A Gravimetric Support Network for Very Long Baseline Atom Interferometry

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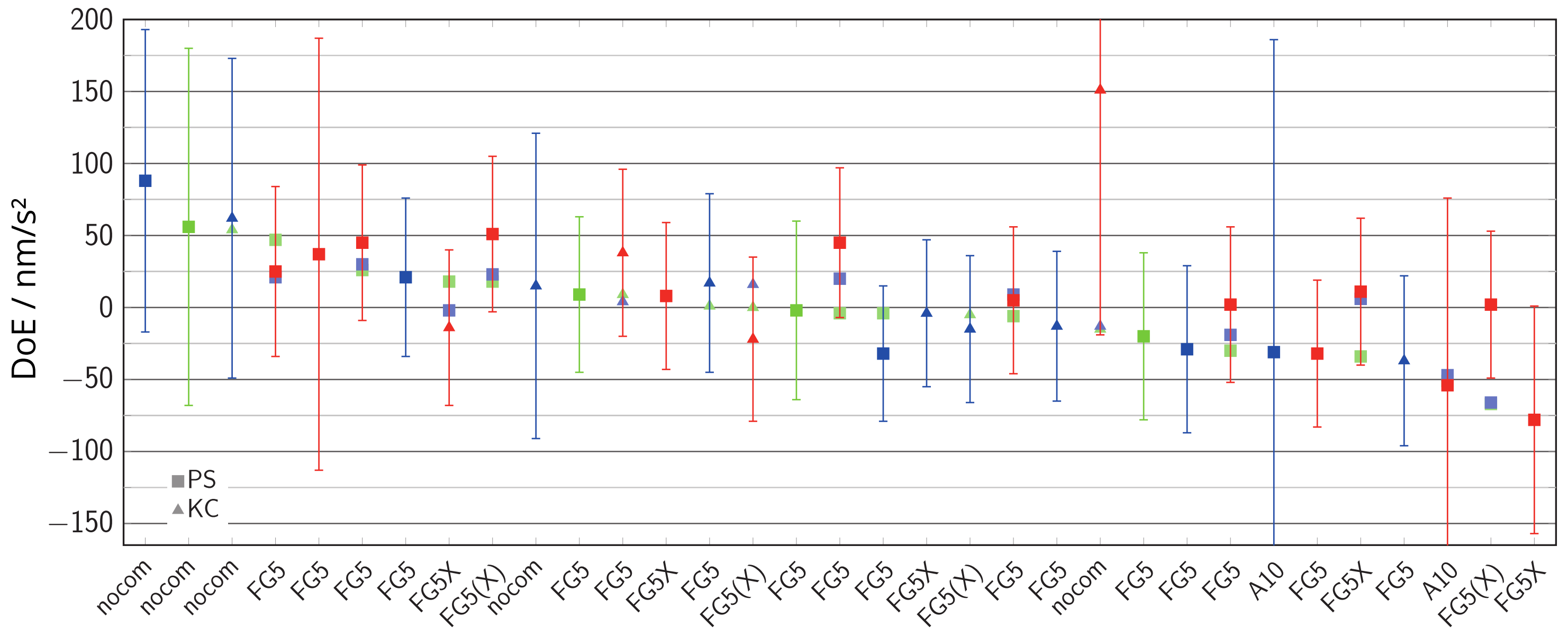
Motivation

The requirements on the accuracy of absolute gravimetric measurements are shifting towards the 10 nm/s² order of magnitude and beyond for applications in geodesy and geophysics. However:

- No superior 'gravity standard' available
- Long term stability: key comparisons Degree of Equivalence (DoE)
- Combinations of AG need to consider individual offsets
- Offsets change due to maintenance, new operator, etc.

