The Stanford Gravitational Reference Sensor

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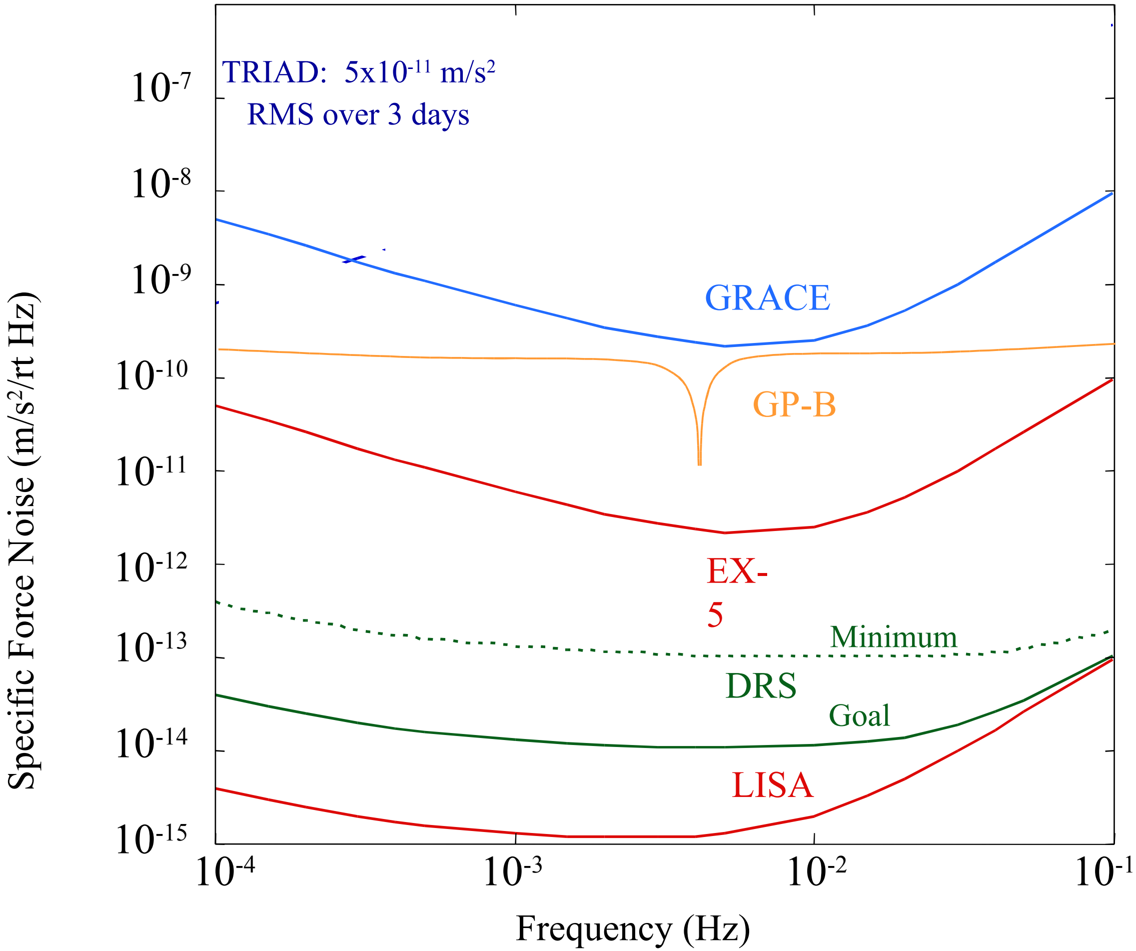
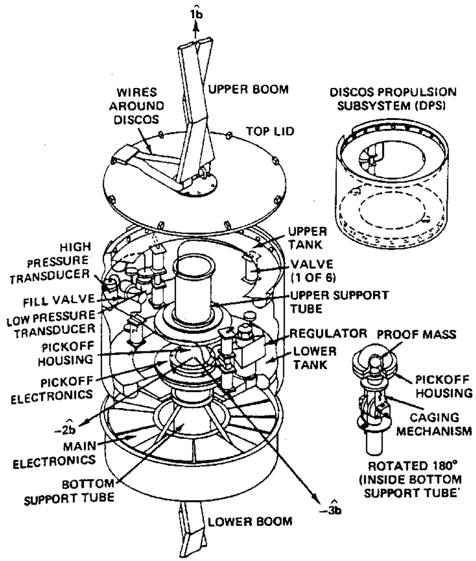
Mission Drag-Free Requirements



Heritage

- Inertial Sensor based on Stanford experience:
  TRIAD (Stanford/APL, 1972)
  GP-B (Stanford, 2004)

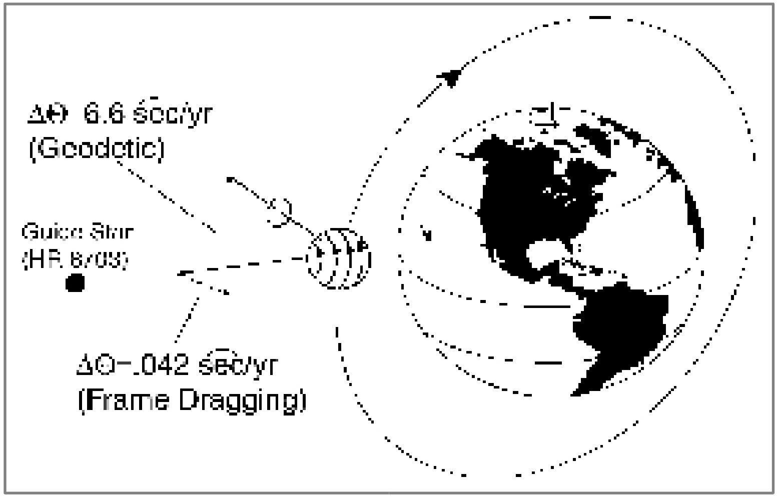
- Earlier sensors used spherical test masses
  Fewer degrees of freedom to control
- Proposed LISA sensor uses a faceted test mass
  Control position of laser beam on test mass
  Allows validation at picometer level
- Test mass is 4-cm cube of Au/Pt alloy
  Dense, to reduce motion in response to forces
  Low magnetic susceptibility, used on TRIAD
- Position sensing and charge management design derived from GP-B



