Advanced accelerometer/gradiometer concepts based on atom interferometry

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Towards a Roadmap for Future Satellite Gravity Missions, Graz, 30 September 2009

Outline

- Introduction to inertial sensors based on atom interferometry

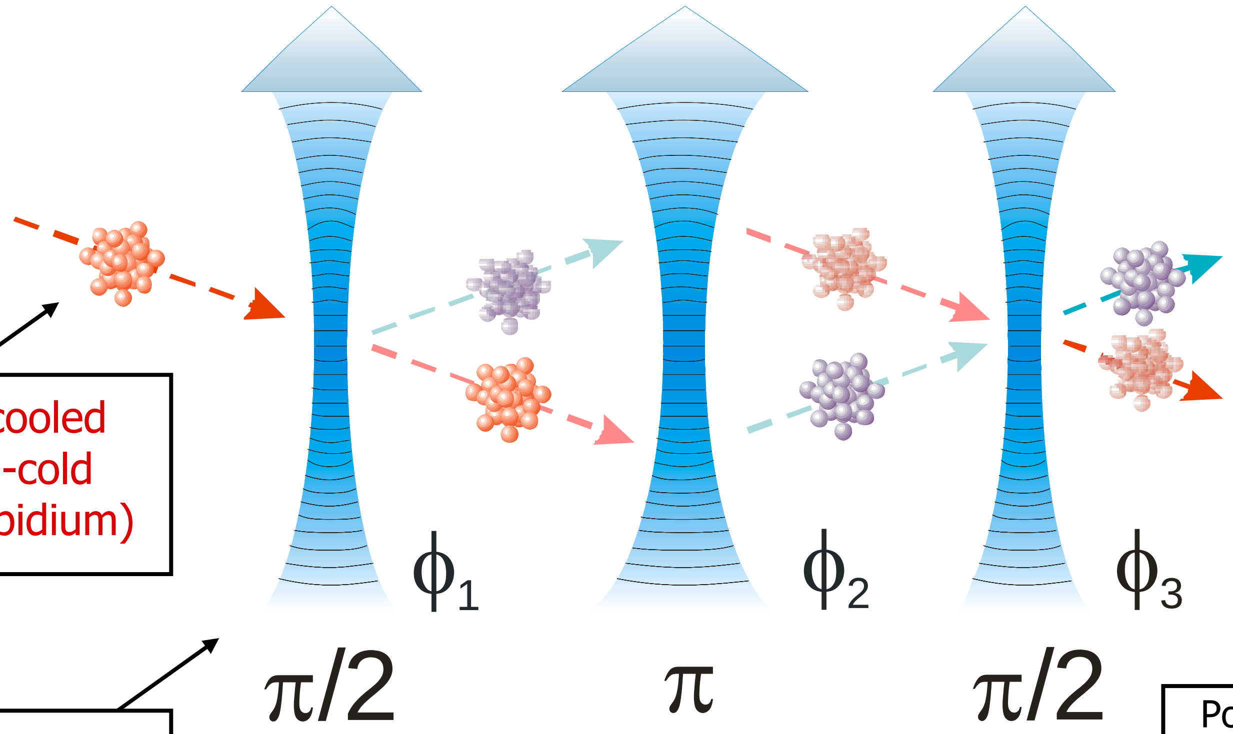
- Potential benefits of gravity sensors in space based on A.I.

- Current technology status and ongoing work on mobile interferometers

Inertial Sensors based on Atom Interferometry

Graphics by IQO Hannover

Interferometry Sequence



Input: Laser-cooled cloud of ultra-cold atoms (e.g. Rubidium)

Using pulses of laser light as mirrors and beamsplitters

Population of excited state after pulse sequence

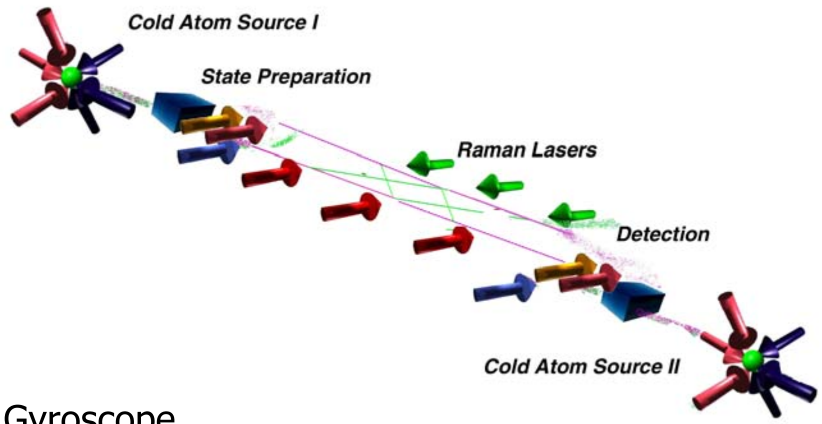
$$P_{|2\rangle} = \frac{1}{2}[1 + \cos(\Delta\phi)]$$

External contributions to phase difference Δφ

Acceleration term	$\Delta\phi_{\text{acc}} \propto kgT^2$
Rotation term	$\Delta\phi_{\text{rot}} \propto \vec{A} \cdot \vec{\Omega}$

Inertial Sensors based on Atom Interferometry

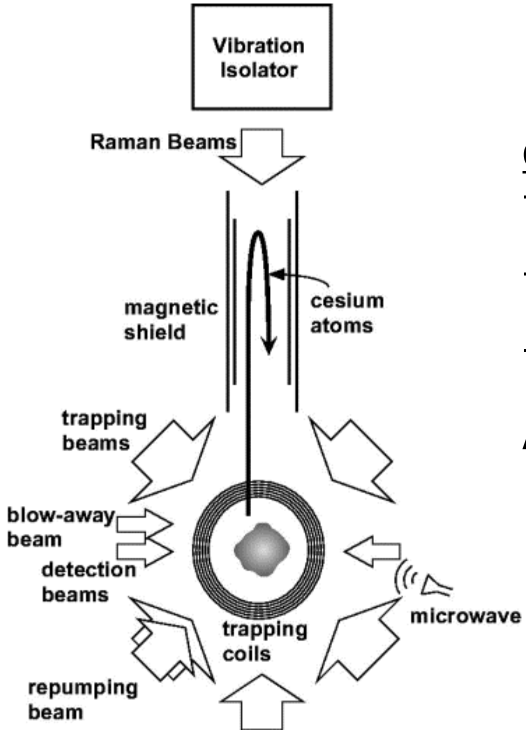
Gyroscope and Gravimeter



Gyroscope
- Two atomic clouds launched simultaneously in opposing directions
- Raman beams perpendicular to atomic propagation
- Differential measurement

$\Delta\varphi_{acc} = 0$

Measurement of Ω



Gravimeter
- One atomic cloud launched upwards (fountain)
- Raman beams parallel to atomic propagation
- No enclosed area

