Testing Einstein with Orbiting Gyroscopes

[+ some remarks on STEP]

Symposium on Geometry & the Universe

Stony Brook

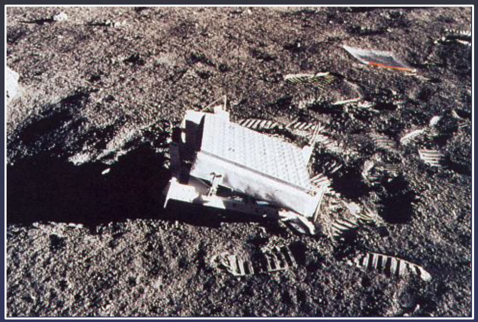
20-21 October 2005

Francis Everitt

Roadmap for a Gravity Probe

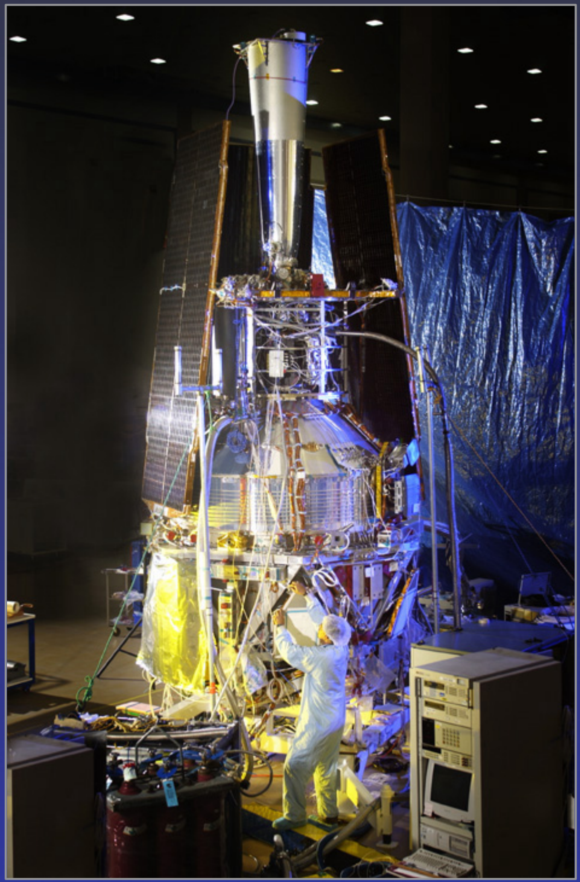
- GP-B & the drama of launch
- Basic experiment concept
- Near Zeroes & why we need them
- On-orbit
- Dither & aberration: 2 secrets of GP-B
- Calibration/verification
- Wider lessons, with some remarks on STEP

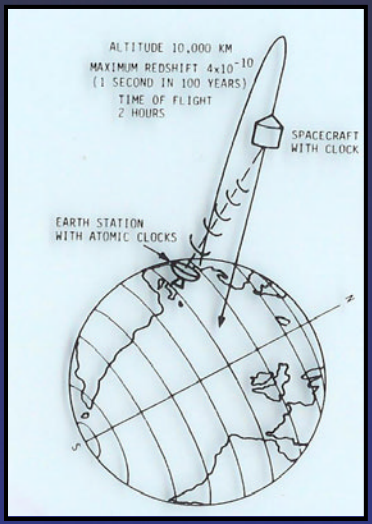
Testing Einstein – NASA's Contributions



Laser Ranging: to
reflectors on Moon (1968+)

Gravity Probe B
Two new effects with ultra-accurate gyroscopes

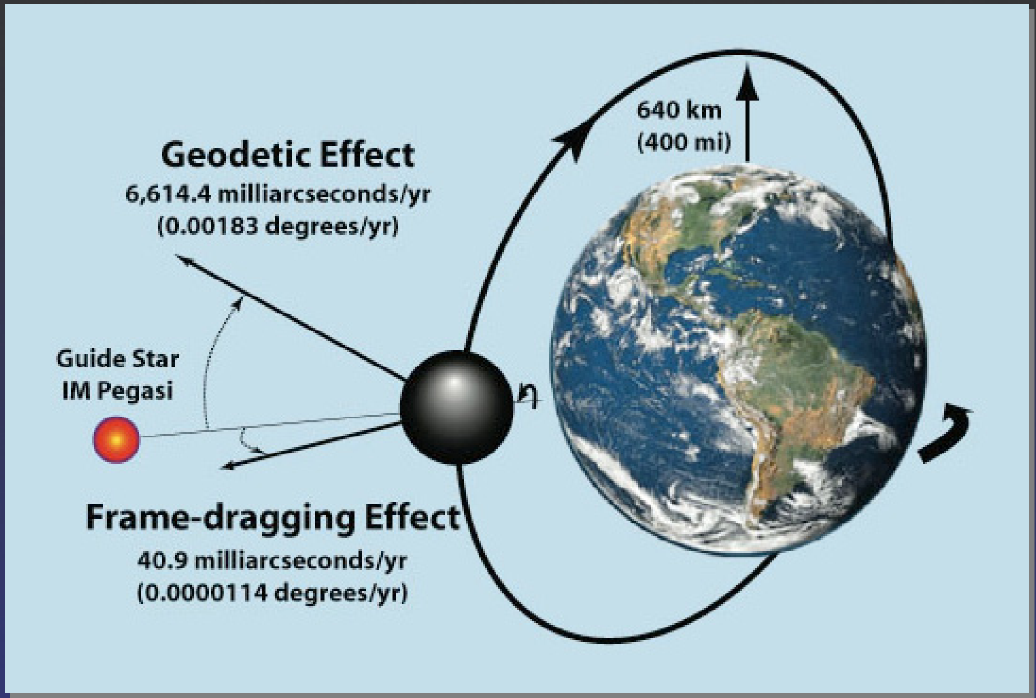




The Gravity Probe A
clock experiment (1976)

Radar Time Delay:
- to Viking Lander on Mars (1976)
- to Cassini spacecraft
  around Saturn (1999+)

The Relativity Mission Concept



"If at first the idea is not absurd, then there is no hope for it."
-- A. Einstein

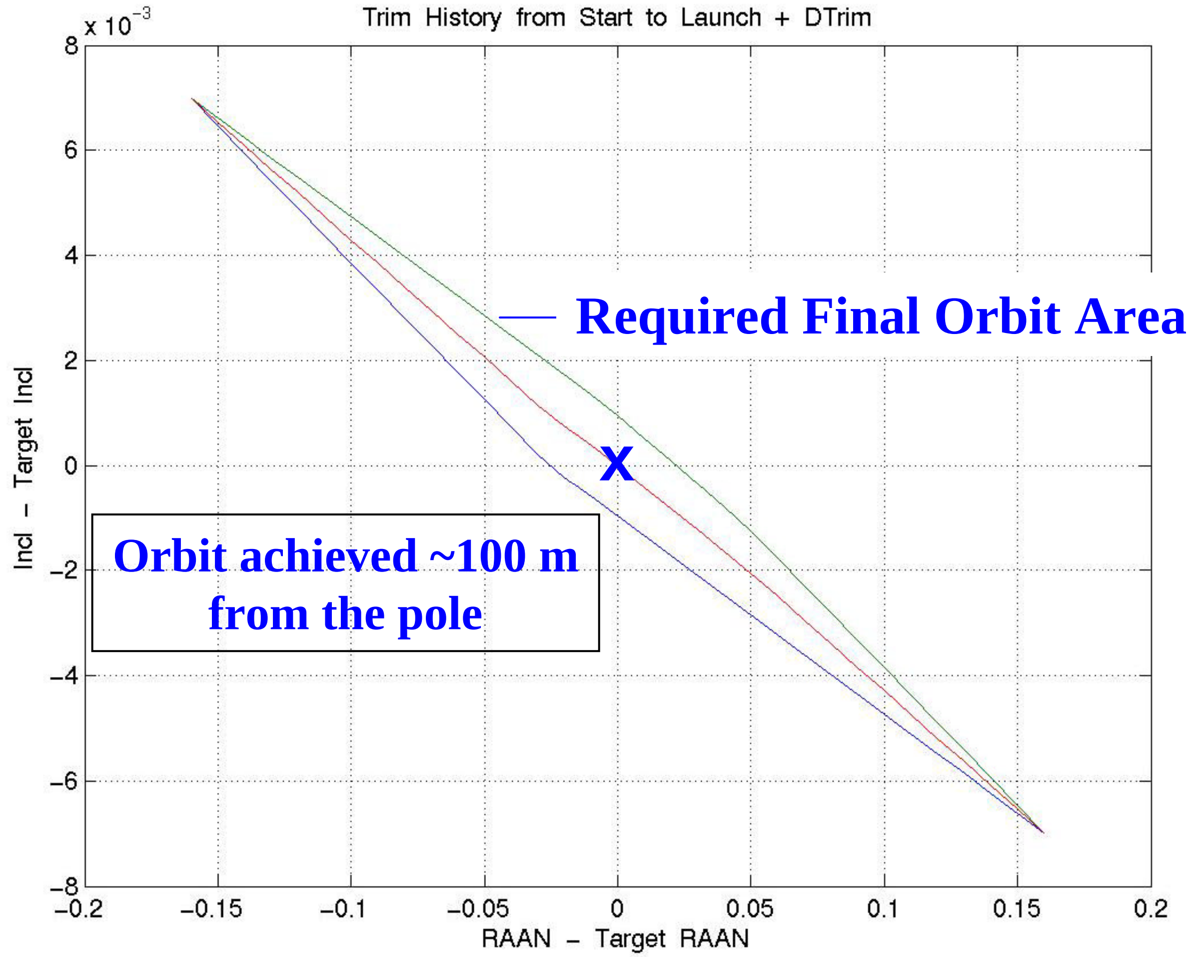
- Basic formula: *Leonard Schiff*

$$\boldsymbol{\Omega} = \frac{3GM}{2c^2R^3}(\boldsymbol{R}\times\boldsymbol{v}) + \frac{GI}{c^2R^3}\left[\frac{3\boldsymbol{R}}{R^2}(\boldsymbol{\omega}\cdot\boldsymbol{R}) - \boldsymbol{\omega}\right]$$

- Oblateness correction: ** Dan Wilkins (Physics), John Breakwell (Aero/Astro)*

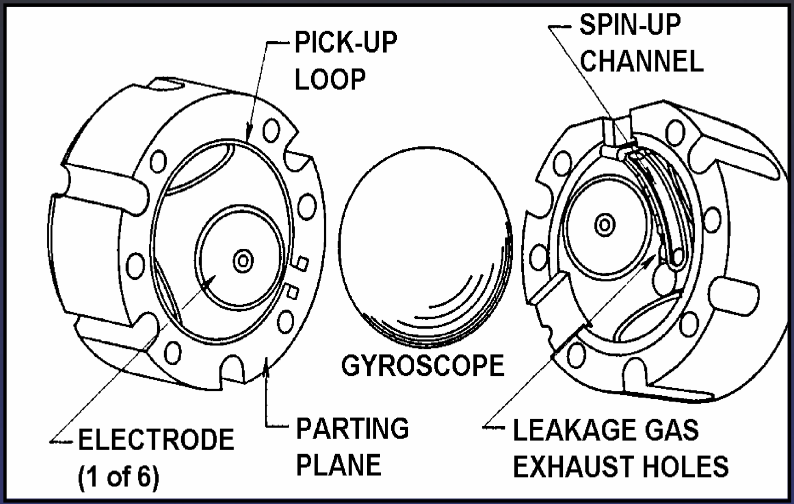
Launch: April 20, 2004 – 09:57:24

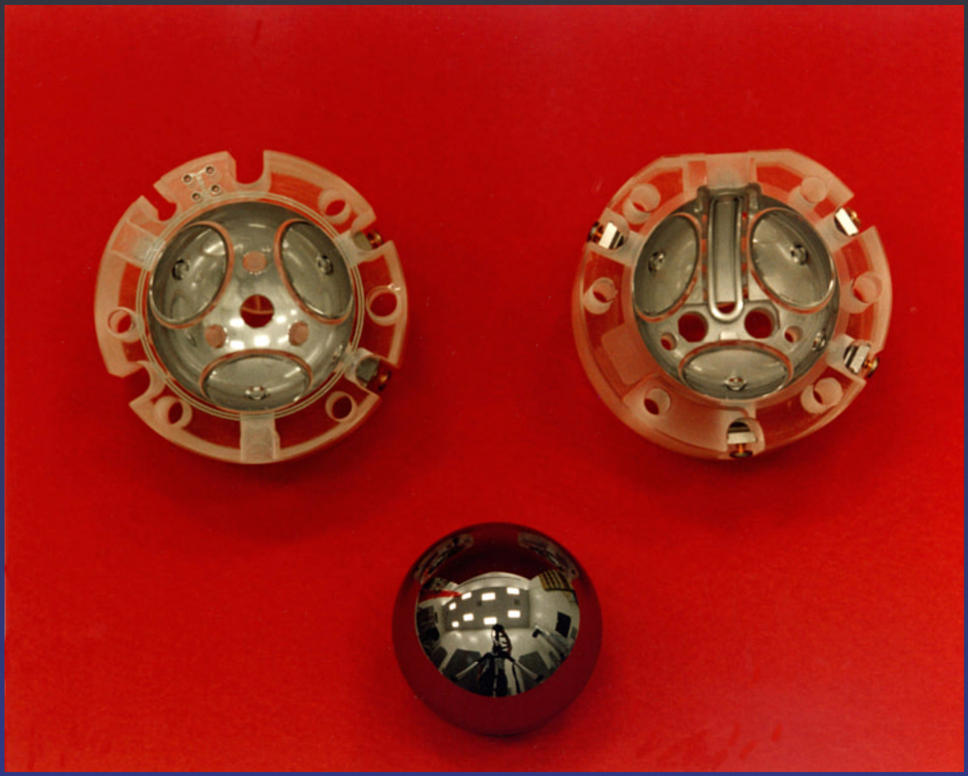
Boeing & Luck -- A Near Perfect Orbit



Delta II Nominal Accuracy

Gyro I: Overview

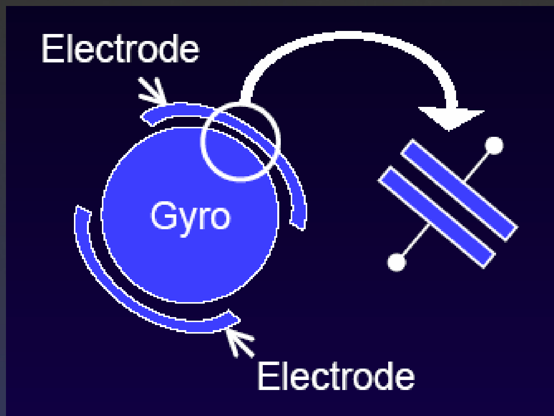




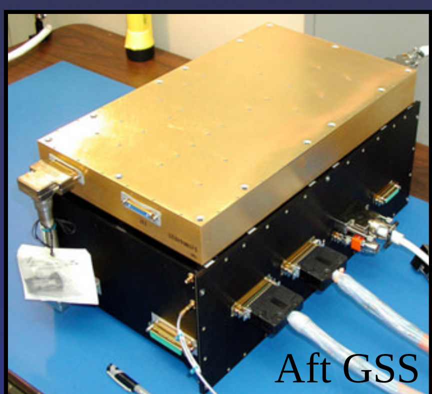
- **Electrical Suspension**
- **Gas Spin-up**
- **Magnetic Readout**