TRIAD sensor- 1972

GP-B Flight Gyroscope

GP-B Launch: April 20, 2004



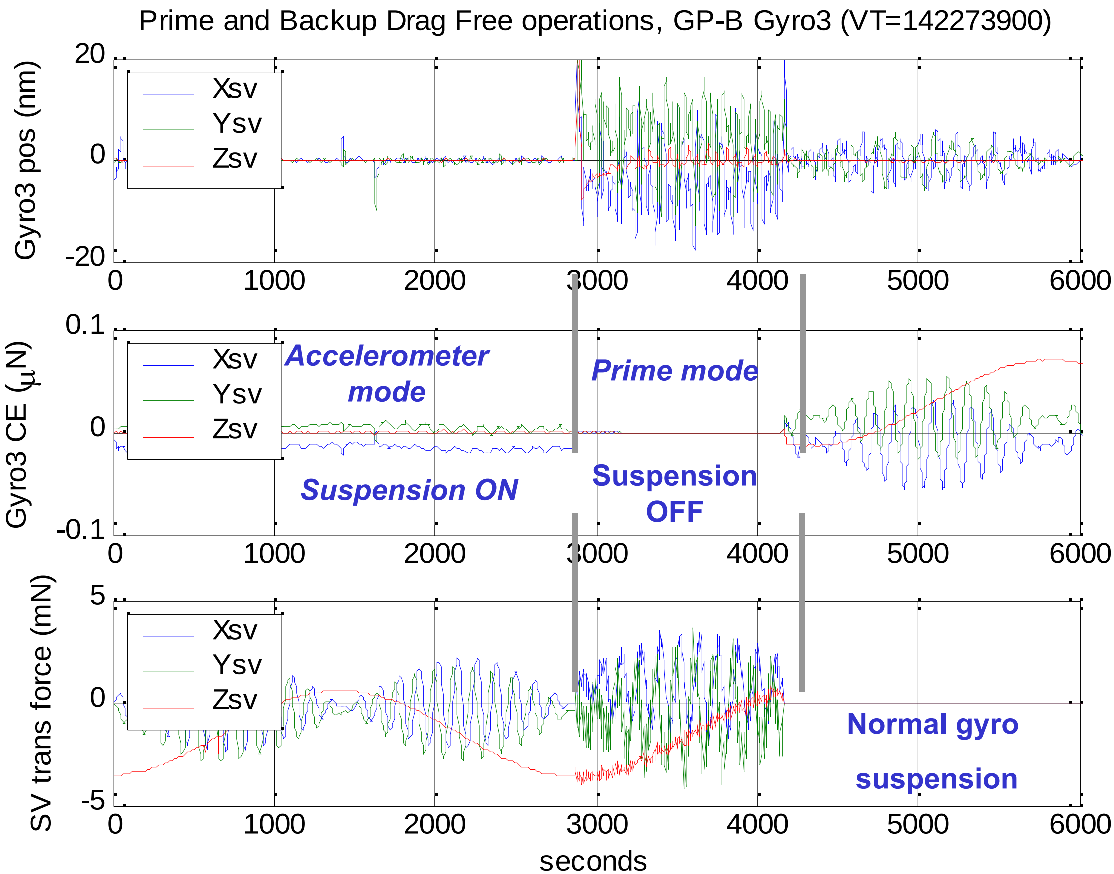
$$\Omega = \left(\gamma + \frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\vec{R}\times\vec{v}\right) + \left(\gamma + 1 + \frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\vec{R}}{R^2}\left(\vec{\omega}_e\cdot\vec{R}\right) - \vec{\omega}_e\right]$$

GP-B Technologies

30 years of GRS technology development for TRIAD and GP-B are a very significant stepping stone.
GP-B has showed on-orbit validation of key GRS technologies.

- Drag-free Control — 10^{-10} m/s^2 level
- Electrostatic Positioning System — 0.45 nm rms position noise
- Charge Control System — < 5pC control

