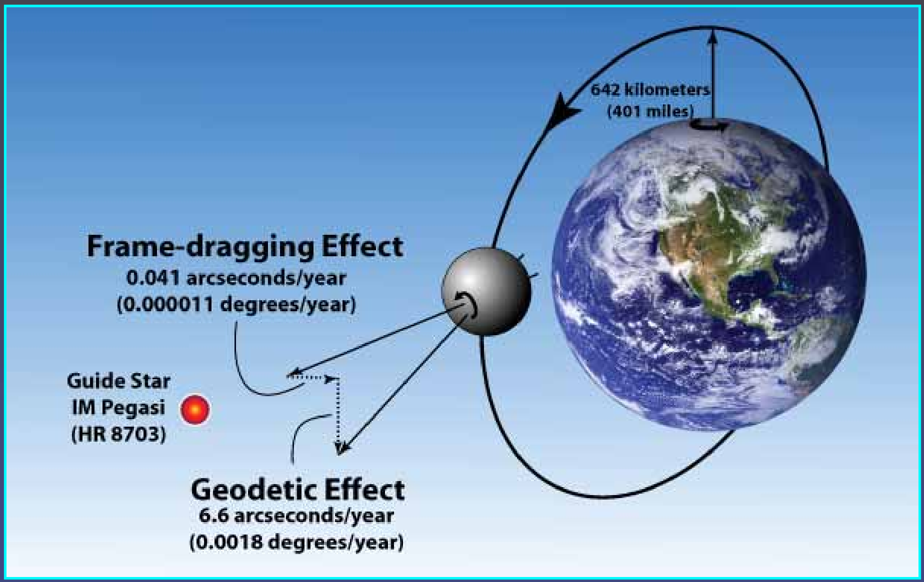
Testing Einstein in Space: The Gravity Probe B Mission

A Stanford "Brainstorm" with NASA MSFC & Industry

Francis Everitt

18 May 2006

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)*

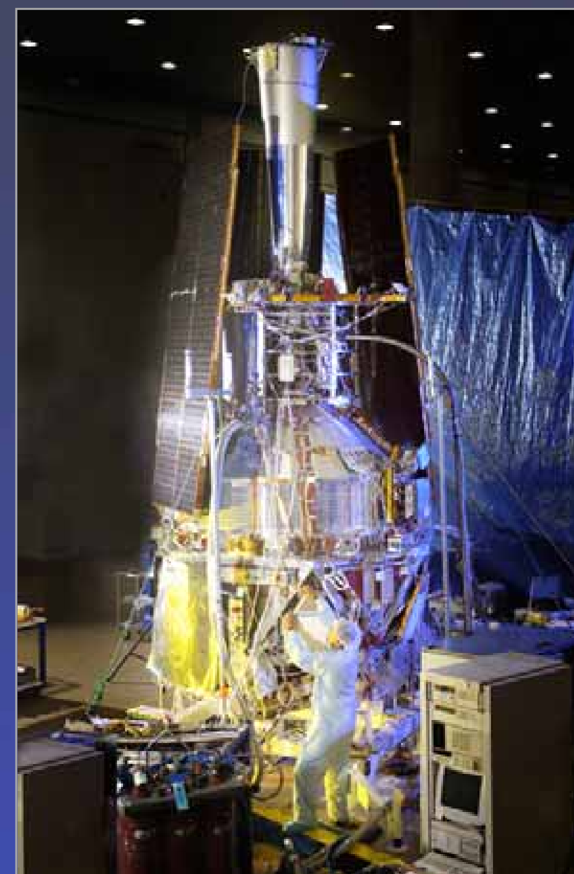
Testing Einstein – NASA's Contributions

Laser Ranging:

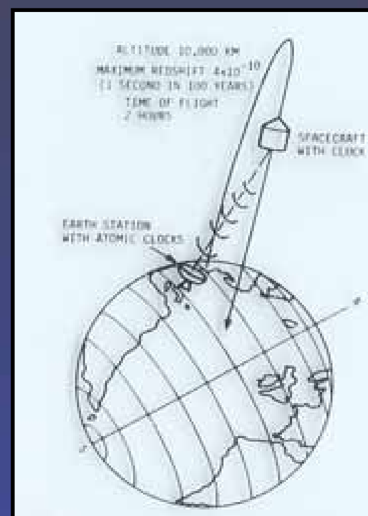
to reflectors on Moon (1968+)

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+)

GP-B: 7 Interfolded Stories

Co-PIs:

Brad Parkinson

John Turneaure

Dan DeBra

- Testing Einstein
- Unexpected Technologies
- Two SU Departments: *Physics & Aero-Astro*
- Students: *79 + 13 PhDs, 353 U/G, 55 high school*
- Spin-Offs: *drag-free, porous plug, autofarm, + + + +*
- NASA-Stanford-Industry Symbiosis
- *"A very interesting management experiment"* – J. Beggs, 1984

Co-Investigators:

Sasha Buchman

Mac Keiser

John Lipa

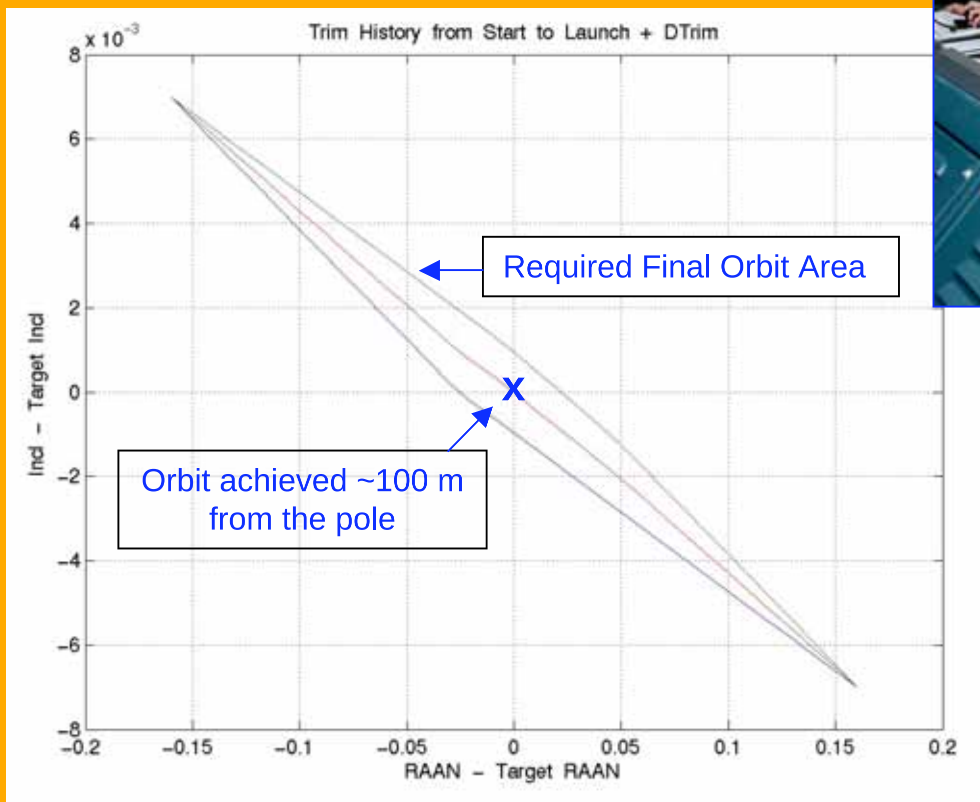
Jim Lockhart

Barry Muhlfelder

Mike Taber

Launch: April 20, 2004 – 09:57:24

Boeing & Luck – A Near Perfect Orbit

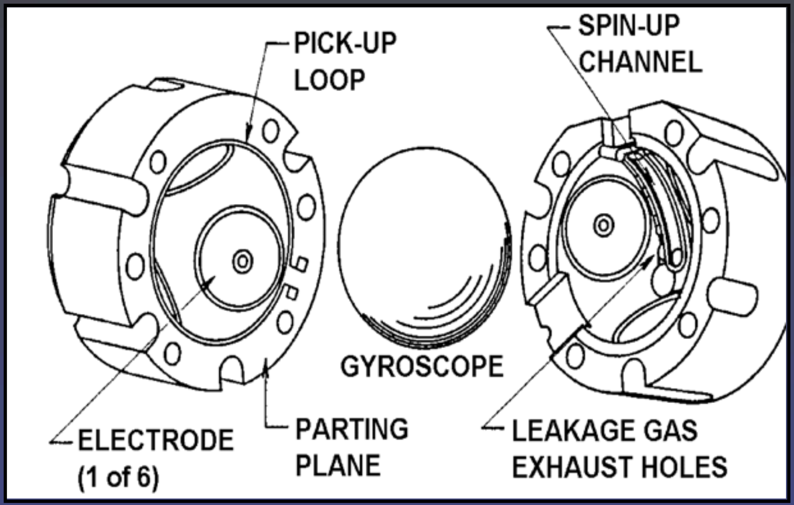


Delta II Nominal Accuracy

Waiting the moment….

…. AFTER with Dave King

The GP-B Gyroscope

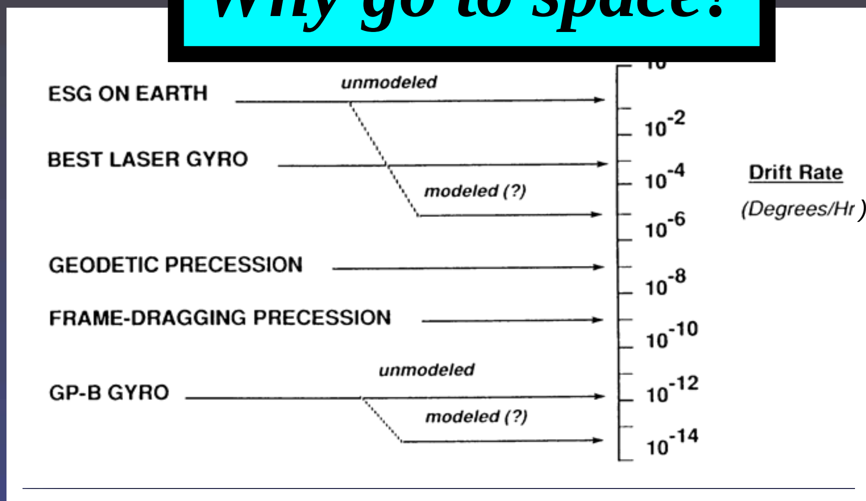


- **Electrical Suspension**
- **Gas Spin-up**
- **Magnetic Readout**
- **Cryogenic Operation**

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

Near Zeros & Why We Need Them

Why go to space?