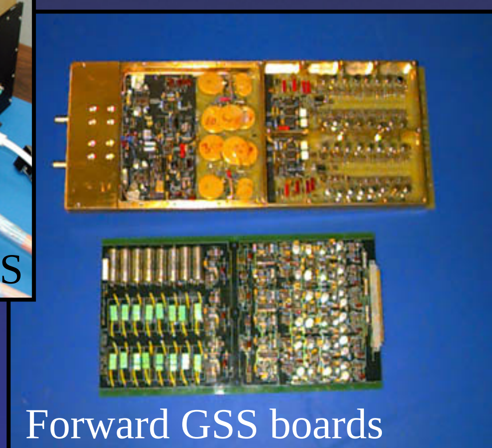
"Everything should be made as simple as possible, but not simpler."
-- A. Einstein

Gyro II: Suspension Characteristics



- Operates over 9 orders of magnitude of g levels
- Range of motion within cavity (15,000 nm) for:
  - science (centered in cavity)
  - spinup (offset to spin channel ~ 11,000 nm)
  - calibration (offset, 200 nm increments)
- Alignment (roll phased voltage variation)


Aft GSS


Forward GSS boards

Analog ground-based version:
John Nikirk, Dick Van Patten &
John Gill (Aero/Astro)

Digital flight version:
* Bill Bencze (EE) & joint Stanford-Lockheed Martin team, including
3 Aero/Astro, 2 EE PhDs &
6 undergraduates (4 departments)

Nanometer references {
- thickness of sheet of paper ~ 100,000 nm
- diameter of atom ~ .1 to .5 nm

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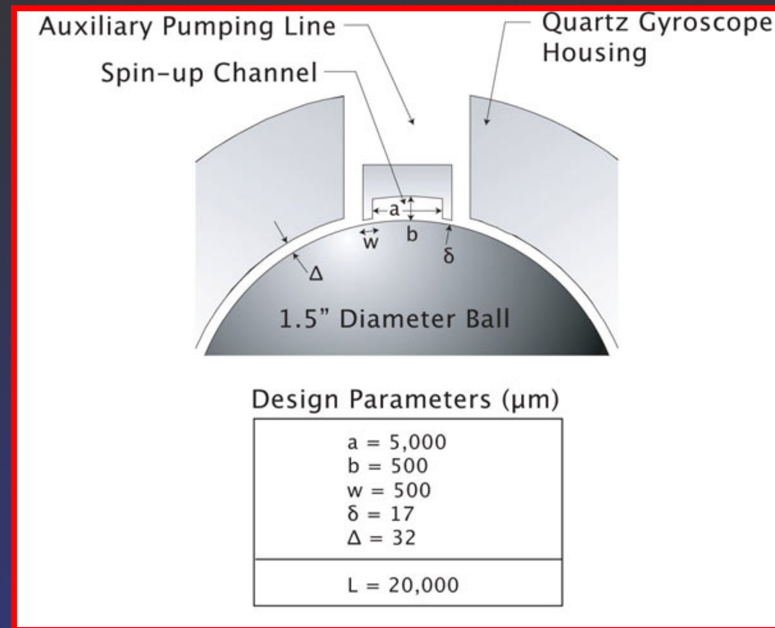
Gyro III: The Spin-up Problem(s)

Torque Switching Requirement

$T_r/T_s < \Omega_0\, t_s \sim 10^{-14}$

T_s, T_r - spin & residual cross-track torques
t_s - spin time; Ω_0 - drift requirement



Differential Pumping Requirement

spin channel ~ 10 torr (sonic velocity)

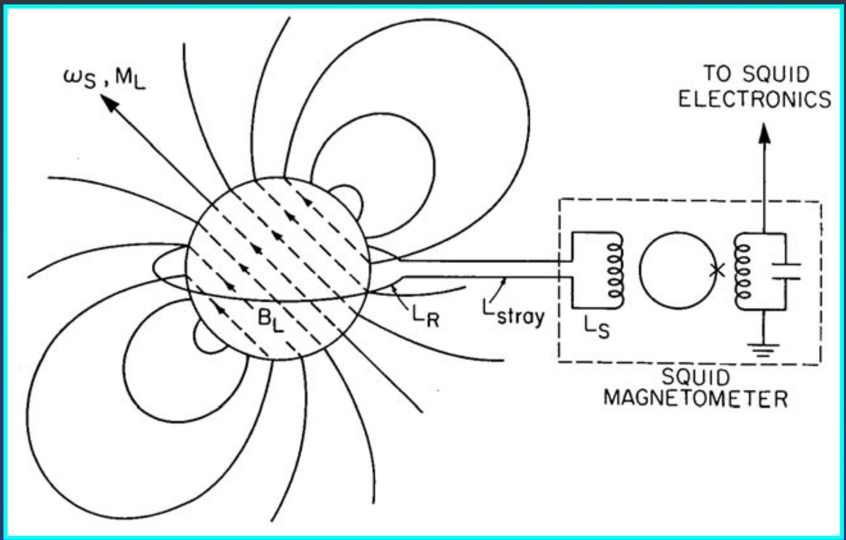
electrode area < 10^{-3} torr

➡

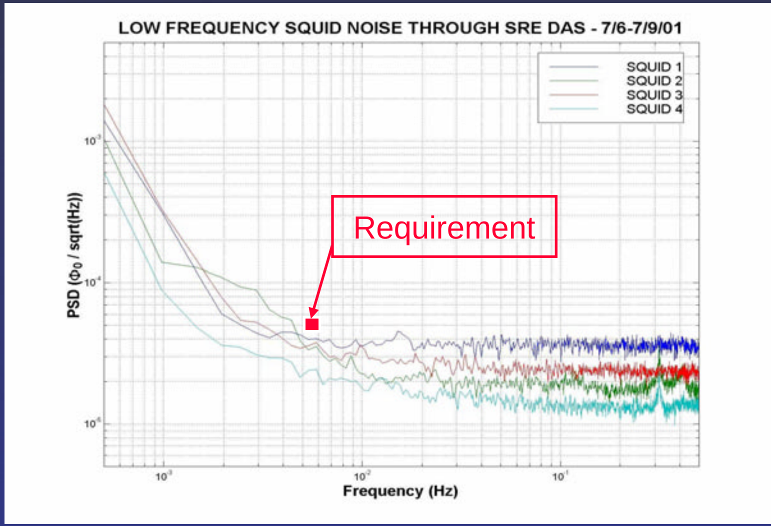
* Dan Bracken (Physics)
Don Baganoff (Aero/Astro)
+ refinements by John Lipa, John Turneaure & several students

"Any fool can get the steam into the cylinders; it takes a clever man to get it out again afterwards." -- G. J. Churchward, ~ 1895

Gyro IV: London Moment Readout



"SQUID" ⟶ 1 marc-s in 5 hours



Jim Lockhart (* Physics & SFSU)

Barry Muhlfelder (HEPL)

* Greg Gutt & * Ming Luo (EE)

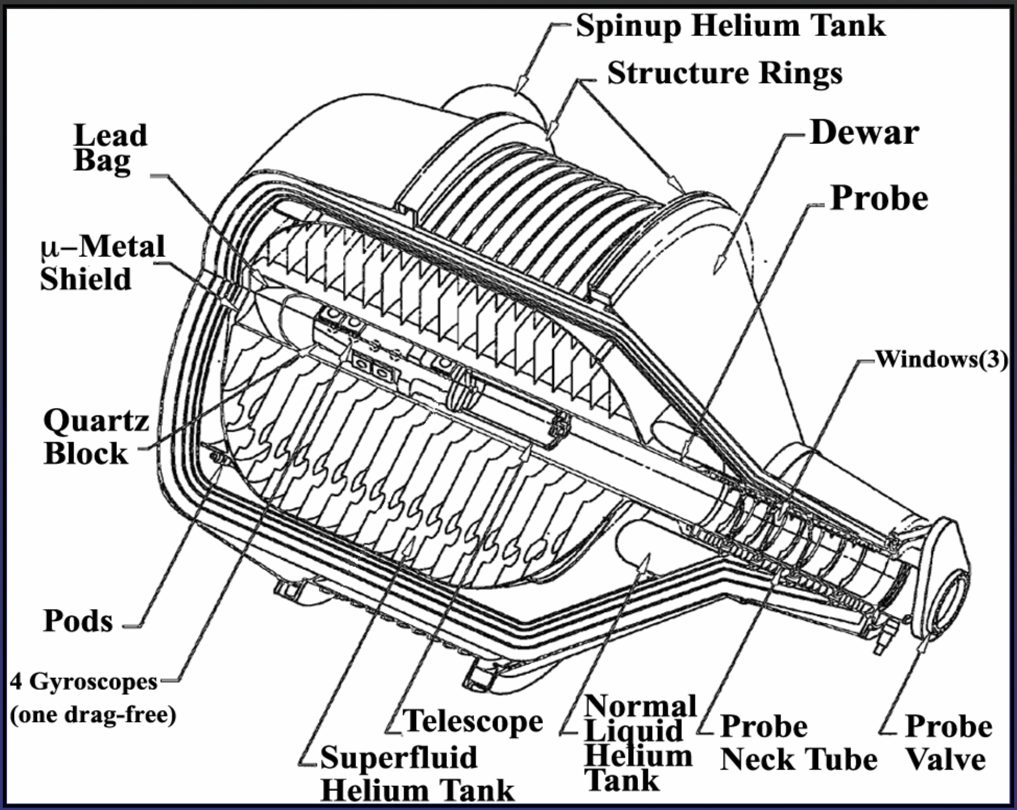
Bruce Clarke (HEPL)

Terry McGinnis (Lockheed)

+ many more

- Noise performance
- DC trapped flux < 10^{-6} gauss
- AC shielding > 10^{12}
- Centering stability < 50 nm

The GP-B Cryogenic Payload



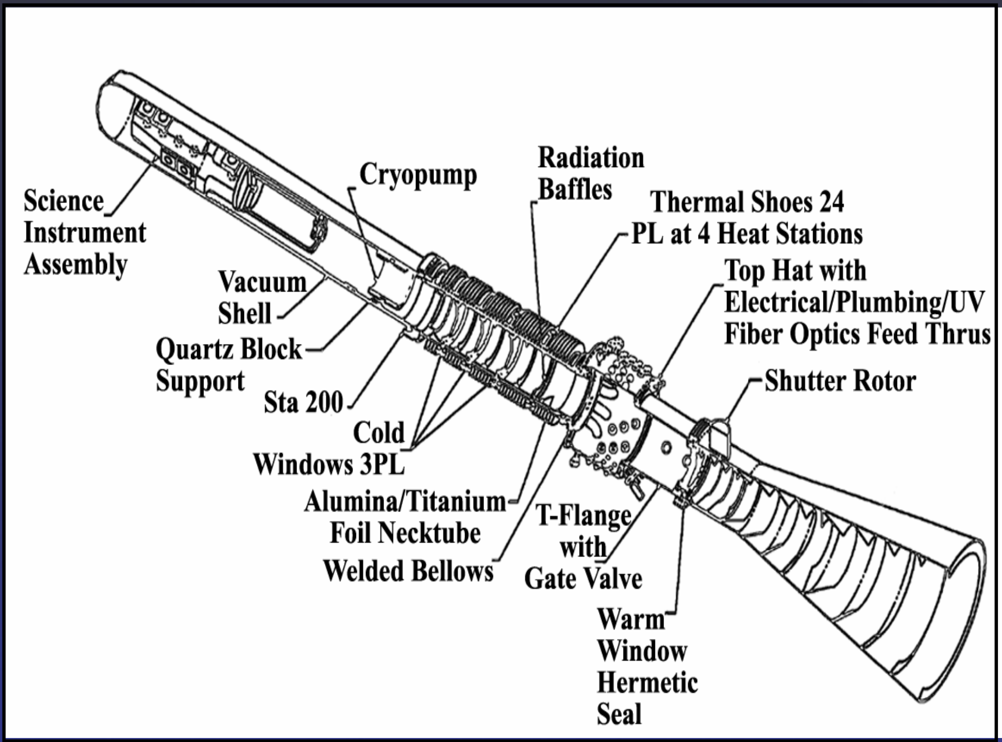
Two notable doctoral dissertations:

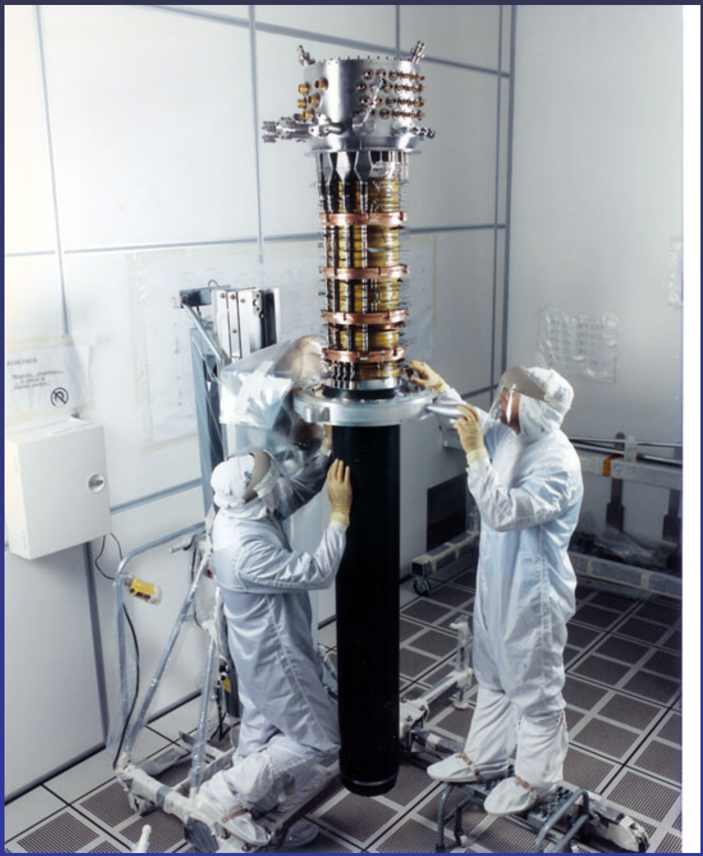
* Peter Selzer (Physics) - porous plug for space
* John McCuan (Math) - helium tidal studies

