

Atom Interferometer Gravity Gradiometer (AIGG): Testbed for the next-generation gravity recovery mission

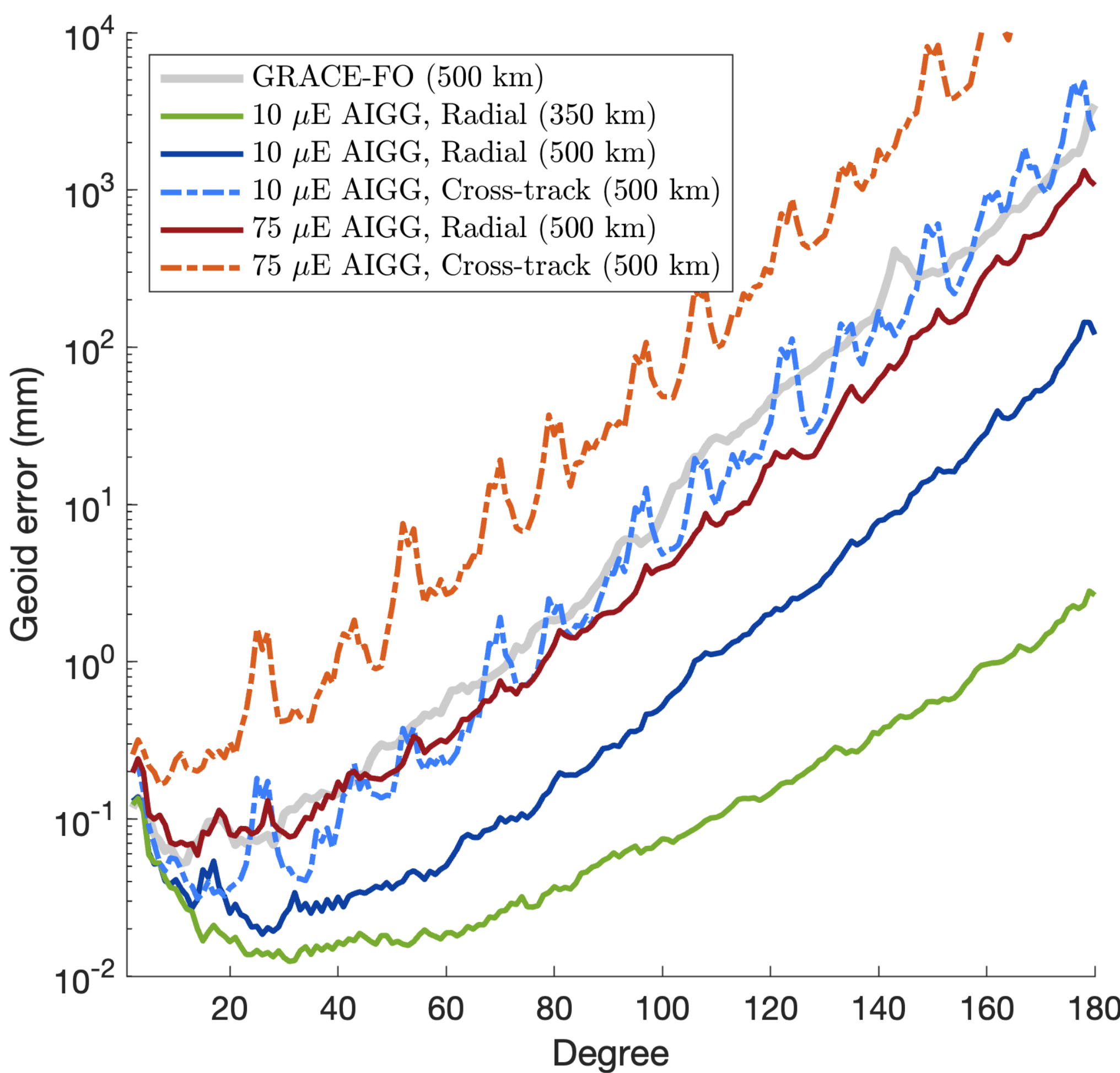
