A Sounding Rocket Test of the WEP (SR-POEM)

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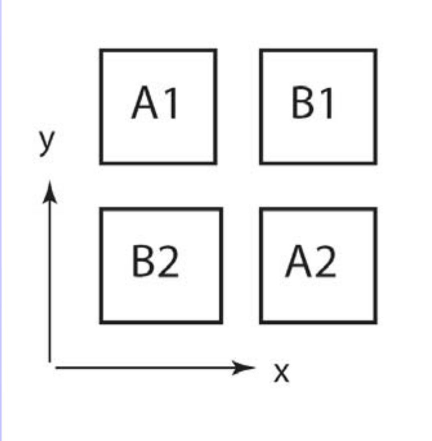
Mission Concept

- For a single pair of substances, $\sigma(\eta) \leq 10^{-16}$.
  - 1000 fold advance over present best result.
- WEP test in sounding rocket payload.
  - Experiment duration 400 to 800 s.
  - Payload ≈ 200 kg.
- Non-recoverable payload (like orbiting payload).
- Low cost (not like orbiting payload).

Work on SR-POEM started this month with support from NASA-Astrophysics.

Instrument Concept

- Derived from POEM (derived from JILA test).
- 4 test mass assemblies (TMA) observed by 4 tracking frequency laser gauges (TFG).
- Double difference observable.



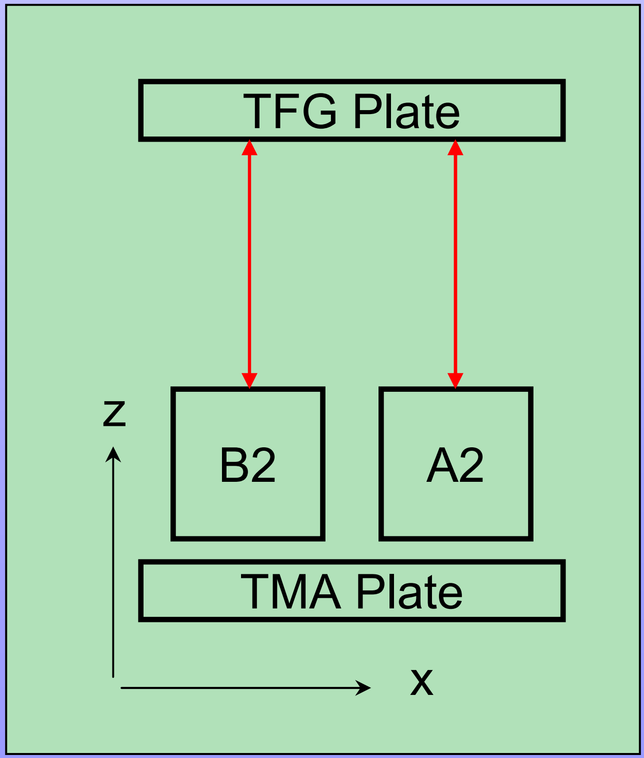
D1=L(A1)-L(B1)

D2=L(B2)-L(A2)

DD=D1-D2=DA-DB

DA=L(A1)+L(A2)

DB=L(B1)+L(B2)



Experiment Concept

- TMA (about 0.5 kg) in free fall for 40 s per drop.
- Experiment includes about 8 drops.
- Payload inversion between drops.

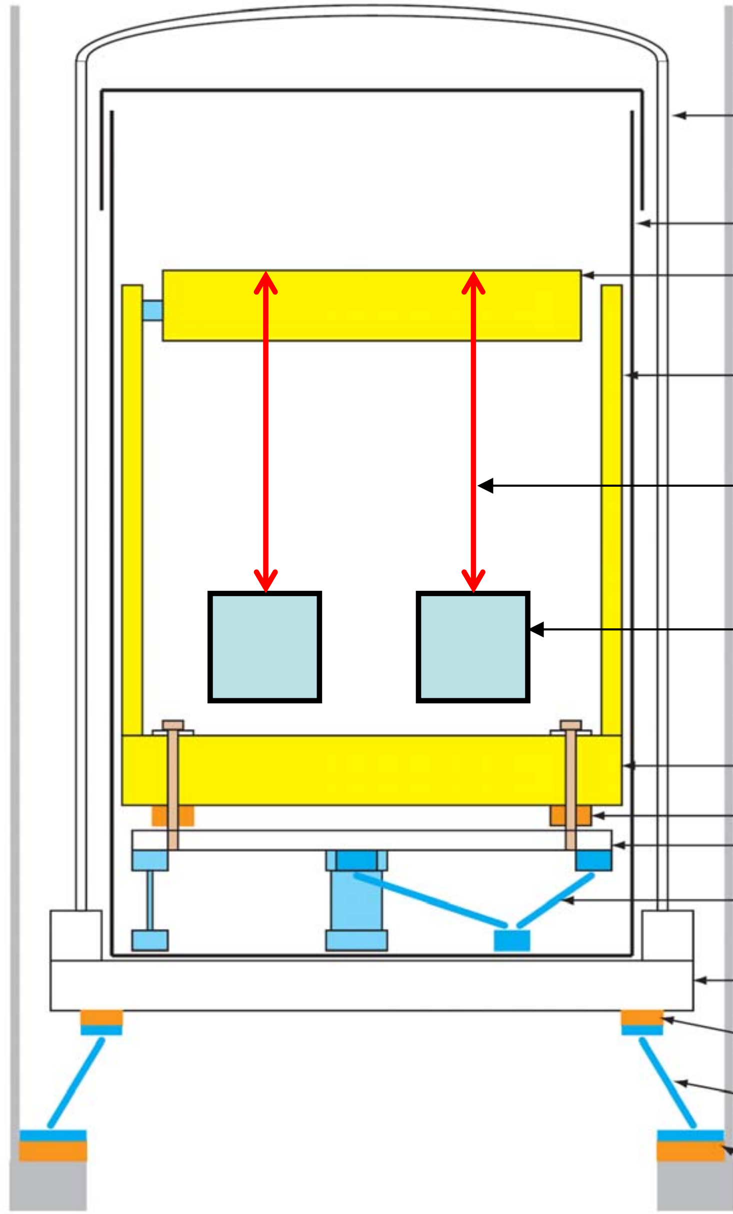
Inversion cancels most remaining systematic errors:

In payload frame, gravity from local mass is fixed and WEP signal reversed by inversion.

Earth's gravity gradient is symmetric and thus the same after inversion (except for higher order term which is too small to matter.)

Experiment Housing

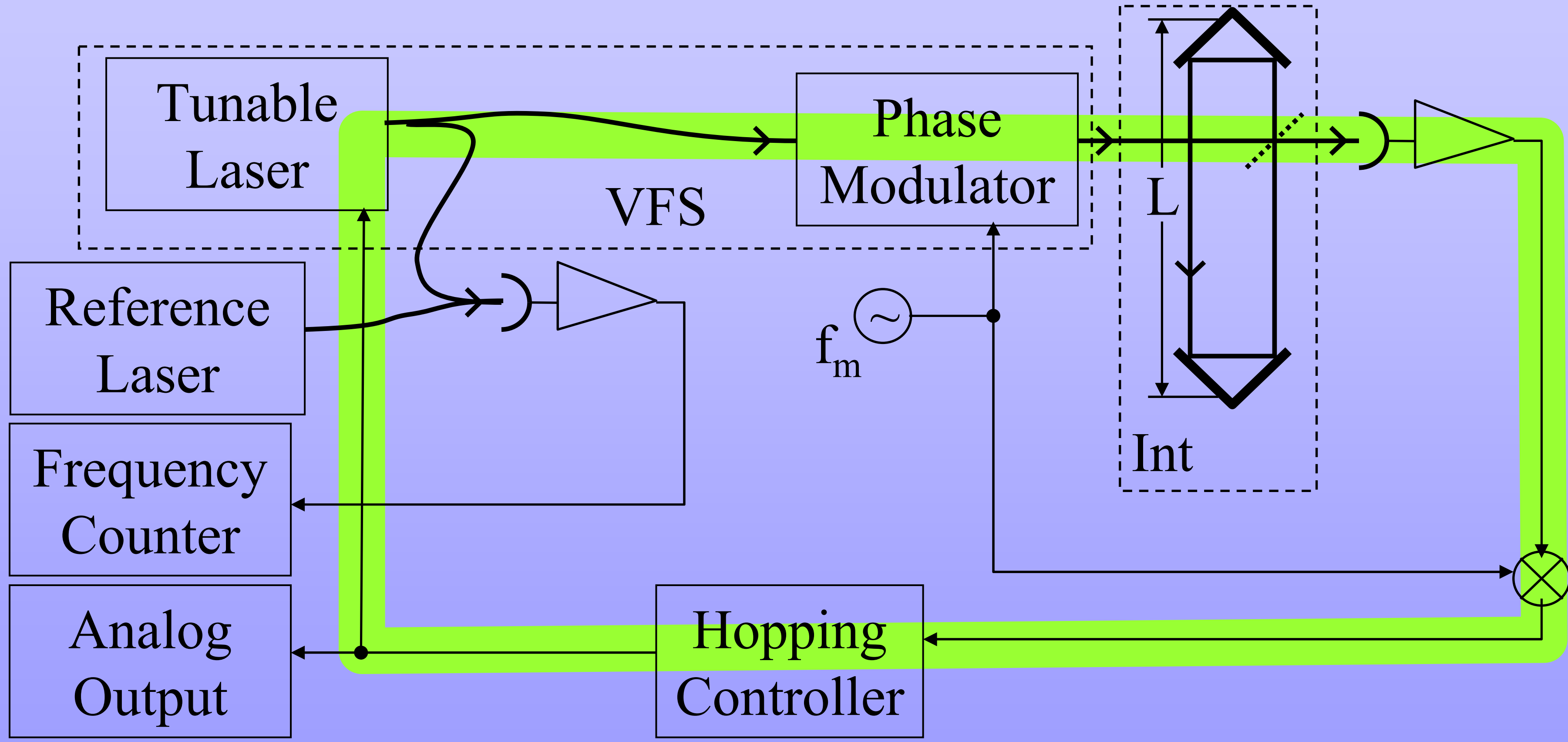
Precision instrument inside vacuum chamber inside 14 inch payload tube. Not shown here are the two vacuum ports at the upper end of the chamber, the capacitance gauge electrode sets, and the TFG optics.