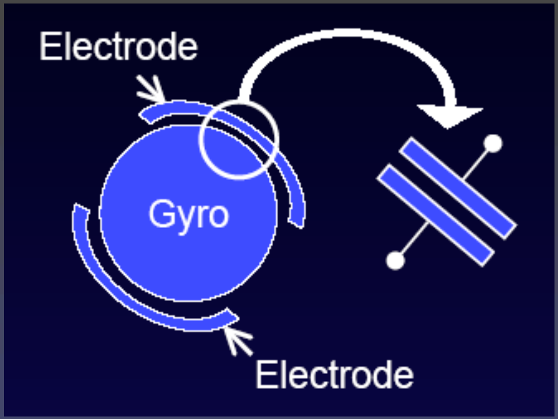
0.1 marcsec/yr = 3.2 × 10^{-12} deg/hr – the width of a human hair seen from 100 miles

Seven Near Zeros

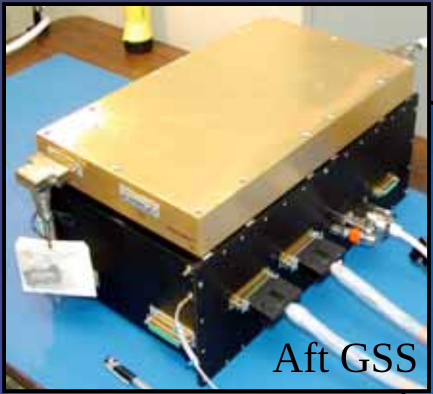
1) rotor inhomogeneities
2) "drag-free"
3) rotor asphericity
4) magnetic field
5) pressure
6) electric charge
7) electric dipole moment

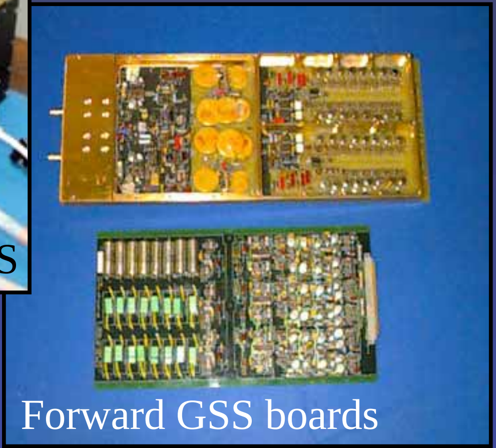
Near-Zero vs. Near-Infinite Physics

Gyro I: 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)*

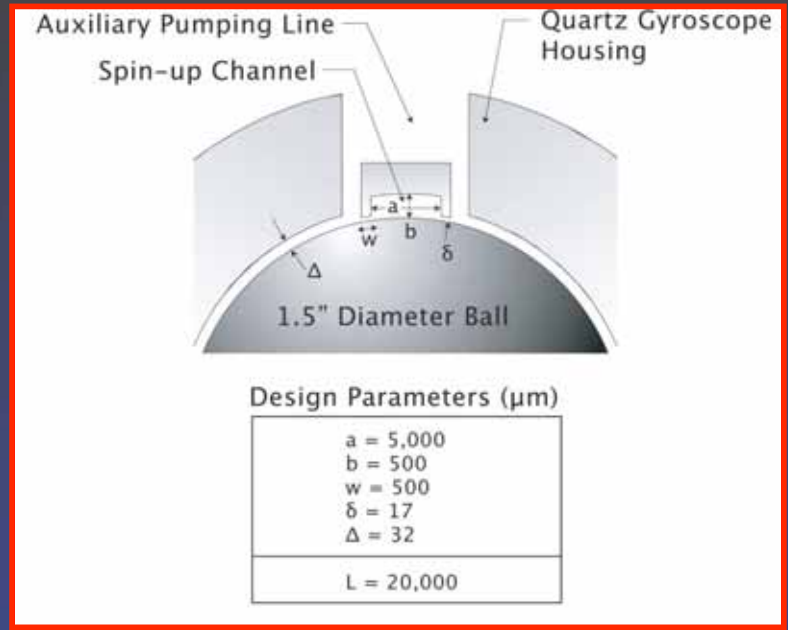
Nanometer references
- thickness of sheet of paper ~ 100,000 nm
- diameter of atom ~ .1 to .5 nm

Gyro II: The Spin-up Problem(s)

1 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



2 Differential Pumping Requirement

spin channel ~ 10 torr (sonic velocity)

electrode area < 10^{-3} torr

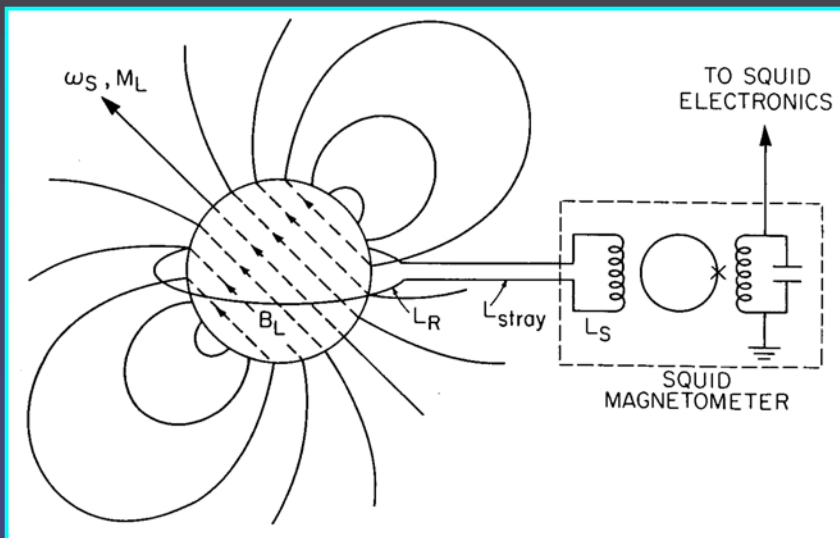
* Dan Bracken (Physics)
Don Baganoff (Aero/Astro)
+ Gerry Karr (MSFC), John Lipa, John Turneaure & 4 students

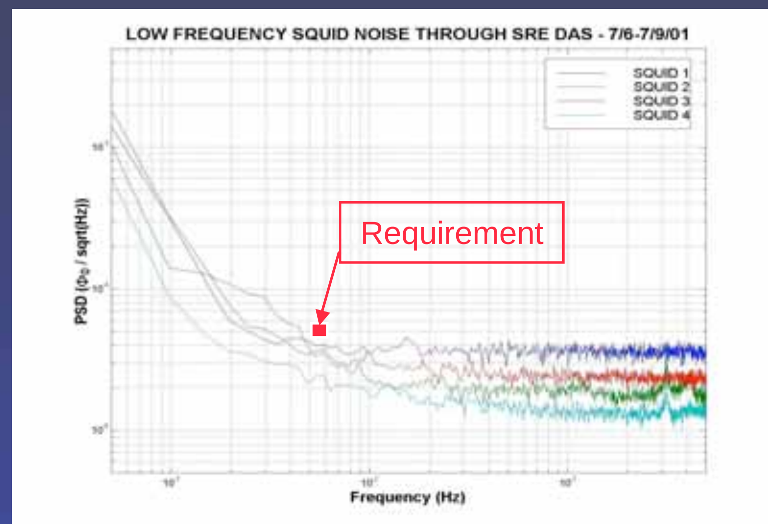
3

"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 III: London Moment Readout

“SQUID” ⟶ 1 marc-s in 5 hours





Jim Lockhart (* Physics & SFSU)

Barry Muhlfelder (Physics HEPL)

* Greg Gutt & * Ming Luo (EE)

Bruce Clarke (Physics HEPL)

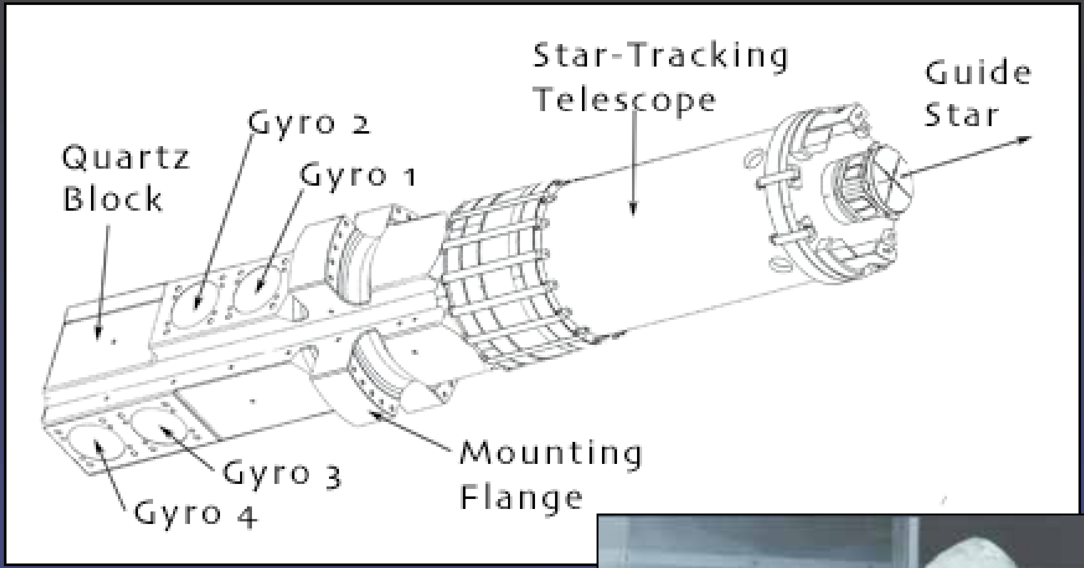
Terry McGinnis (Lockheed)

+ many more

- Noise < 190 marc-s/$Hz^{1/2}$
- DC trapped flux < 10^{-6} gauss
- AC shielding > 10^{12}
- Centering stability < 50 nm

The GP-B Instrument

Don Davidson

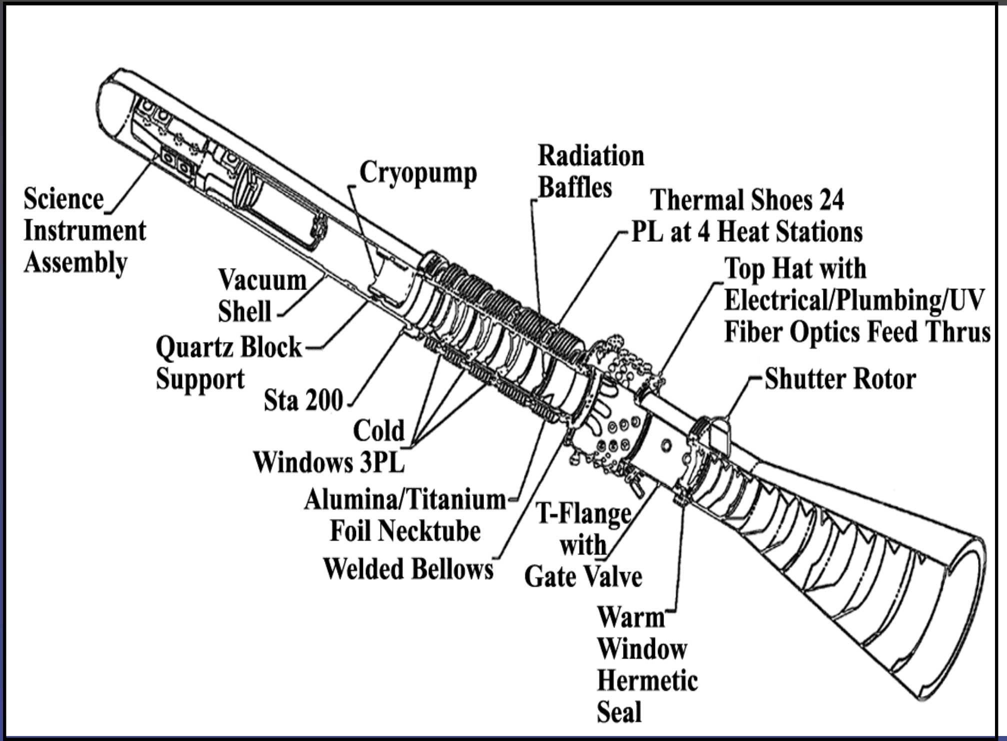


"Design a precision apparatus as if it were made of jello – if it is stable then, it may just work." -- H.A. Rowland, ~1900

Assembly & alignment: *Doron Bardas (Physics), * Robert Brumley (EE!) Paul Bayer, Chris Gray, John Stamets + students*

