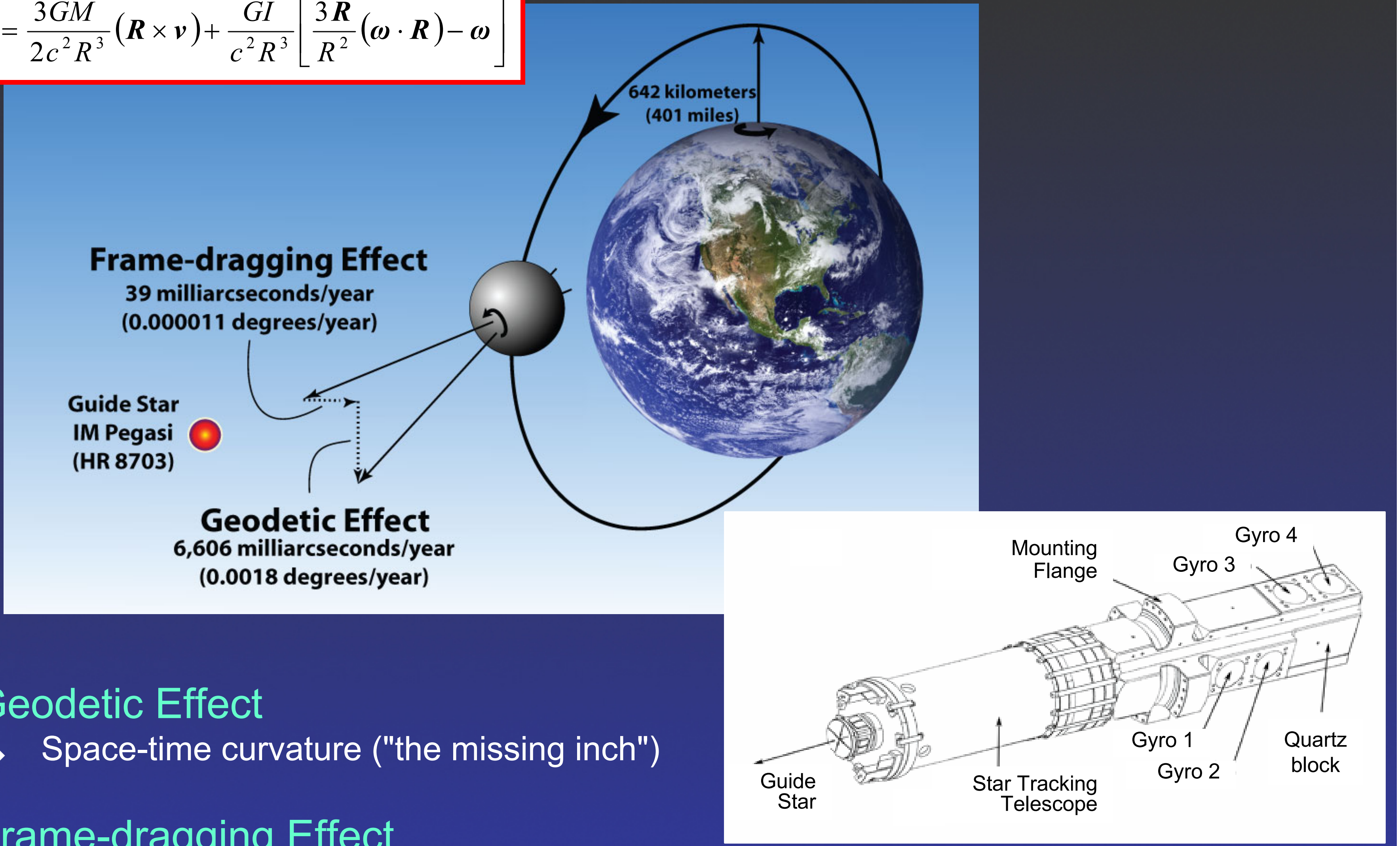
Gravity Probe B + a Hint of STEP

SLAC Summer Institute
XXXV

C.W. Francis Everitt
9 August 2007

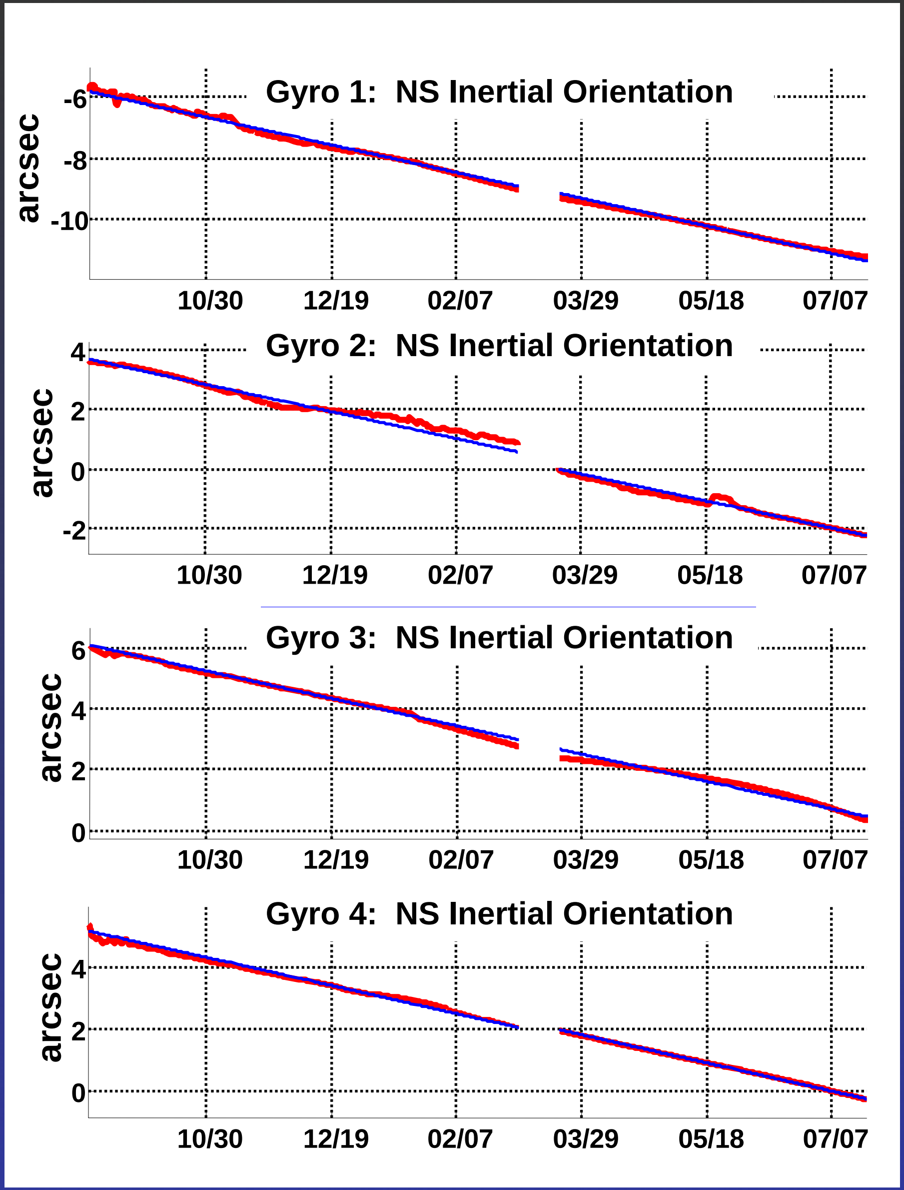
The Relativity Mission Concept

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



- Geodetic Effect
  - Space-time curvature ("the missing inch")
- Frame-dragging Effect
  - Rotating matter drags space-time ("space-time as a viscous fluid")