Payload in ground testing at Stanford, August 2002

The GP-B Flight Probe

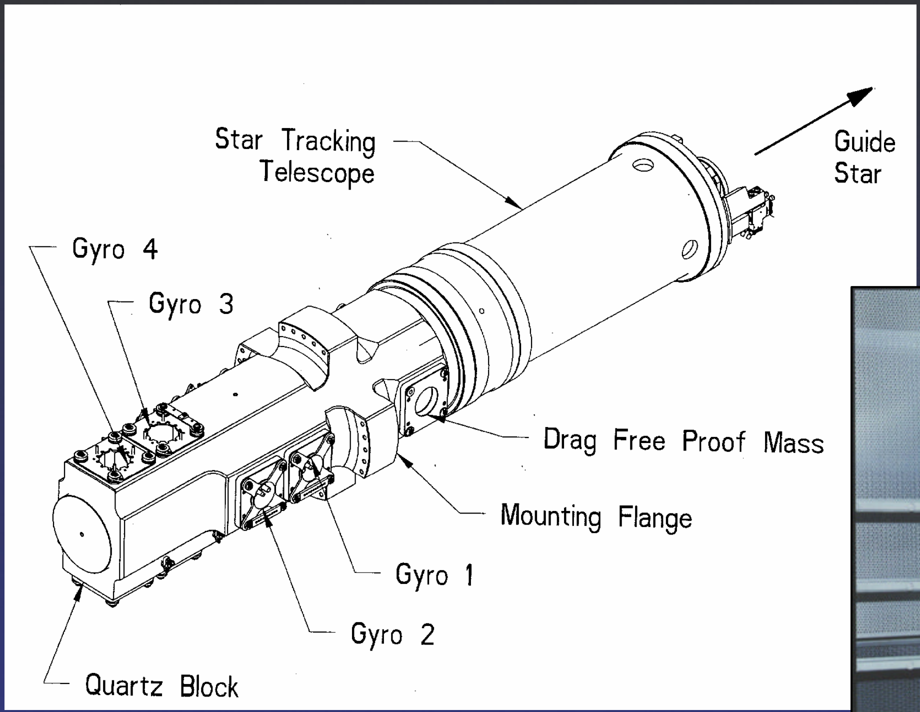
Lockheed Martin Lead: Gary Reynolds





Assembled probe at Lockheed prior to shipment to Stanford

Alignment, Bonding & Cryogenic Stability



"Design a precision apparatus as if it were made of jello – if it is stable then, it may just work."
-- H.A. Rowland, ~1900

Assembly & alignment: *Doron Bardas (Physics), * Robert Brumley (EE!)*

Silicate bonding: *Jason Gwo (Berkeley Chemistry!)*

Near Zeros & Why We Need Them

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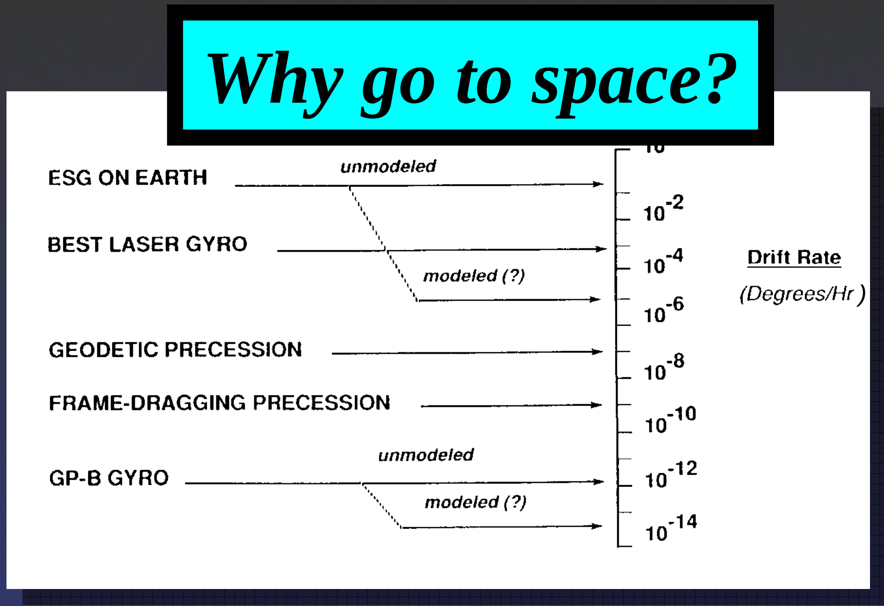
LOCKHEED MARTIN



1 marcsec/yr = 3.2 $\times$ 10^{-11} deg/hr

Six Crucial Near Zeros

1) rotor inhomogeneities
2) "drag-free"
3) rotor asphericity
4) magnetic field
5) pressure
6) electric charge

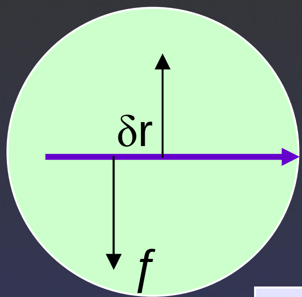
GP-B Co-PIs:

Brad Parkinson
Dan DeBra
John Turneaure

0.1 marcsec is the width of a human hair seen from 100 miles

- **Gyroscope drift**
  $\leq$ 0.05 marcsec/yr
- **Readout error effect**
  $\leq$ 0.08 marcsec/yr
- **Guide star proper motion uncertainty**
  $\leq$ 0.09 marcsec/yr

Mass-Unbalance, Drag-Free: 1st & 2nd Near Zeros



Drift-rate	$\Omega = T / I\omega_s$
Torque	$T = M f \delta r$
Moment of Inertia	$I = 2Mr^2/5$

requirement $\Omega < \Omega_0 \sim 0.1$ *marc-s/yr* (1.54×10^{-17} rad/s)

$$f \frac{\delta r}{r} < \frac{2}{5} v_s \Omega_0$$

$v_s = \omega_s r = 950$ cm/s (80 Hz)

On Earth (f = g)	$\frac{\delta r}{r} < 5.8 \times 10^{-18}$ *(ridiculous)*
Standard satellite ($f \sim 10^{-8}$ g)	$\frac{\delta r}{r} < 5.8 \times 10^{-10}$ *(unlikely)*
GP-B drag-free ($f \sim 10^{-12}$ g cross- track average)	$\frac{\delta r}{r} < 5.8 \times 10^{-6}$ *(straightforward)*

GP-B rotor $\frac{\delta r}{r} \sim 3 \times 10^{-7}$

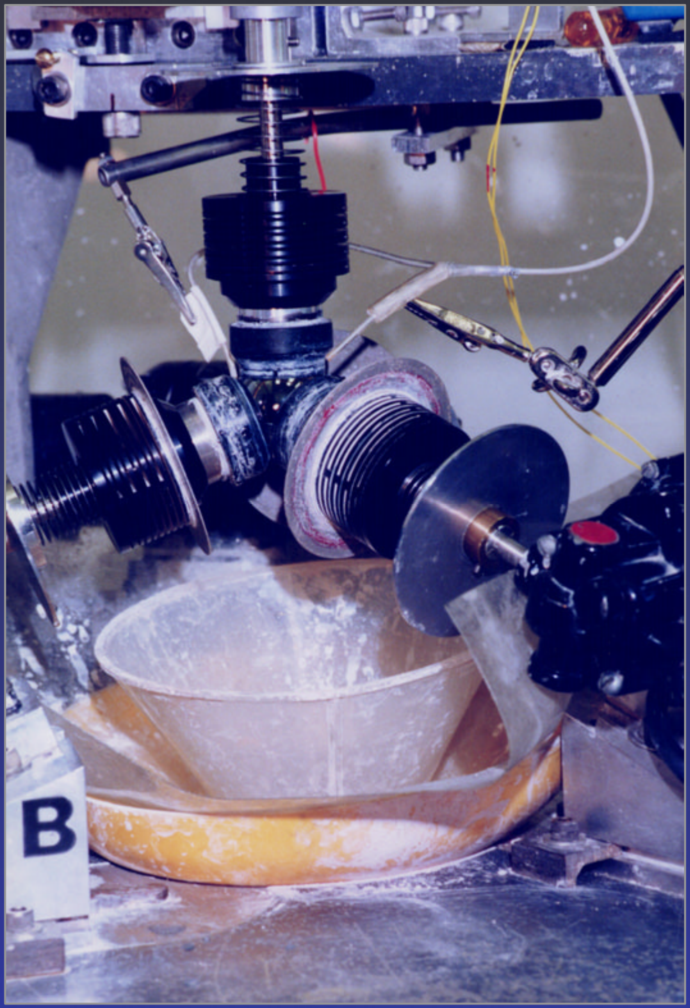
drift-rate for the drag-free GP-B < 0.01 marc-s/yr

Drag-free eliminates mass-unbalance torque -- and key to understanding/quantification of other support torques

Asphericity: 3^{rd} Near Zero -- Making

- Self-aligning laps
- Uniform rotation-rate, pressure
- 6 combinations of directions, reversed 2 & 2 every 6 seconds
- Continuous-feed lapping compound
- Controlled pH
- Interested, skilled operators!

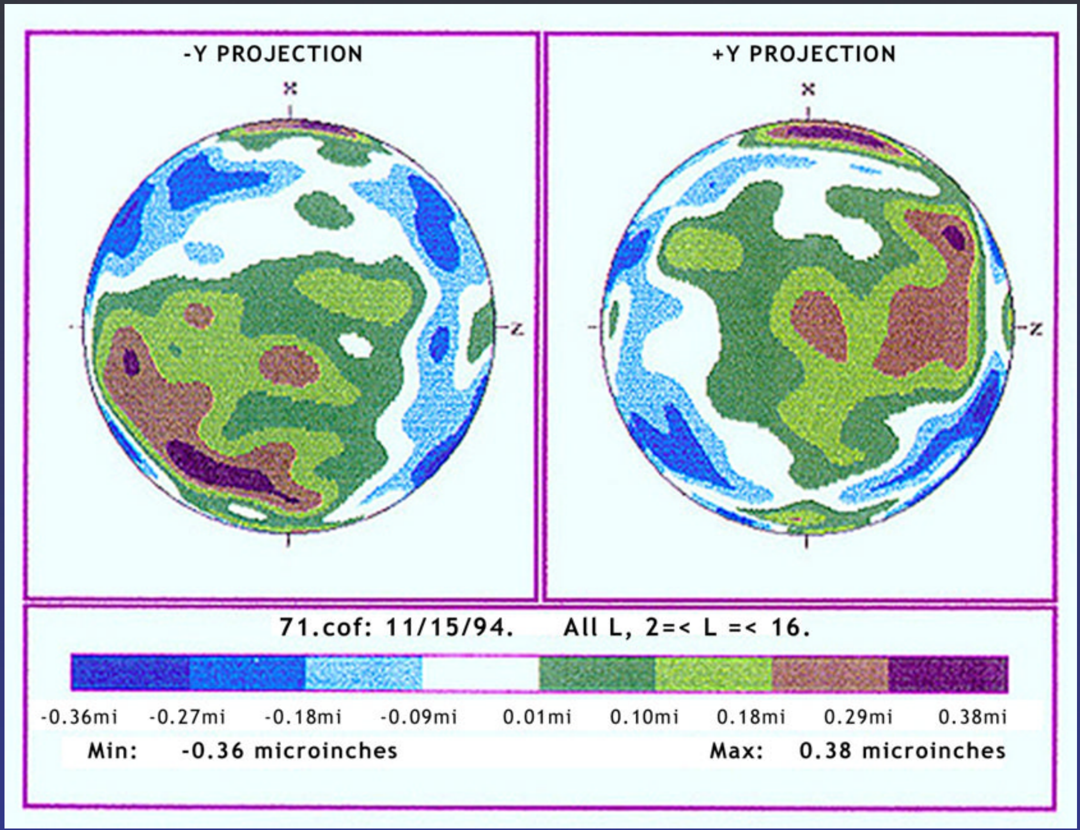
MSFC	STANFORD
Wilhelm Angele	Thorwald van Hooydonk
John Rasquin	Frane Marcelja
Ed White	Victor Graham (visitor)



Asphericity: 3rd Near Zero -- Measuring

Students 1988 - 1992

* Grace Chang (A/A)
* Rebecca Eades (Math)
* Benjamin Lutch (undeclared)
* Dave Schleicher (Comp Sci)
* Dieter Schwarz (EE)
* Michael Bleckman (Hamburg)
* Christoph Willsch (Göttingen)

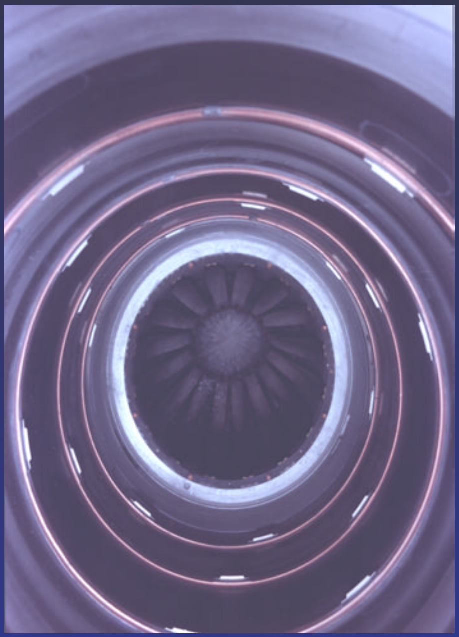


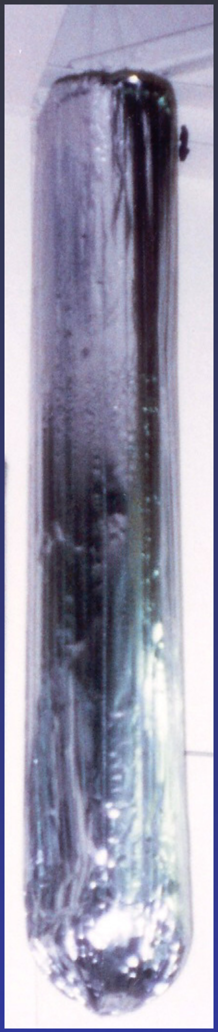
Roundness Measurement to ~ 1 nm

Ultra-low Magnetic Field: 4th Near Zero

Superconducting Lead Bag Technology

- flux = field x area
- successive expansions
  ➡ stable field levels ~ 10^{-7} gauss
- 10^{-12} [=120 dB!] ac shielding through combination of cryoperm, lead bag, local superconducting shields & symmetry





* Blas Cabrera (1976 Physics PhD)

Dewar bag
Jim Lockhart (* Physics, SFSU),
Mike Taber (* Physics, HEPL),
Chuck Warren, Dave Murray

