

Quantum Gravimeters

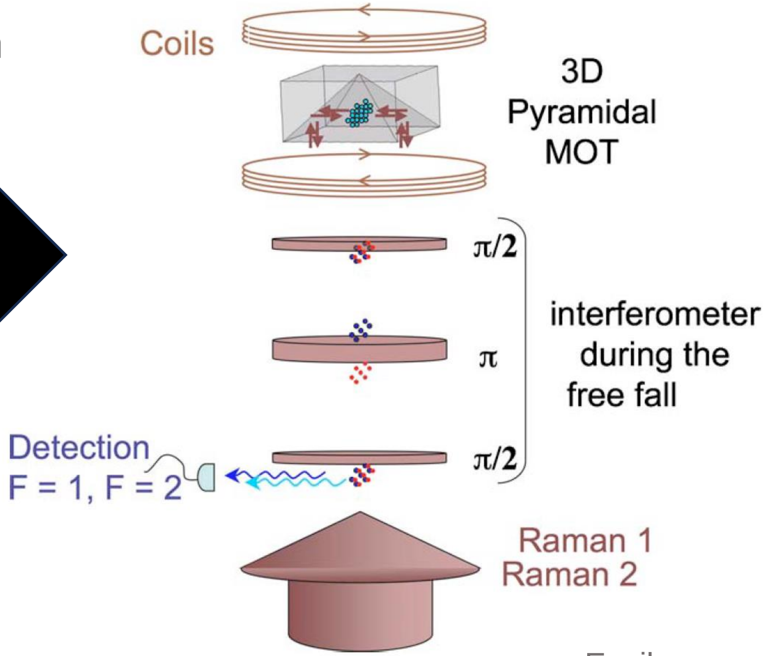
- Quantum gravimeters use the wave-like properties of matter to measure gravity
- Source: cold Atoms of 87Rb

- 2017: First commercial Quantum gravimeter by Exail : AQG
- Absolute gravimeters: drift free, no need for calibration, no moving parts
- **→ can be used for gravity mapping <u>and</u> gravity monitoring (continuous and time-lapse)**