Seeing General Relativity Directly



Red: Raw flight data
Blue: With torque modeling (4 gyros co-processed)

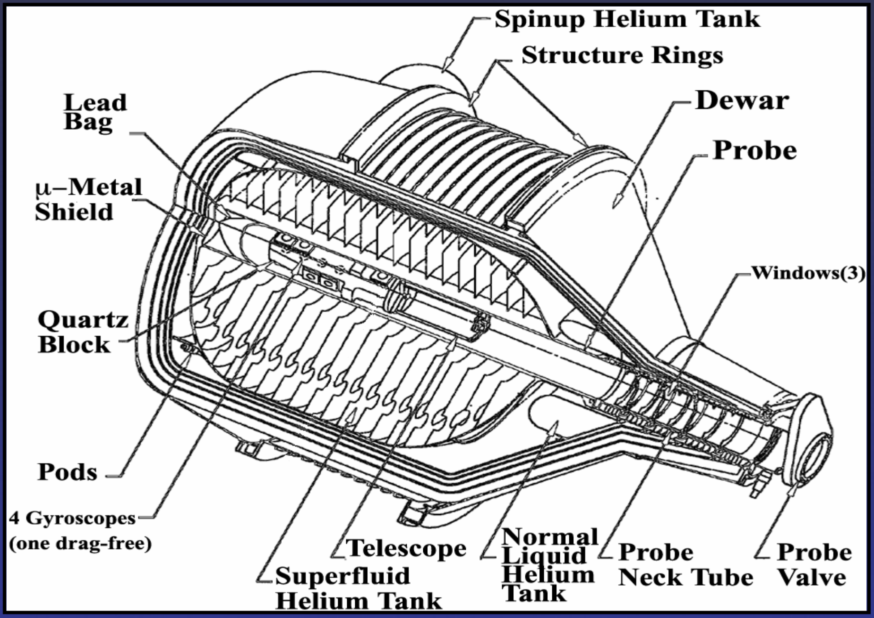
Geodetic effect	marc-s/yr
Einstein expectation	- 6571 ± 1*
4-gyro result (1σ)	- 6578 ± 9
Overall error estimate ≤ 97 marc-s/yr based on gyro-to-gyro disagreements & other not yet fully analyzed systematics	
SQUID noise limit (4-gyro)	
- 353 day continuous	± 0.12
- segmented data	± 0.5 - 0.9

* -6606 + 7 solar geodetic + 28 ± 1 guide star proper motion

1 marc-sec/yr = 3.2×10^{-11} deg/hr – width of a human hair seen from 10 miles

The GP-B Challenge

◆ Gyroscope (G)	10^7 times better than best 'modeled' inertial navigation gyros
◆ Telescope (T)	10^3 times better than best prior star trackers
◆ G – T	→ <1 marc-s subtraction within pointing range
◆ Gyro Readout	→ calibrated to parts in 10^5



Basis for 10^7 advance in gyro performance

Space

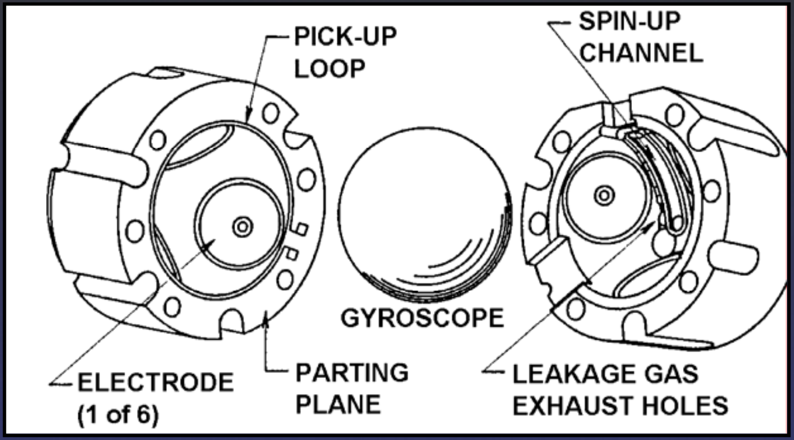
- reduced support force, "drag-free"
- roll about line of sight to star