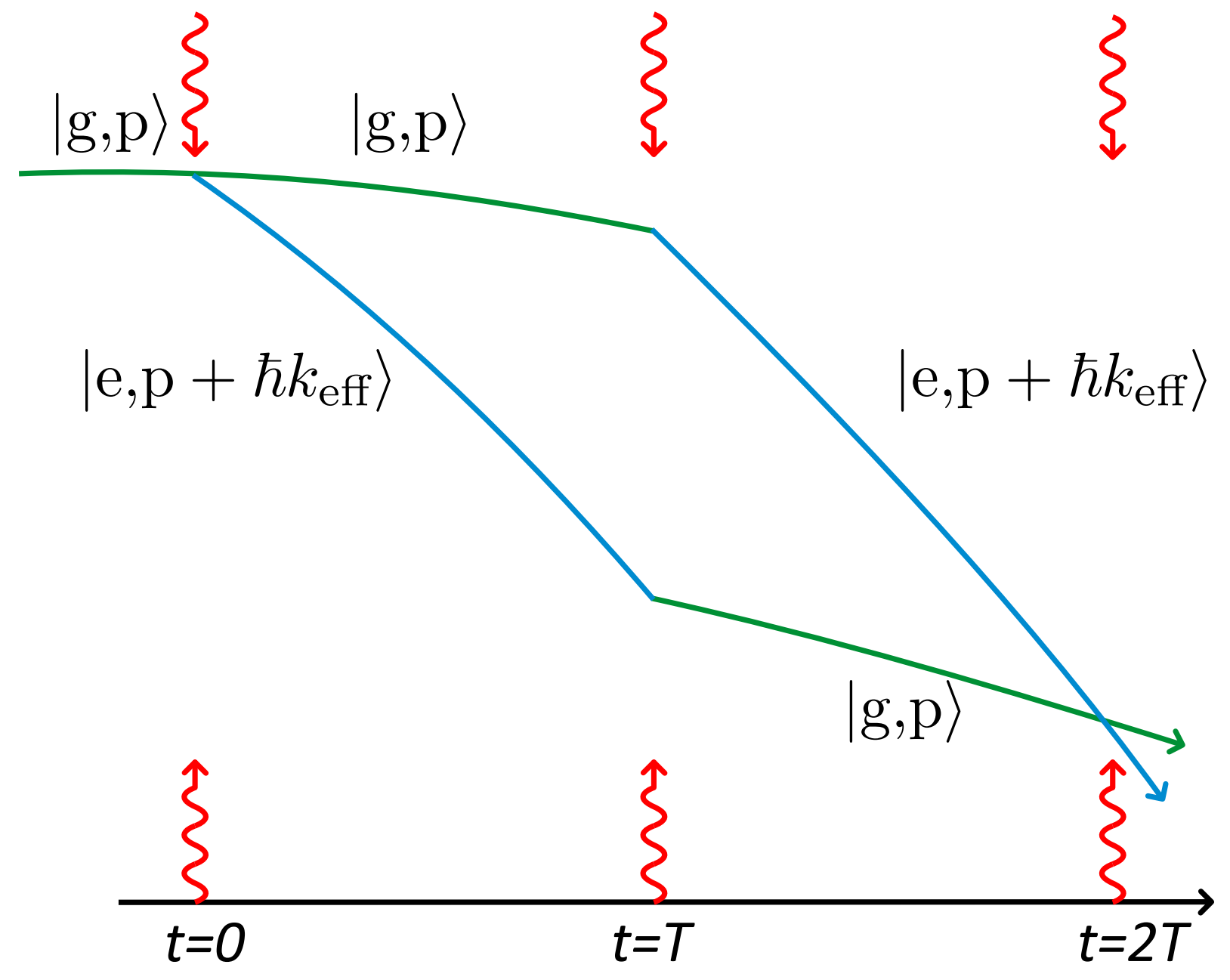


Participants of AG comparisons EURAMET.M.G-K1 (2011), CCM.G-K2 (2013) and EURAMET.M.G-K2 (2015) [1,2,3] ; nocom: non-commercial developments, errorbars: rms of the expanded uncertainties of measurements to determine DoE.

Can stationary, large scale atom interferometers provide new a 'gravity standard'?

Gravity and Atom Interferometry

Light pulses can be used to manipulate atomic wavepackets and thus build atom interferometers (AI). The well-known Mach-Zehnder geometry can be used to probe the acceleration of free-falling atoms.



Space-time diagram of an atomic Mach-Zehnder interferometer

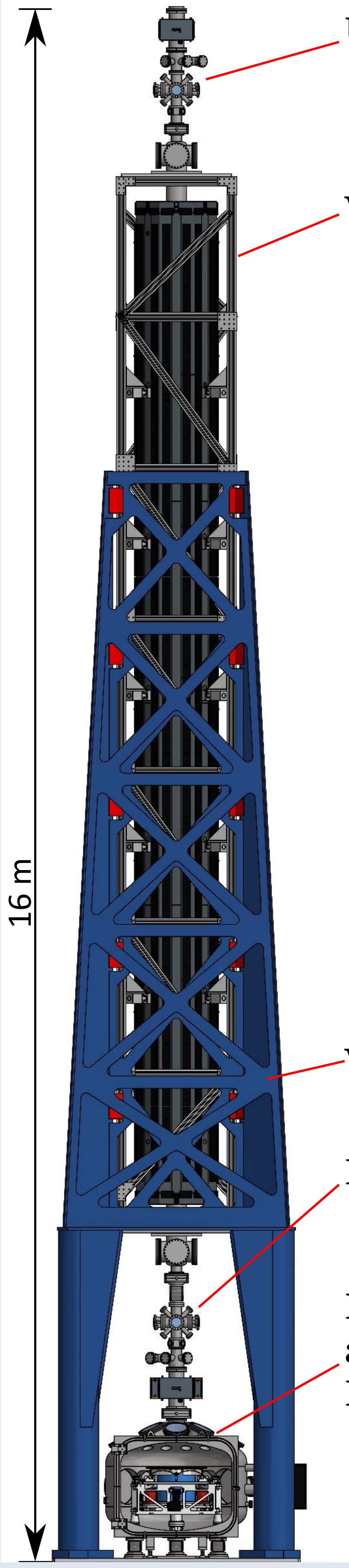
To first order, the interferometer phase shift is proportional to g, the pulse separation time T and the momentum transfer through the laser light $\hbar k_{\mathrm{eff}}$. A frequency chirp α compensates the Doppler shift due to the free fall.