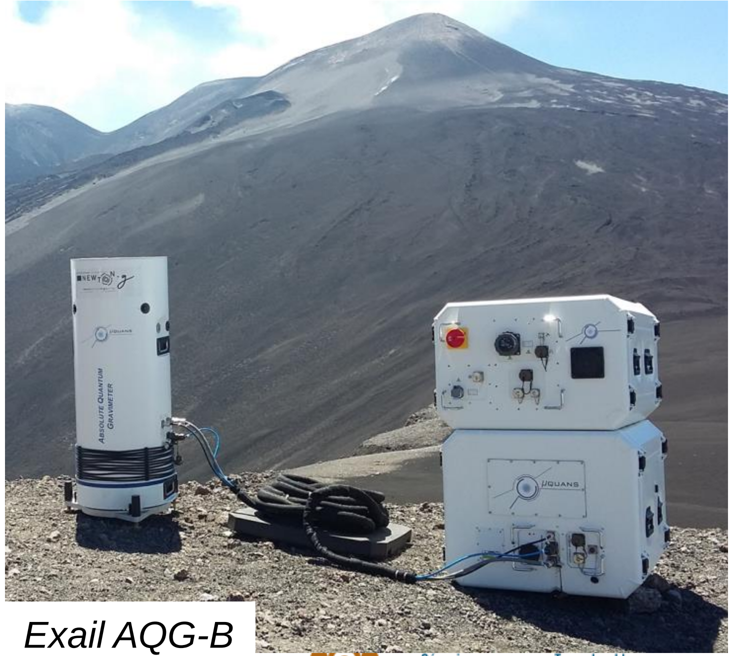
$$g = a$$

Kasevitch and Chu 1991



source: Exail

Exail 2017

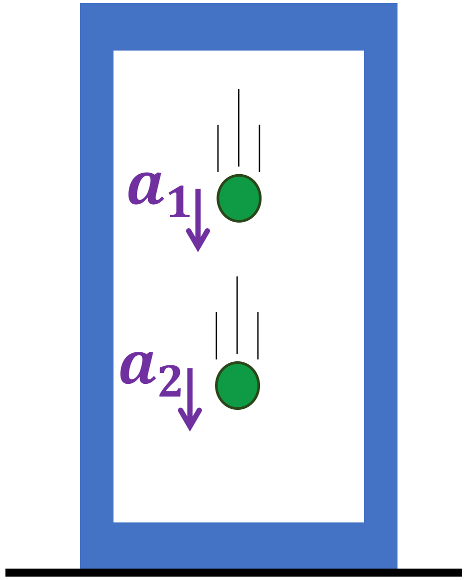


Exail AQG-B

Gravity measurements

Quantum Gravity gradiometers

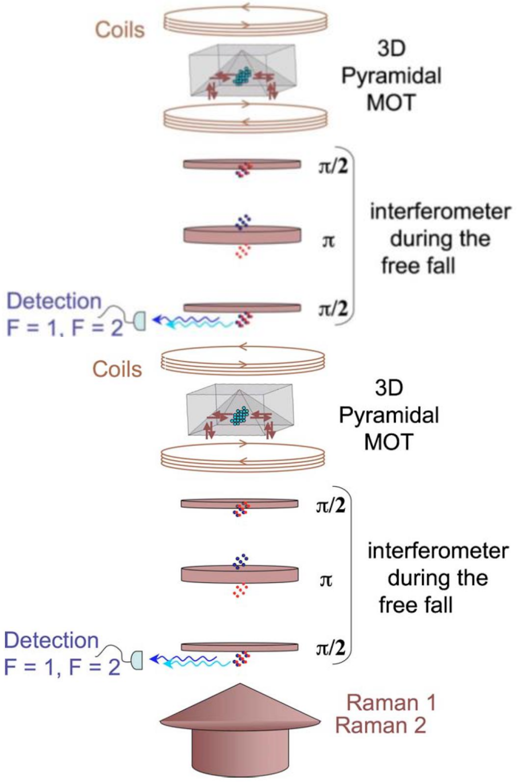
- Measurement of the vertical gravity gradient
- 2019: First commercial Quantum gradiometer by Exail : DQG