Tracking Frequency Laser Gauge (TFG)

- Developed around 1990 for POINTS.
  - Recent further development.
  - Now being developed under NASA-APRA.
  - See Phillips & Reasenberg, RSI, **76**, 064501, 2005.
- Has advantages over traditional heterodyne laser gauge. (5 applicable here)

TFG Block Diagram, DFB Realization

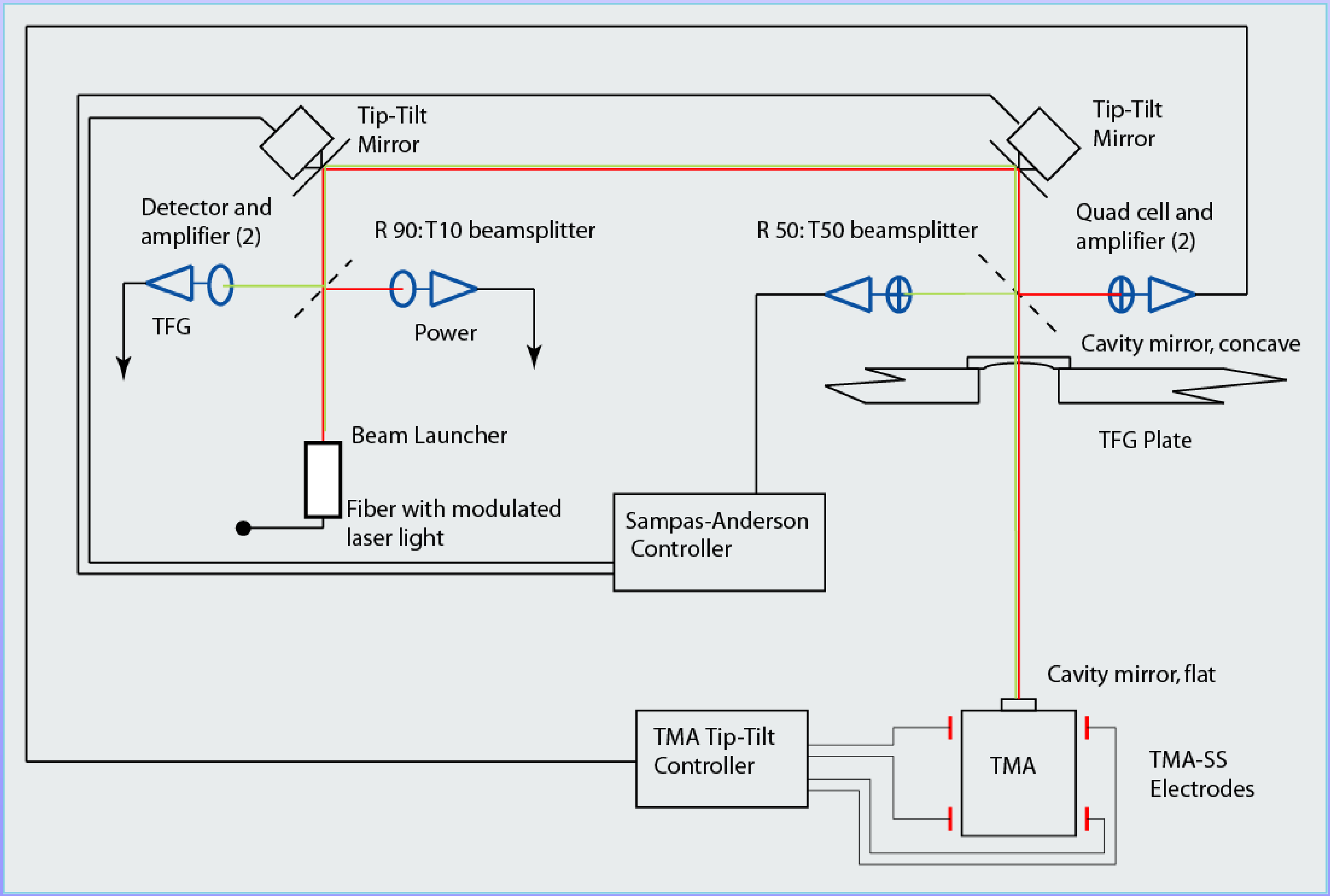


Tracking Frequency laser Gauge: loop closed by Pound-Drever-Hall locking.

TFG: Six Advantages

1. Intrinsically free of the nm-scale cyclic bias characteristic of the heterodyne laser gauge (e.g., Hewlett-Packard, Zygo).
2. Uses one beam, not two: simplifies the beam launcher.
3. Distance changes measured by a radio frequency: more stable and more easily measured than RF phase.
4. Able to operate in a resonant cavity: improves precision, suppresses misalignment error and supports servo-based alignment.
5. Suppress polarization error from non-normal incidence in a cornercube (nm scale).
6. Measures absolute distance with a minimum of added cost or complexity.