$$\Delta\phi_{\mathrm{acc}} = (k_{\mathrm{eff}}g - \alpha)T^2$$

Very Long Baseline Atom Interferometery [4]

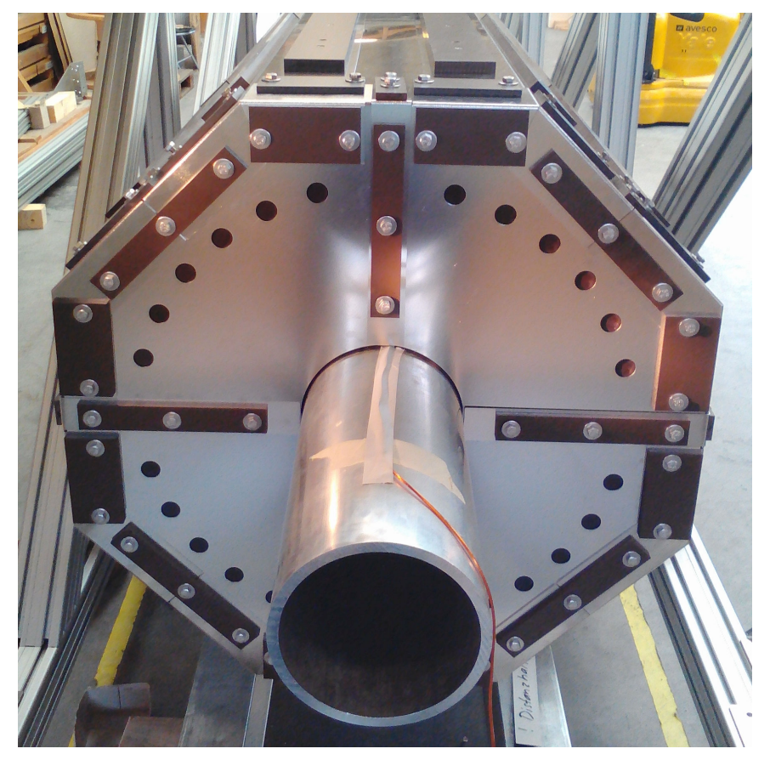
Capabilities

- Fundamental physics, e.g. test the universality of free fall [5]: Eötvös ratio 7×10^{-13}
- Gravimetry: instability at 1 s <1 nm/s² (drop) and <70 pm/s² (launch)
- Gradiometry: instability at 1 s $<5\times10^{-10}$ s^{-2}



Upper atomic source (Rb, Yb)
- Free fall 2T= 0.8 s

VLBAI baseline [6]
- 10.5 m-long ultrahigh vacuum pipe, pressure $<1\times10^{-9}$ mbar
- Residual field <4 nT, long. gradients <2.5 nT/m.