Magnetic material testing
John Mester, Grace Brauer

On-Orbit: GP-B Mission Operations

Program Manager – Gaylord Green

Anomaly Room

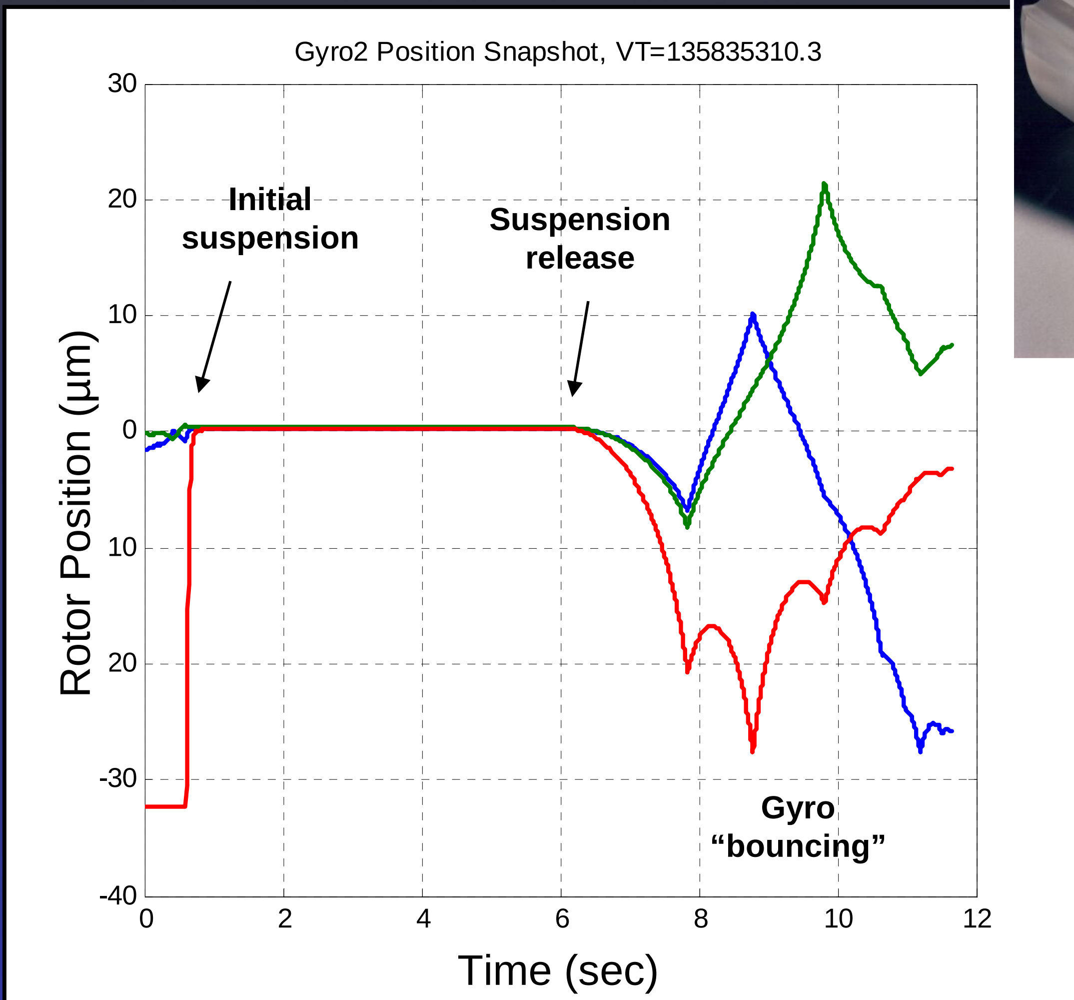
Mission Operations Center

Marcie Smith (NASA Ames)
Kim Nevitt (NASA MSFC)
Rob Nevitt (NavAstro)
Brett Stroozas (NavAstro)
Lewis Wooten (NASA MSFC)
Ric Campo (Lockheed Martin)
Jerry Aguinado (LM)

+ many more

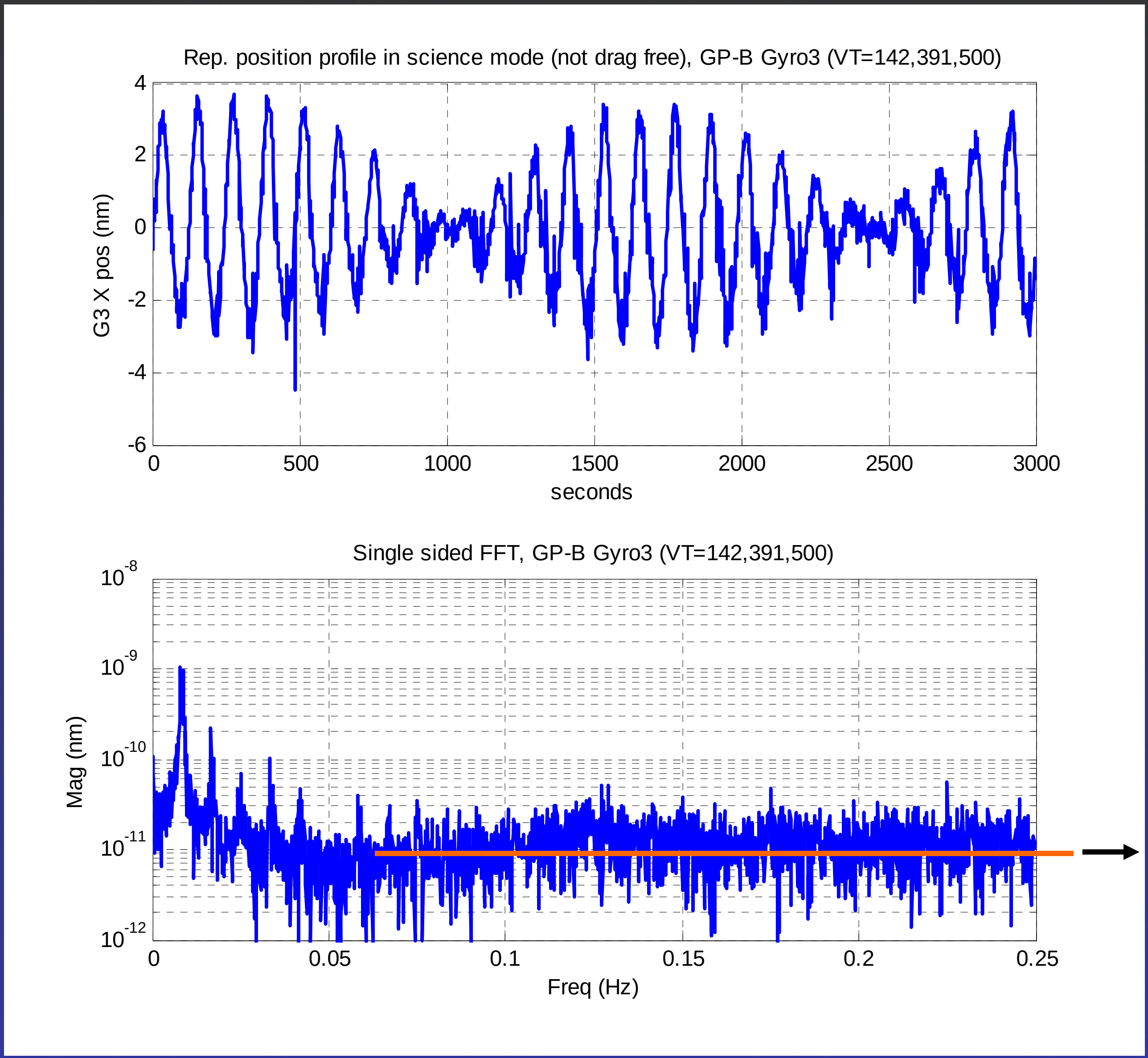
GP-B Gyro On-Orbit Initial Liftoff

Initial Gyro Levitation and De-levitation using analog backup system



David Hipkins (HEPL)
* Yoshimi Ohshima (A/A)
Steve Larsen (LM)
Colin Perry (LM)
+ many more!

Suspension Performance On-Orbit

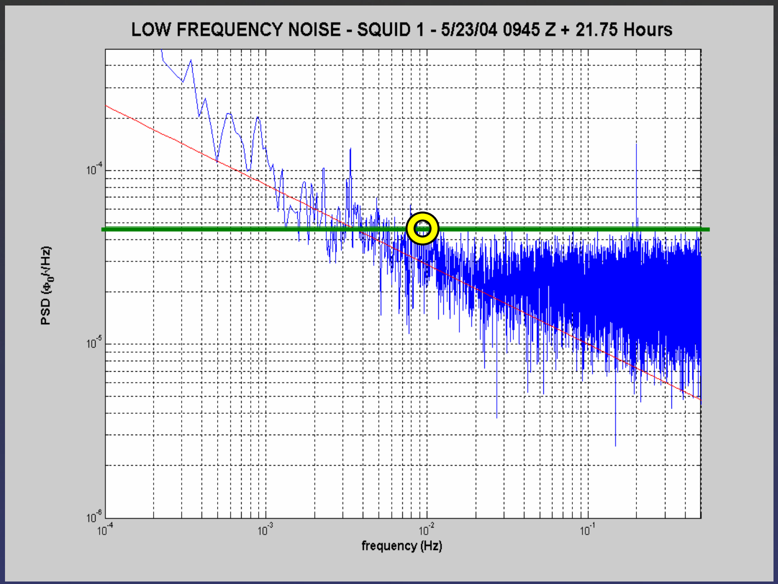


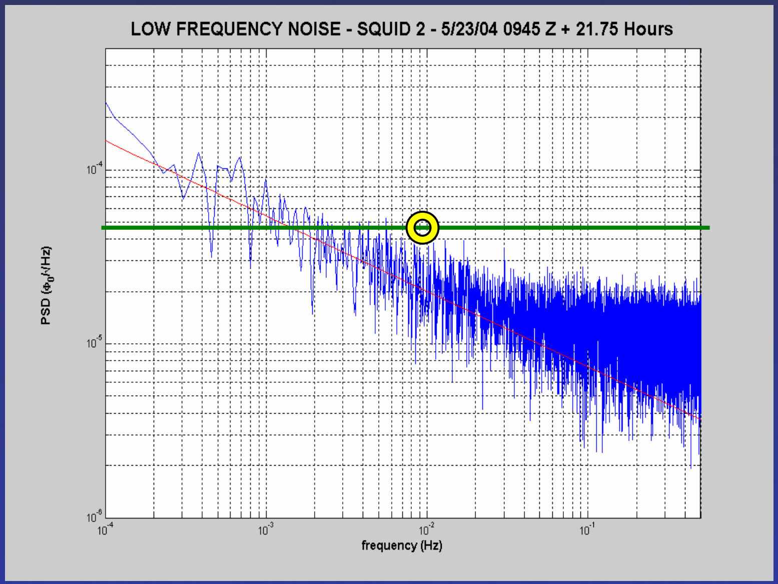
Gyro position – non drag-free gravity gradient effects in Science Mission Mode

Measurement noise – 0.45 nm rms

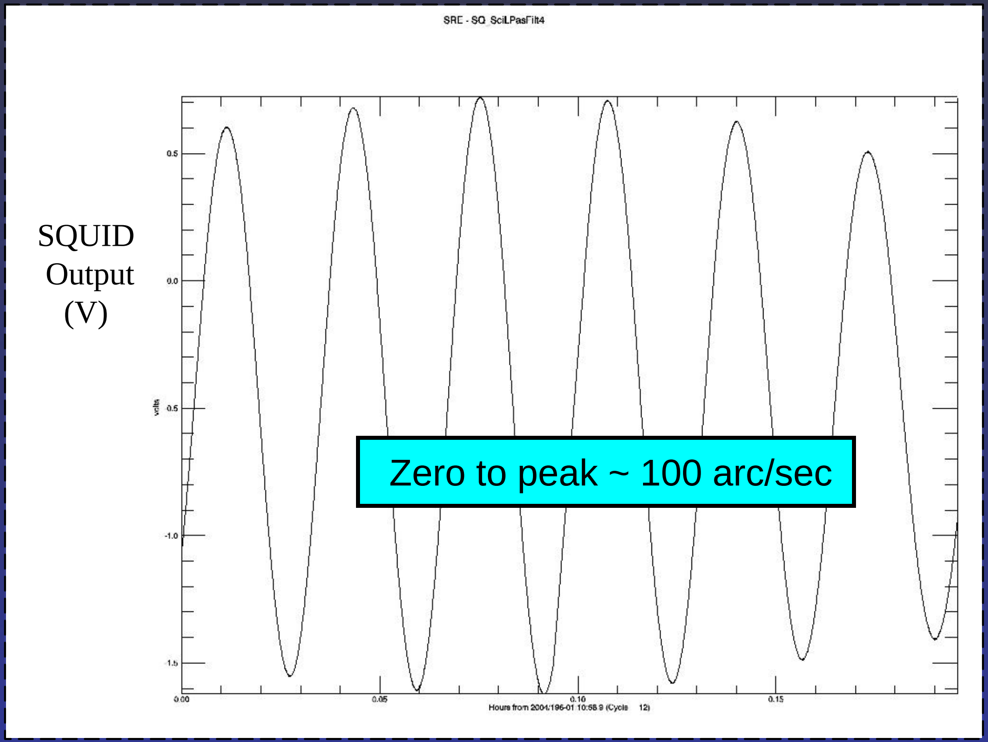
Noise floor

Gyro Readout Performance On-Orbit I

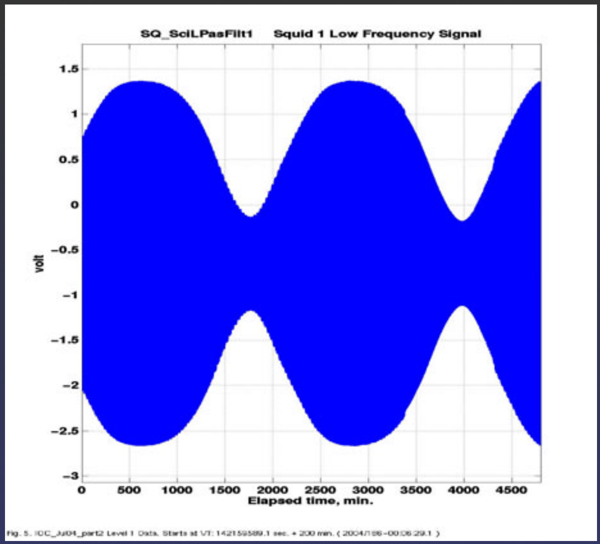




Bruce Clarke, Barry Muhlfelder + the team



Mass Unbalance $\left(\& \frac{\Delta I}{I}\right)$: 1st Near Zero

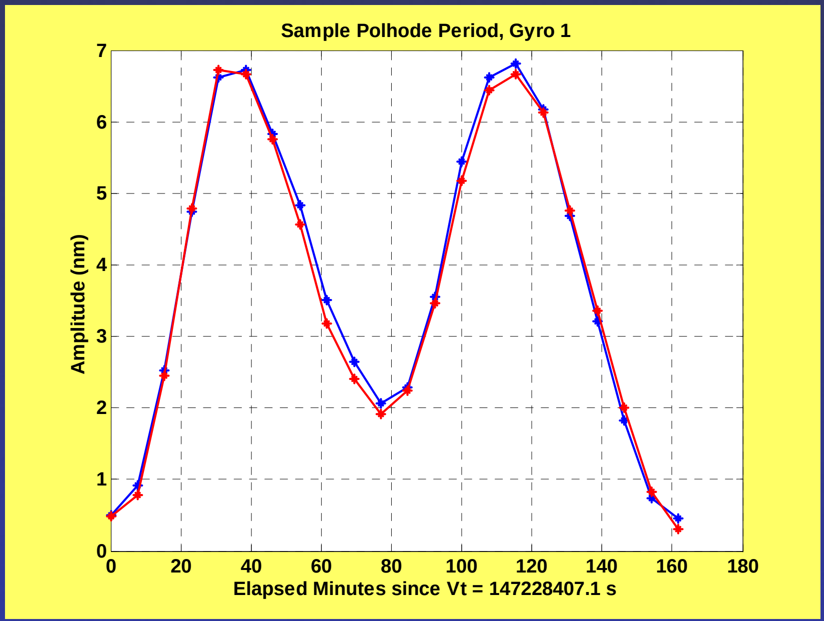


Gyro # 1 @ 3 Hz

36-hour Polhode Period

$\frac{\Delta I}{I} < 2 \times 10^{-6}$

Mac Keiser & Paul Shestople + the team



Gyro # 1 @ 79.3858 Hz

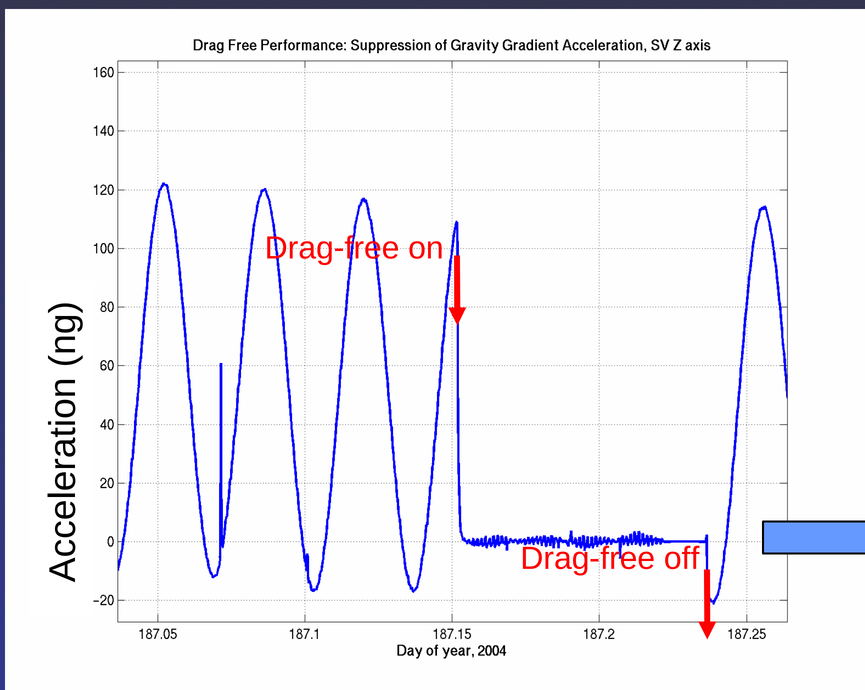
Mass Unbalance (nm)