Laser Gauge Alignment



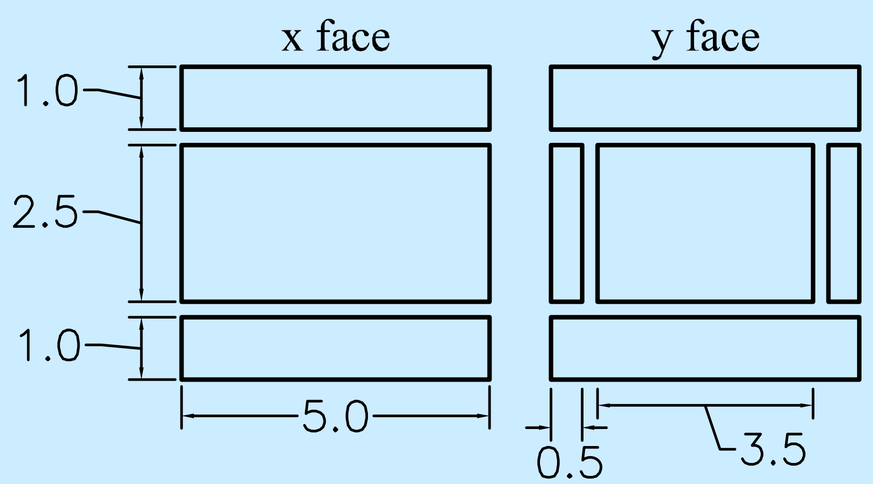
TMA Suspension System

- Can observe and control 6 degrees of freedom.
  - All active during setup and inversion.
- Coriolis force: measure E-W velocity.
  - Transverse position measurements made before and after TFG measurements.

Skipped: Capacitance Gauge Plates

The capacitance gauge is the sensing portion of the TMA-SS

Interelectrode gaps are 0.25 cm. The long bars are drive electrodes and the large rectangle is the sense electrode. Not shown, grounded shield around the sense electrodes.



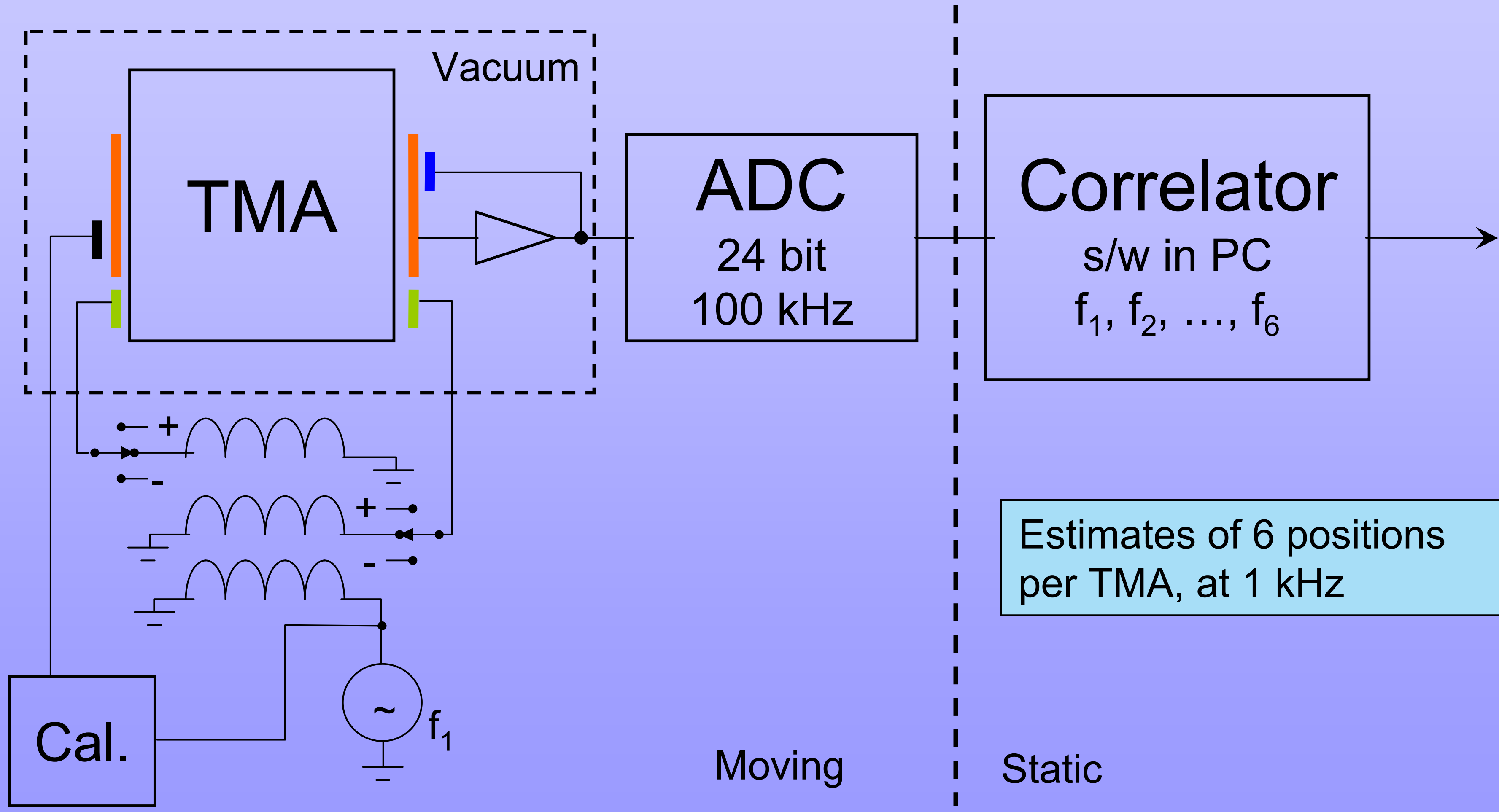
Dimensions are in cm.