Drag Free Performance



Positioning performance

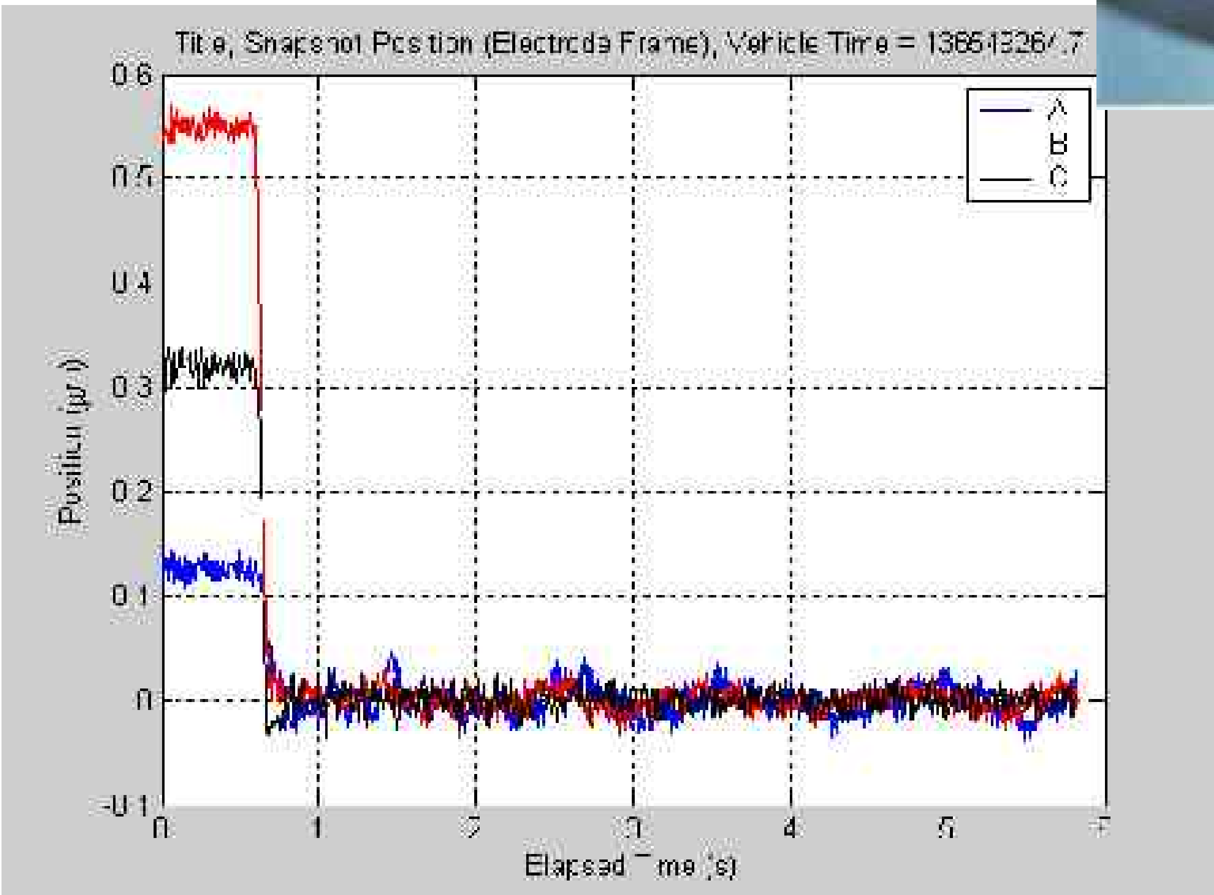
Drag-free: 5.0 nm RMS

Backup drag-free: 0.6 nm RMS

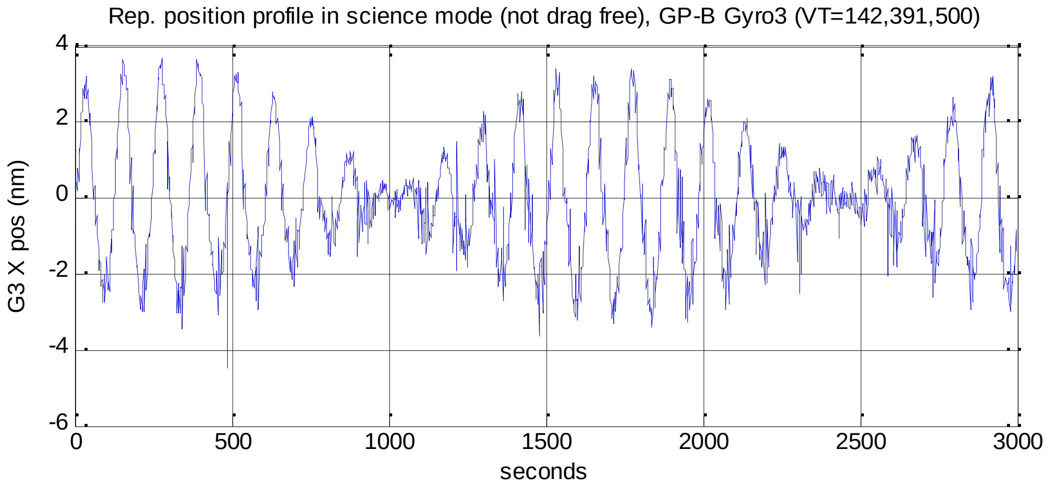
Normal suspension: 6 nm peak from gravity gradient.

GP-B Gyroscope Suspension

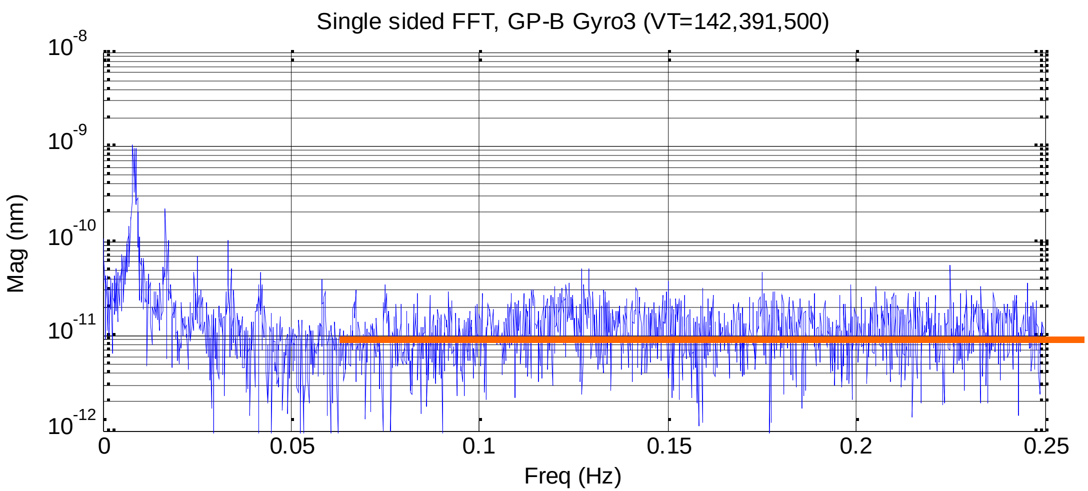
Gyro #4 Digital Levitation



Position Measurement Performance



Representative gyro position trace showing non drag-free gravity gradient effects in Science Mission Mode