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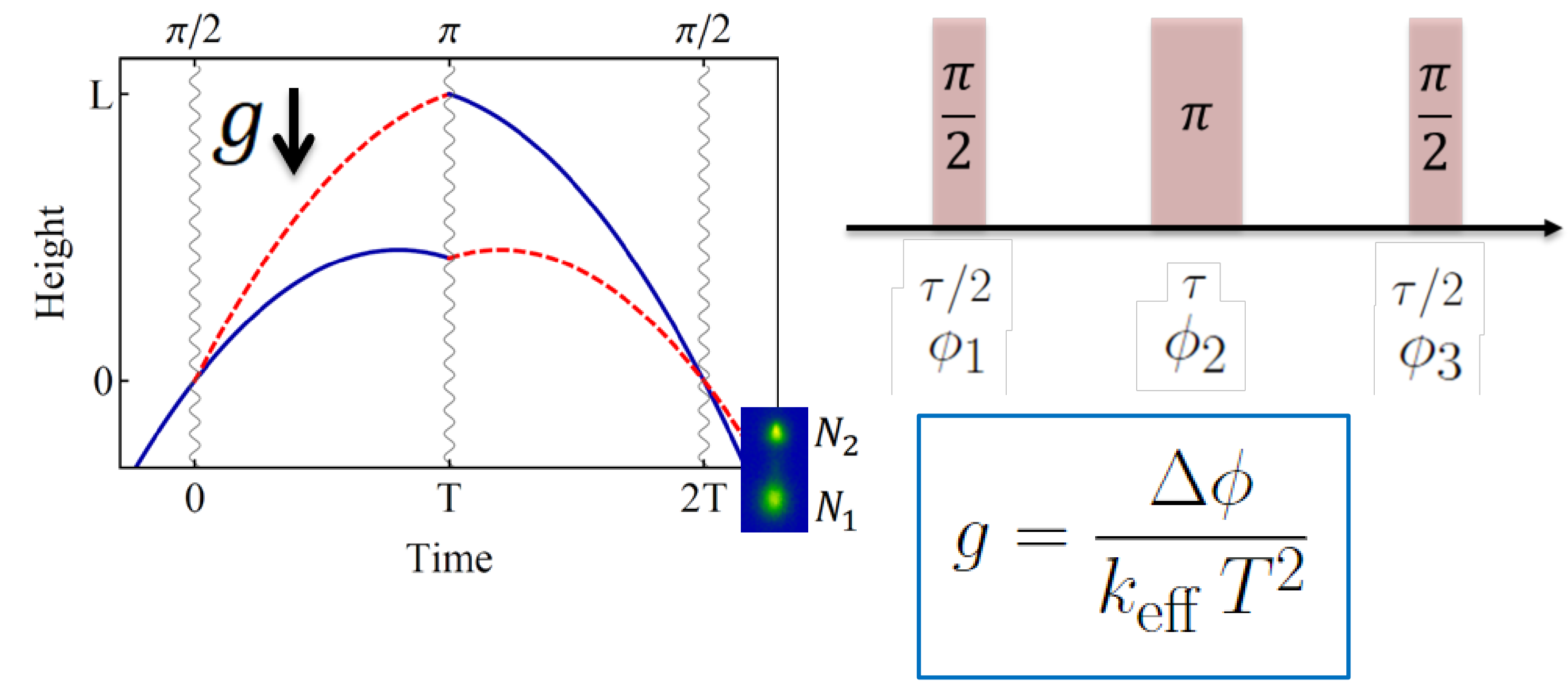
Science justification:

Continuous gravity recovery missions, like the GRACE series, are a cornerstone for understanding the Earth's mass over time. This data is critical to understanding climate processes, solid Earth science and oceanography. As underlined in the 2018 Earth Science Academies of Science decadal study, achieving gravity gradients at spatial scales of 100-200 km with an accuracy of < 1 cm water equivalent RMS will require either large constellations of gravity satellites or **development of new gradiometer technology**. As shown in simulation data, a cold atom interferometer with **10 μ E sensitivity in a radial orbit configuration** can achieve **10x better performance** than GRACE-FO in a single satellite.



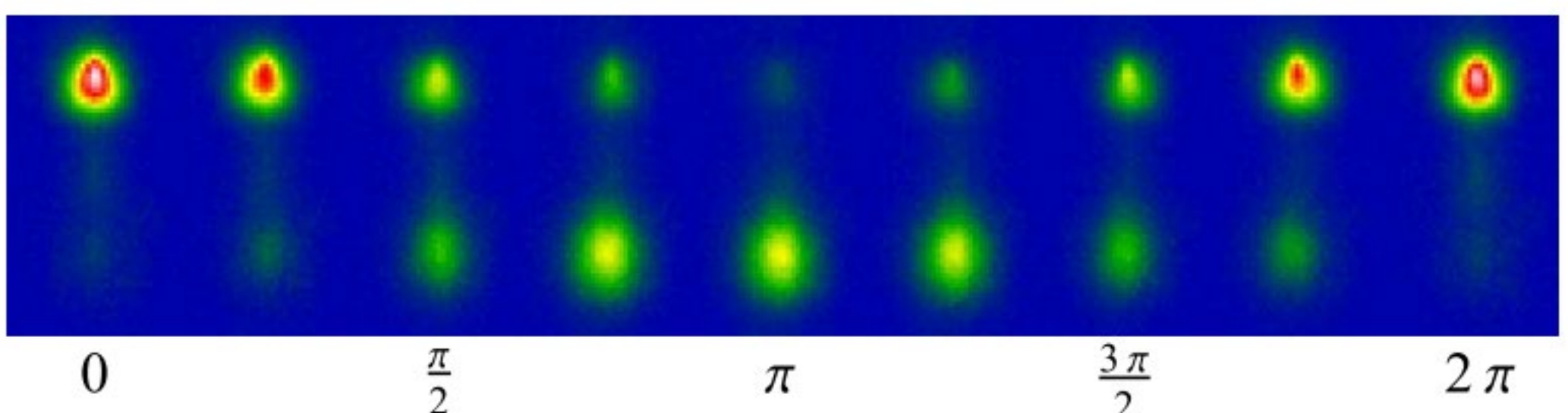
As shown above, a single AIGG with 10-5 E sensitivity in a radial orbital configuration at 350 km (green line) or 500 km altitude (dark blue) achieves 10x better sensitivity than GRACE-FO (gray line).

Cold atom gravimetry basics:



Cold atom gravity gradiometry basics:

In AIGG, ultra-cold (<10 nK) Cs atoms are manipulated by near-resonant laser pulses. In each gravimeter head, a sequence of three pulses effectively splits each atom cloud along two paths, in analogy to an optical Mach-Zehnder interferometer (see schematic in lower left). The relative phase between atoms travelling along each path is proportional to the local gravitational acceleration and inversely proportional to the effective momentum between paths (k_{eff}) and the interaction time between pulses (T).