Plan of capacitance gauge electrodes.

These electrodes are deposited on glass plates (ULE or Pyrex) that are later joined to form a box. Any significant open areas are filled with grounded shields, and the small remaining gaps are covered with resistive material, which leaks off charge. A ground plane on the back of each plate covers the drive electrodes but not the sense electrode (because it would add capacitance and thus decrease sensitivity.)

Skipped: POEM Capacitance Gauges

Collaboration with Winfield Hill, Rowland Institute at Harvard



Estimates of 6 positions per TMA, at 1 kHz

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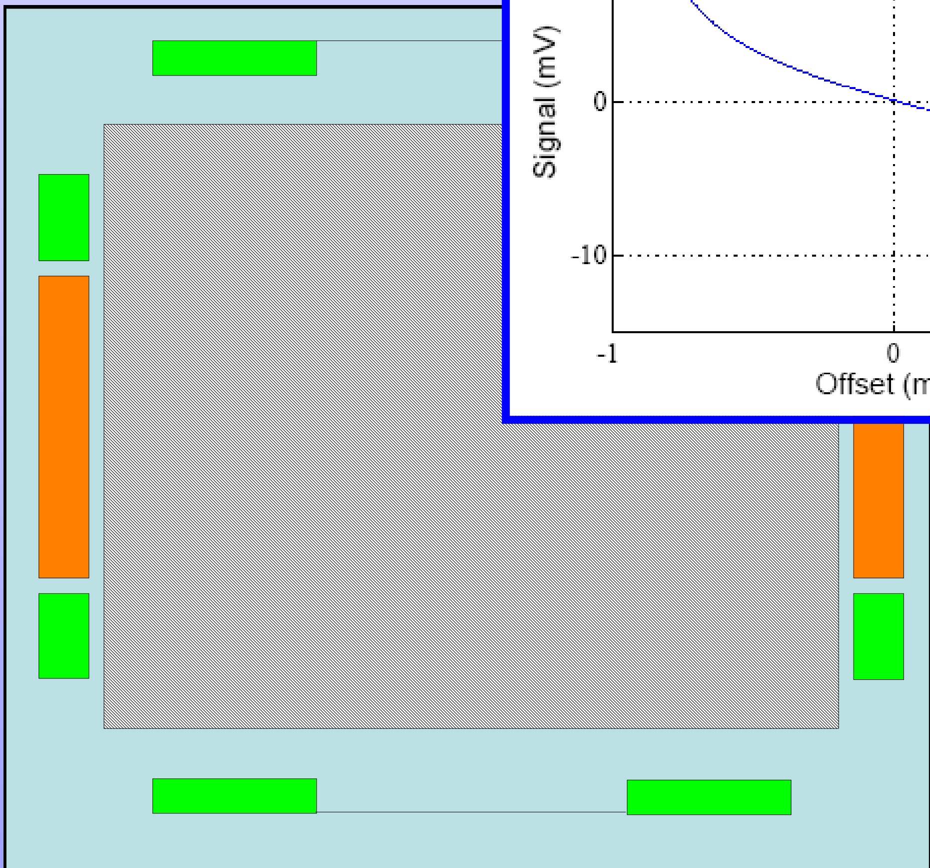
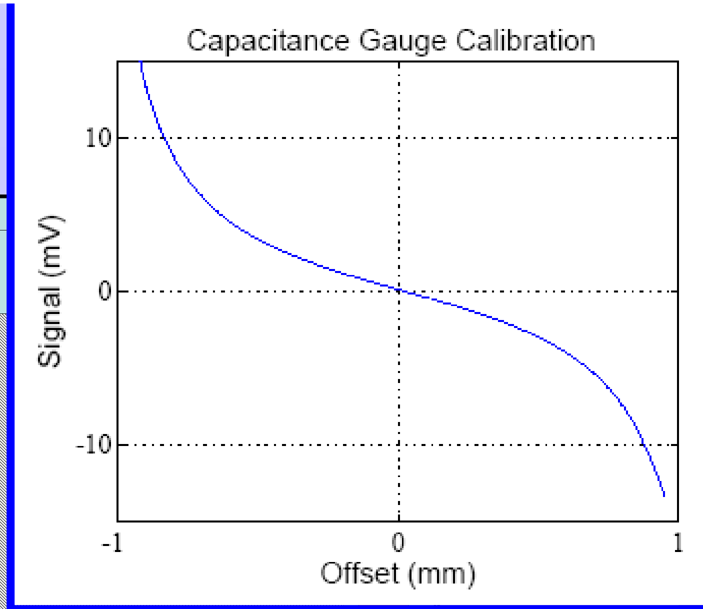




TMA, exclusive of feet.

Drive plates, 3 of 5 sets.

Pick-up ring.

Drive:	0.1 V rms, 10 – 20 kHz
Sensitivity:	< 8 nm @ 1 s.
Electrode gaps:	1 mm (nominal)

Charge on TMA

- TMA potential at liftoff g 100 mV.
- Measure by applying DC field to capacitance gauge electrodes and neutralize, e.g., with UV LED.