$$g = \frac{(a_1+a_2)}{2}$$

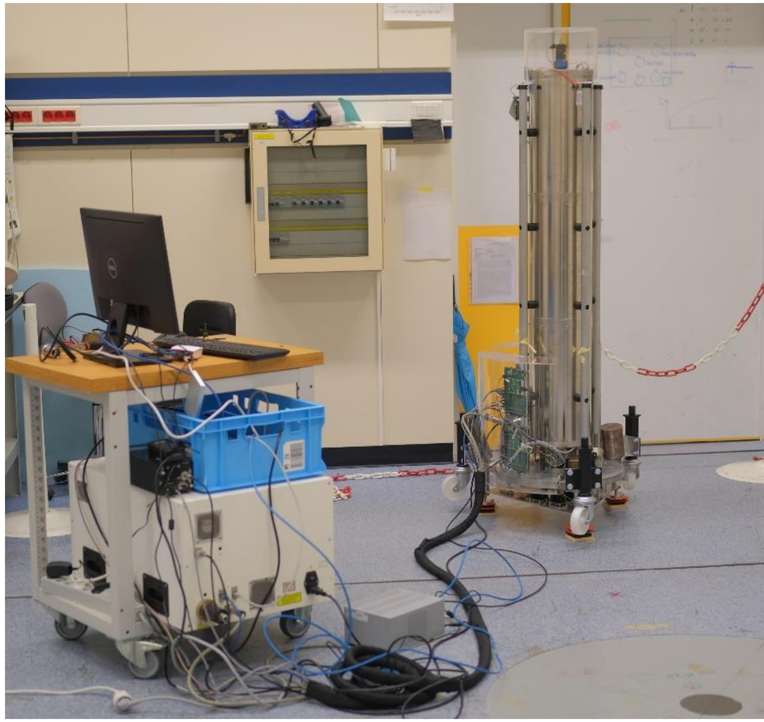
$$\Gamma_{zz} = \frac{(a_1-a_2)}{L}$$

Kasevitch



source: Exail

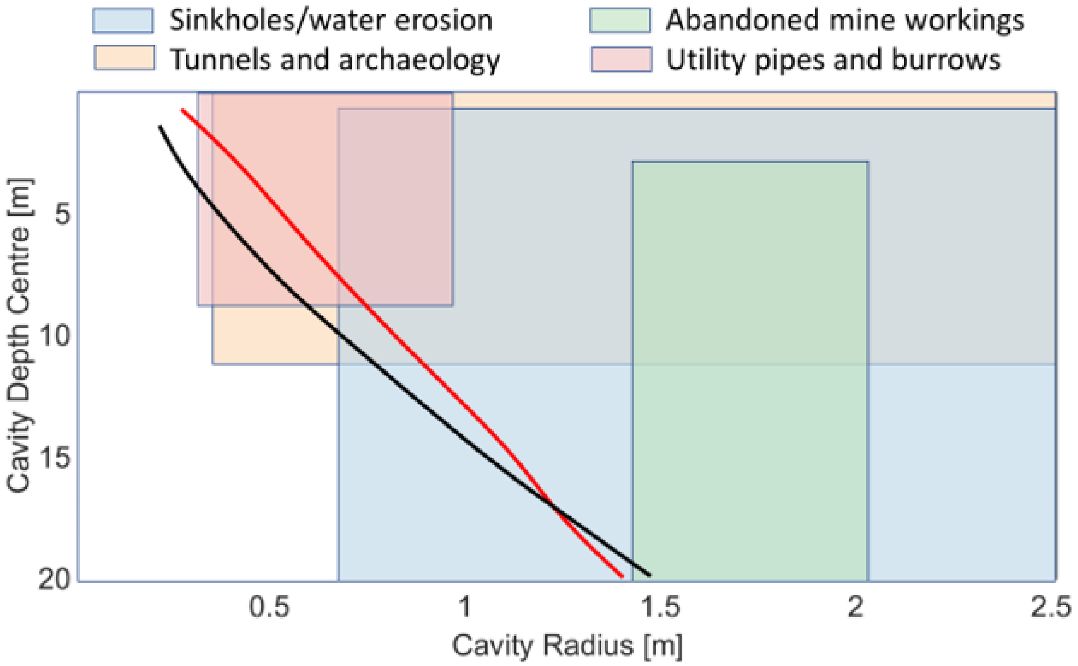
Exail 2019



Exail DQG

Quantum Gravity gradiometers

- Using the vertical gravity gradient allows for enhanced detection of shallow structures, wrt gravity
- The processing for gravity gradient is simpler than that of gravity

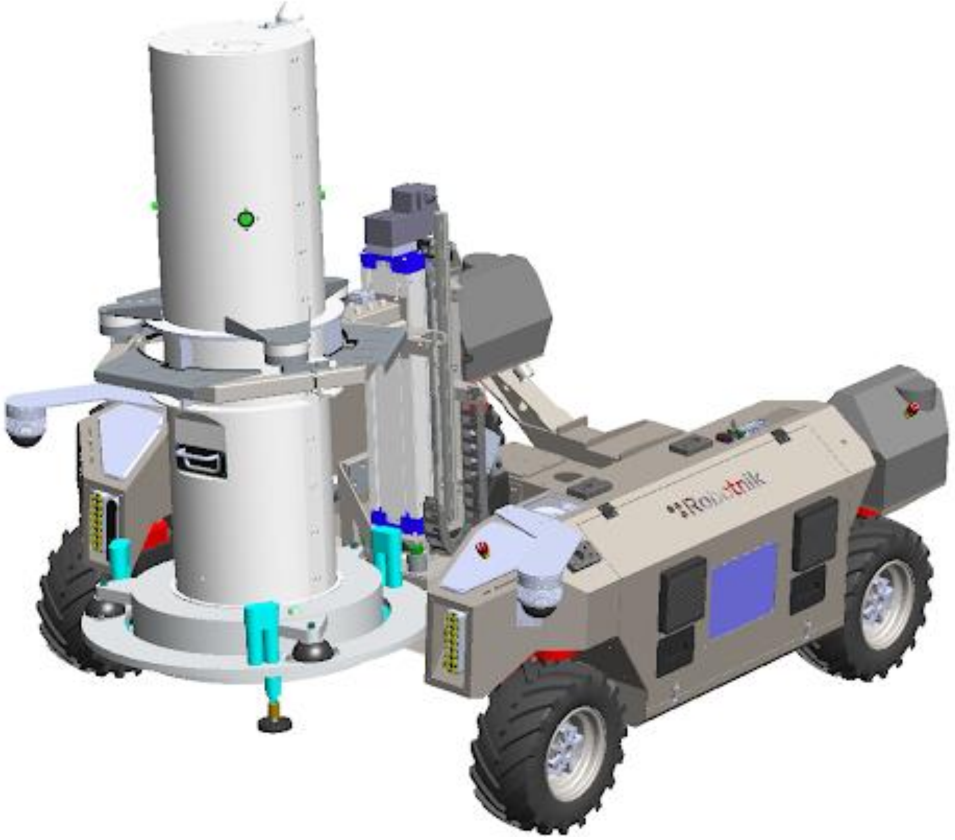


Detectabilty threshold for DQG (black line) and AQG (red line), for tunnel-like cavities, as a function of their depth and radii, from FIQUgS project

Quantum Gravity gradiometers

FIQUgS Horizon Europe project

- The goal of FIQUgS is to take QGs to the next level
- The DQG will be adapted to outdoor gravity surveys:
  - better SWaP and stability
  - operated by a robotic carrier
  - coupled with GPR
- → Semi automatized measurements



- First outdoors DQG survey successfully performed recently over an archeological structure, results will be presented at EQTC 2024 in Lisbon next week !