$\Delta\varphi_{rot} = 0$

Measurement of *g*

External contributions to phase difference Δφ

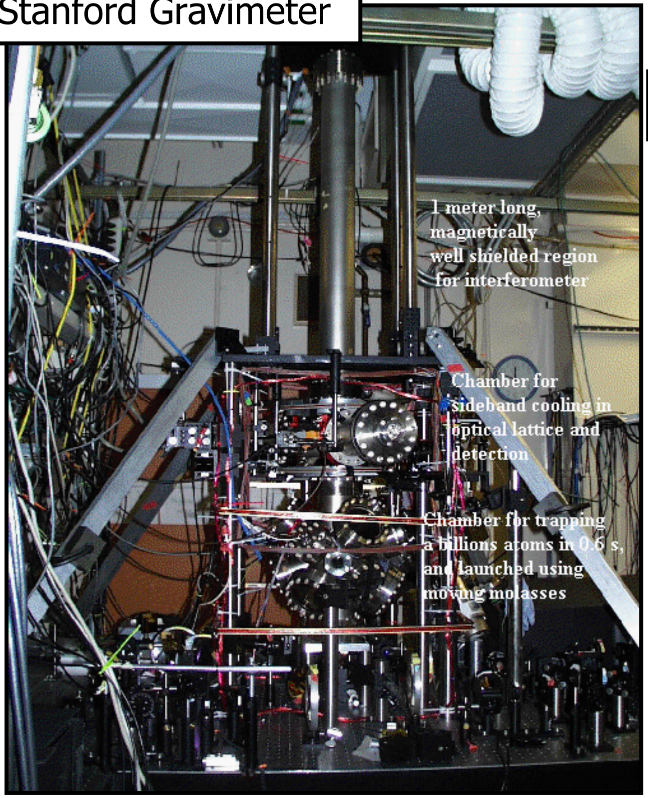
Acceleration term $\Delta\phi_{\mathrm{acc}} \propto kgT^2$

Rotation term $\Delta\phi_{\mathrm{rot}} \propto \vec{A}\cdot\vec{\Omega}$

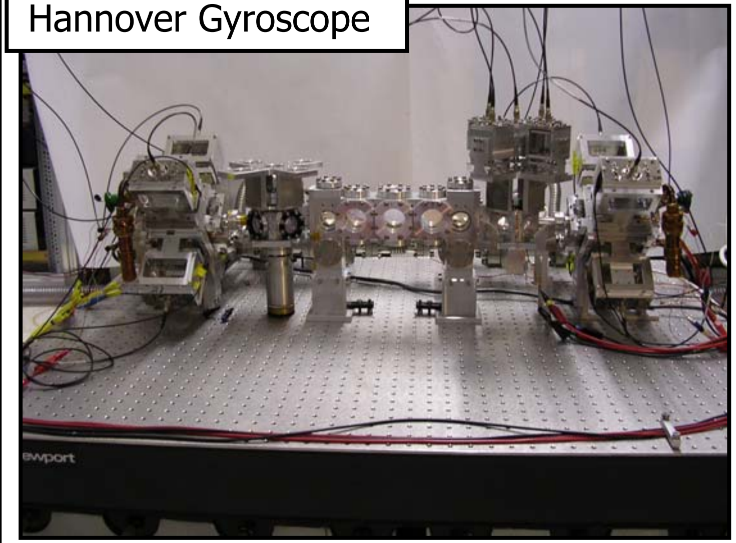
Inertial Sensors based on Atom Interferometry

Some (of many) existing laboratory-based setups

Stanford Gravimeter



Hannover Gyroscope



Florence Gradiometer

Best (published!) results for laboratory experiments:

$4 \cdot 10^{-9}$ g (absolute accuracy),

4 E/sqrt(Hz) (gradient)

Gravity sensors in space: Benefits of atom interferometry

Gravimetric sensors based on atom interferometry do not suffer from

- Bias problems
- Signal and scale factor drifts
- Mechanical vibrations (in gradiometry)

Sensitivity of an atom interferometer:

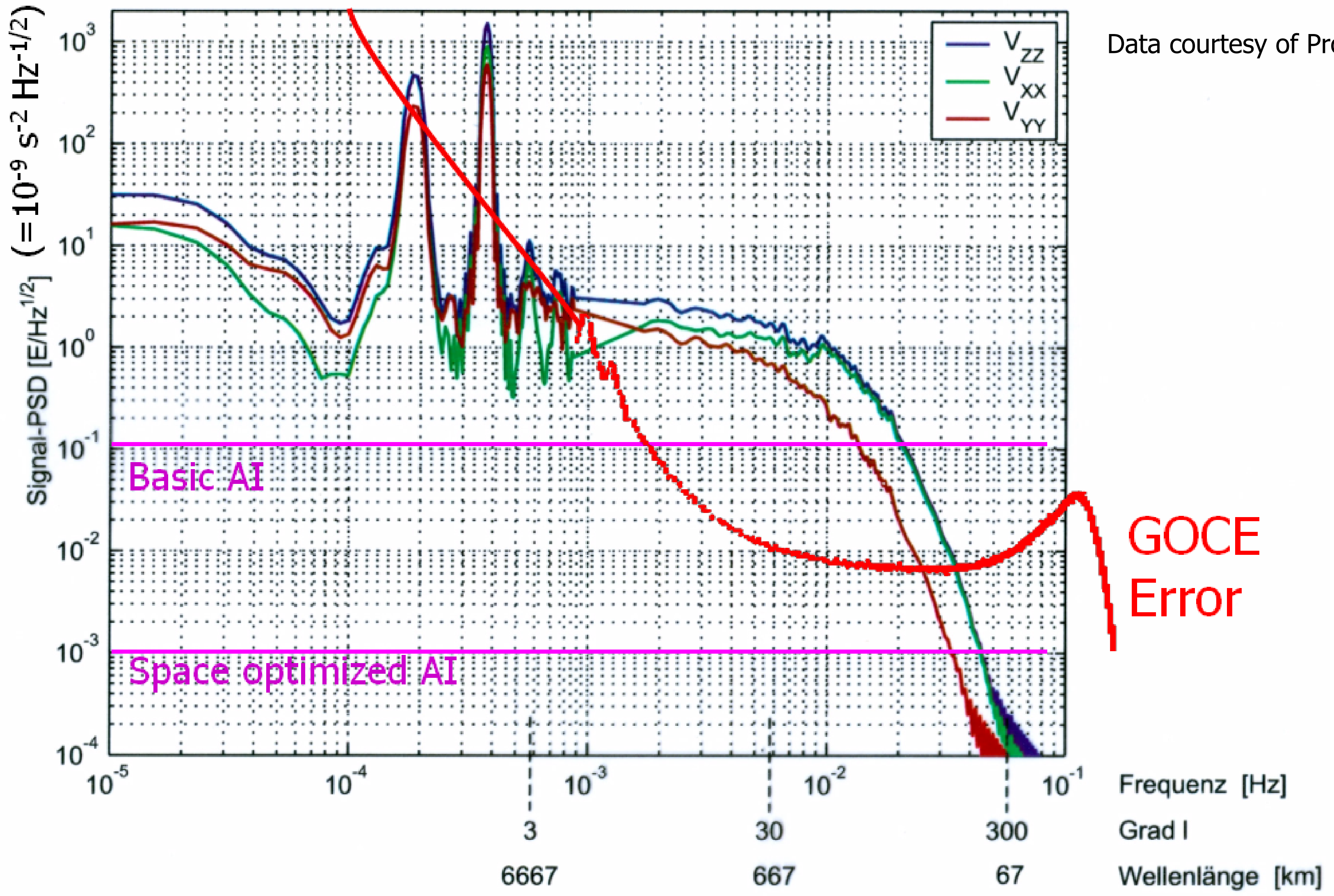
$$\Delta g/\sqrt{T} \propto \frac{1}{\mathrm{SNR}} \frac{1}{k_{\mathrm{eff}}} \frac{1}{T^2}$$