  Sun, *et al. LISA-LIGO Charging Workshop, 2007.*

  - Before reaching altitude at which drag is low (800 km).
  - Make TMA voltage g rms variation over surface.
- Effect of small constant charge on TMA cancels in payload inversions.

Surface Potential Variation

- Classical solution: gold or graphite (Aerodag).
- Recent LISA work by Robertson et al.
  - Class. Quantum Grav. **23** (2006) 2665-2680
  - New materials studied: Au over Nb, diamond-like carbon, TiC, indium tin oxide (ITO), Au over ITO.
  - Many achieve 1 to 2 mV rms wrt mean.
- Measurements done with 3 mm Kelvin probe.
  - Needs to be smaller and more sensitive.
  - They and GSFC are investigating improvements.

Surface Potential Variation for SR-POEM

- Assume: 1 mV rms, 3 mm spacing (top and bottom) =>$2\times3\times10^{-16}$ g.
  - Decreased by possible top-bottom cancelation.
- Measured time variation of PSD at 1/140 Hz, averaging over 4 cycles: $\delta a=1.2\times10^{-17}$ g.
  - Very conservative estimate.
- Good enough, and further …
  - Temperature in SR-POEM 100- to 1000-fold more stable (see below). => SR-POEM has stable vacuum environment.
- Need additional testing under SR-POEM conditions.

Caging (Uncaging)

- Clean metals tend to cold weld.
- Candidate design concepts:
  - Non-stick materials with possible separate ground point.
  - Contact at bottom of hole to hide the surface potential of contact area.
- Synergy with LISA.

Thermal Stability

- Two concerns:
  - Direct effect on apparent double-difference acceleration measured with TFG (thus on η).
  - Indirect by moving payload mass.
- Direct effect made small by:
  - Use of ULE glass for precision structure.
  - Layered passive thermal control.
  - Symmetry of thermal leaks.

Thus far, unable to find a problem.

Thermal Time Constants

- The precision instrument hardly sees the external temperature changes.
- Vacuum chamber gold coated inside and out.
  - Emissivity, $\varepsilon = 0.02$.
- Payload tube ($\varepsilon = 0.1$) to chamber,
  $\tau = 1.5 \times 10^5$ s.
- Chamber to metering structure ($\varepsilon = 1$),
  $\tau = 1.4 \times 10^5$ s.
- Chamber to TFG plate ($\varepsilon = 1$),
  $\tau = 5.5 \times 10^5$ s.

Thermal leaks

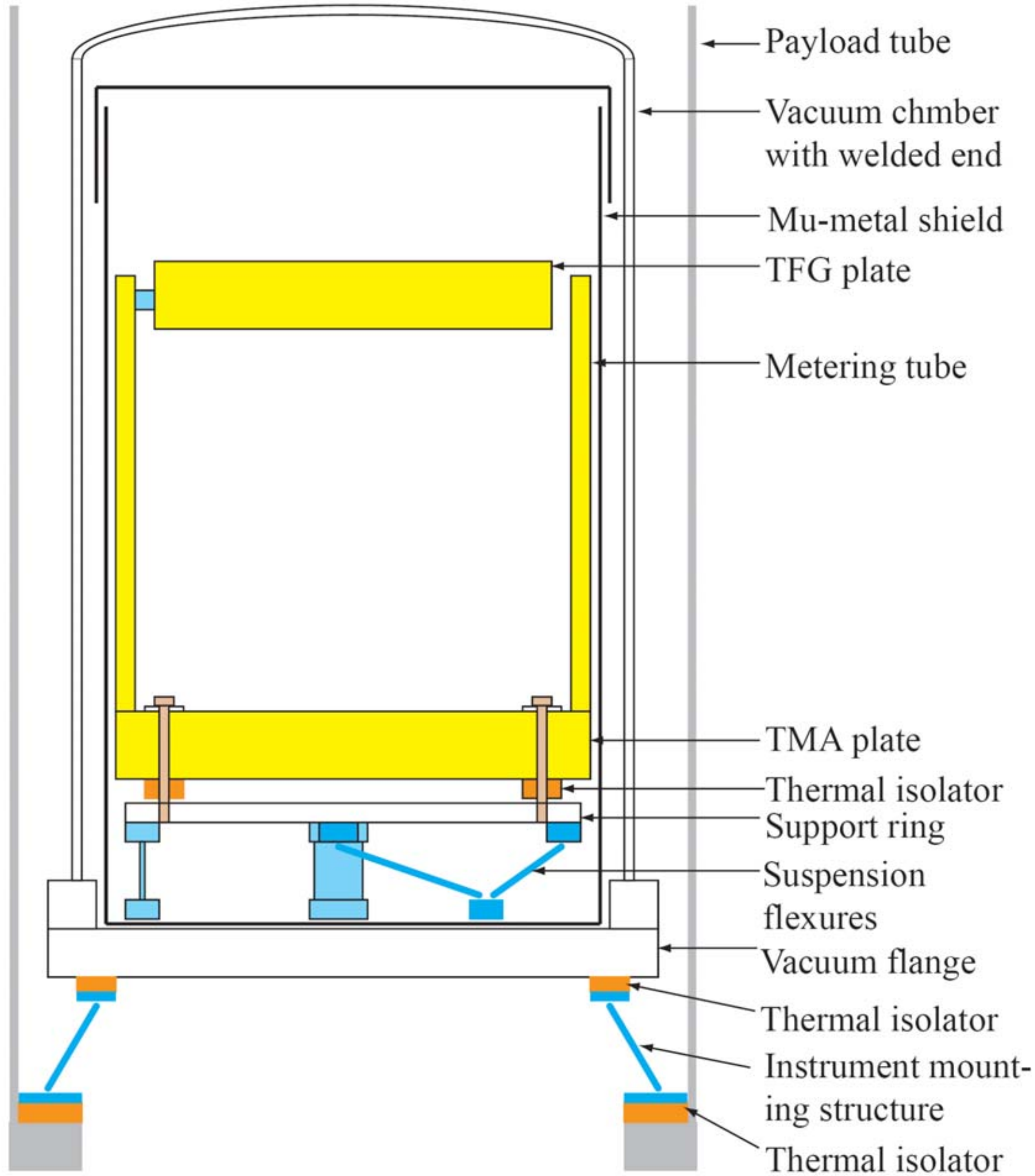
Vacuum flange to TMA plate, radiative: 6 mW/K