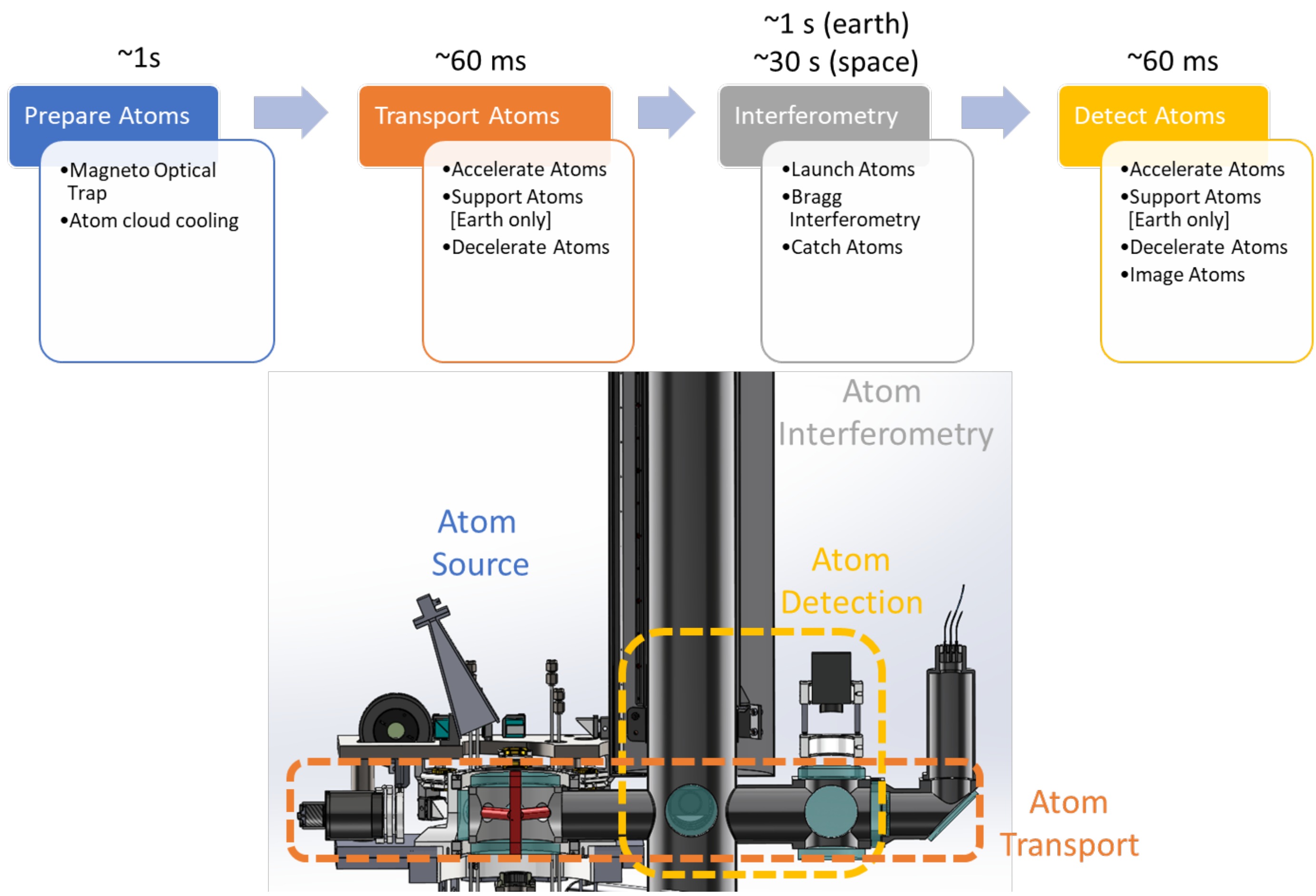


$$|G_{zz}| = \frac{\Phi}{k_{\text{eff}} T^2 L}$$

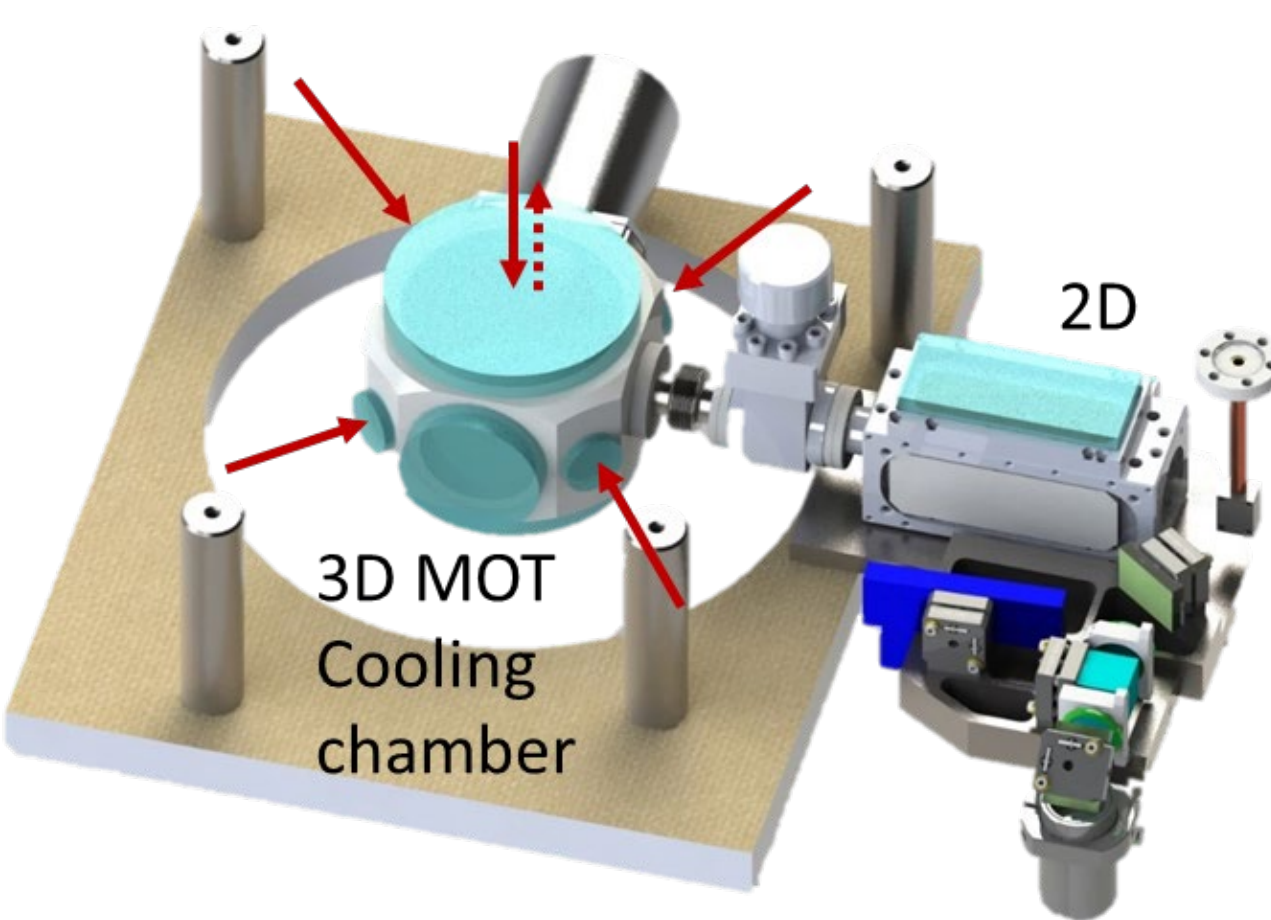
For gravity gradiometry, two separate atom interferometers (labelled upper, U and lower, L in figure above) separated by a baseline distance, L , interact with a common interferometry beam and the relative phase between upper and lower clouds (Φ) is proportional to the gravity gradient, G_{zz} . AIGG is designed to test the atom interferometry architecture, laser optical systems, advanced cooling and readout techniques required for a long-interaction time ($T > 15$ s) science-grade gravity gradiometer. Targeted sensitivity is **1 E/per shot** terrestrially which would correspond to **10^{-5} E in orbit**

AIGG: key technology test bed

AIGG is the only experimental realization of a full science grade ultracold gravity gradiometer capable of reaching decadal required sensitivities. This testbed consists of an integrated, two-source gradiometer designed to cool more than 10^7 Cs atoms to <50 nK with a common Bragg beam across a baseline of 2m. The full sequence of preparation, cooling, transport, interferometry and detection is shown below