Decrease Δg by

- Increasing wavevector k_{eff} (larger area needed)
- Increasing time T (going into space, using colder atoms i.e. BEC)
- Increasing atom number N (high-power loading MOTs needed)

Gravity sensors in space: Benefits of atom interferometry

GOCE gradient spectrum vs. Atom interferometry



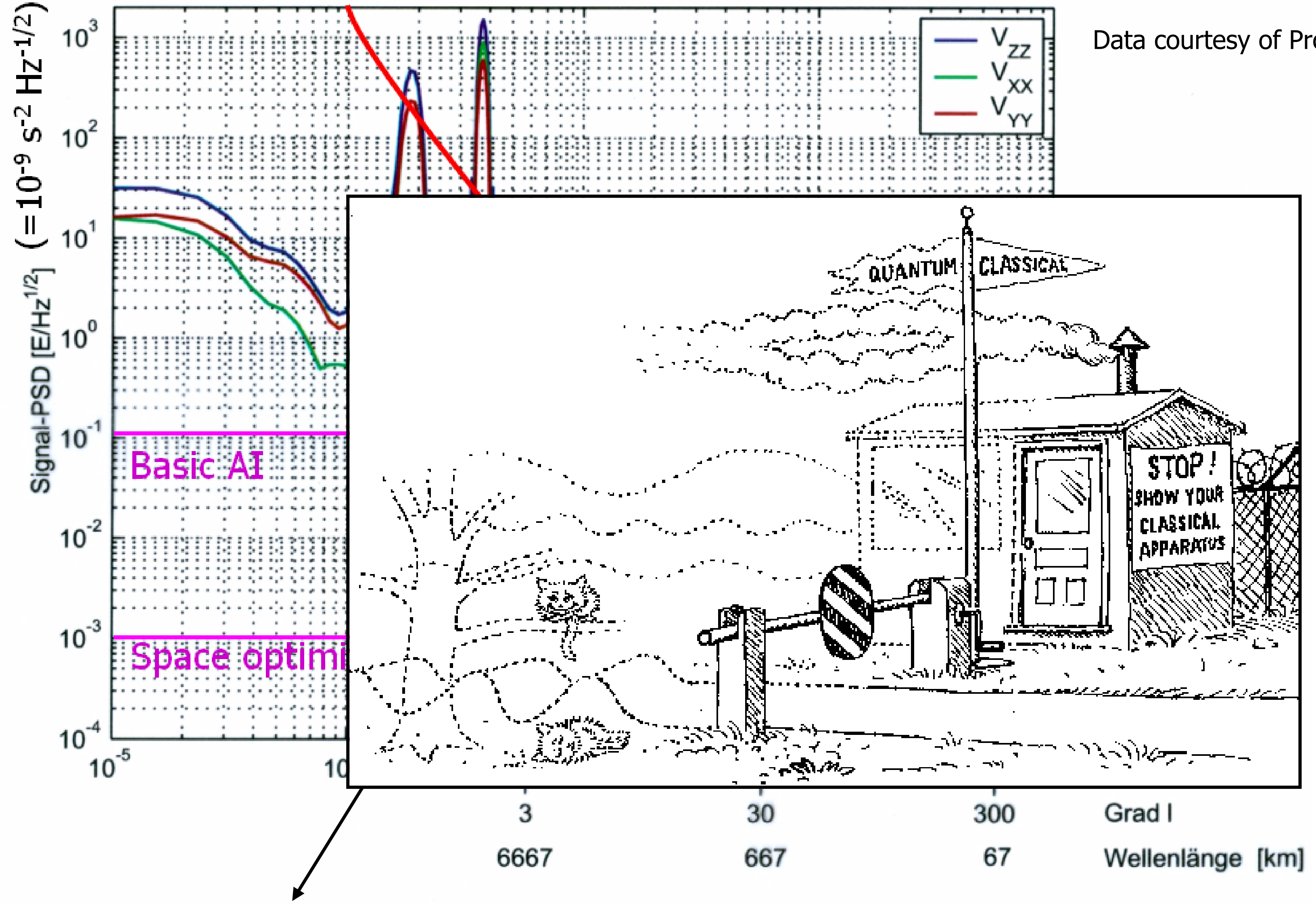
Data courtesy of Prof. J. Müller

Advanced AI (squeezing, Heisenberg-limited detection,...)

Gravity sensors in space: Benefits of atom interferometry

GOCE gradient spectrum vs. Atom interferometry

Data courtesy of Prof. J. Müller



Advanced AI (squeezing, Heisenberg-limited detection,...)

Gravity sensors in space: Benefits of atom interferometry

Conclusion: When employing atom interferometry on gravity satellite missions,

- lower orbits are possible
  ➔ Higher spatial resolution
- a broader frequency range is observable by one single satellite
  ➔ Higher temporal resolution
- signal sensitivity would be better than on current missions
  ➔ Higher precision

Gravity sensors in space: Benefits of atom interferometry

Possible mission scenarios

Candidate Concept 1

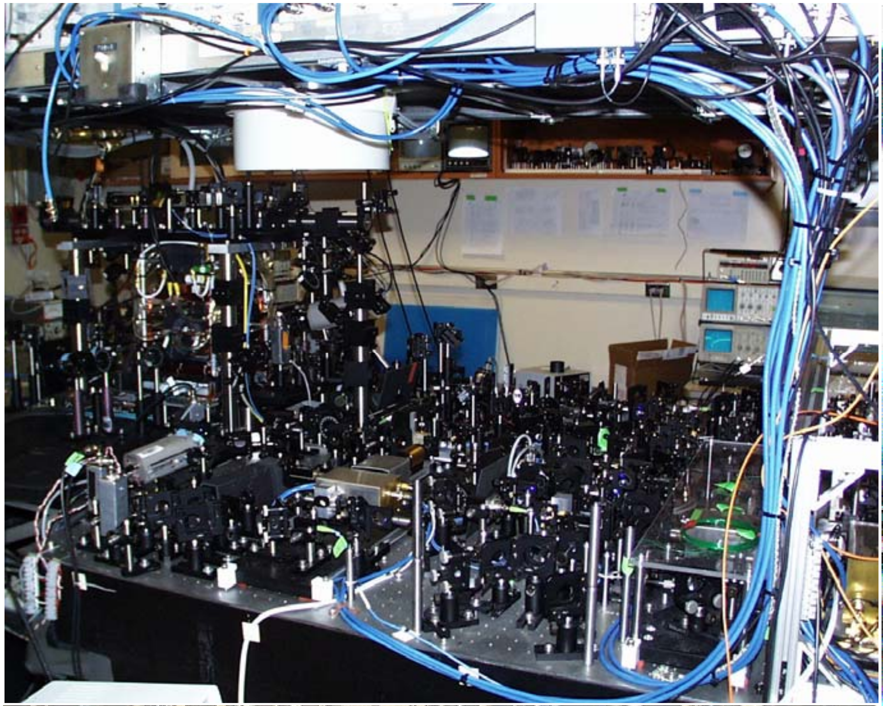
- Single satellite (GOCE-like) using Mach-Zehnder interferometry, 3-axis
- Conceivable sensitivity:
  10^{-12} ms^{-2} @ T=10s, SNR=1000:1
  10^{-12} s^{-2} Hz$^{-1/2}$ (=1 mE Hz$^{-1/2}$) @ baseline=1m
- Optional: Multi-photon transitions for high k_{eff}
- Technology already demonstrated outside of lab environment, possible to measure complete gravity gradient tensor **plus absolute value**
- No calibration problems
- Only moderate sensitivity gain with respect to convential methods