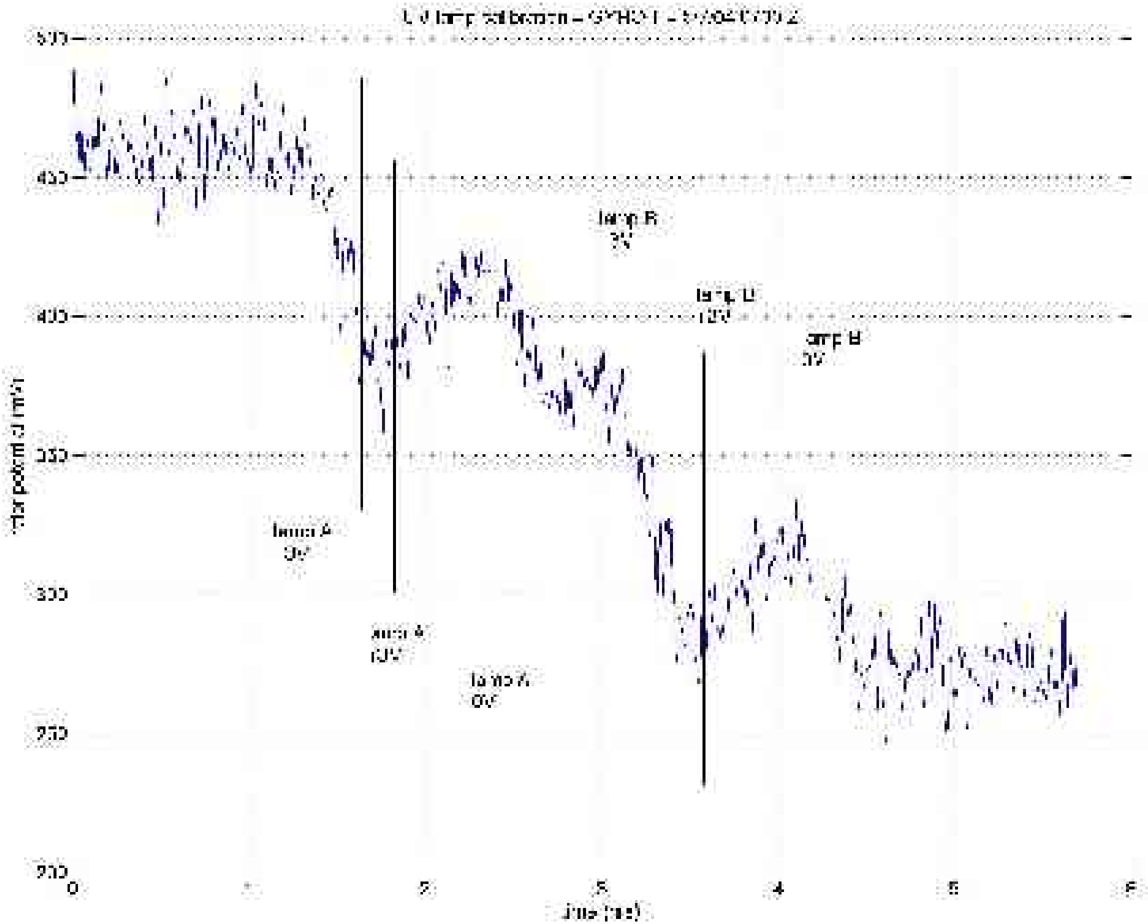


Measurement noise 0.45 nm rms

Noise floor

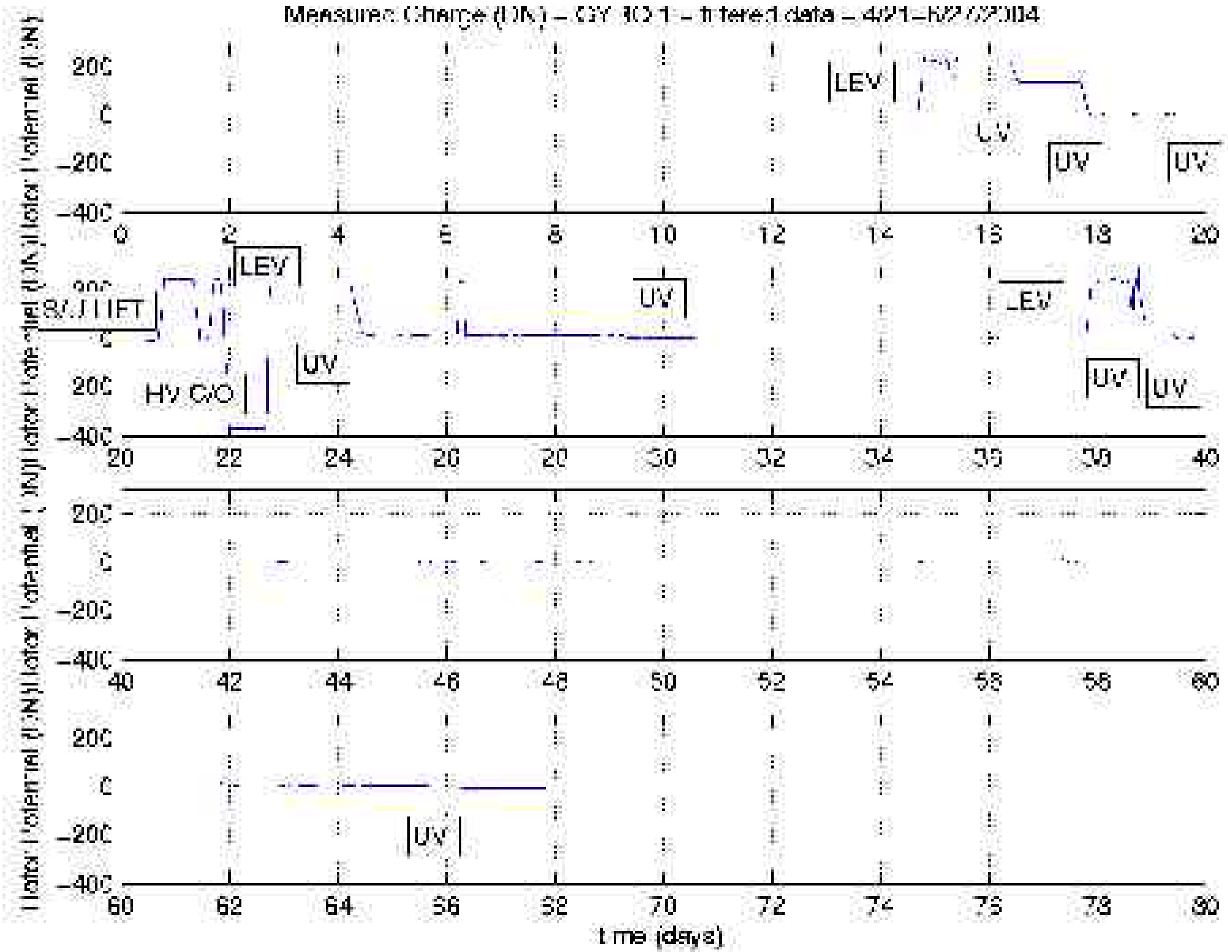
GP-B Charge Management

Gyro #1 UV System Calibration



GP-B Charge Management

Gyro #1 Charge Control (mV)

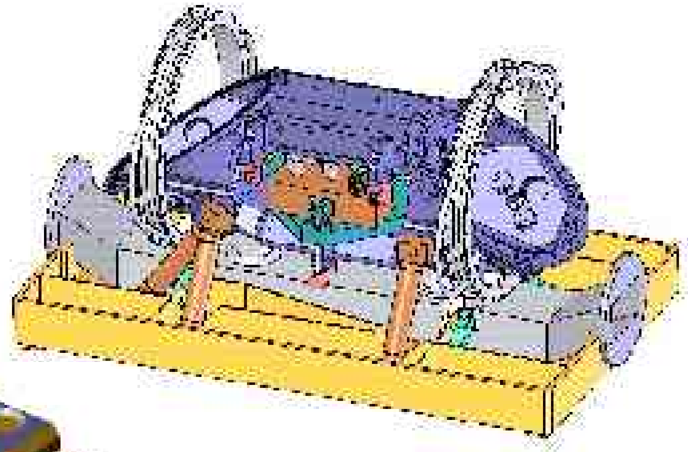


GRS Overview

Salient Features

- Test mass noise < 2.8×10^{-14} m/s^2/√Hz, 1 mHz to 30 mHz
- Position measurement to < 3 nm/√Hz, 1 mHz to 30 mHz
- Accelerometer mode
- Validation of thruster performance
- Force noise diagnostics
- Validation of drag free environment models