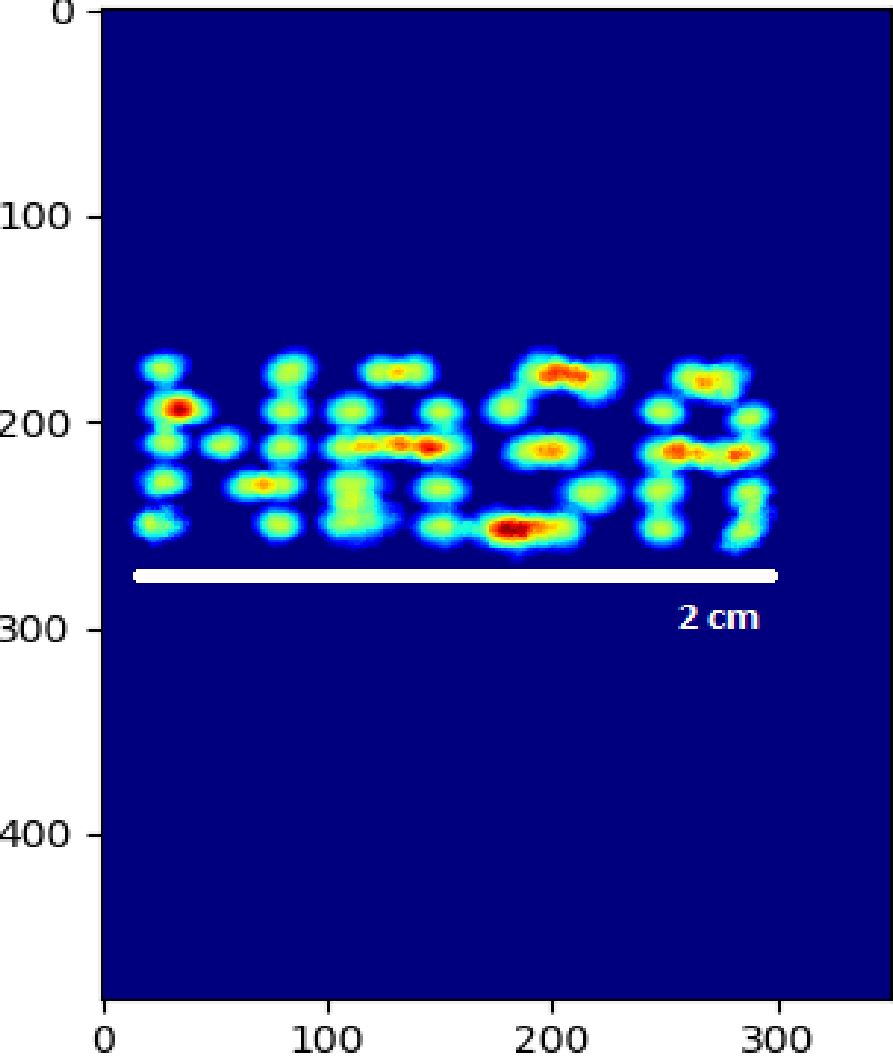
Advanced cooling and optical transport



A key technological requirement for high sensitivity gravity gradient measurements is providing a high-brightness ($>10^7$ atoms) source at <3 nK. In AIGG, each atom source is designed to provide efficient sub-Doppler cooling in a compact, integrated form factor as shown to the left.

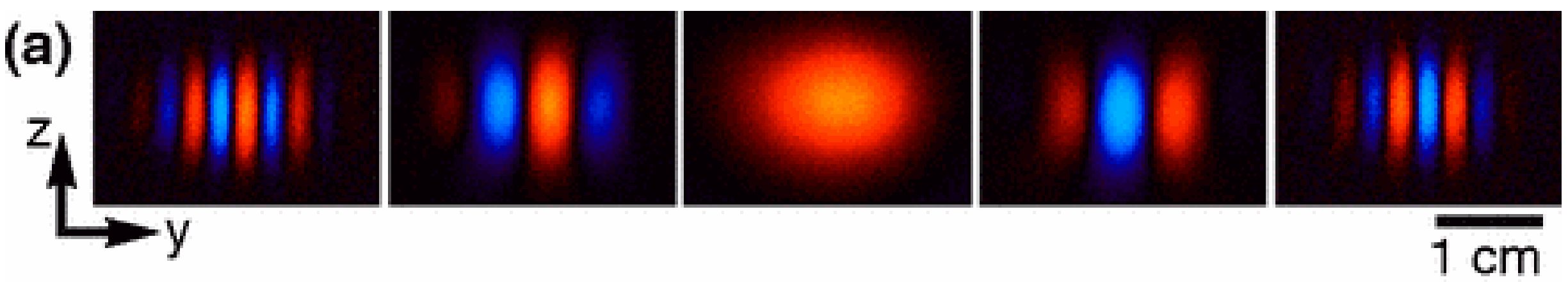
Additionally, achieving near-quantum projection limited noise and to enable interleaved operation, a science-grade instrument requires transportation of the cooled atom clouds from separate cooling, interferometry and measurement chambers. AIGG achieves this via moving optical lattices, achieving low atom-loss transportation over 10s of cm. The demonstration of the transport control achievable in AIGG is shown in the composite figure to the right

Composite image (47 shots)