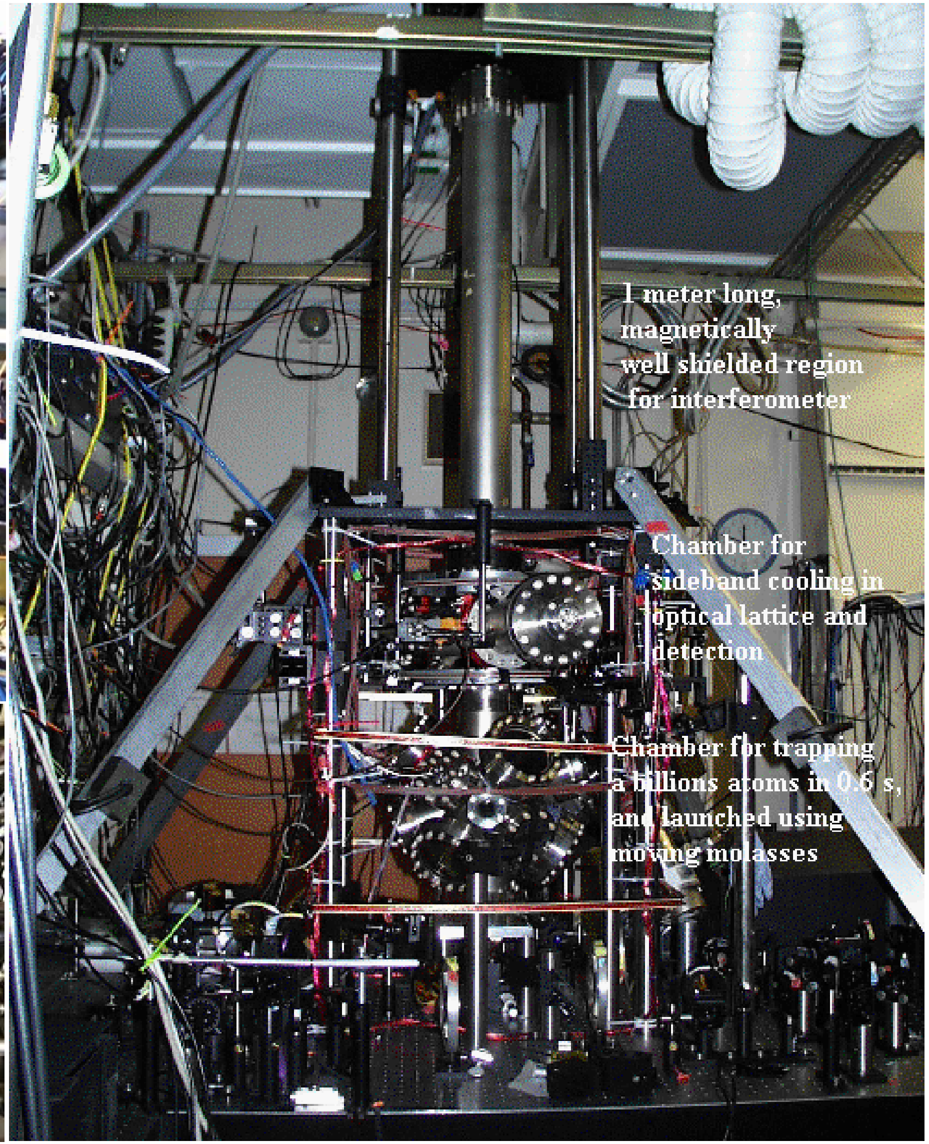
Candidate Concept 2

- Multiple ultra-compact satellites, size of approximately one soda bottle each
- Using entangled ensembles as sources, Heisenberg-limited detection and other advanced concepts
- Conceivable sensitivity:
  10^{-15} ms^{-2} @ T=10s, SNR=1000:1
  Gradiometric sensitivity probably not limited by atom interferometer but by mission complexity (i.e. eqiuvalent to GRACE follow-up mission employing LISA technology)
- Possible to measure complete gravity gradient tensor **plus absolute value at very high sensitivity**
- No calibration problems
- Technology still in development
- Improved sensor performance might not fully translate into improved mission performance (i.e. limited by system complexity issues)

Current work on mobile atom interferometers

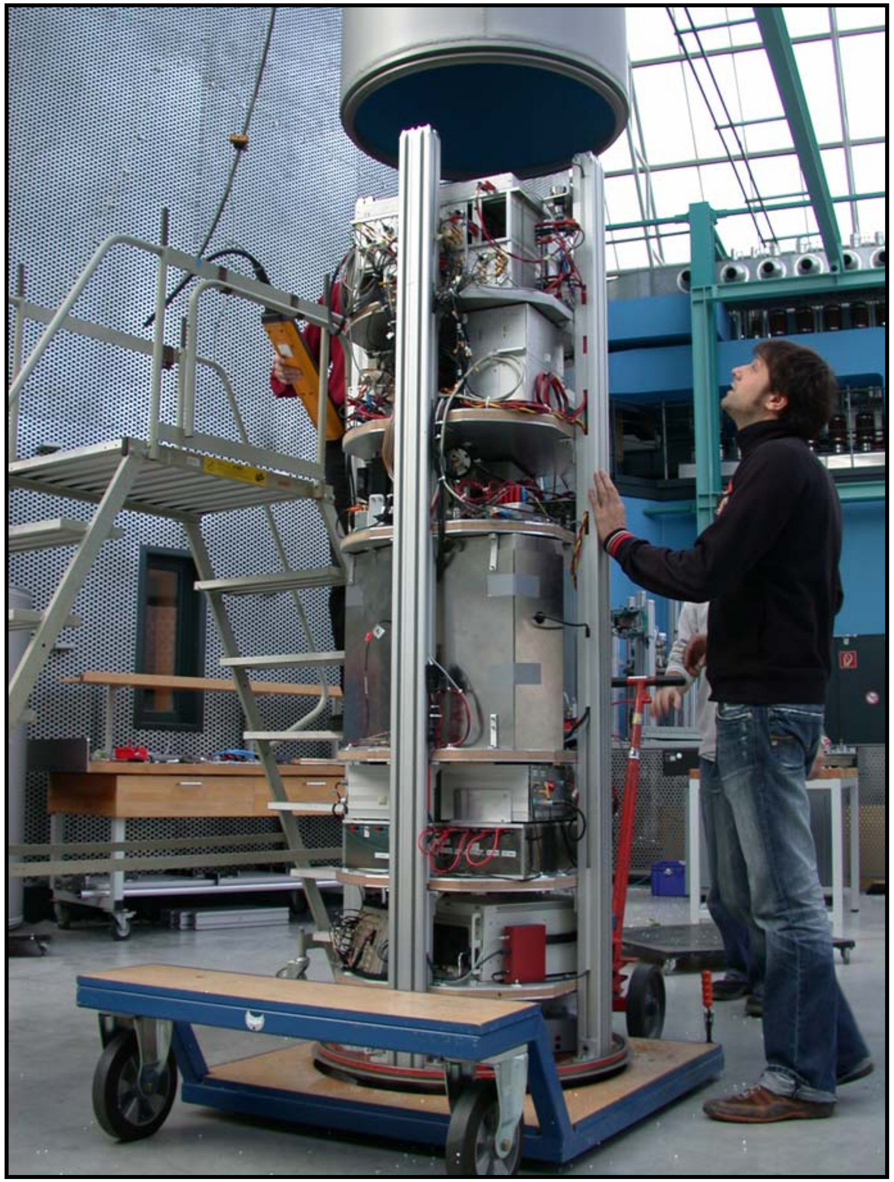
The challenge: Fit laboratory experiment...