Gyro #	1	2	3	4
Prelaunch estimate	18.8	14.5	16.8	13.5
On-orbit data	6.9	4.4	3.3	6.0

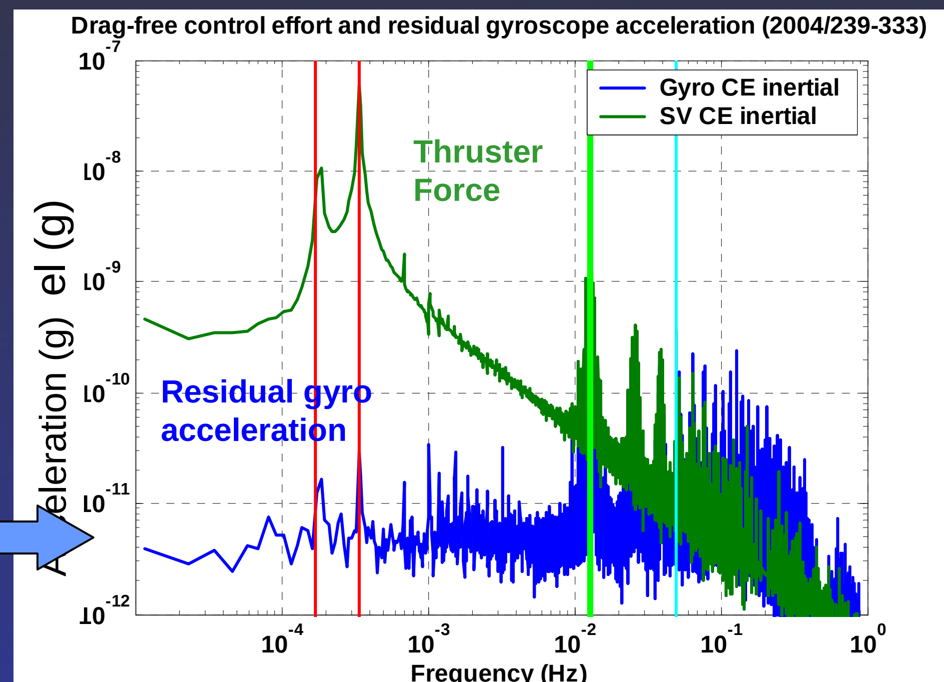
Drag-Free: 2nd Near Zero

Lockheed Martin Attitude/Translational Control
Design Lead: Jon Kirschenbaum

Toward guide star



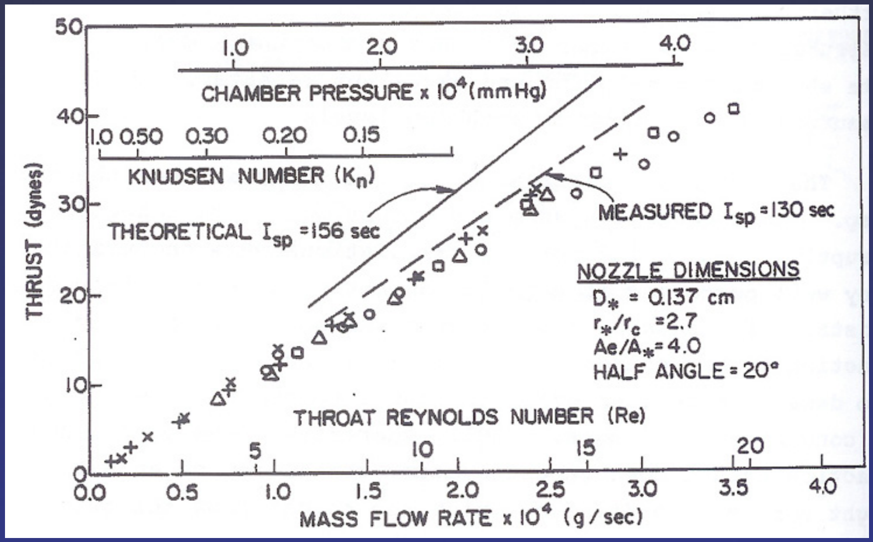
Cross track



Demonstrated accelerometer (drag free) performance better than 10^{-11} g DC to 1 Hz

Boil-off, Altitude & Thrust -- A Subtle Combination

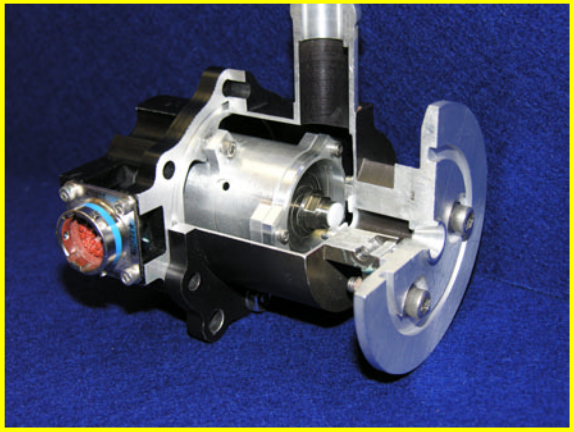
- A very different control system
  - Continuous flow ⟶ proportional thrusters
  - Reynolds' # $\rho v l/\eta \sim 10$!! -- flowing like honey
- Thrust calibration: * John Bull + * Jen Heng Chen (A/A)



He specific impulse vs.mass flow rate

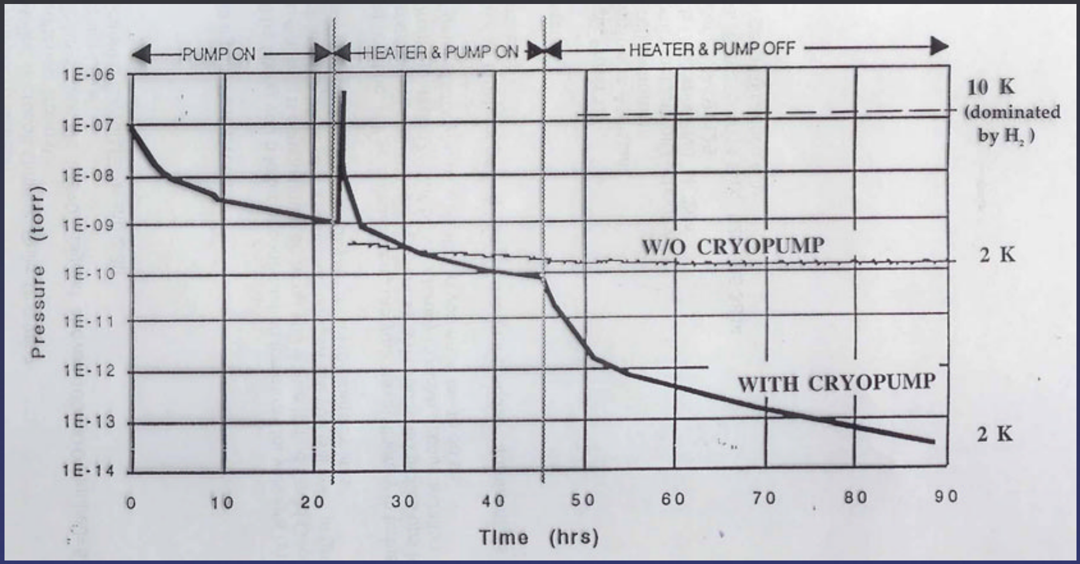
- Lockheed Martin thrusters: Jeff Vanden Beukel

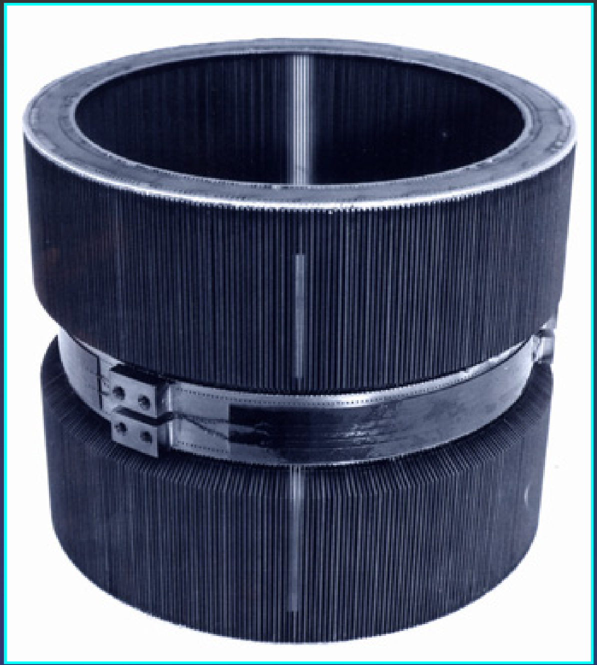
* Yusuf Jafry (A/A) with LM team



Ultra-low Pressure: 5th Near Zero

Low Temperature Bakeout (ground demonstration)





The Cryopump

Gyro spindown periods on-orbit (years)

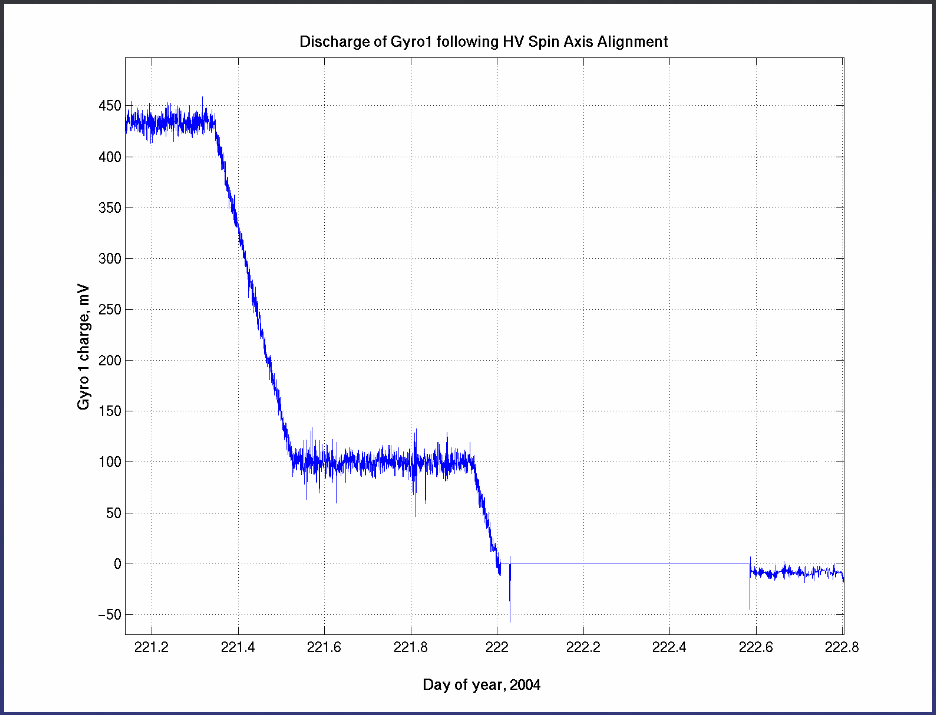
	before bakeout	after bakeout
Gyro #1	~ 50	15,800
Gyro #2	~ 40	13,400
Gyro #3	~ 40	7,000
Gyro #4	~ 40	25,700

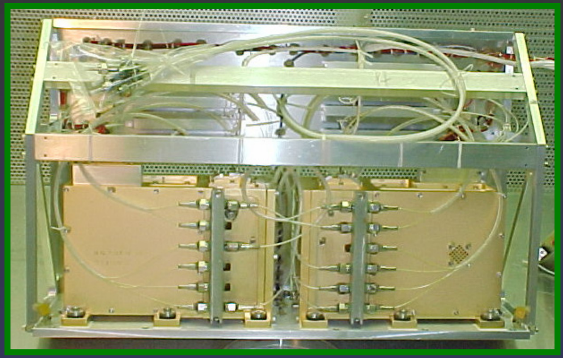
John Lipa, John Turneaure (Physics) + students; adsorption isotherms for He at low temperature,* Eric Cornell, (undergraduate honors thesis)

pressure < 1.5 x 10^{-11} torr
(+ minute eddy-current damping effects?)