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

The GP-B Cryogenic Probe



Assembled probe at Lockheed prior to shipment to Stanford

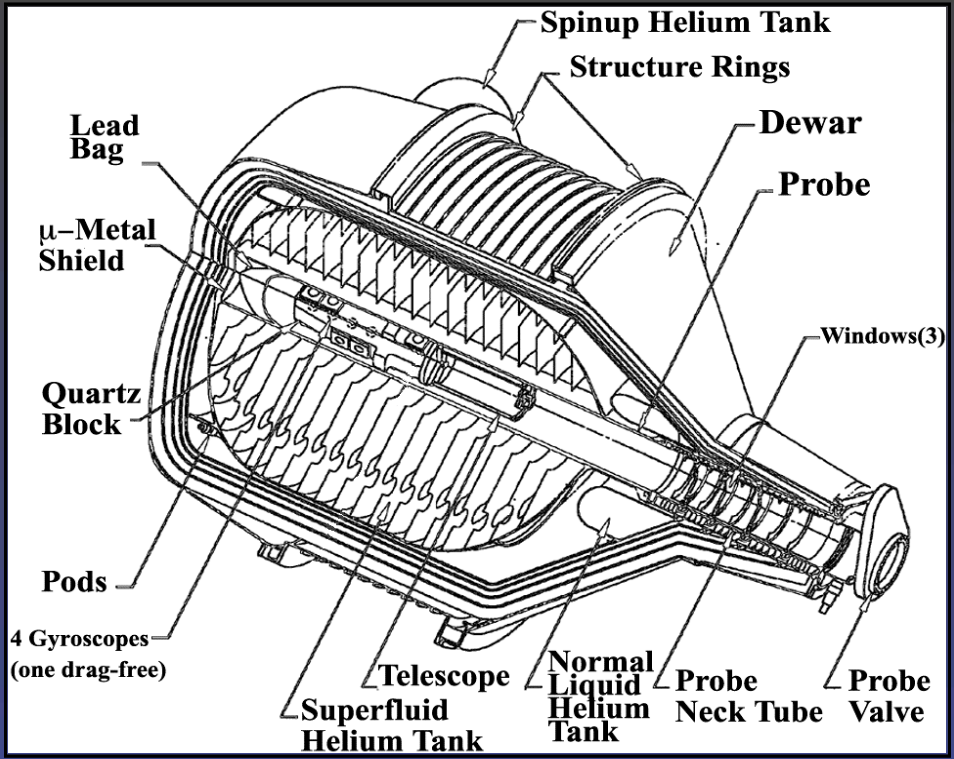
Probe & Dewar Development Team

Lockheed: Dick Parmley - Lead, Gary Reynolds, Kevin Burns, Mark Molina & many other heroes

Stanford: Mike Taber, Dave Murray, Jim Maddocks + students

The Dewar Council

The GP-B Cryogenic Payload



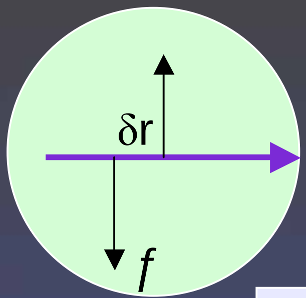
Payload in ground testing at Stanford, August 2002

Controlling He in Space: the Porous Plug

First demonstration: Peter Selzer (SU Physics)

Engineered for space: Gene Urban, et al. (MSFC)
Bill Davis (Ball Aerospace), Sidney Yuan (Lockheed)

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 $\Omega < \Omega_0$ *~ 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 ($f \sim 10^{-11}$ g cross-axis average)	$\frac{\delta r}{r} < 5.8 \times 10^{-6}$ *(attainable)*

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

drift-rate for the drag-free GP-B < 0.05 marc-s/yr

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

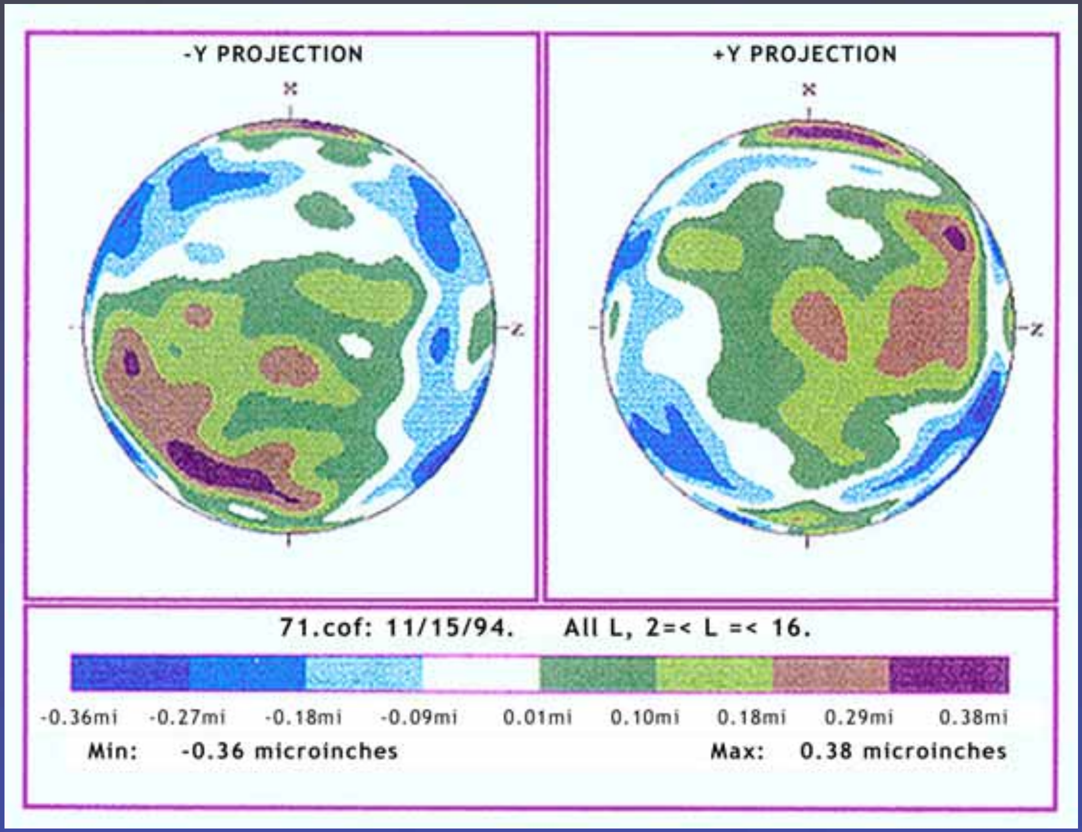
Asphericity: 3rd Near Zero – Making

- 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)
	+ Dan DeBra & students

Asphericity: 3rd Near Zero – Measuring

Work initiated by Graham Siddall & RTH



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 φ = field H x area A
- successive expansions
  ➡ stable field levels ~ 10^{-7} gauss
- 10^{-12} [= 240 dB!] ac shielding through combination of cryoperm, lead bag, local shields & symmetry

* Blas Cabrera (1975 Physics PhD)

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

Magnetic material testing:
John Mester, Grace Brauer

Students & the Development of GP-B

79 Doctorates (29 Physics; 49 A/A, ME, EE; 1 Math.)

15 Master's Degrees, 5 Engineer's Degrees

13 Doctorates at Other Universities (University of Alabama - Huntsville, Purdue, Harvard, MIT, University of Wisconsin, University of Aberdeen – Scotland)

~ 353 Undergraduates from 11 Departments

~ 55 High School Summer Students

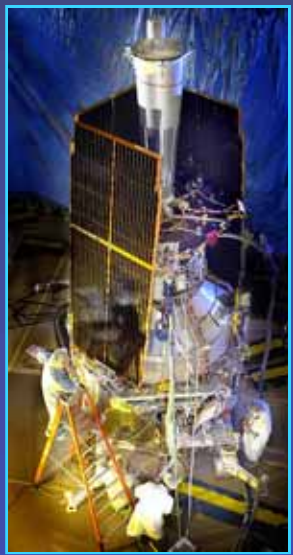
Currently: 3 Doctoral Candidates, 4 Master's & 2 U/G, + Summer Students