Current work on mobile atom interferometers

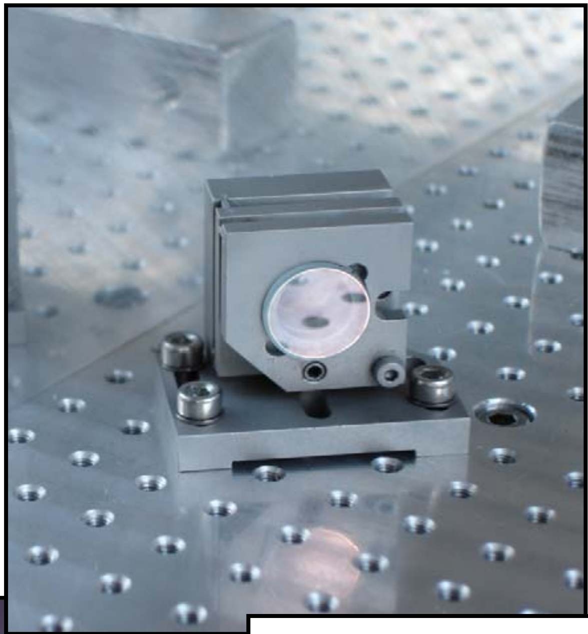
...into transportable (and robust!) setup