DRS chassis and interferometer



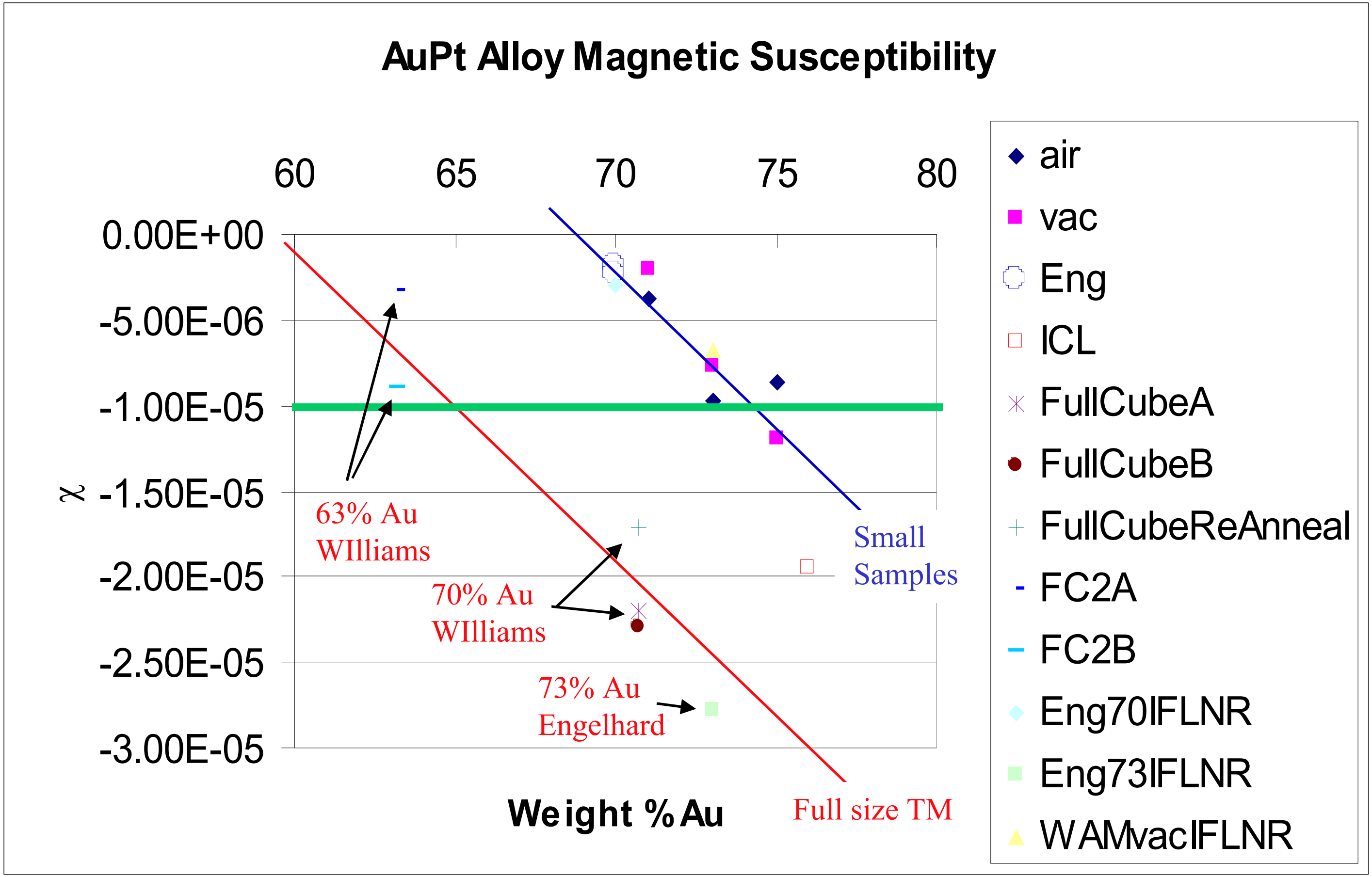
BeO Housing

Gravitational Reference Sensor Technologies

- Test mass is 4-cm cube of Au coated Au/Pt alloy
- Beryllia housing with plated Au electrodes
- Vacuum system supporting 10^{-5} Pa EOL
- Caging system capable of supporting launch loads and re-caging
- Capacitive sensing system providing < 3 nm/√Hz measurement
- Electrostatic forcing system providing 2×10^{-7} m/s^2 peak acceleration

GRS Test Mass Prototype

Test Mass Magnetic Susceptibility



Engelhard 73% material is outside current GRS requirement (green line), 2% impact to noise margin.

Precision Reference Housing

- Electrode isolation groove BeO sample end-milled at Axsys.
- Stepped Precision Alignment BeO Walls.
- Bulk Precision Alignment Alumina Reference Walls.
- Precision tooling sphere demonstrated.
- 7 EM BeO housing walls received 3 weeks early.
- Alignment performance verified in test.
- Laser milling demonstrated.
- All 72 flight BeO blanks delivered by Brush Wellman on schedule.

Kelvin Probe Measurements at GSFC: Contact Potential Difference Variations

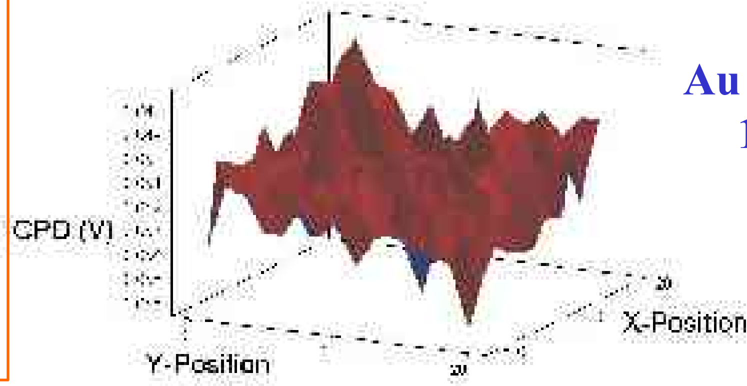
Two coatings studied: gold (Au) and diamond like carbon (DLC), to avoid cold welding when caging

3 mm probe used, 1cm x 1cm area studied

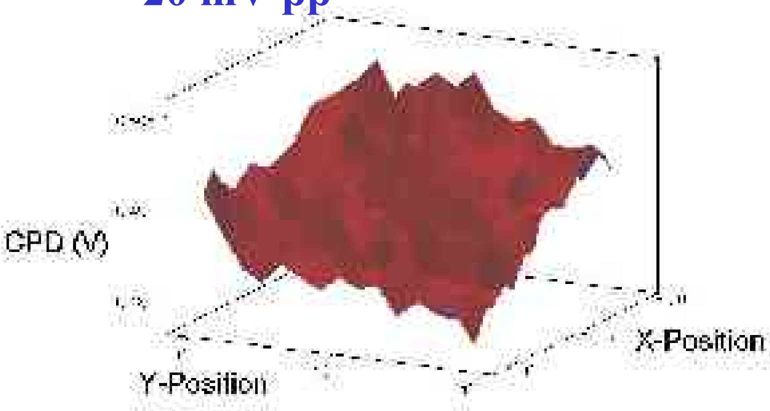
Conclusions:

- DLC essentially as good as Au
- Both meet requirements

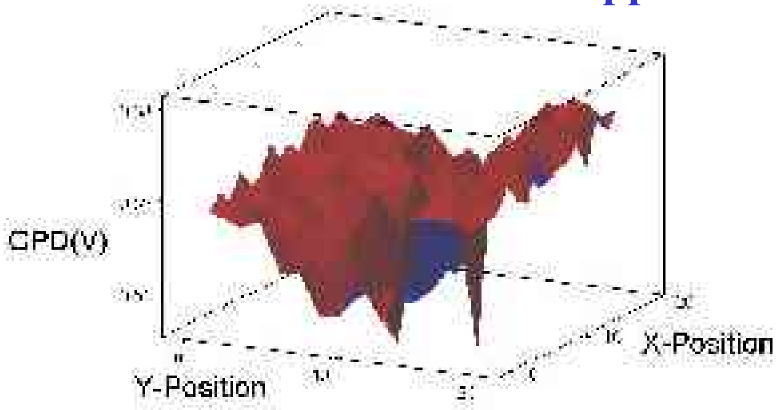
Au on Alumina
10 mV pp



DLC/Au/BeO
20 mV pp



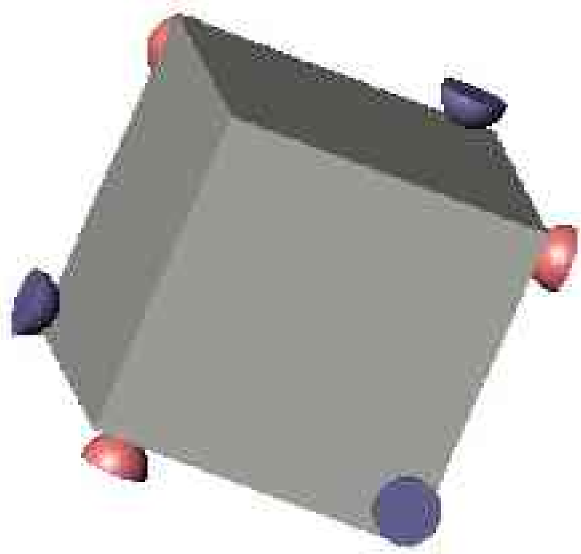
DLC/Au/Ti
20 mV pp

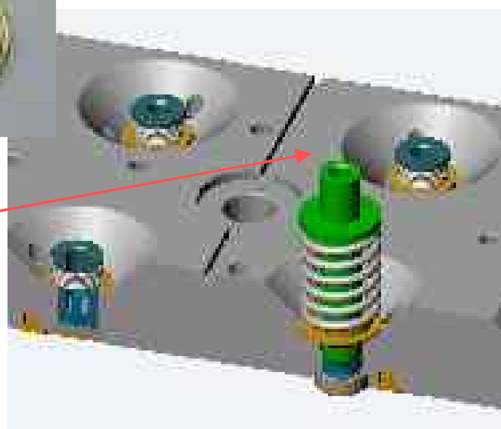


data taken in collaboration with Jordan Camp and John Blackwood, GSFC

Caging Design

- Test mass constrained by 6 travel-limited push actuators.
- Travel overlap = 0.1mm.
- Static loads taken by 3 pads + pneumatic pressure.
- Dynamic loads taken by all pads and actuator stiffness.
- Pads pivot to self-align to TM face.
- Actuators powered by central pressure supply
- Plungers normally retracted, receded 0.1mm into housing wall





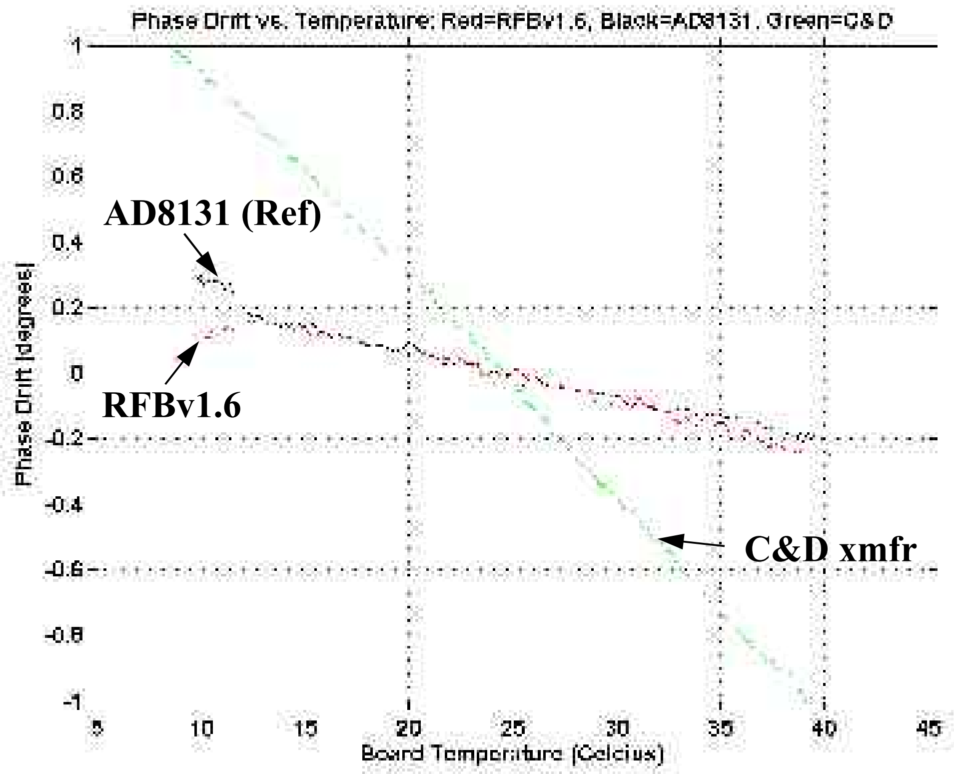
plunger unit: sits on top of pad unit

- Pads mimic wall properties: BeO, gold and DLC coatings.
- Pads are self aligning
- Pad diameter is 5mm
- Return spring provides uncaging force > 10N

Analog Electronics Testing

Eight RFB 1.6 boards populated and under test

- No PCB defects
- All analog circuits functioning as expected
- Firmware complete and digital interface tested