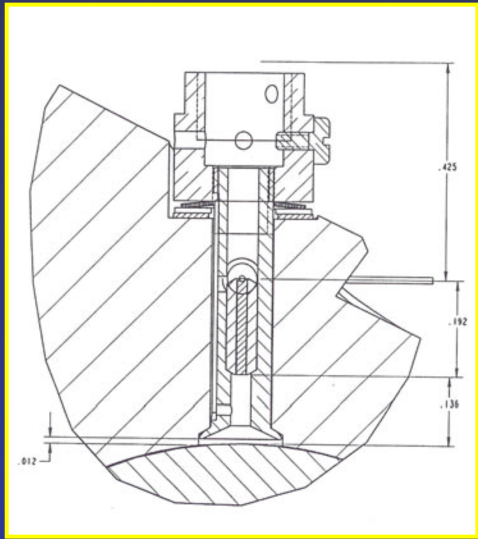
Rotor Electric Charge: 6th Near Zero

Discharge of Gyro #1





Ti Steering Electrode



Saps Buchman, Dale Gill, Bruce Clarke (Physics, HEPL)
+ * Brian DiDonna & * Ted Quinn (Physics)

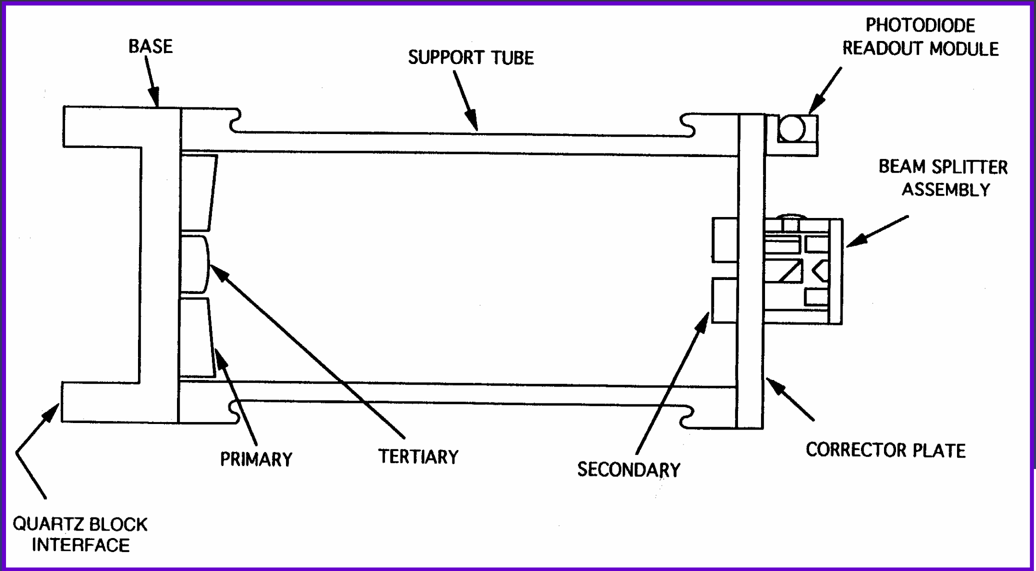
Typical charge rates ~ 0.1 mV/day

Star Tracker I: Concept

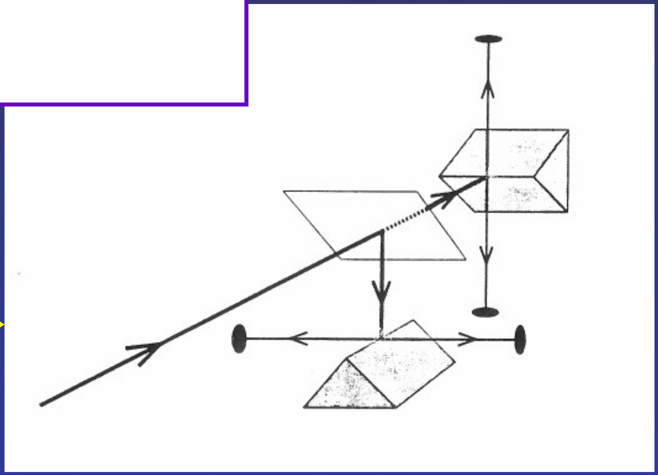
Design Lead: Don Davidson, Davidson Optronics, Inc. & OID

Some dimensions

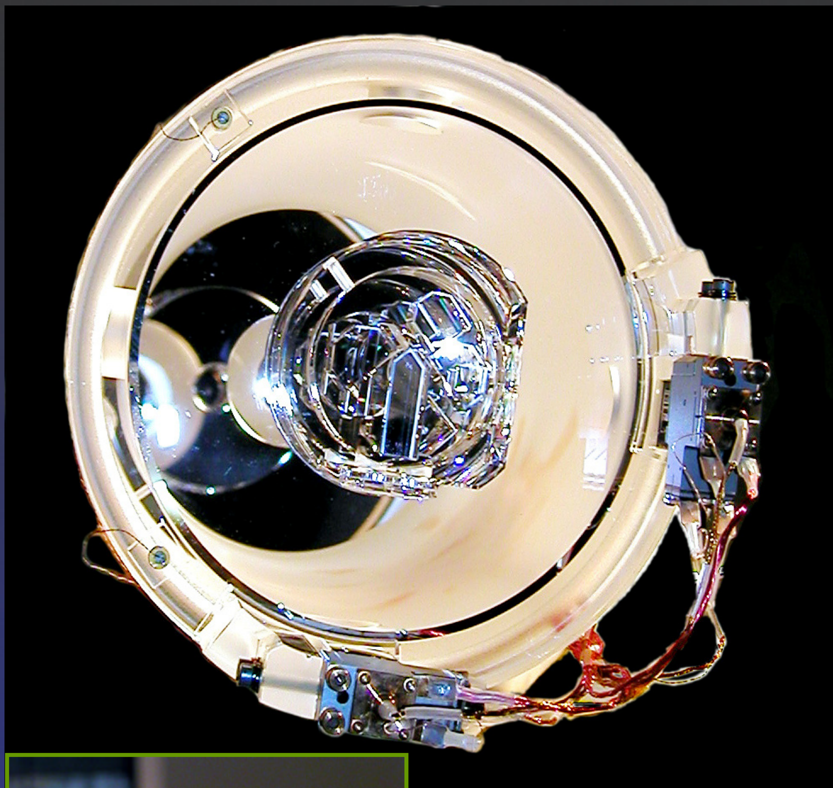
Physical length	0.33 m
Focal length	3.81 m
Aperture	0.14 m
<u>At focal plane</u>	
Image dia.	50 µm
0.1 marc-s	0.18 nm



Beam splitter assembly (detail)



Star Tracker II: Under Test



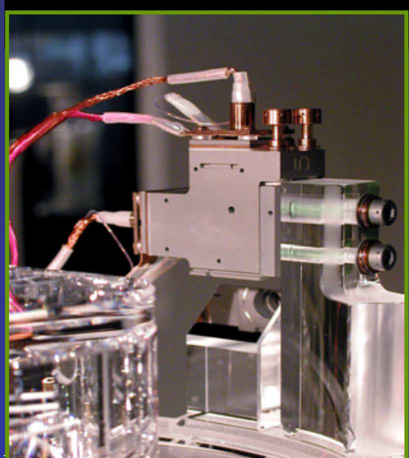
John Lipa, Jason Gwo, Suwen Wang (Physics, HEPL), Bob Farley (Lockheed), John Goebel (NASA Ames)

Telescope development

* Mo Badi (Ap Phys), * Dana Clark (ME),
* Chris Cumbermack (Pre-med!),
* Howard Shen (EE) + 6 others

Artificial Star #3

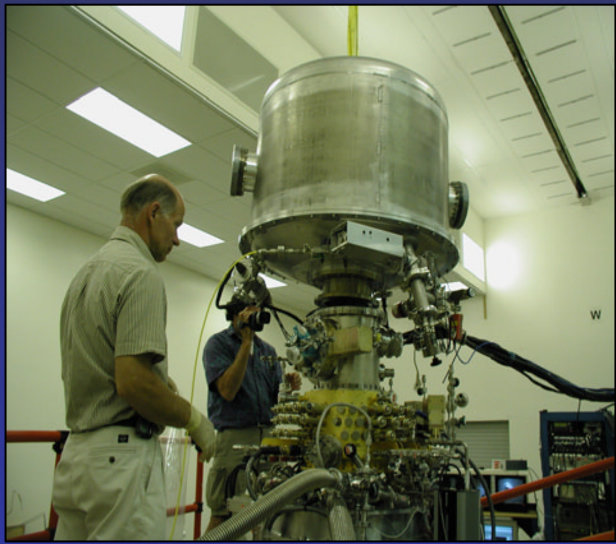
* Ted Acworth, * Rob Bernier



Detector Package

Si Diode Detector

Artificial Star #3



Star Tracker III: Acquiring Star

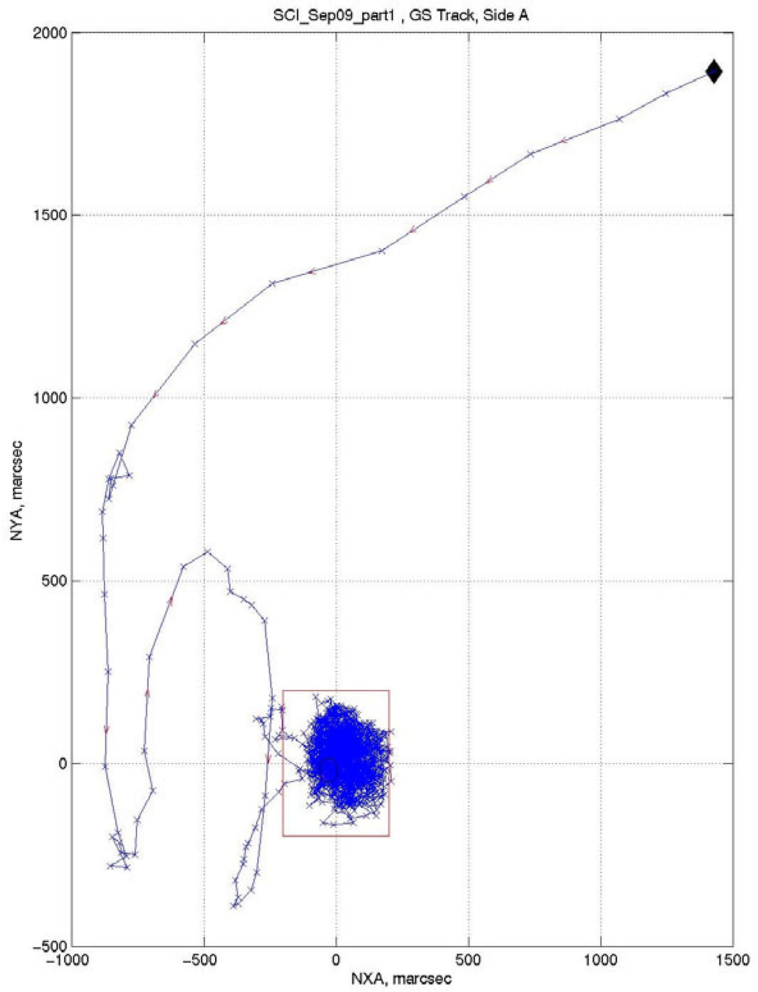
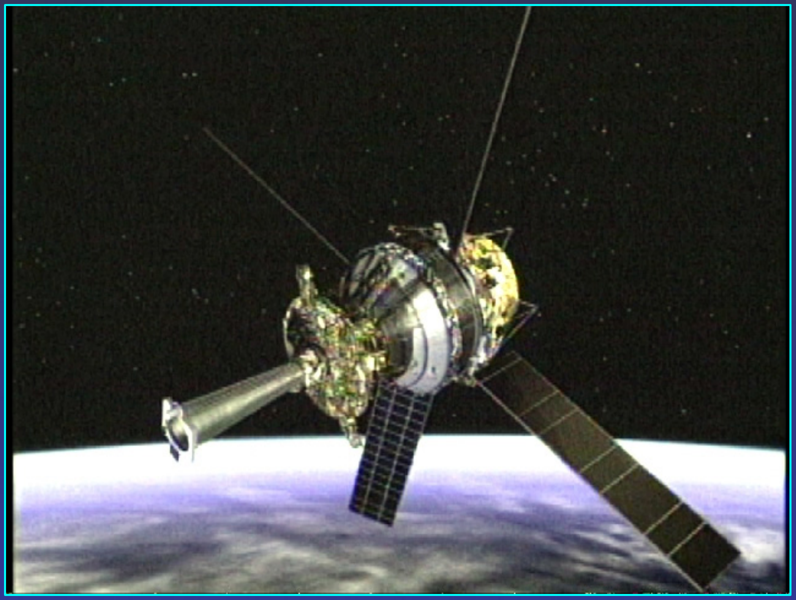


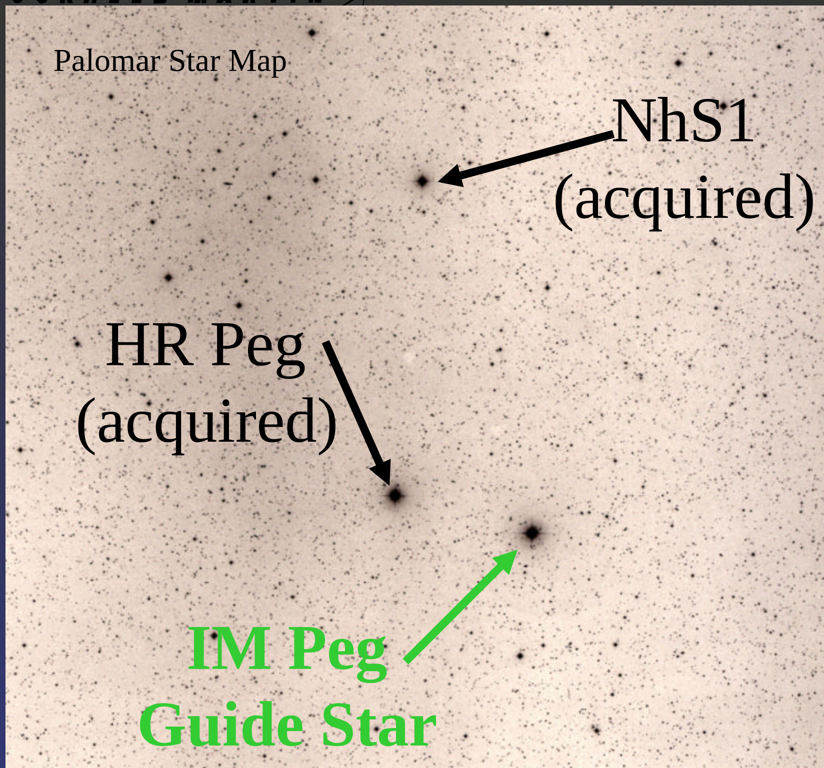
Fig. 705. SCI_Sep09_part1−L2 . GS Track (during GS Valid), Side A Start time: 148031616 sec. Total: 54.0 min

Drive-in time ~ 110 s

RMS pointing ~ 90 marc-s

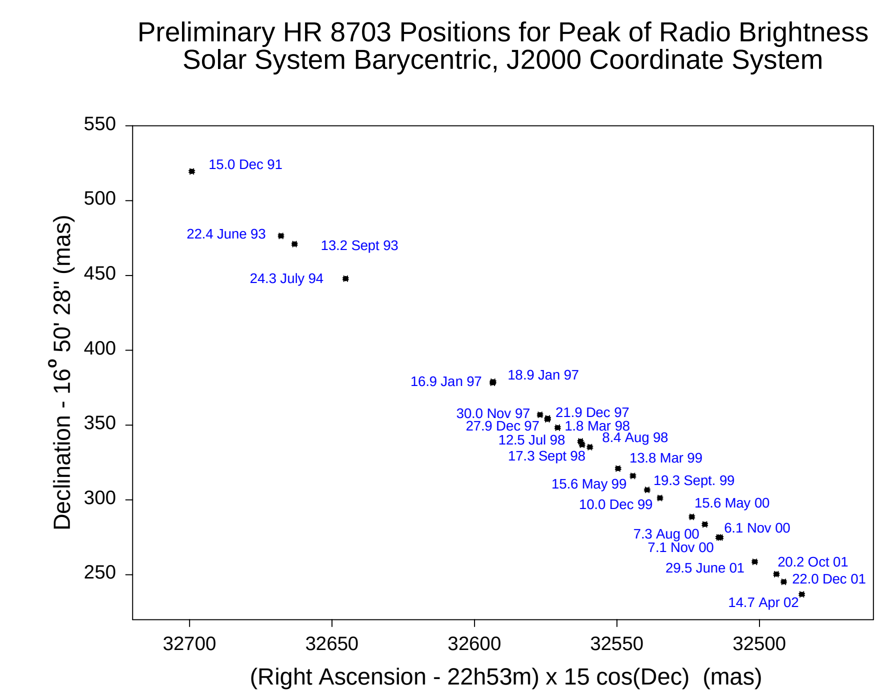


IM Peg (HR 8703) Guide Star Identification



Very Large Array, Socorro, New Mexico

- Optical & radio binary star
- Magnitude - 5.7 (variable)
- Declination - 16.84 deg
- Proper motion measured by SAO using VLBI