cryogenic porous plug

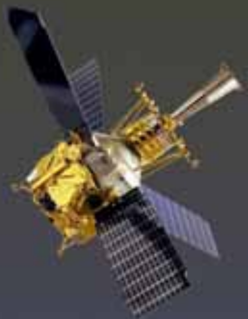
TRIAD drag-free satellite, 1972

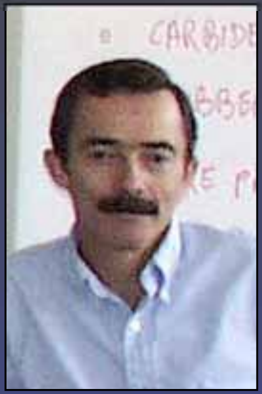
GP-B/GPS airplane landing

silicate bonding



Completion & Departure





Bill Reeve

Hugh Dougherty

Bob Schultz

Norm Bennett

On-Orbit: GP-B Mission Operations

Anomaly Room

Gaylord Green

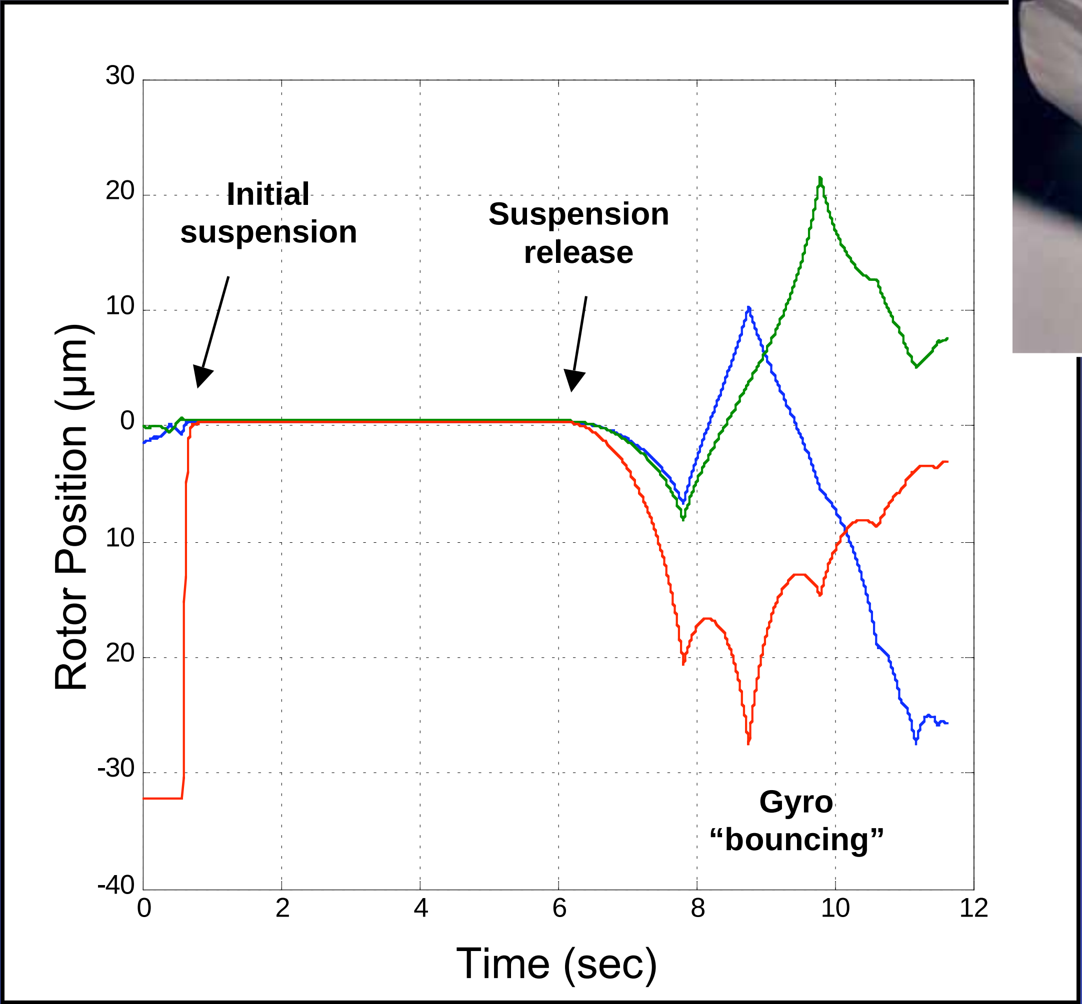
MOC

Marcie Smith

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

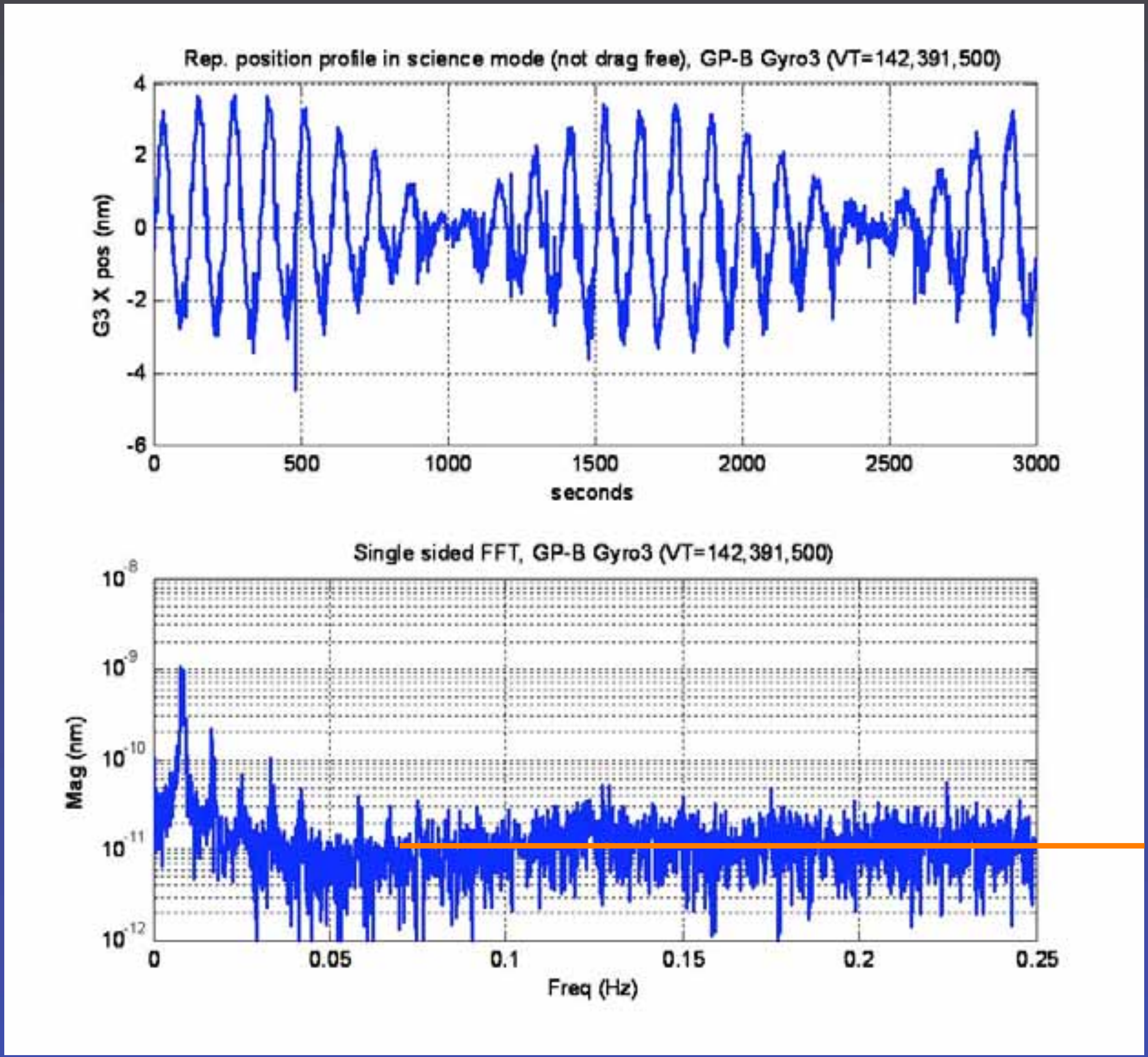
GP-B Gyro On-Orbit Initial Liftoff

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

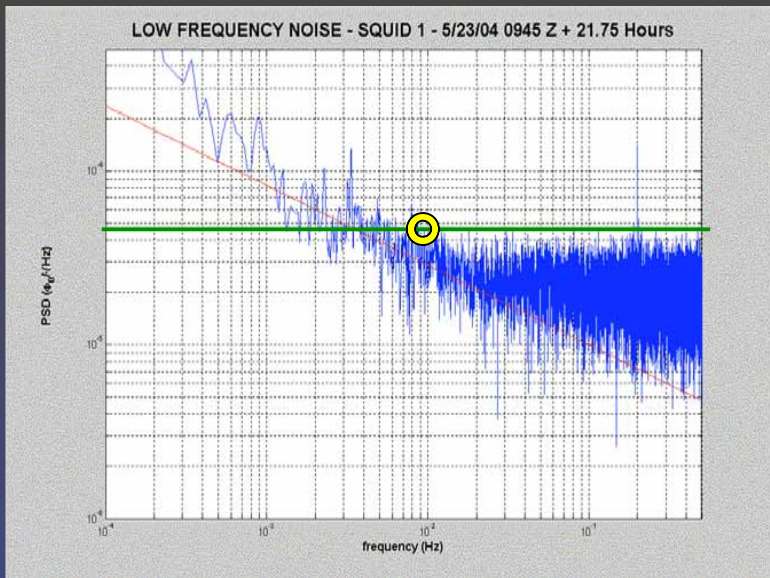


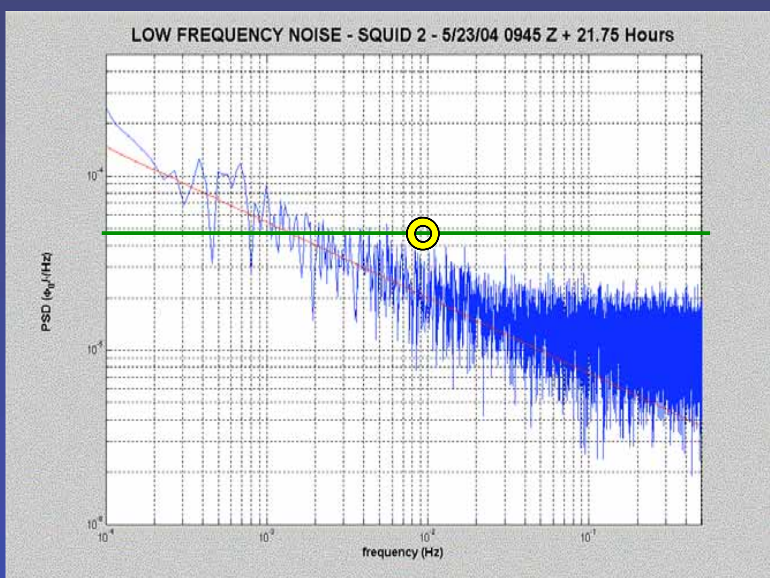
<u>Gyro position</u> – non drag-free gravity gradient effects in Science Mission Mode

<u>Measurement noise</u> – 0.45 nm rms

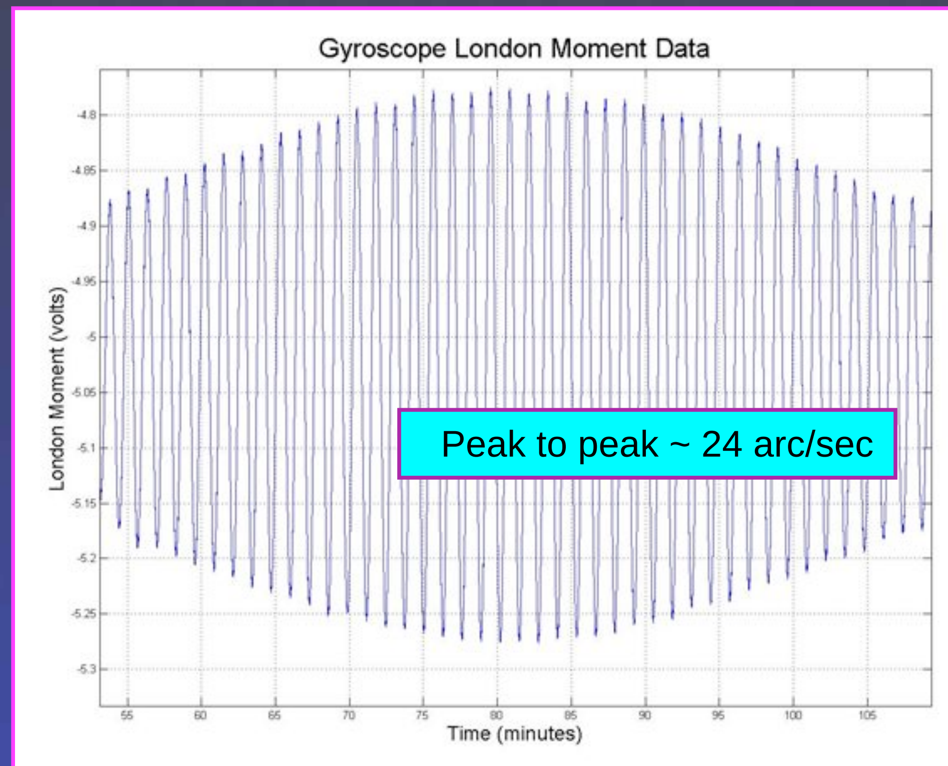
Noise floor

Gyro Readout Performance On-Orbit I

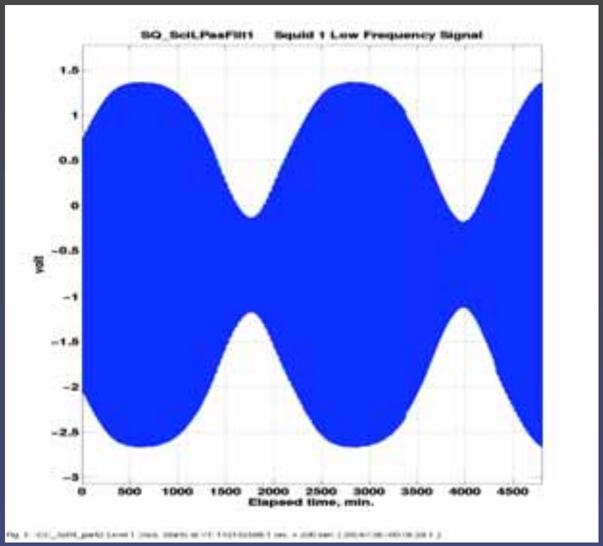




Bruce Clarke, Barry Muhlfelder, Jim Lockhart (SFSU), Terry McGinnis (LM) + the team



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

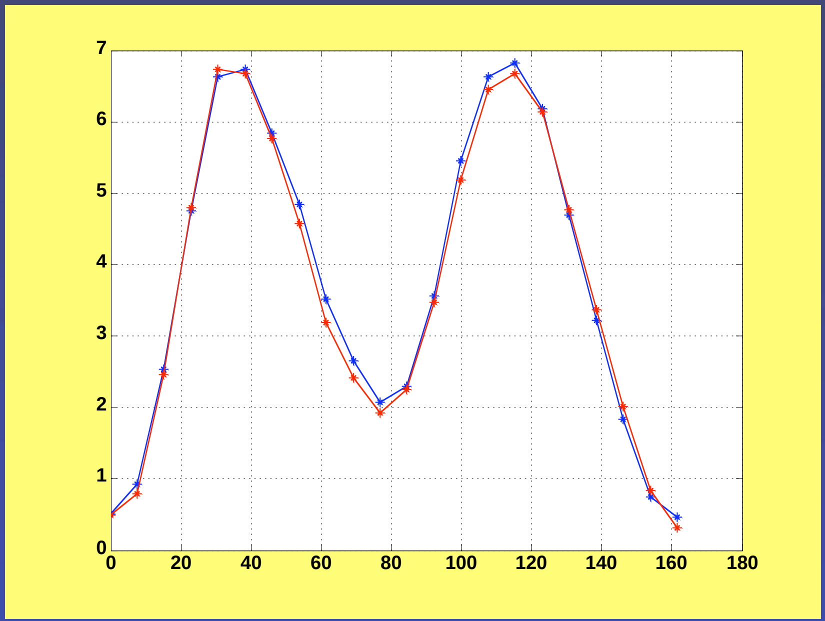


David Santiago (* Physics), * Michael Salomon (A/A)

Gyro # 1 @ 3 Hz

36-hour polhode period

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



Paul Shestople, * Michael Dolphin (A/A)