Support ring to TMA plate, conductive: 56 mW/K

Vacuum flange to support ring, conductive: similar

Vacuum flange to TMA plate, total: 34 mW/K ($\tau=10^5$ s)

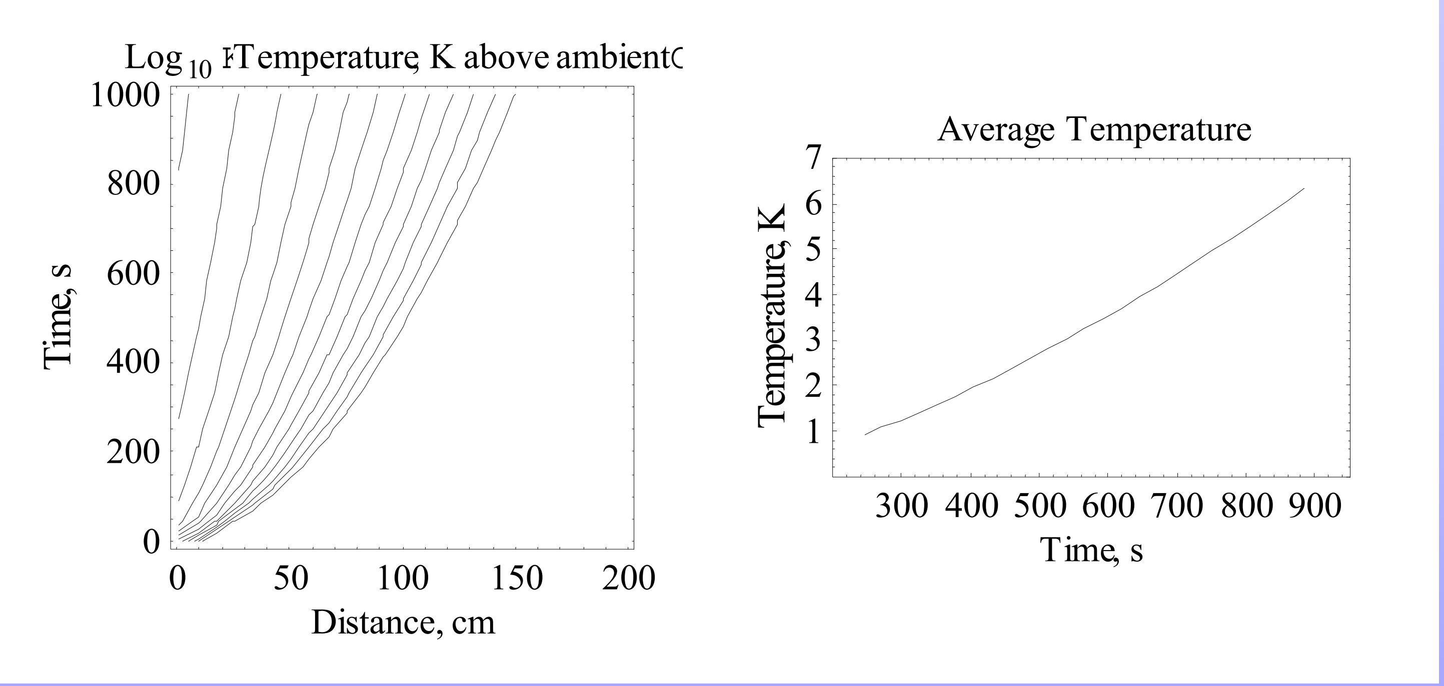
Cables?



Indirect Thermal Effect
Largest sources

- Heat pulse from hot skins
  - Skins typically increase ≈ 130 K.
  - Skins are insulated, and ejected after ≈ 100 s.
  - Increase in temperature of 14 inch tube ≈ 1 K.
- Radiative cooling at 4mK/s for 1000 s.
  - Inversions expose one side of payload to warm Earth, decreasing cooling on two sides by 0.1 K over 500 s of experiment.
- Electronics (transmitter) heating payload.
  - Typical transmitter heat rise ≈ 0.04 K/s.