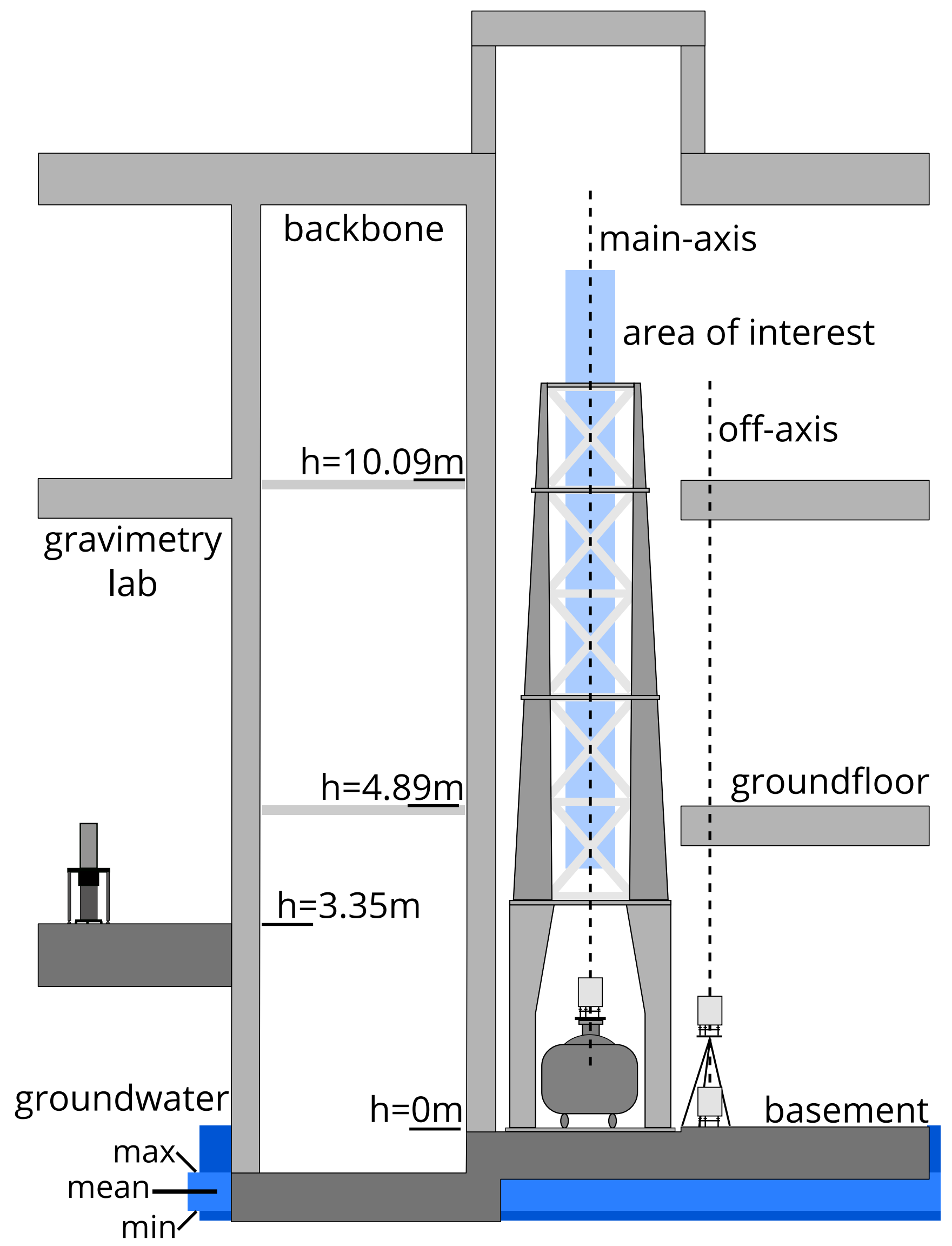
Magnetic shield and baseline
IMEDCO AG (Switzerland)
Peter Fierlinger (TU Munich)
IQ (LUH)