Ground-based & Space Observations of IM Peg

John Goebel (NASA Ames)

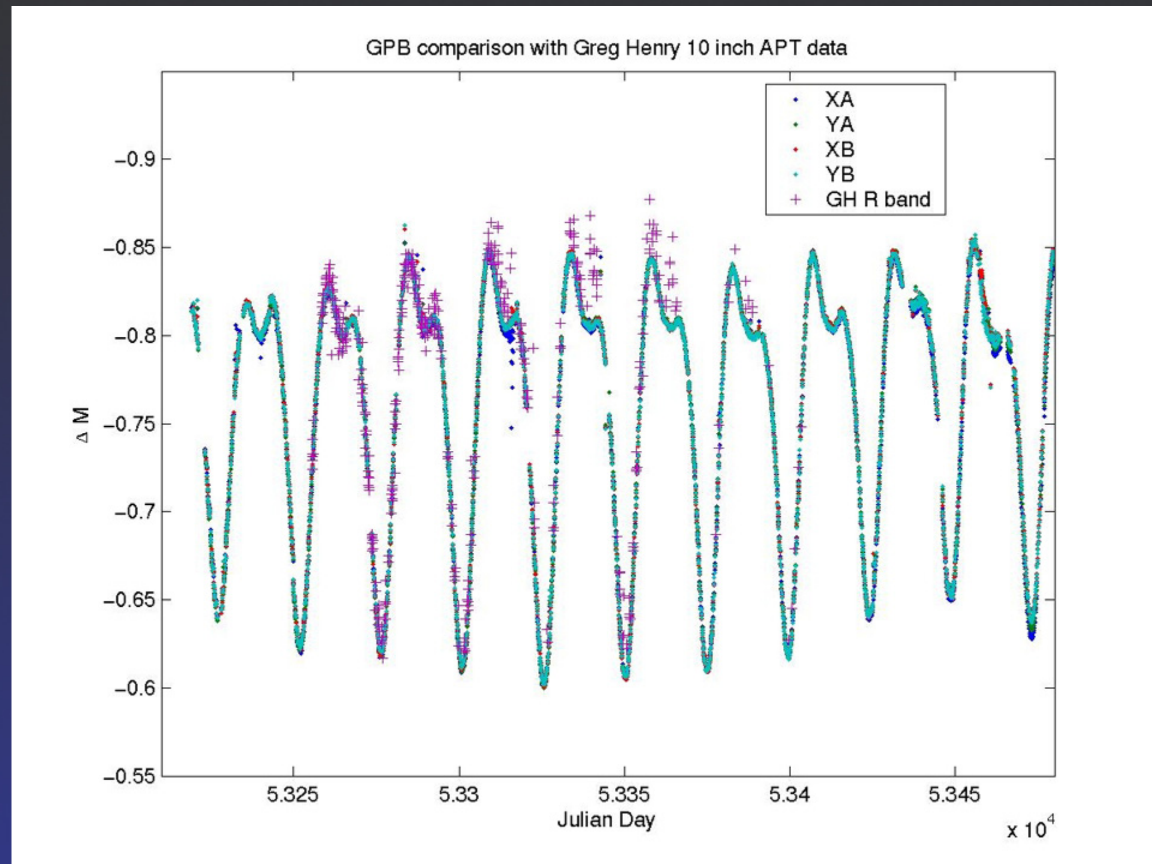
Suwen Wang (Stanford)

Michael Ratner (SAO)

Greg Henry (U of Tenn.)

Jeff Kolodziejczak (NASA Marshall Center)

Svetlana Berdyugina (ETH, Switzerland)



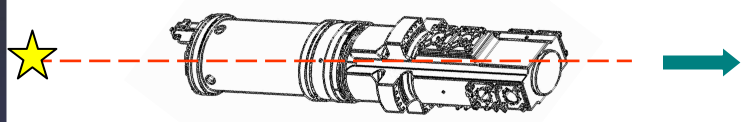
+++++ GP-B flight data (*peaked toward red*)

■■■■ G. Henry's ground-based data (*visible light*)

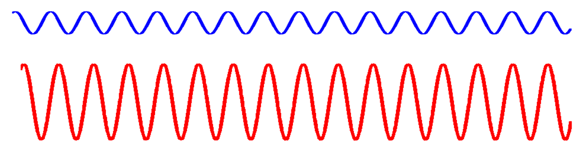
Through GP-B, IM Peg will be most completely characterized star in the entire heavens!

Dither & Aberration: Two Secrets of GP-B

Dither -- Slow 30 marc-s oscillations injected into pointing system

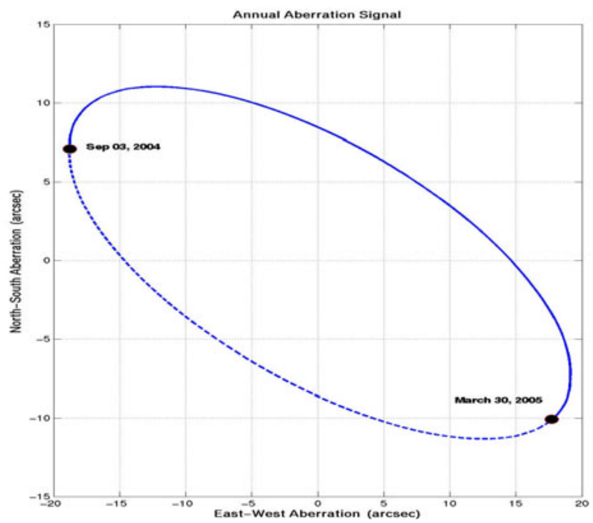


gyro output
telescope output



scale factors matched for accurate subtraction

Aberration (Bradley 1729) -- *Nature's calibrating signal for gyro readout*



Orbital motion → varying apparent position of star (v_{orbit}/c + special relativity correction)

Earth around Sun -- 20.4958 arc-s @ 1 year period
S/V around Earth -- 5.1856 arc-s @ 97.5 min period

→ Continuous accurate calibration of GP-B experiment

3 Phases of In-flight Verification

A. Initial orbit checkout (128 days)

- re-verification of all ground calibrations [scale factors, tempco's etc.]
- disturbance measurements on gyros at low spin speed

B. Science Phase (353 days)

- exploiting the built-in checks [Nature's helpful variations]

C. Post-experiment tests (46 days)

- refined calibrations through deliberate enhancement of disturbances, etc. […learning the lesson from Cavendish]

Data Reduction Team:

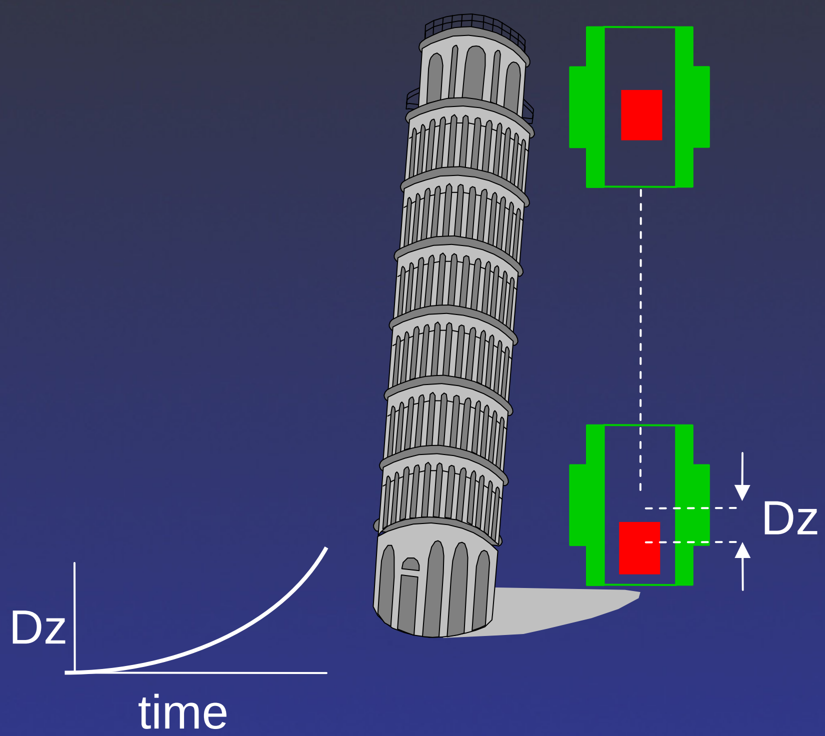
Mac Keiser, * Ed Fei (undeclared), Michael Heifetz, Jie Li, Yoshimi Ohshima (* A/A), * Michael Salomon (A/A), David Santiago (* Physics), Alex Silbergleit, * Sara Smoot (A/A), Vladimir Solomonik, Karl Stahl (* ME)
+ Bill Bencze, Peter Boretsky, Bruce Clarke, Dan DeBra, Barry Muhlfelder, Paul Shestople, John Turneaure, Suwen Wang, Paul Worden

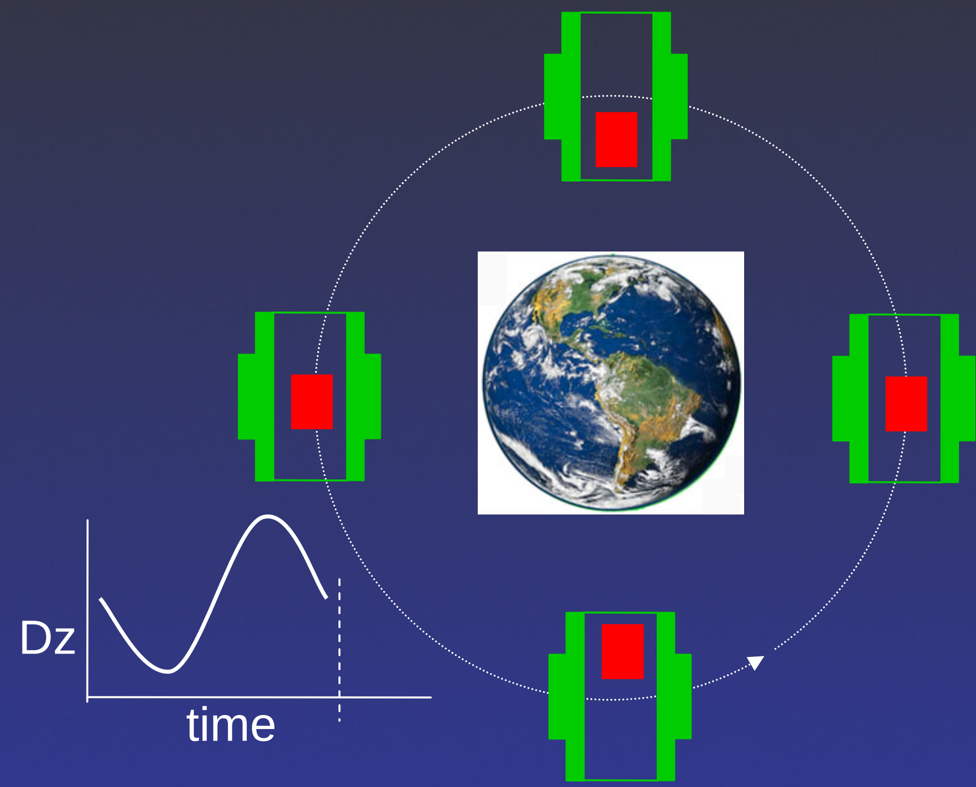
Wider Significance of the GP-B Experience

- Physics-Aero/Astro collaboration from the start
- 'Near Zero' in space
- Some technologies
  - *Drag-free*
  - *Pointing*
  - *Cryogenics*
- Integrated Science/Operations team
- University/industry/NASA collaboration

Satellite Test of the Equivalence Principle

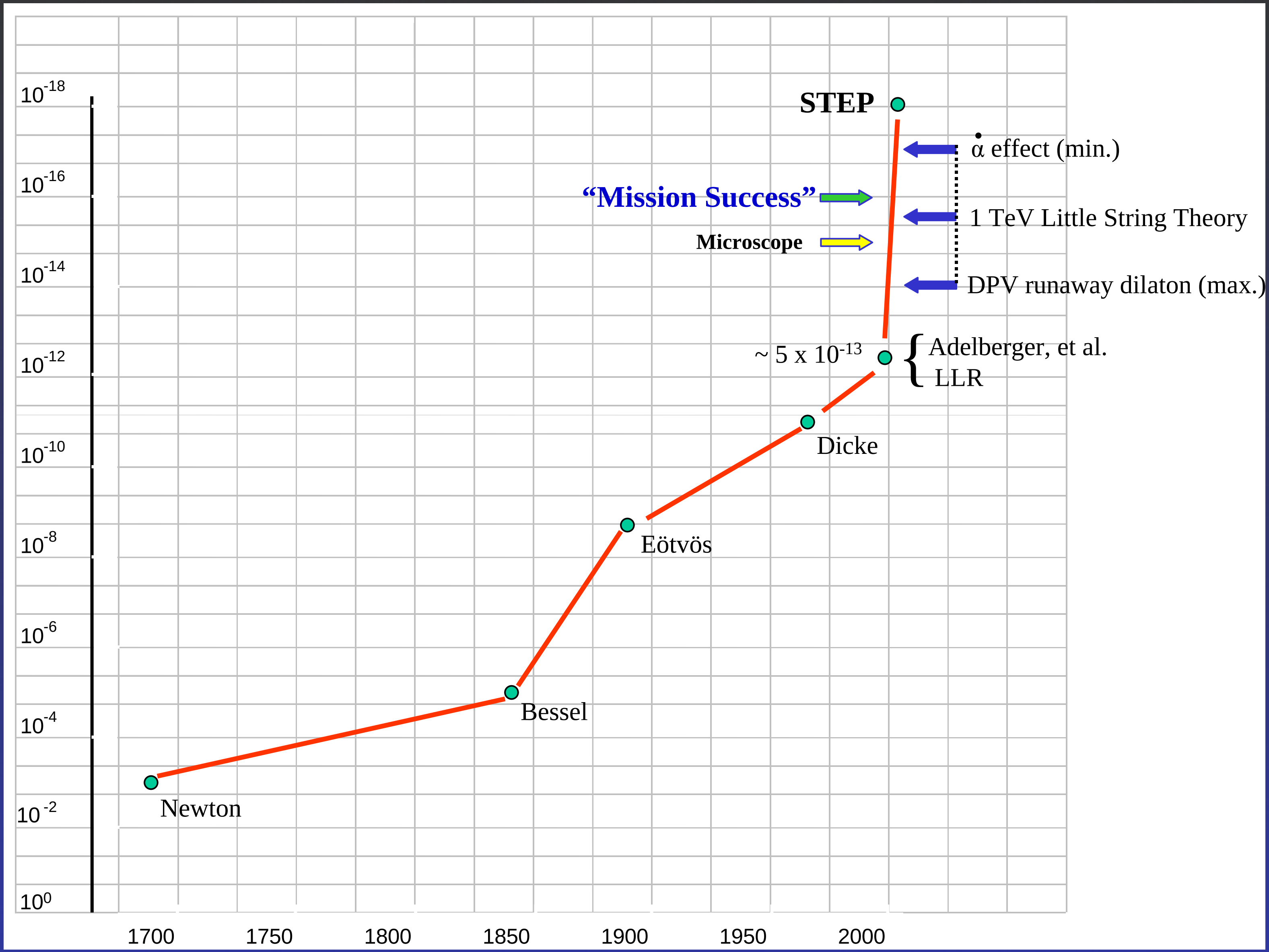
Newton's Mystery { $F = ma$ mass - the receptacle of inertia
$F = GMm/r^2$ mass - the source of gravitation