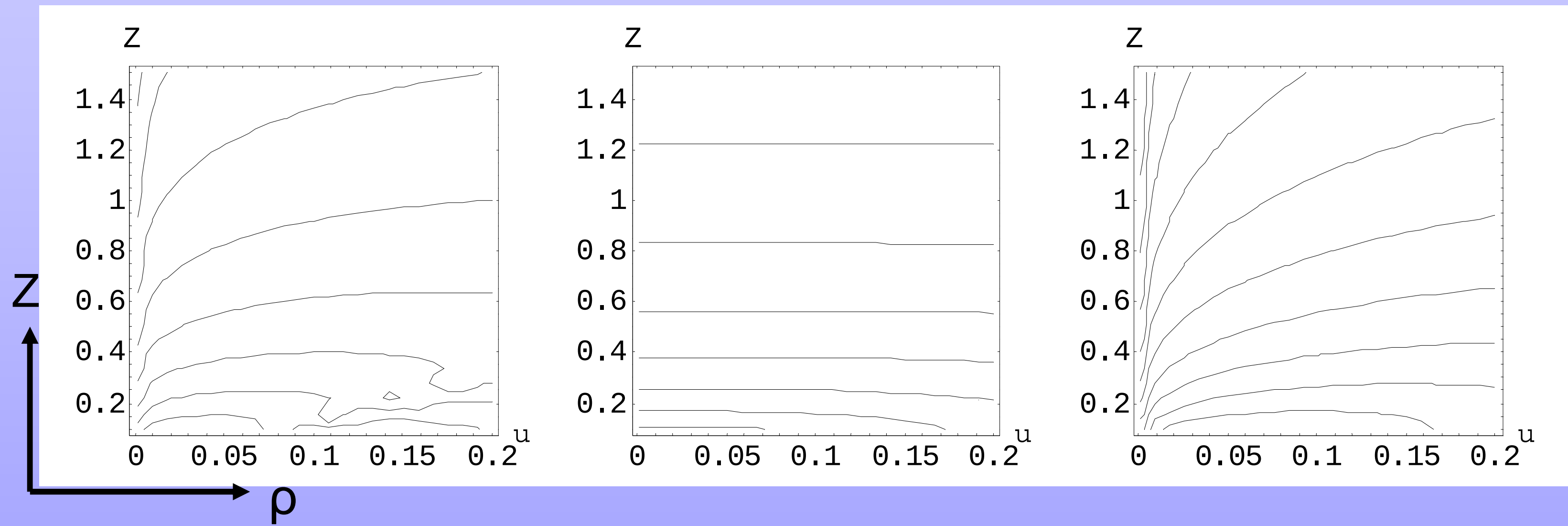
Effect of Transmitter Heating



Solution of heat equation for a 2 m payload tube with one end ramping at 0.04 K/s. Assumes entire shelf at temperature of transmitter and no isolation between electronics shelf and tube.

Contours of Log_{10} $(T-T_0)$ are from 1.5 to -4 in steps of 0.5

WEP-Mimicking Acceleration in “g” from a Displacement by 10 μm of a 10 kg Mass



Displacement in radial direction, contours from 10^{-13} to 10^{-20}

Displacement in azimuthal direction, contours from 10^{-16} to 10^{-22}.

Displacement in the z direction, contours from 10^{-13} to 10^{-22} .

ρ-z plane chosen with azimuth (45 deg) that yields largest effect.

Effect of Transmitter Heat

- During the measurement phase, 1 m of tube will warm by ≈ 6 K, nearly linearly with time.
- CTE(Al) is 23 x 10^{-6} / K.
- Expansion ≈ 138 micron.
- Mass of transmitter section ≈ 36 kg.
- Assume 5 cm off center and 1.5 m from TMA.
- $\Delta(\eta) \approx 1.4 \times 10^{-18}$ before cancellation by inversion.
  - Further, tube could be insulated from shelf.

Earth's Gravity Gradient

at 1000 km altitude

- For TMA 1 cm (z) from payload CM plane, TMA move 16 μm in 40 s. (2×10^{-8} ms^{-2} = $2.7 \times 10^{-9} g_h$)
- For TMA 6 cm radially (ρ) from payload cm, TMA move (inward) 48 μm in 40 s. (6×10^{-8} ms^{-2})
- These motions are very predictable and change slowly with payload trajectory.
- Symmetry: rising vs falling part of trajectory.

Why Does SR-POEM Work?

- TFG supports quick measurements.
  - 0.1 pm/√Hz – requires development.
- Thermally benign environment.
- Double difference observable.
  - Symmetry maintained.
- Payload inversions.
  - Cancel systematic errors.

Concluding Comments

- Goal: $\sigma(\eta) \leq 10^{-16}$ for single pair of substances.
- Sounding rocket experiment is low in cost.
  - Additional flights could test other substances.

If the sounding rocket had launched at the start of this talk, the experiment would be over now!

We are planning to have three post docs work with us on SR-POEM. We have so far made two offers that have been accepted and are looking for a third person.

http://www.cfa.harvard.edu/PAG

Papers and sounding-rocket proposal available.

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