Gyro # 1 @ 79.3858 Hz

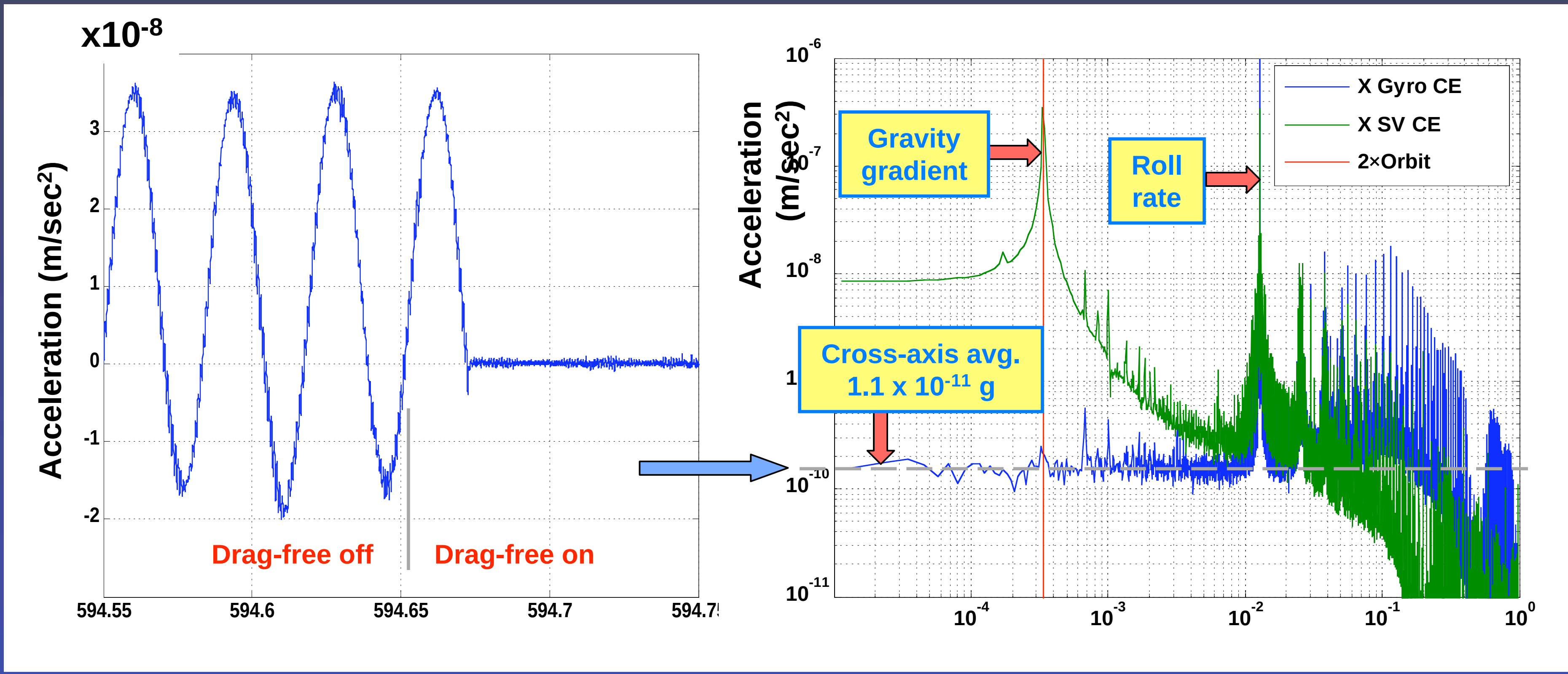
Mass Unbalance (nm)

Gyro #	1	2	3	4
Prelaunch estimate	18.8	14.5	16.8	13.5
On-orbit data	10.1	4.8	5.4	8.2

Drag-Free: 2^{nd} Near Zero

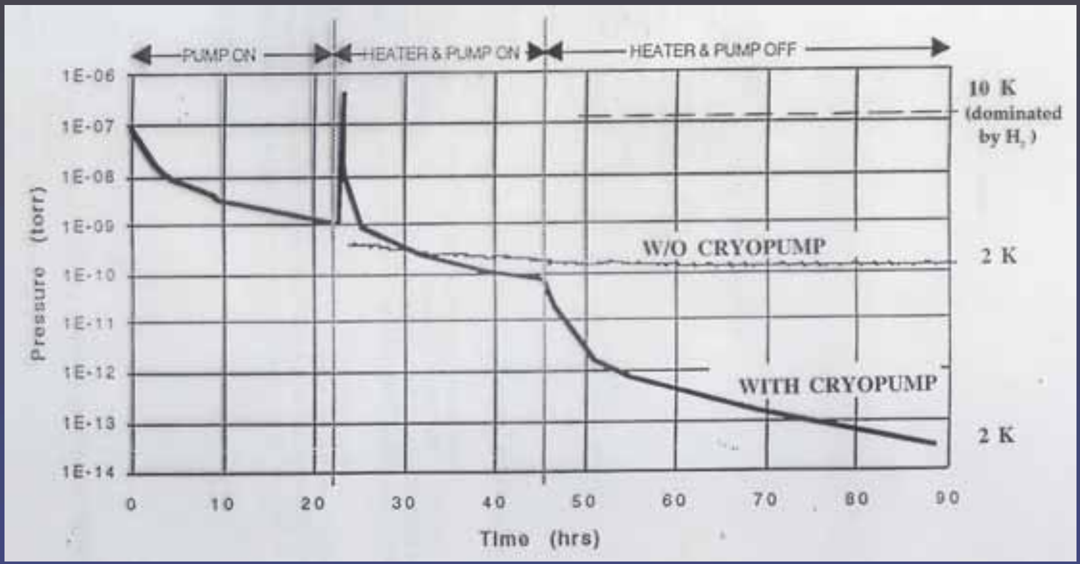
Proportional thruster
He boil off gas – Reynolds number ~ 10 !!

Dan DeBra, * John Bull (A/A), * J-H Chen (A/A),
* Yusuf Jafry (A/A), Jeff Vanden Beukel + team (LM)



Ultra-low Pressure: 5th Near Zero

Low Temperature Bakeout (ground demonstration)



The Cryopump

Gyro spindown periods on-orbit (years)

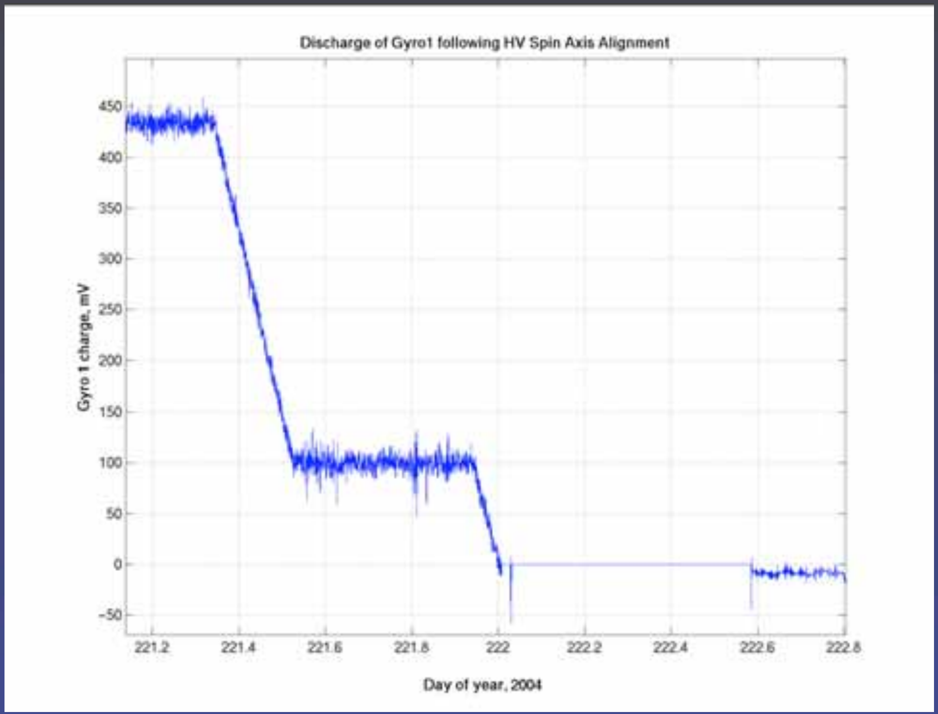
	before bakeout	after bakeout
Gyro #1	~ 50	15,800
Gyro #2	~ 40	13,400
Gyro #3	~ 40	7,000
Gyro #4	~ 40	25,700

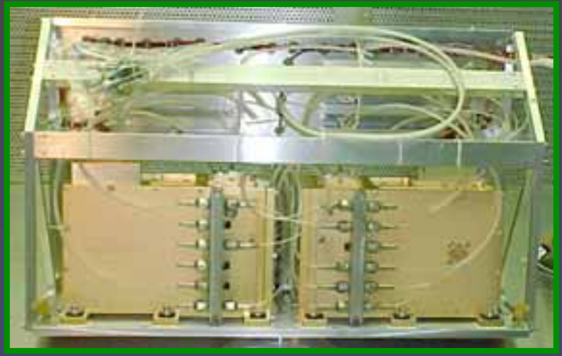
John Lipa, John Turneaure (Physics) + students; adsorption isotherms for He at low temperature,* Eric Cornell, (undergraduate honors thesis)

pressure << 1.5 x 10^{-11} torr
(+ minute patch-effect dampings)

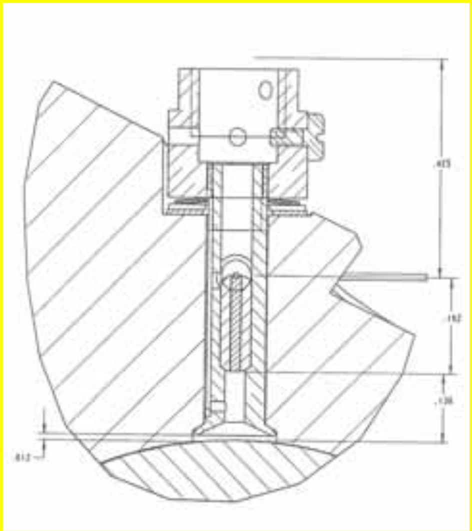
Rotor Electric Charge: 6th Near Zero

Discharge of Gyro #1





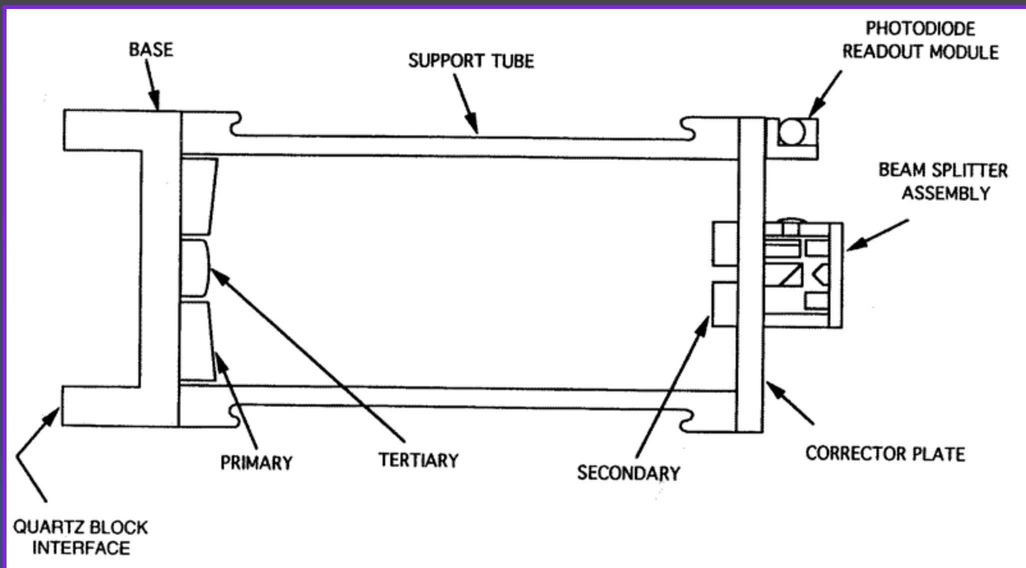
Ti Steering Electrode



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

Typical charge rates ~ 0.1 mV/day

Star Tracker I: Concept



Some dimensions:

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

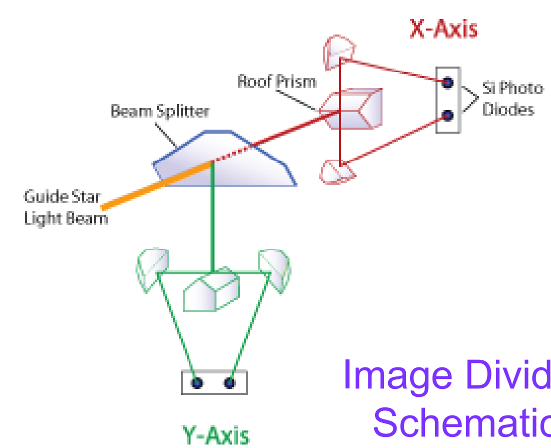
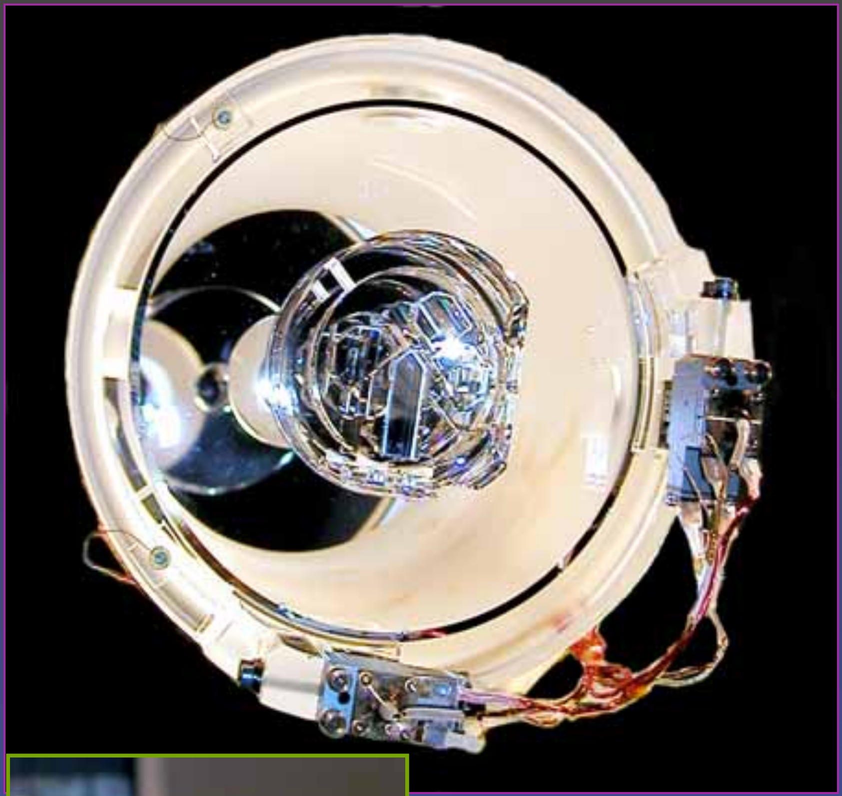


Image Divider Schematic

Don Davidson

Star Tracker II: Under Test



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

Telescope development

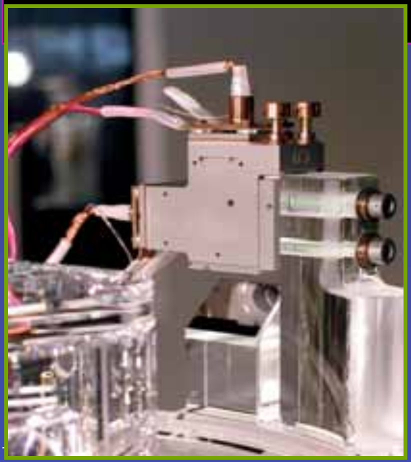
* Mo Badi (Ap Phys), * Dana Clark (ME),
* Chris Cumbermack (Pre-med!),
* Howard Shen (EE) + 6 others

Artificial Star #3

* Ted Acworth (A/A), * Rob Bernier (A/A)

Artificial Star #3

Detector Package



Si Diode Detector

Star Tracker III: Acquiring Star

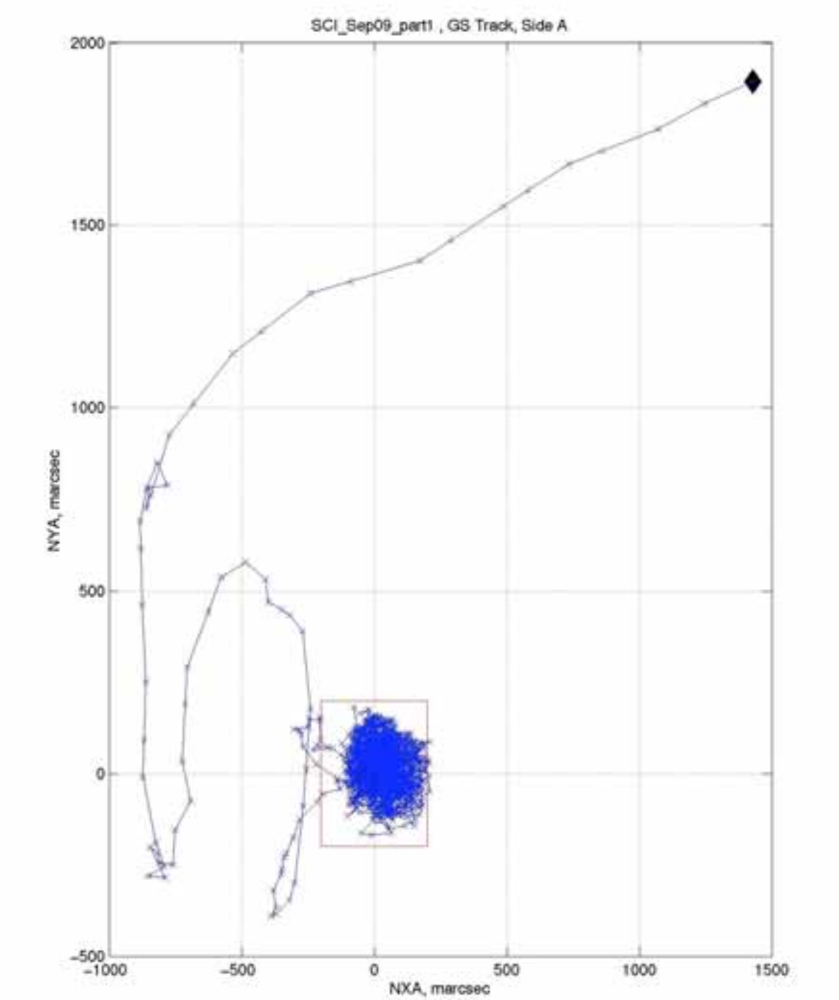


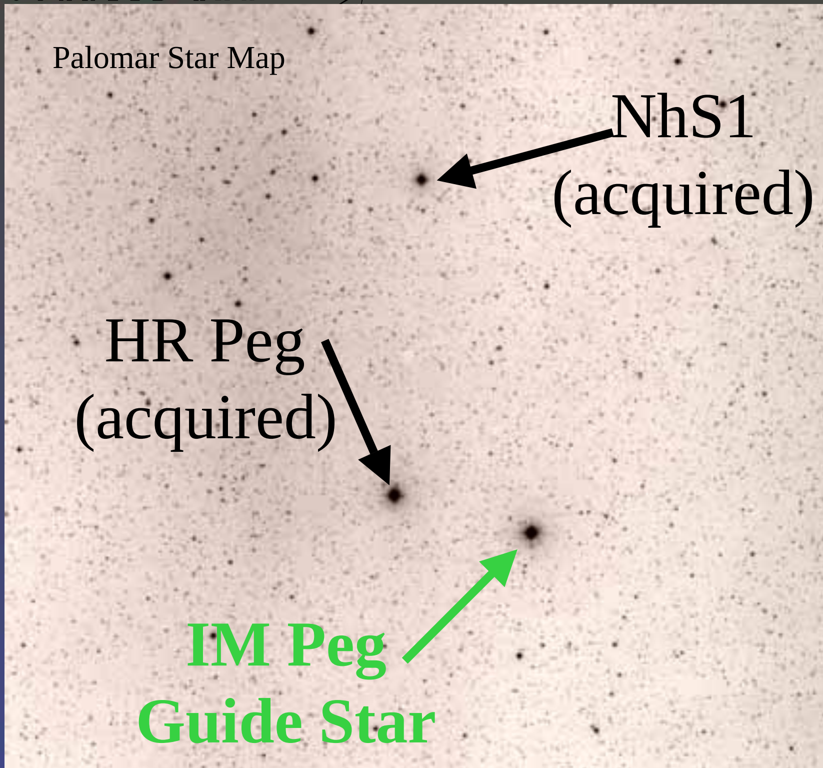
Fig. 705. SCI_Sep09_part1-L2 . GS Track (during GS Valid), Side A Start time: 148031616 sec. Total: 54.0 min

Drive-in time ~ 110 s

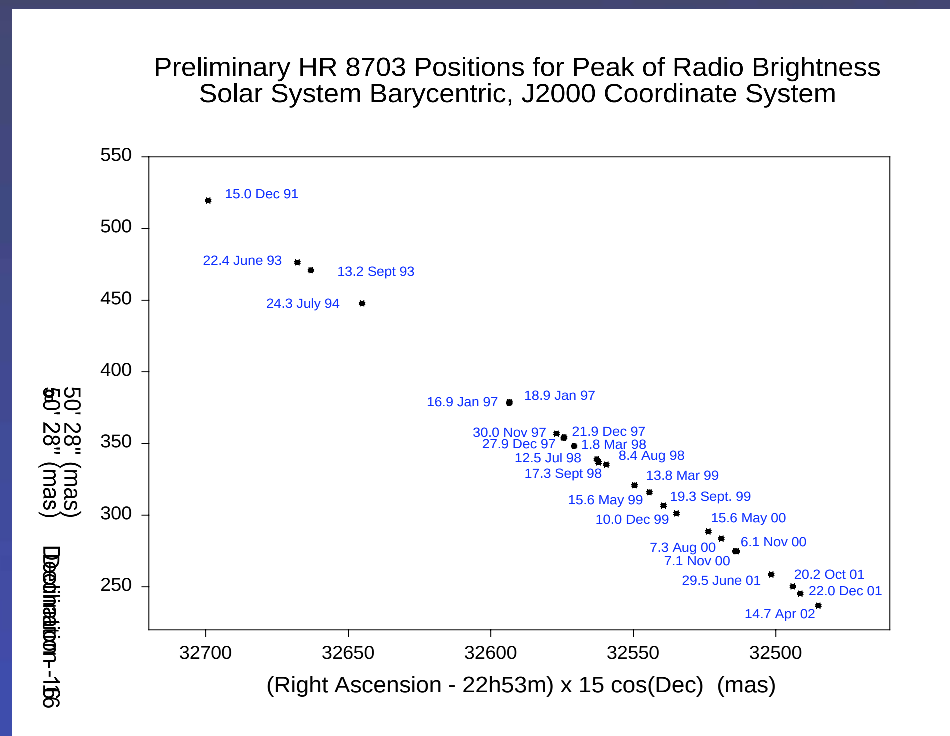
RMS pointing ~ 90 marc-s

Jon Kirschenbaum + team (LM)
Lou Herman (consultant)