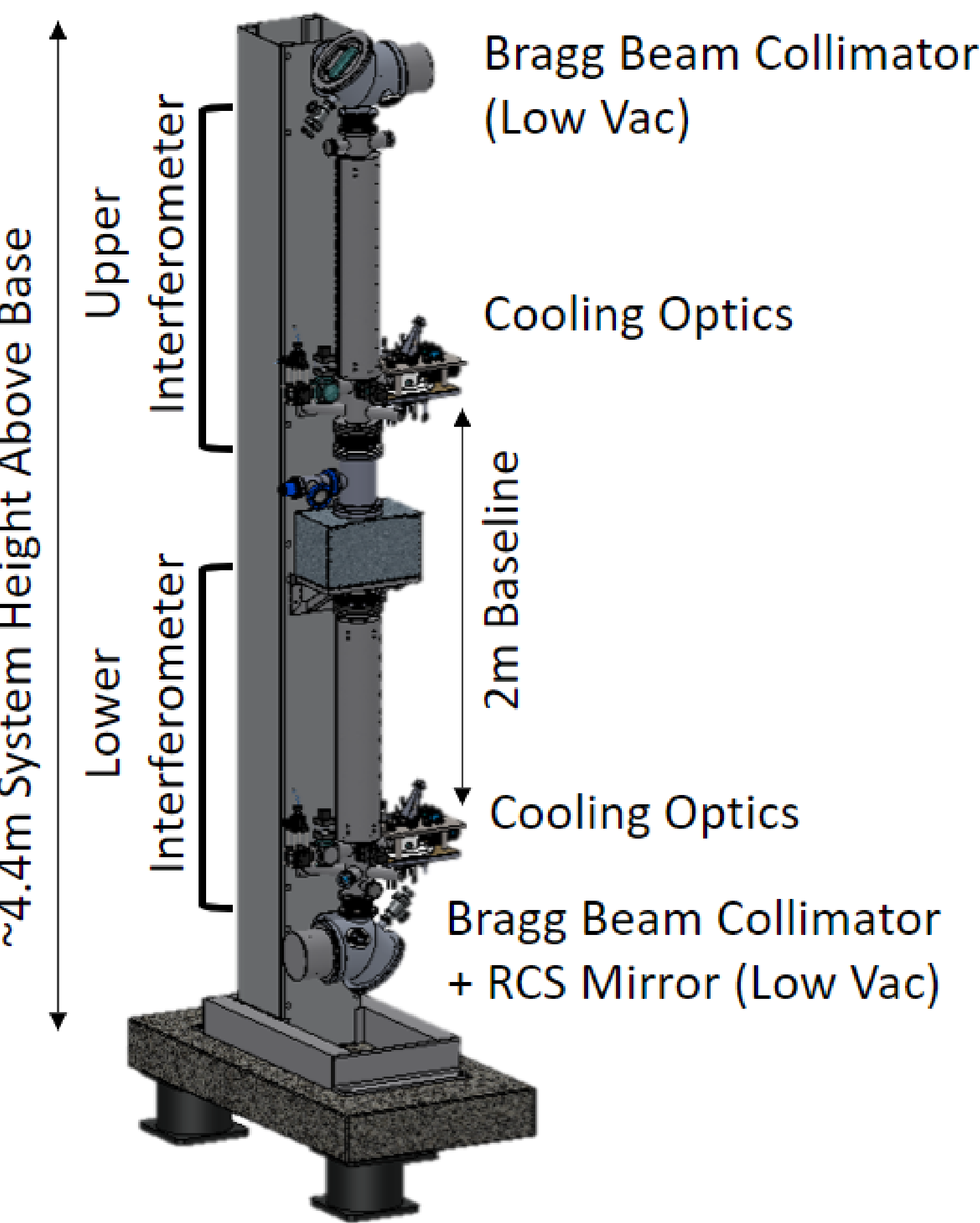


Advanced readout: phase shear and rotation compensation

In order to correct for rotational acceleration in a single axis instrument, the rotation of the instrument about its orthogonal axes must be precisely measured. In order to achieve this in AIGG, an experimental technique of phase shear utilizes the automated rotation of an atom interferometer mirror during the pulse sequence. The resulting spatial fringes across an individual atom cloud is proportional to the rotation rate.



Additionally, to operate in a radial configuration at atom interaction times exceeding 15 seconds, the interferometry beam must rotate in order to ensure the atom cloud remains within the beam. AIGG is the only experimental instrument that includes the automated mirror manipulator within the integrated vacuum system. With terrestrial interaction times exceeding 200 ms, AIGG can test the rotation compensation system terrestrially.



GSFC Mission Design Lab Concept