VLBAI support structure

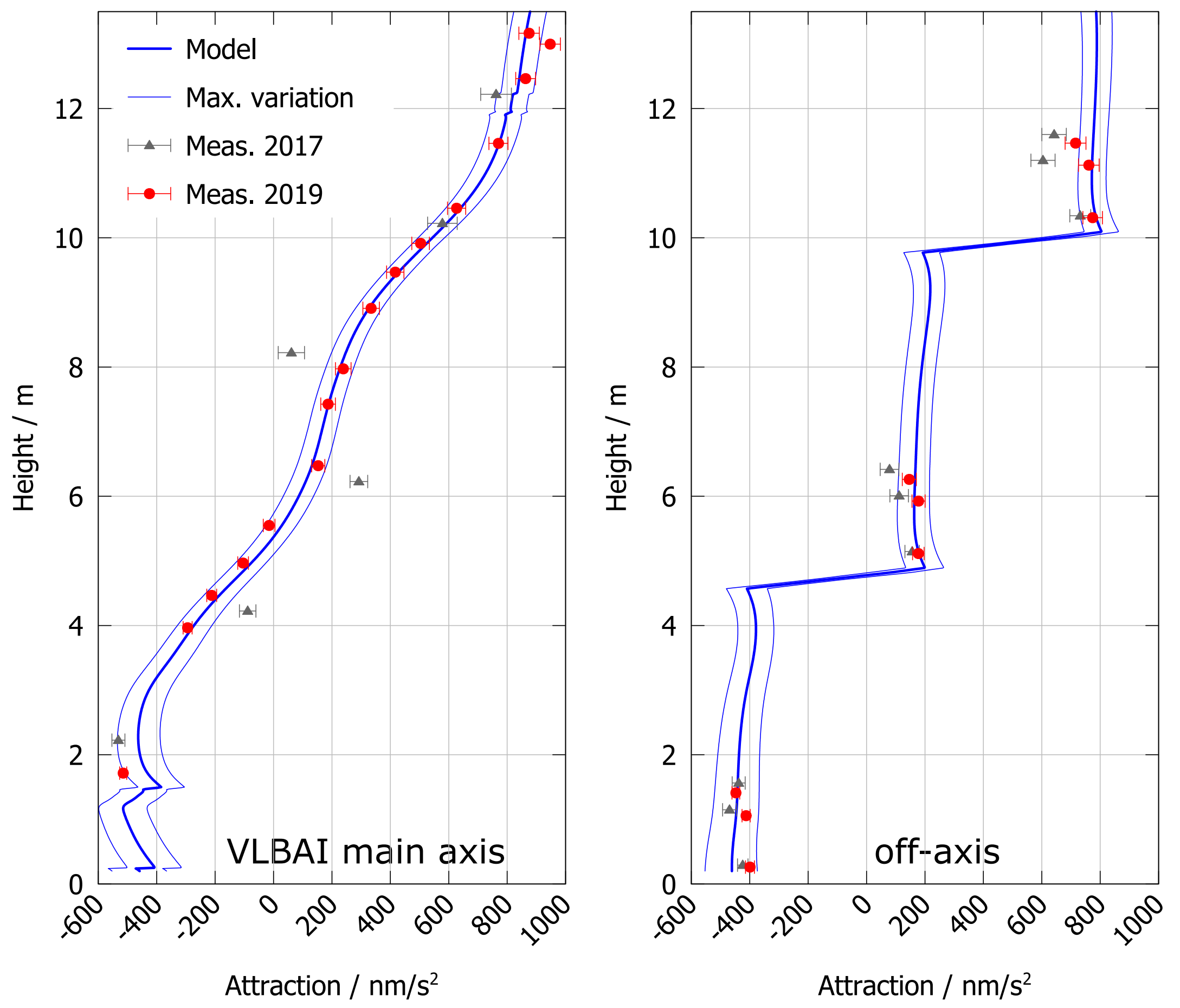
Lower atomic source (Rb, Yb)
- Fountain: 2T = 2.8 s

Inertial reference with seismic attenuation system (SAS) Innoseis (Amsterdam)
- Six degrees of freedom sensing and actuation
- 320 mHz resonance frequency

Gravimetric Measurements and Modelling



HITec building with support structure and SAS tank. Area of interest marks section for VLBAI experiments. Groundwater levels are annual averages and extreme values. Status at the time of second campaign in 2019 is shown.



Model of attraction (±5% variation) and measurements (−*dg/dh*).

Gravimetric control network

- Two campaigns on main- and parallel-axis
- Heights by levelling and laser measurements
- Least squares network adjustment

	2017	2019
Gravimeters	ZLS B-114, CG3M-4492	ZLS B-64, CG3M-4492, CG6-0171
Main axis support	scaffold	aluminum tower
Points (total/VLBAI)	18 / 7	27 / 16
Connections	147	454
Mean σ g network	28 nm/s²	9 nm/s²
σ gravity differences	12…54 nm/s²	5…15 nm/s²

Modelling of HITec and environment

- Determine gravity field prior to installation
- Provide a reference supported by measurements
- Simulate effects of density, geometry, equipment (prism based method for attraction)
- Detailed CAD for VLBAI (polyhedral body with triangulated surfaces)
- Model environmental effects, e.g. groundwater

Monte Carlo simulation of parameters

- Assumption of fixed density (concrete, soil, etc.): variation of density by 5% for model elements
- Final position of VLBAI uncertain on cm-level: variation of ±3 cm (xy) and ±2 mm (z)

Simulation	max. Variation (main/off) nm/s²	mean σ (main/off) nm/s²
Position (xy: ±3cm z: ±0.2cm)	±2.1 / ±3.9	0.6 / 1.2
Density (±5%)	±111 / ±109	24 / 23

Comparison model and measurement

- Measurements adjusted for constant offset and gravity gradients (*dg/dh*)
  dg/dh=free air gradient+model of exterior
- Difference δg=model−measurement (2019)

	rms(δg) nm/s²
VLBAI (aoi)	30
off-axis	33

Next steps

Consider VLBAI baseline in model, measurements...

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