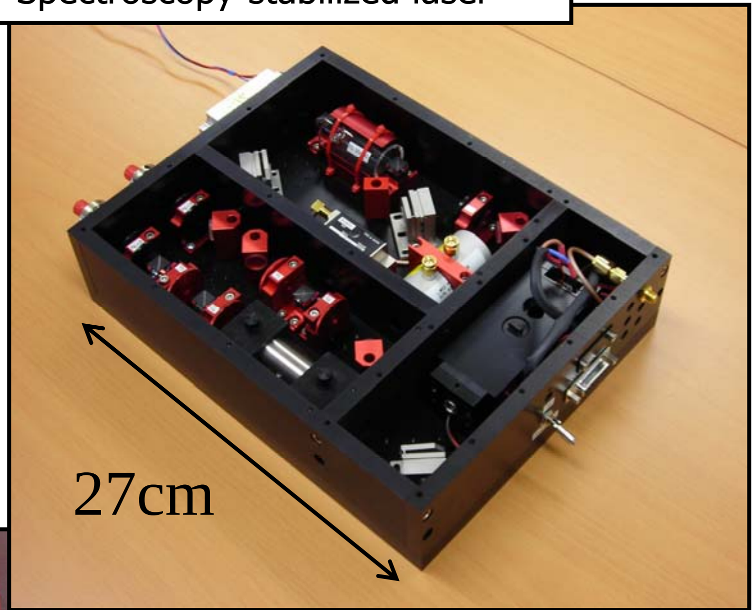


Current work on mobile atom interferometers

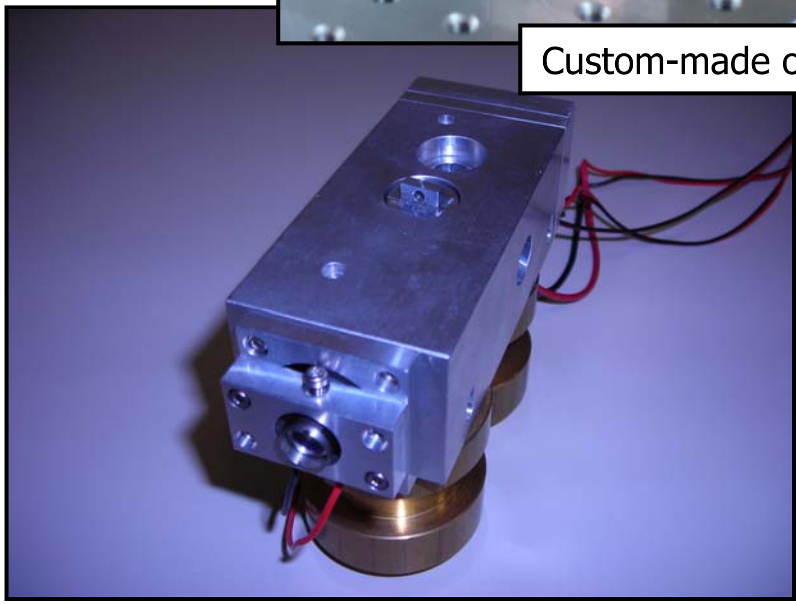
Miniaturized laser systems

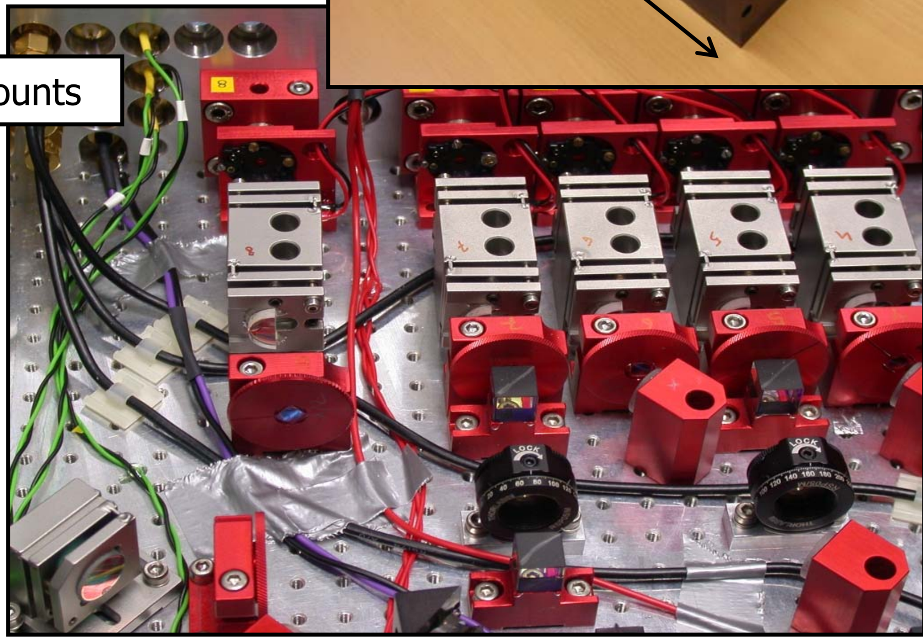
Spectroscopy-stabilized laser





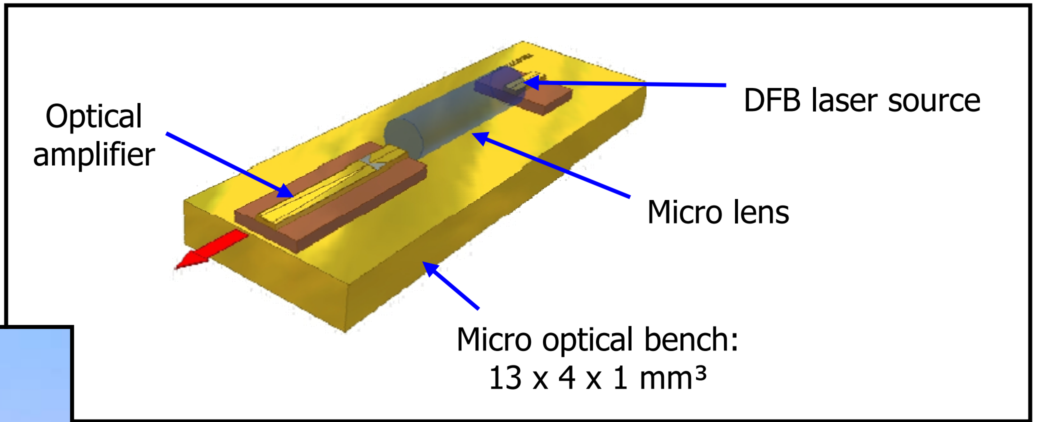
Custom-made optical mounts

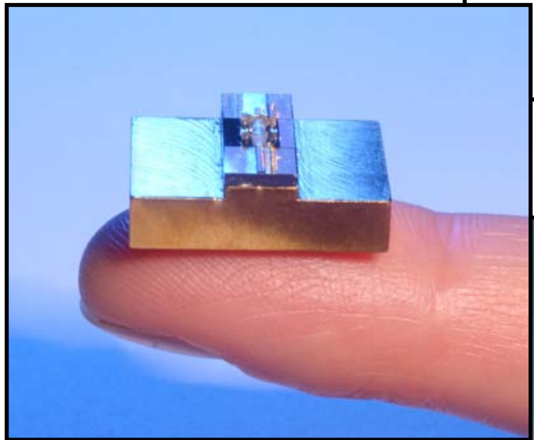


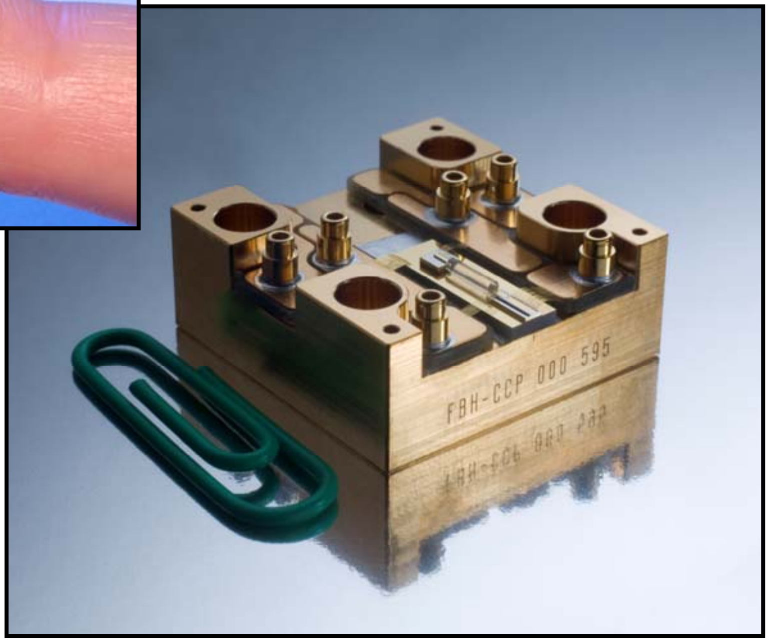


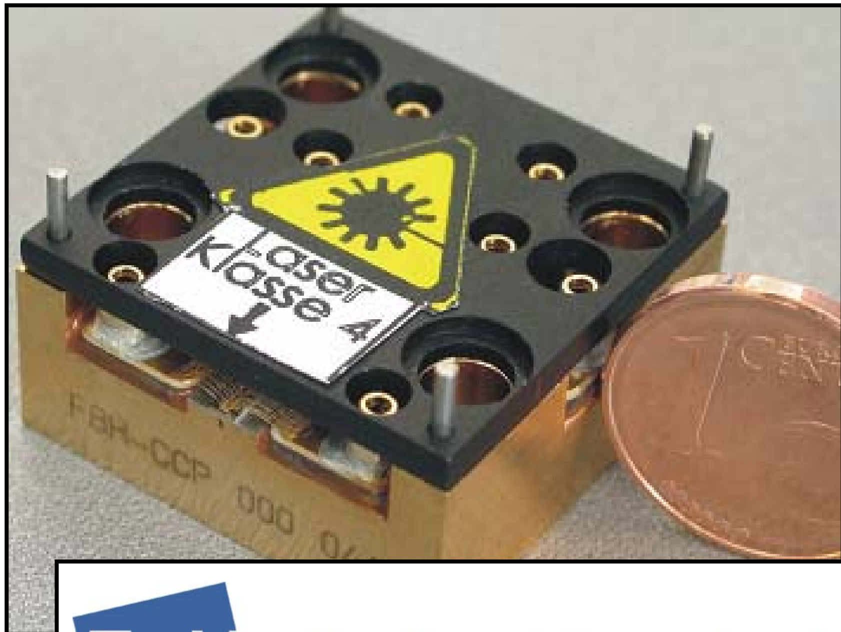
Current work on mobile atom interferometers

Next-generation miniaturized laser sources









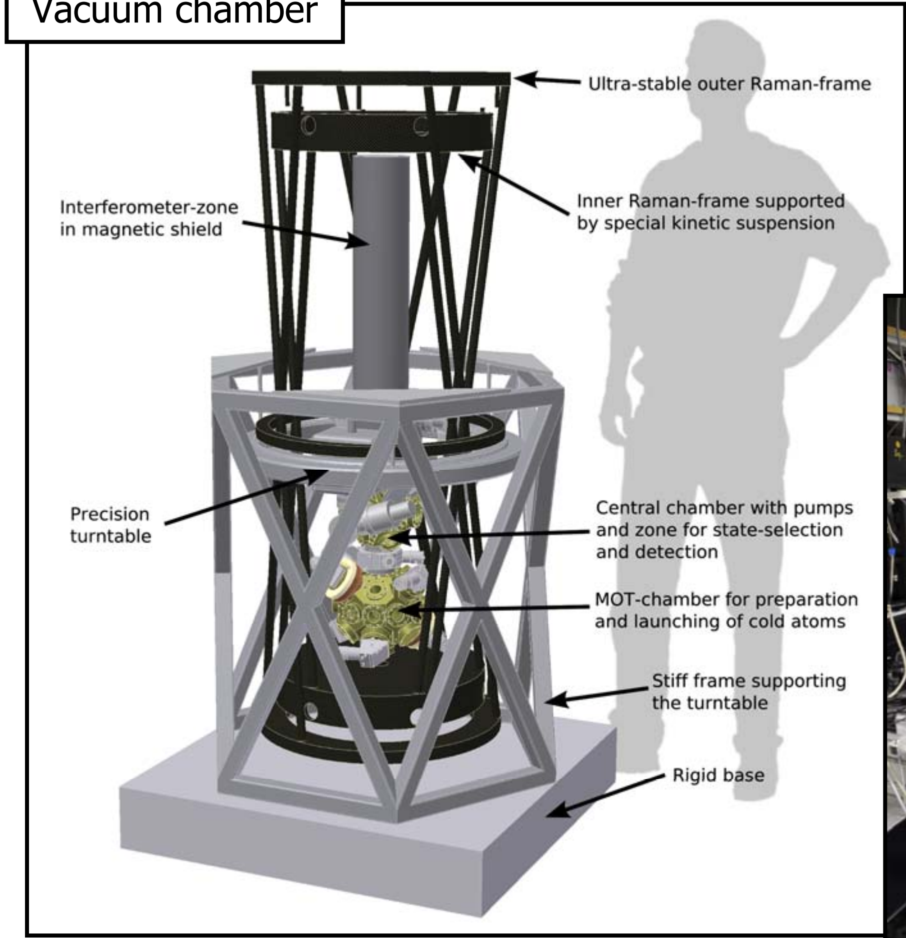
Ferdinand-Braun-Institut
für Höchstfrequenztechnik