IM Peg (HR 8703) Guide Star Identification



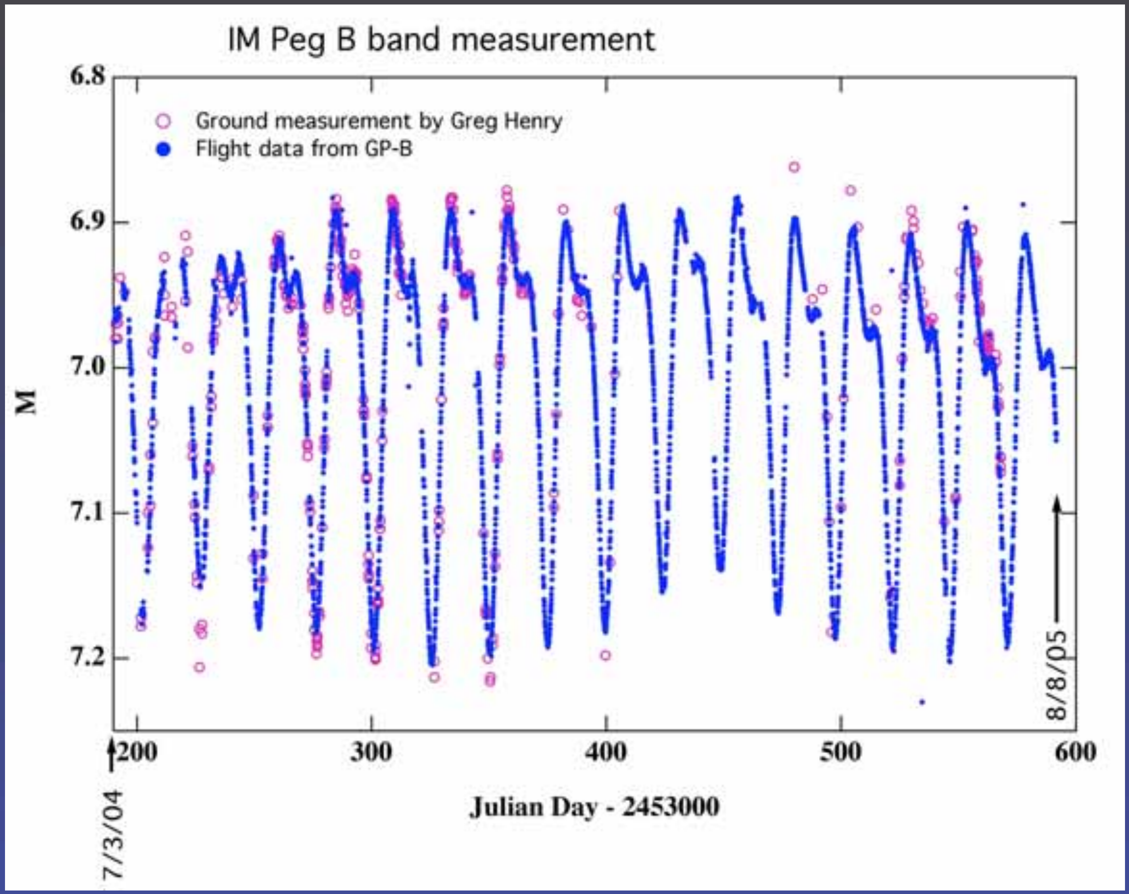
Very Large Array, Socorro, New Mexico



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

Ground-based & Space Observations of IM Peg

John Goebel (NASA Ames)
Suwen Wang (Stanford)
Michael Ratner (SAO)
Dan Lebach (SAO)
Greg Henry (U of Tenn.)
Jeff Kolodziejczak
(NASA Marshall Center)
Svetlana Berdyugina
(ETH, Switzerland)

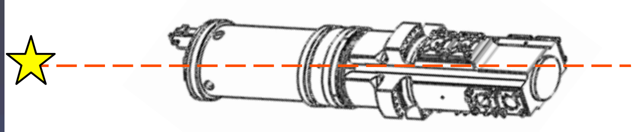


●●●● GP-B flight data
○○○○ G. Henry's ground-based data

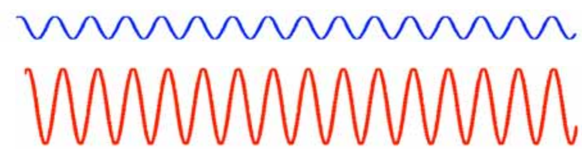
Through GP-B, IM Peg will be most completely characterized star in the entire heavens!

Dither & Aberration: Two Secrets of GP-B

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

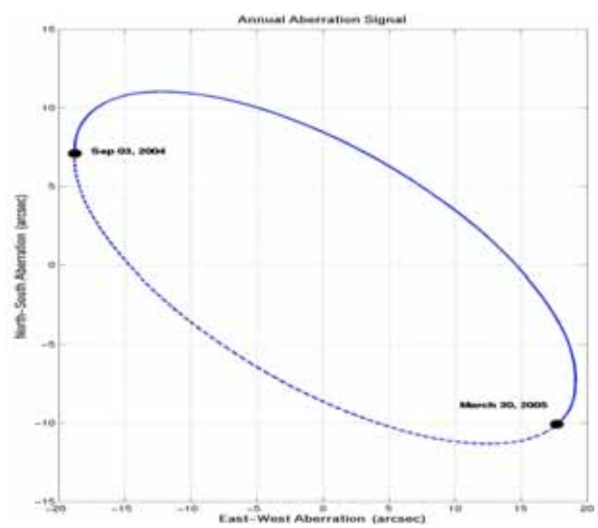


{ gyro output
telescope output



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 (IOC) - 128 days

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

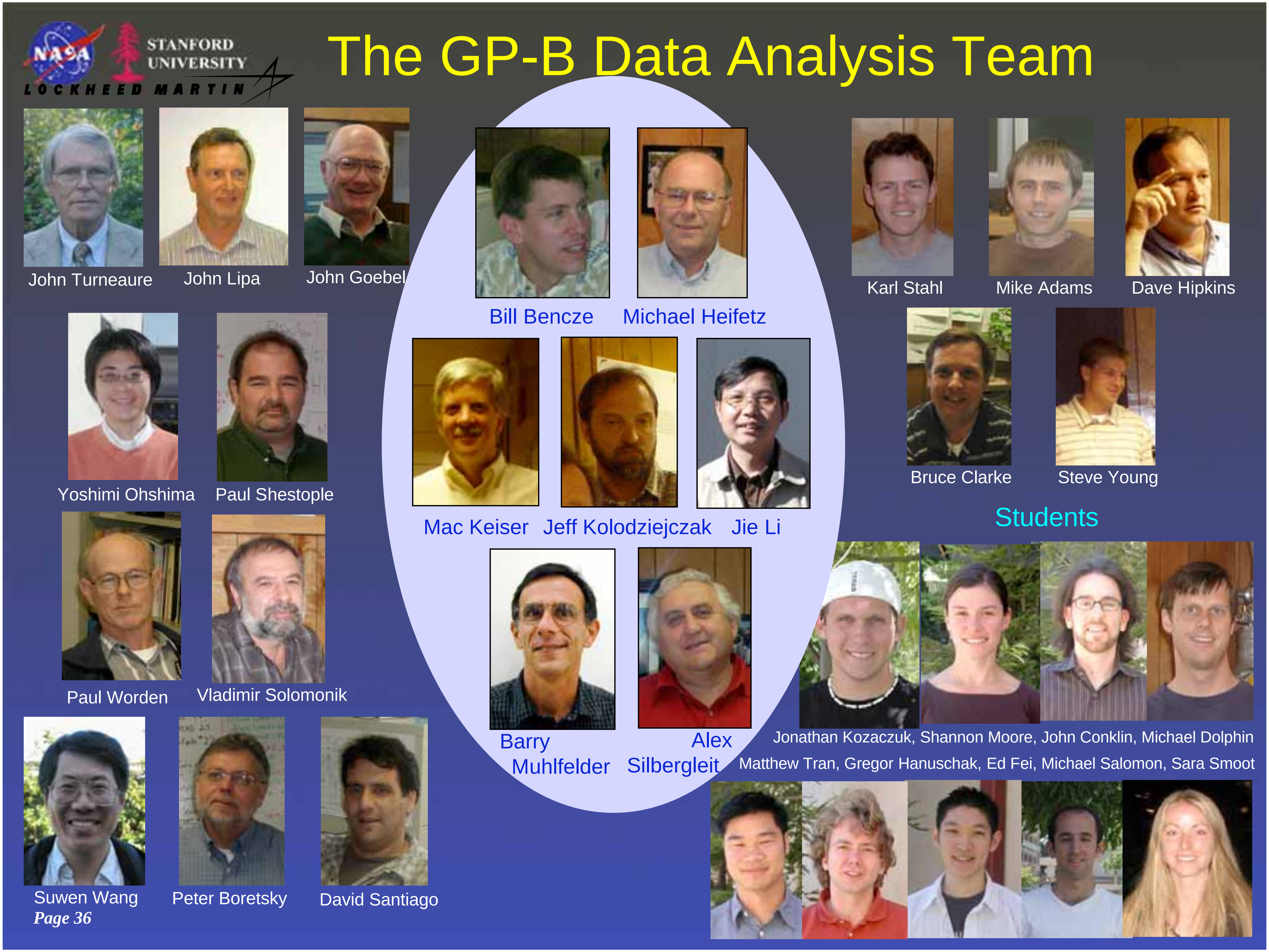
B. Science Phase - 353 days

- 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]

"Always be suspicious of the news you want to hear"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Suwen Wang
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David Santiago
Page 36

The GP-B MSFC-Stanford Collaboration

Dick Potter

Joyce Neighbors

Rein Ise

- The First Phase, 1965 - 1982
  - Technologies
  - The 1971 Ball Aerospace study
  - MSFC 1980 - 1982 in-house Phase B
- Academia & Industry
  - What each can bring
  - Defining requirements
  - Structuring a contract
- Flight Development Phase, 1984 - 2004
  - The Management Experiment
  - Risk-based, value-added management
  - Specific MSFC technical contributions
- The Calder-Jones Report

Rex Geveden

Tony Lyons

"*What we are doing here is a cross between an academic program and a Silicon Valley start-up*"
– Brad Parkinson to FE, 1985

Wider Significance of the GP-B Experience

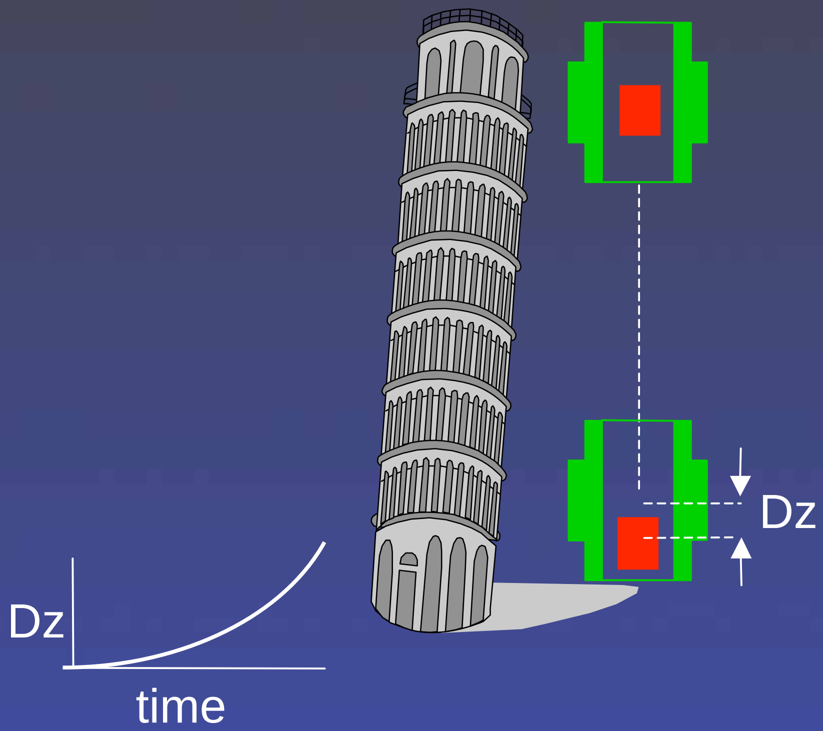
- Physics-Aero/Astro collaboration
- Sophisticated technologies
  - *Drag-free, Pointing, Cryogenics*
- 'Near Zero'
- Integrated Science/Operations team