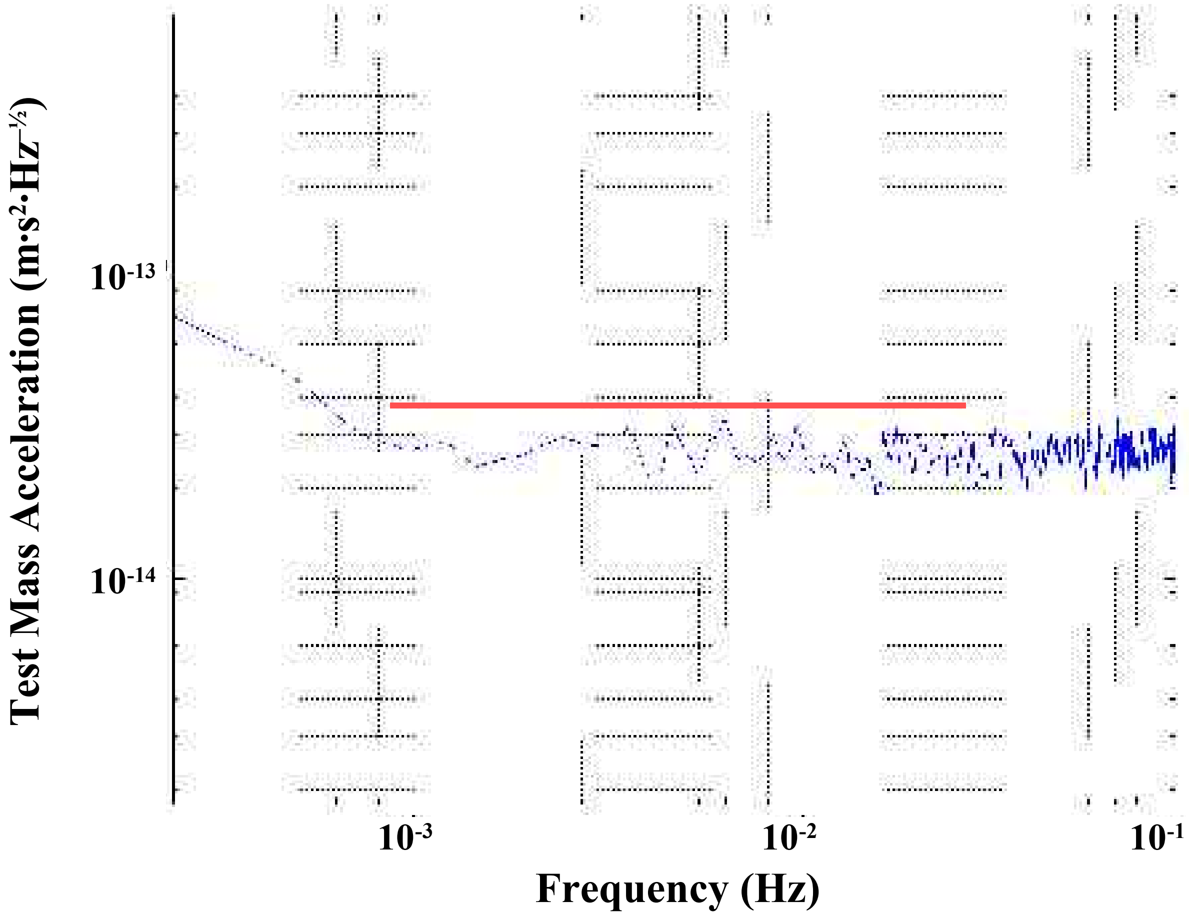
RFBv1.6 differential output driver testing shows phase temperature coefficient performance equivalent to the best commercial balanced drivers (e.g. AD8131).

Noise Budget

Source	Requirement (10^{-15} m·s^{-2}·Hz$^{-½}$)	CBE (10^{-15} m·s^{-2}·Hz$^{-½}$)
Coupled Spacecraft Motion (Sensitive)	14	14
Coupled Spacecraft Motion (Transverse)	3.8	3.8
Coupled Spacecraft Motion (Orientation)	4.5	4.5
ES Suspension – Backaction	10	10
Dielectric Effect	2.2	2.2
Test Mass Charge Variation	10	10
Lorentz Force	1.0	1.0
Magnetic Field Interactions	2.7	**5.4**
Housing Temperature Gradient	4.0	4.0
Residual Gas Pressure Damping	4.5	4.5
Interferometer Laser Pressure Variation	0.5	**2.6**
Time Varying Mass Attraction	10	10
Low Frequency Suspension Force	4.5	4.5
Control Force Cross-talk	2.3	2.3
Total Acceleration Noise	**24.8**	**25.2**
GRS System Margin	***13.0***	***12.1***
Level 3 Requirement	***28***	***28***

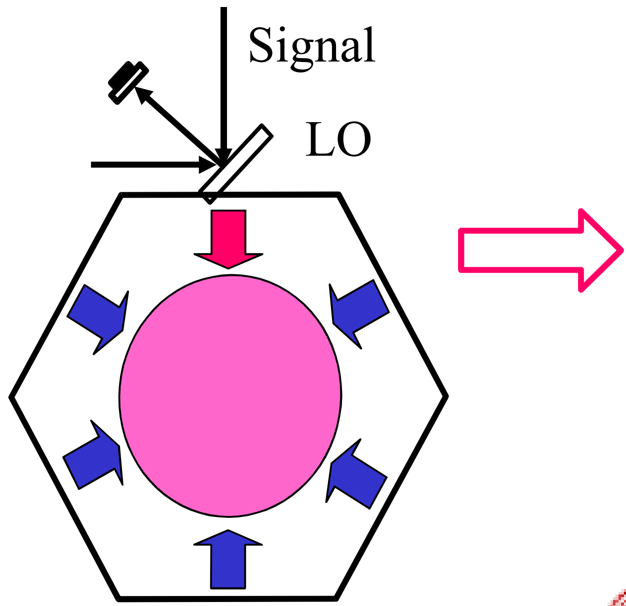
CBE = current best estimate

GRS Performance Simulation Results



Advanced Concepts - Stanford

- Single proof mass (PM) per S/C
- Non constraint GRS
- Multiple stage disturbance isolation
- Gravitational sensor separation from S/C
  Interferometry
  - Measure PM position in housing
  - Use housing for interferometry
- Fiber utilization
- Reflective Optics



GRS with double sided grating for PM and interferometer reference

GRS Path to Flight

April, 2003	GRS Established Technology Readiness Level 5
May, 2004	GRS Subsystem Critical Design Reviews
August, 2004	DRS Critical Design Review
May, 2005	GRS Delivered to JPL
January, 2006	DRS Delivered to ESA
May, 2008	LAUNCH