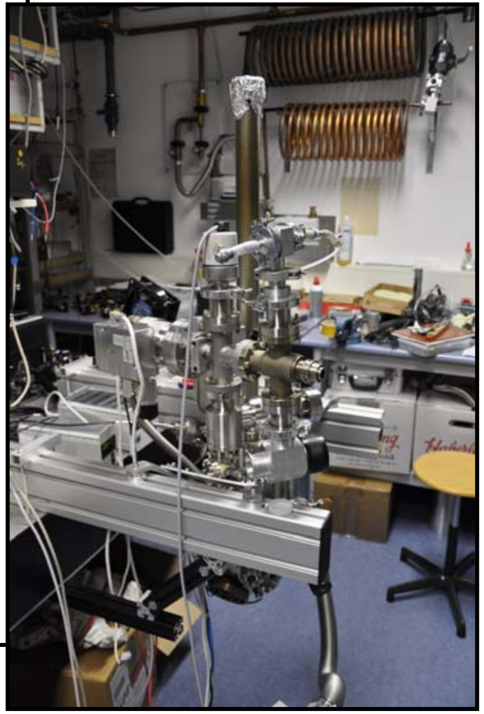
Current work on mobile atom interferometers

Mobile atom interferometer: GAIN (earth-bound)

Laser Systems, Electronics, Computer, Diagnostics

Vacuum chamber





Current work on mobile atom interferometers

Mobile atom interferometer: GAIN (earth-bound)

- Compact: three ~ 1 m^3 Modules (interferometers assembly + two 19" racks for laser system and electronics)
- Robust: critical components based on technology developed for the high g-loads in drop tower experiments
- Mobile: designed to be „truckable" and for use at a variety of interesting locations

Targeted sensitivity:

$1 \cdot 10^{-9}$ g / sqrt(Hz) at a SNR of 300:1 (intrinsic noise only)

$1 \cdot 10^{-8}$ g / sqrt(Hz) at a SNR of 30:1 (under realistic vibration conditions)

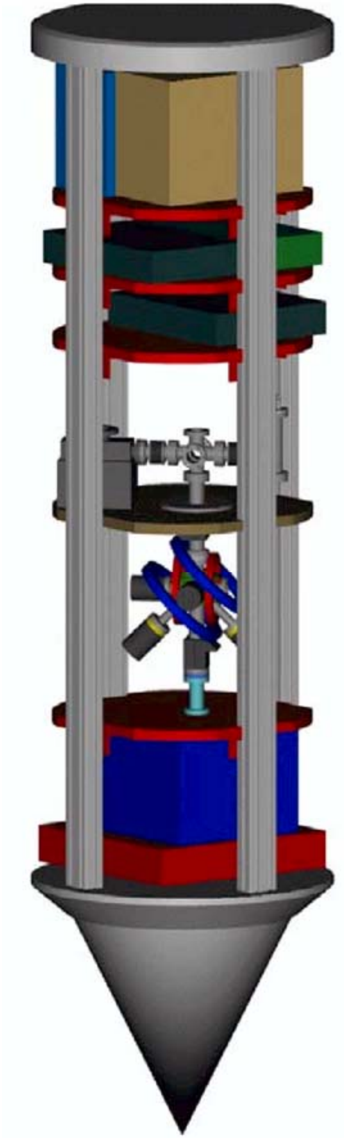
Targeted absolute accuracy: $5 \cdot 10^{-10}$ g