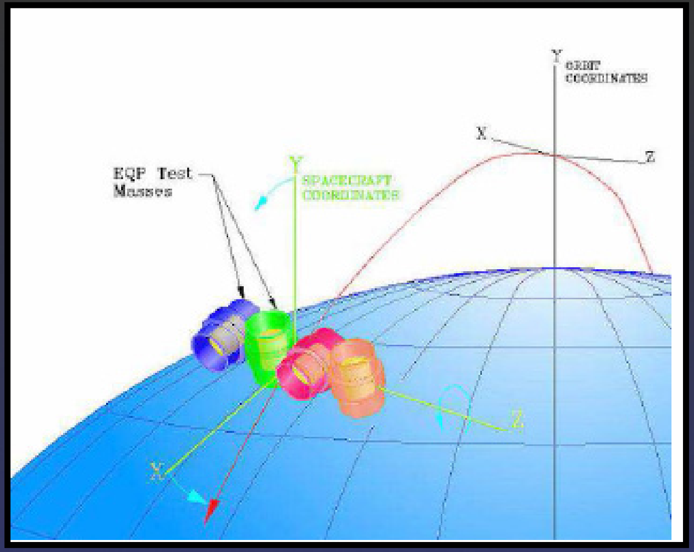
Orbiting drop tower experiment {
* More time for separation to build
* Periodic signal

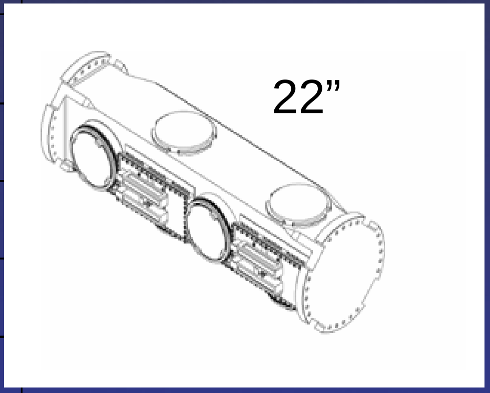
Space > 5 Orders of Magnitude Leap

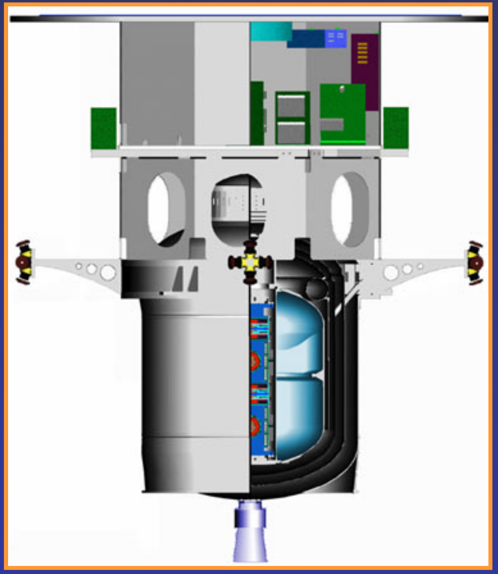


STEP International Collaboration

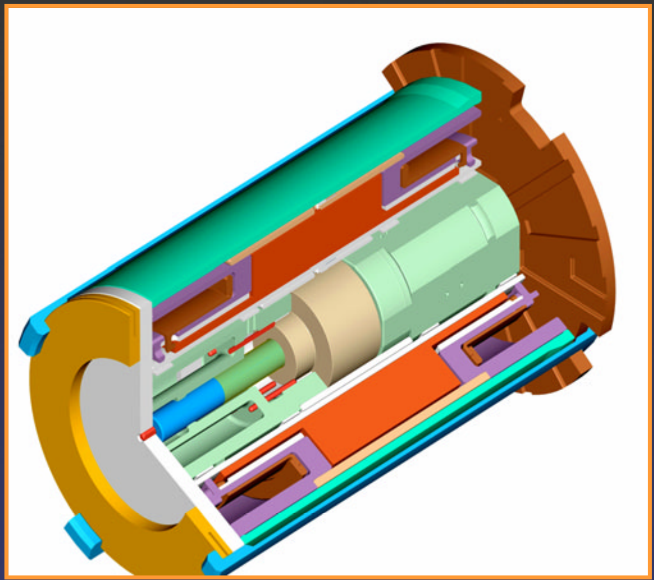
Research Center Partners
Stanford University
University of Birmingham, UK
ESTEC
FCS Universität, Jena, Germany
Imperial College, London, UK
Institut des Hautes Études Scientifiques, Paris
ONERA, Paris, France
PTB, Braunschweig, Germany
Rutherford Appleton Laboratory, UK
University of Strathclyde, UK
Universitá di Trento, Italy
ZARM, Universität Bremen, Germany



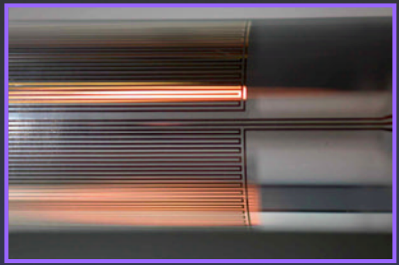




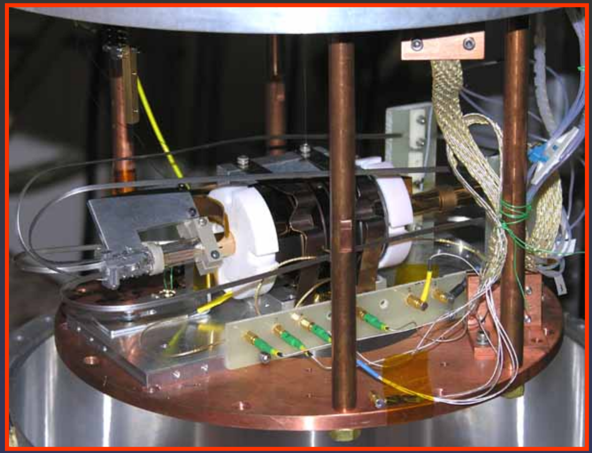
Some Elements of the STEP Mission



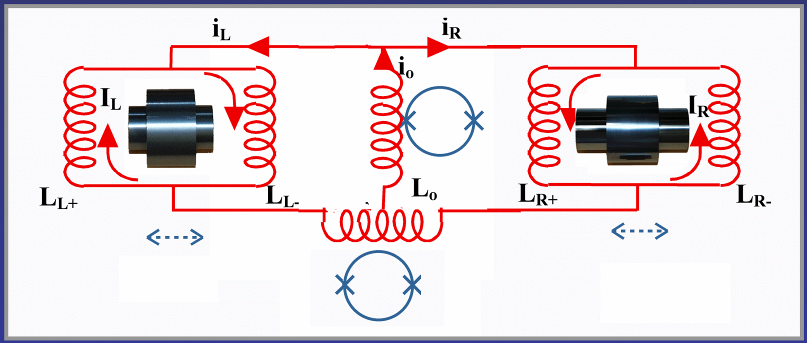
assembled flight instrument



magnetic bearing

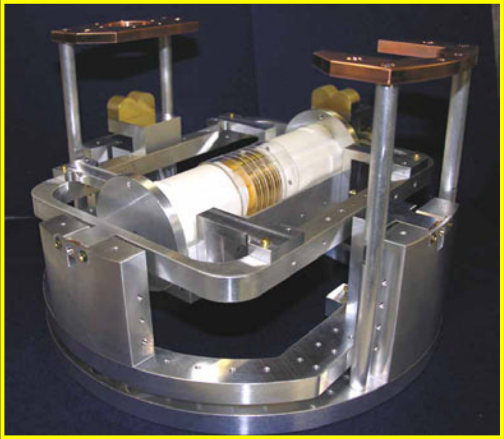


bearing under test



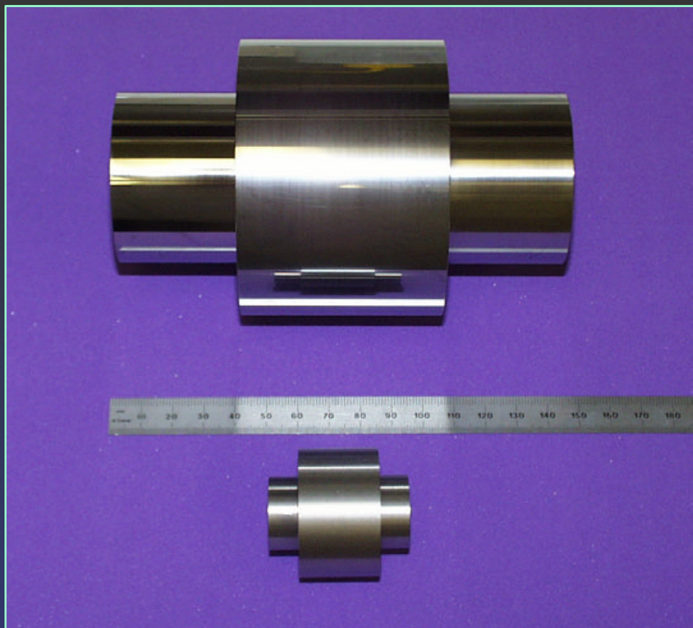
differential SQUID readout

SQUID assembly



2-axis tilt platform

Test Mass Shape & Composition



Dimensions give 6th order insensitivity to gravity gradient disturbances from spacecraft -- μm tolerances

Test masses as 'different' as possible

Material	Z	N	$\left(\frac{N+Z}{\mu}-1\right)10^3$ Baryon Number	$\frac{N-Z}{\mu}$ Lepton Number	$\frac{Z(Z-1)}{\mu(N+Z)^{1/3}}$ Coulomb Parameter
Be	4	5	-1.3518	0.11096	0.64013
Si	14	14.1	0.8257	0.00387	2.1313
Nb	41	52	1.0075	0.11840	3.8462
Pt	78	117.116	0.18295	0.20051	5.3081

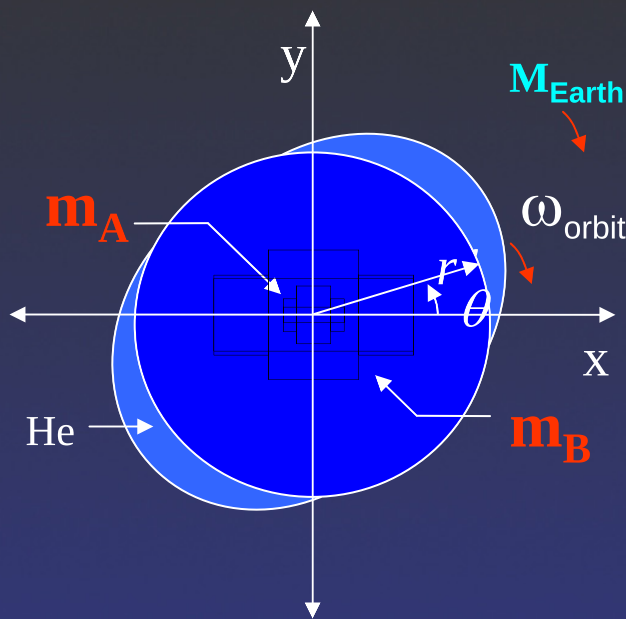
Damour C&QG 13 A33 (1996)

STANFORD UNIVERSITY

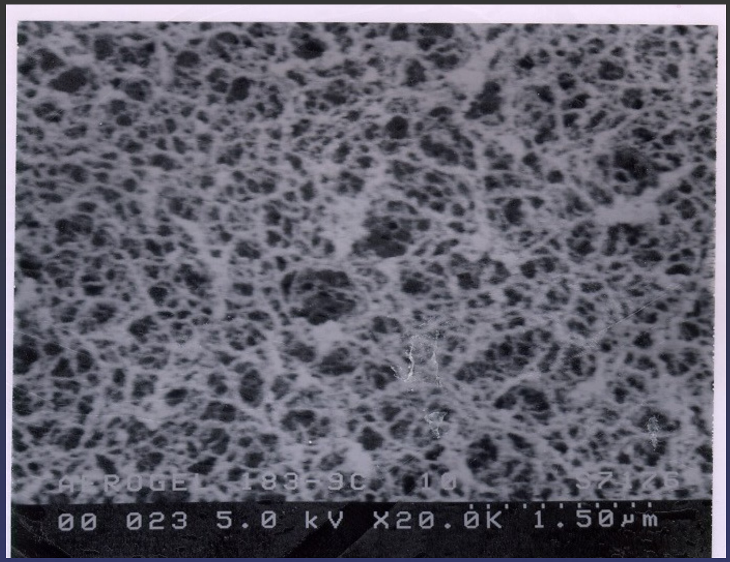
LOCKHEED MARTIN

Helium Tide Control

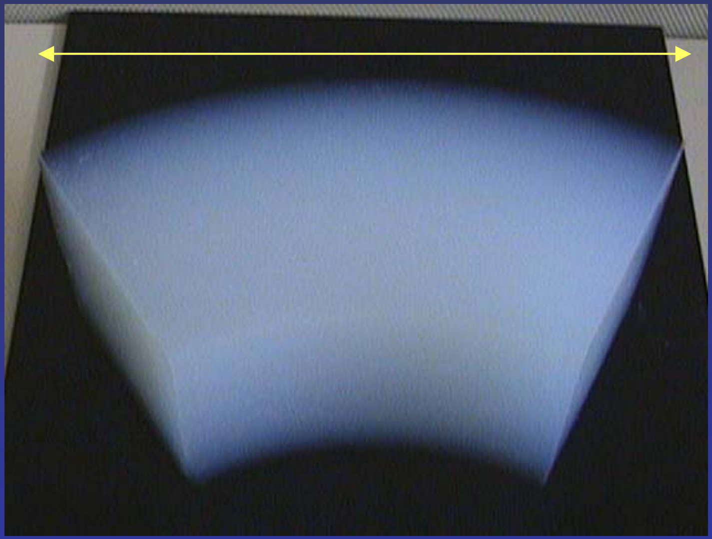
Silica Aerogel Constraint



- void sizes 100 to 1000 nm
- confines He even in 1g
- passed cryogenic shake test



250 mm



STEP: a Landmark in Fundamental Physics

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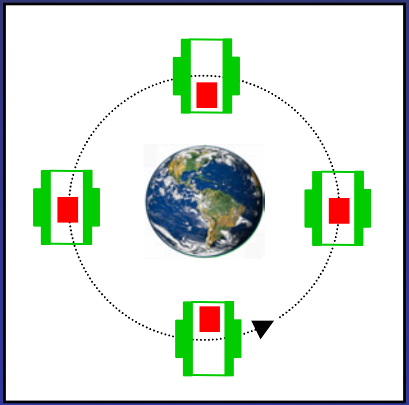
What Physics has done for Space?

"I guess one of the reasons we got here today was because of a gentleman named Galileo….who made a rather significant discovery about falling objects in gravity fields."

--David Scott

What Space can do for Physics?



"STEP (and probably only STEP) has the potential of discovering new forces in Nature that would tell us a lot about why the universe is as it is, and what its ultimate state will be."

--Thibault Damour