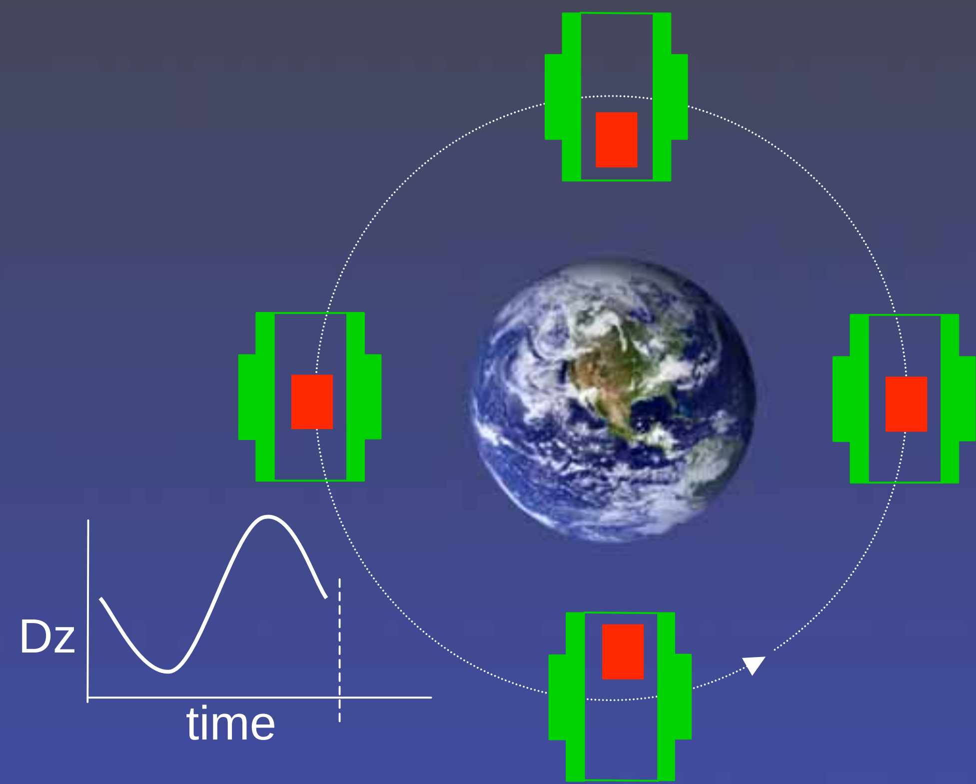
Onward to STEP & LISA

Satellite Test of the Equivalence Principle -- STEP

Newton's Mystery {

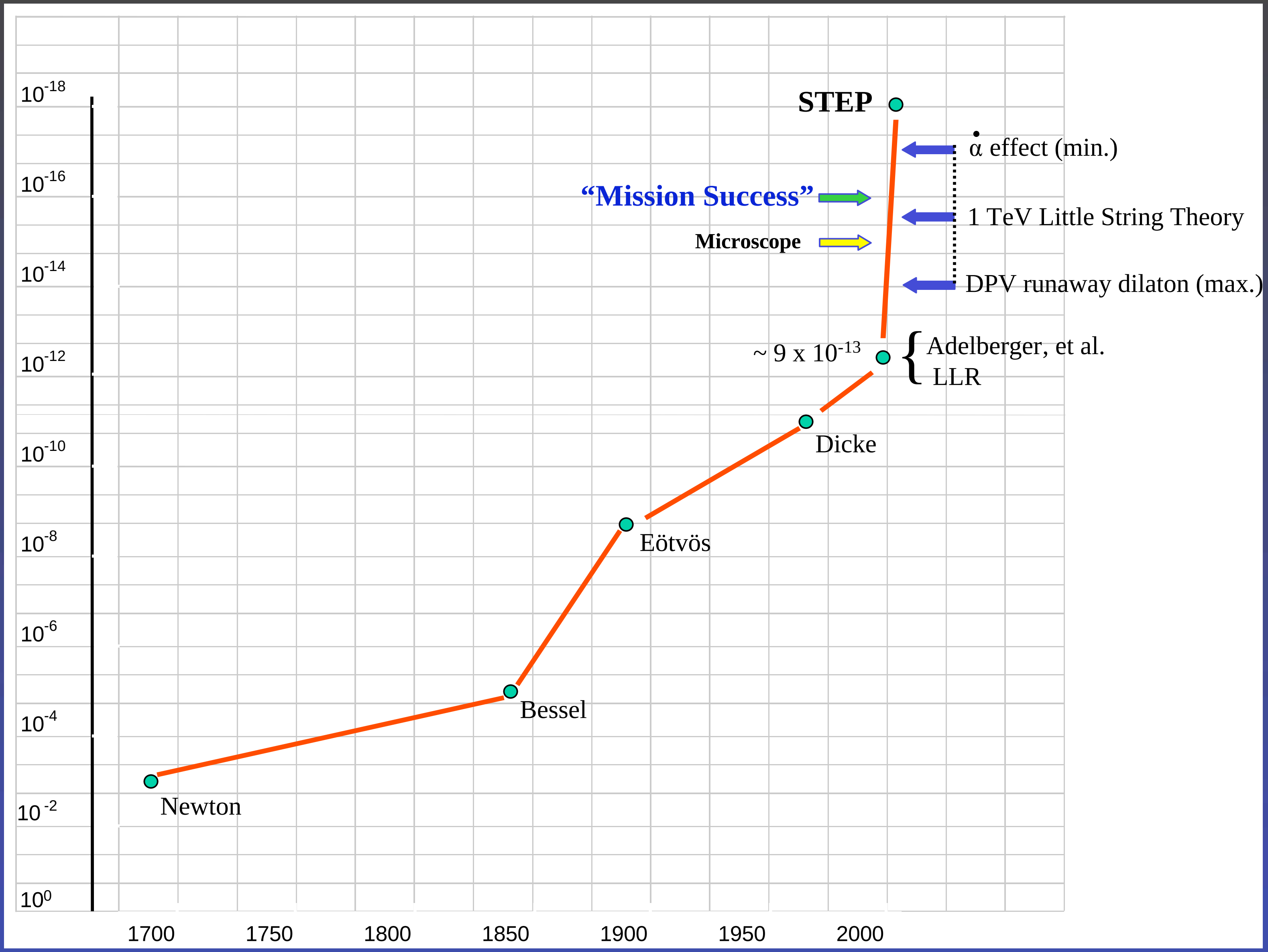
- $F = ma$ — mass - the receptacle of inertia
- $F = GMm/r^2$ — mass - the source of gravitation



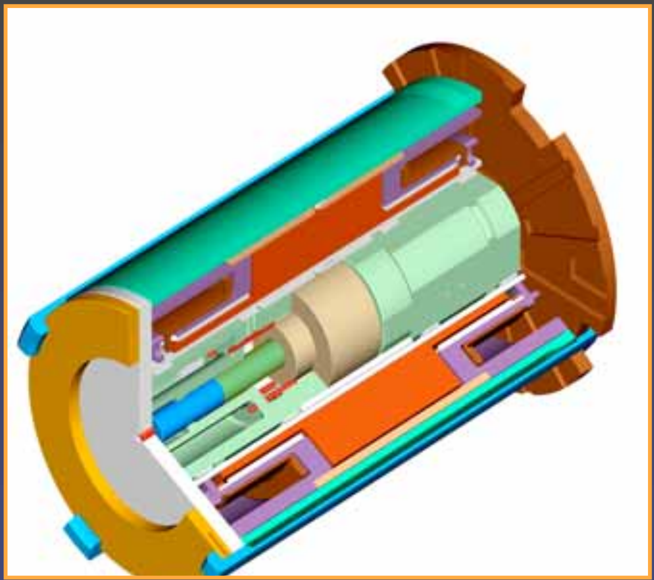


Orbiting drop tower experiment {
* More time for separation to build
* Periodic signal

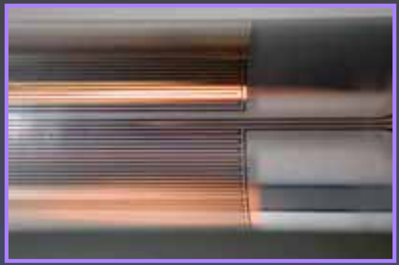
Space > 5 Orders of Magnitude Leap



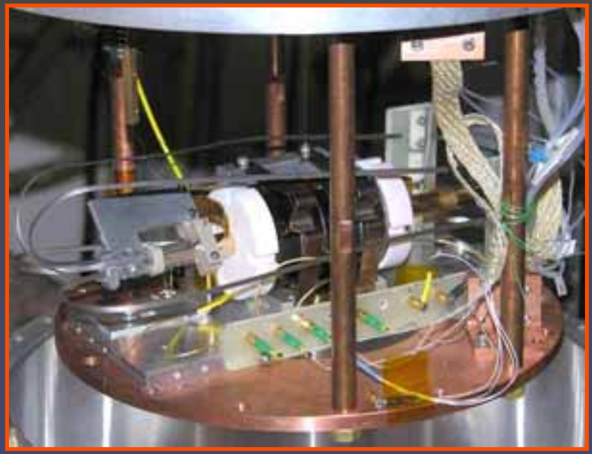
Some Elements of the STEP Mission



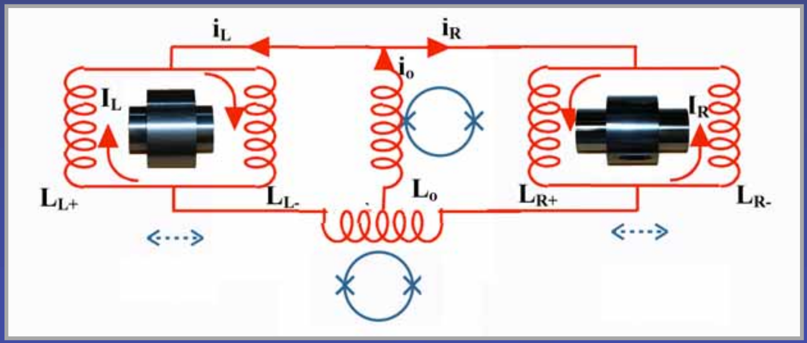
assembled flight instrument



magnetic bearing



bearing under test



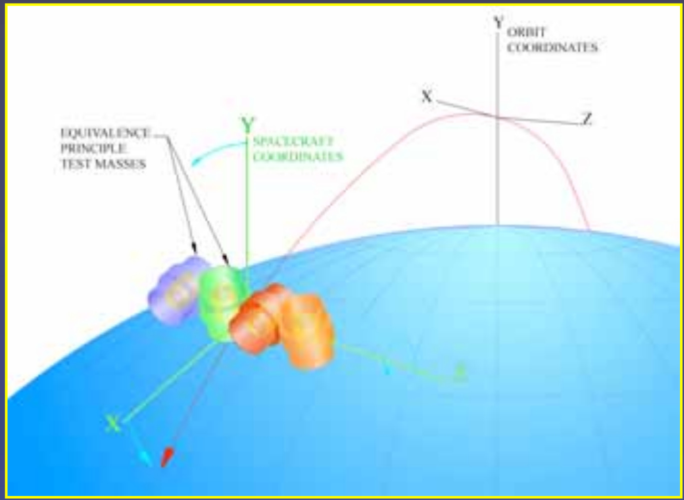
differential SQUID readout

SQUID assembly

2-axis tilt platform

STEP: Credibility and Impact

- Robust Equivalence Principle data
  - *4 accelerometers, each $\eta \rightarrow 10^{-18}$ in 20 orbits*
- Positive result (violation of EP)
  - *Discovery of new interaction in Nature*
  - *Strong marker for Grand Unification theories*
- Negative result (no violation)
  - *Overturns two most credible approaches to Grand Unification*
  - *Places severe constraints on new theories*



"…the existence of weak... long-range dilaton or moduli fields is an essential part of [string] theory and **a test of EP five-orders-of magnitude beyond the existing limit would be fantastically important**."

-- *David Gross, 2004 Nobel Prize in Physics*