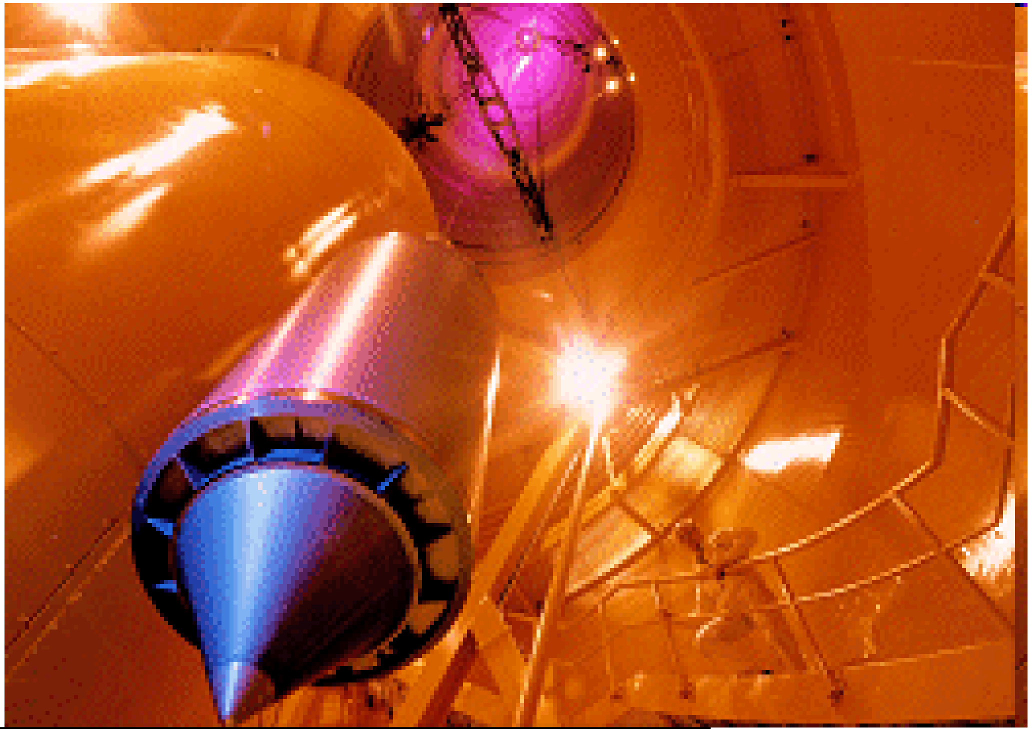
First laser system environmental test

EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

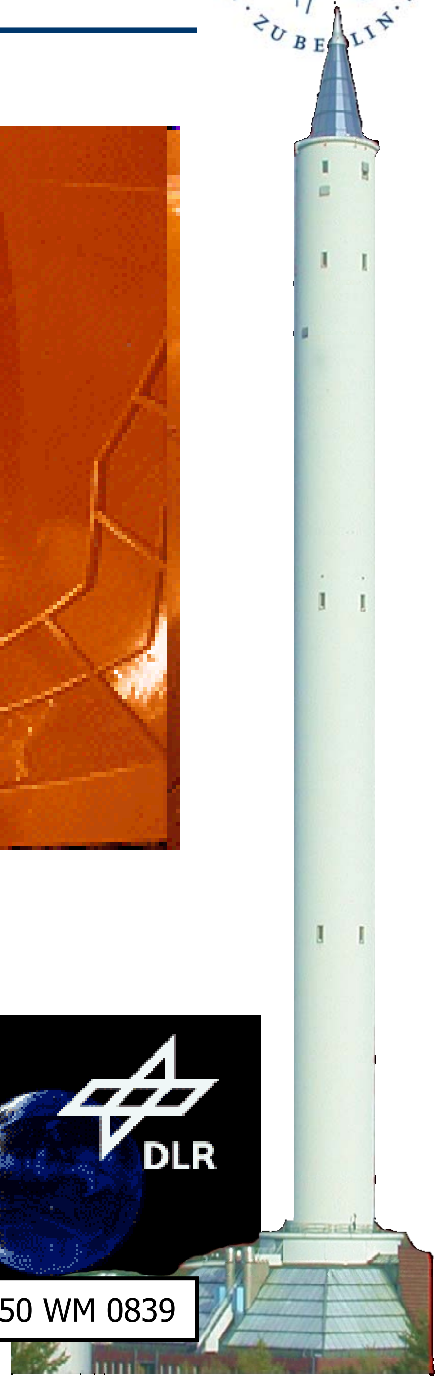
Current work on mobile atom interferometers

Drop-tower project: QUANTUS





- Goal: To create a platform for ultra-cold atom experiments in a microgravity environment
- 4.7 s of microgravity (catapult configuration: 9 s)
- Current status: 160 Bose-Einstein Condensates in microgravity created, expansion time of 1s!
- Next steps: Interferometry applications in freefall



DLR project 50 WM 0839

Current work on mobile atom interferometers

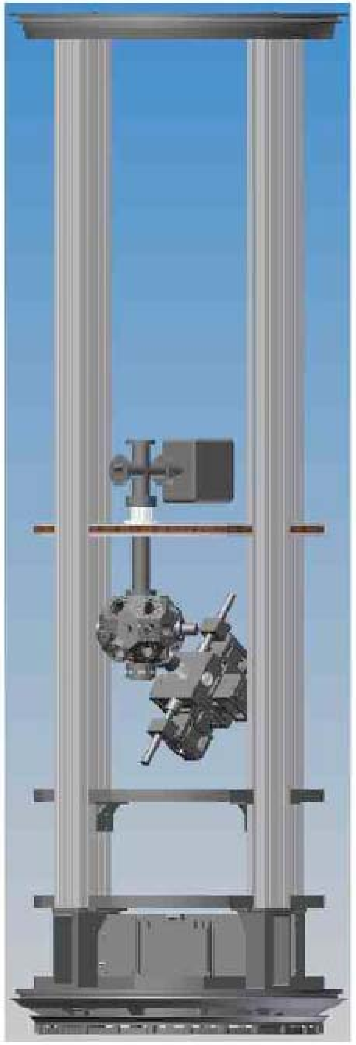
Drop-tower project: QUANTUS

2012/13: Technology demonstration – first launch of cold atoms!

DLR project 50 WM 0839

Current work on mobile atom interferometers

Space Atom Interferometer (SAI)



Goals:

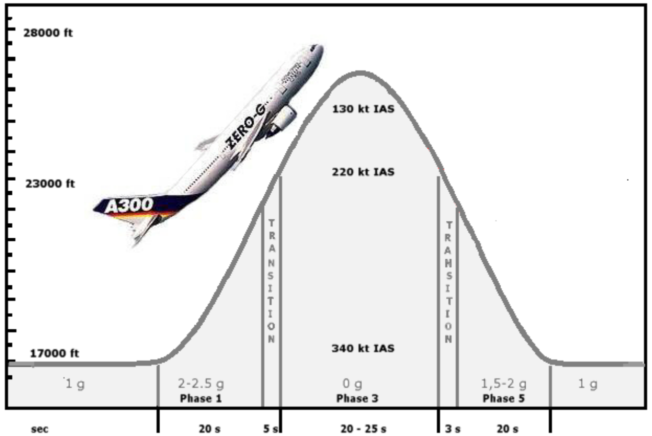
- To demonstrate the possibility of a space-compatible atom interferometer sensor
- Build a sensor and test it at system and subsystem level

Status:

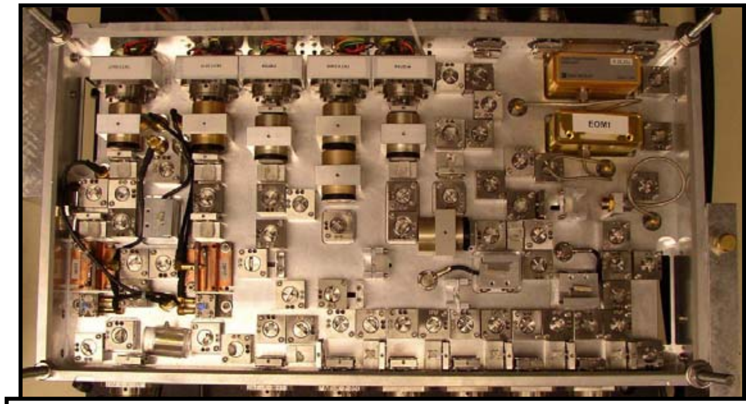
- Vacuum chamber components and laser systems built, assembly begun
- Design drop-tower compatible

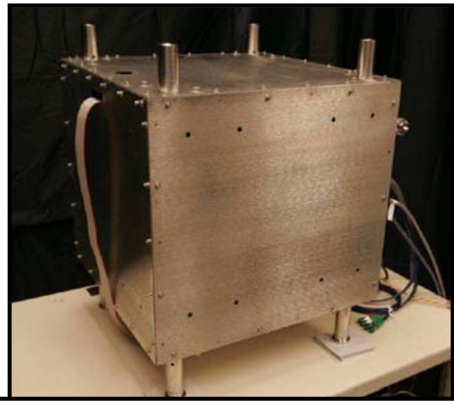
Current work on mobile atom interferometers

Some further mobile cold atom experiments



ICE project (SYRTE, ONERA, IOTA): Cold atom experiments on parabolic flights
http://www.ice-space.fr/ and Eur. Phys. J. D **53**, 353–357 (2009)





M. Kasevich gradiometric sensor projects – DARPA financed
Achieved bias stability $<10^{-10}$ g

Summary

- Employing atom interferometry on satellite gravity missions offers significant improvements in resolution and precision

- Sensitivities could potentially reach dimensions of 10^{-15} ms^{-2} or well below 1 mE in space

- Efforts are well underway towards mobile and space-optimized setups

http://www.physik.hu-berlin.de/qom