Cryogenics

- magnetic readout & shielding
- thermal & mechanical stability
- ultra-high vacuum technology

Modeling *ad hoc* [externally calibrated] vs *physics-based*

The GP-B Gyroscope



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

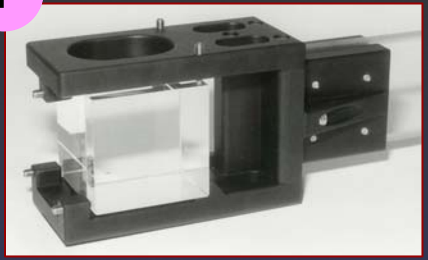
> *"Everything should be made as simple as possible, but not simpler."*
> -- A. Einstein

Challenge 1: $< 10^{-11}$ deg/hr Classical Drift

Seven Near Zeros

1) Rotor inhomogeneities	$< 10^{-6}$	met
2) "Drag-free" (cross track)	$< 10^{-11}$ g	met
3) Rotor asphericity	< 10 nm	met
4) Magnetic field	$< 10^{-6}$ gauss	met
5) Pressure	$< 10^{-12}$ torr	met
6) Electric charge	$< 10^{8}$ electrons	met
7) Electric dipole moment	**0.1 V-m**	**issue**

1



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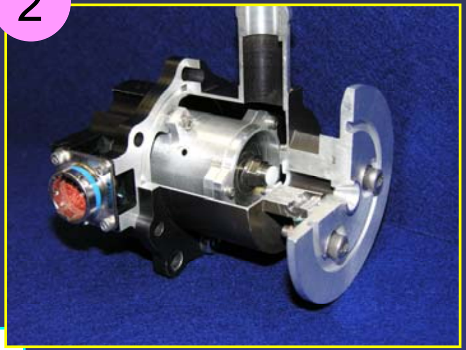

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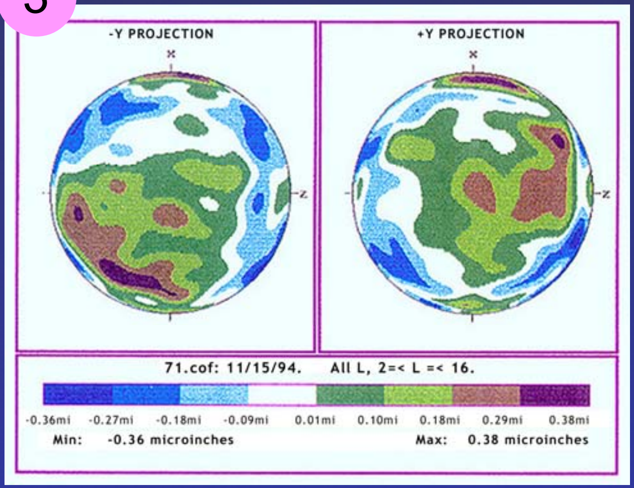

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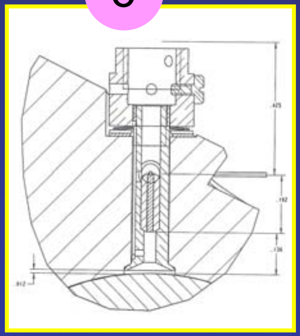
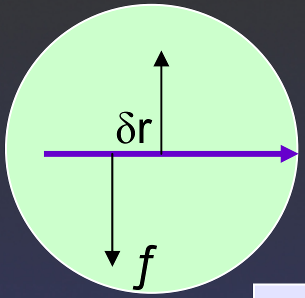


Mass-Unbalance, Drag-Free:

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)

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

$v_s = \omega_s r = 950$ 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)	$\frac{\delta r}{r} < 5.8 \times 10^{-7}$ *(attainable)*

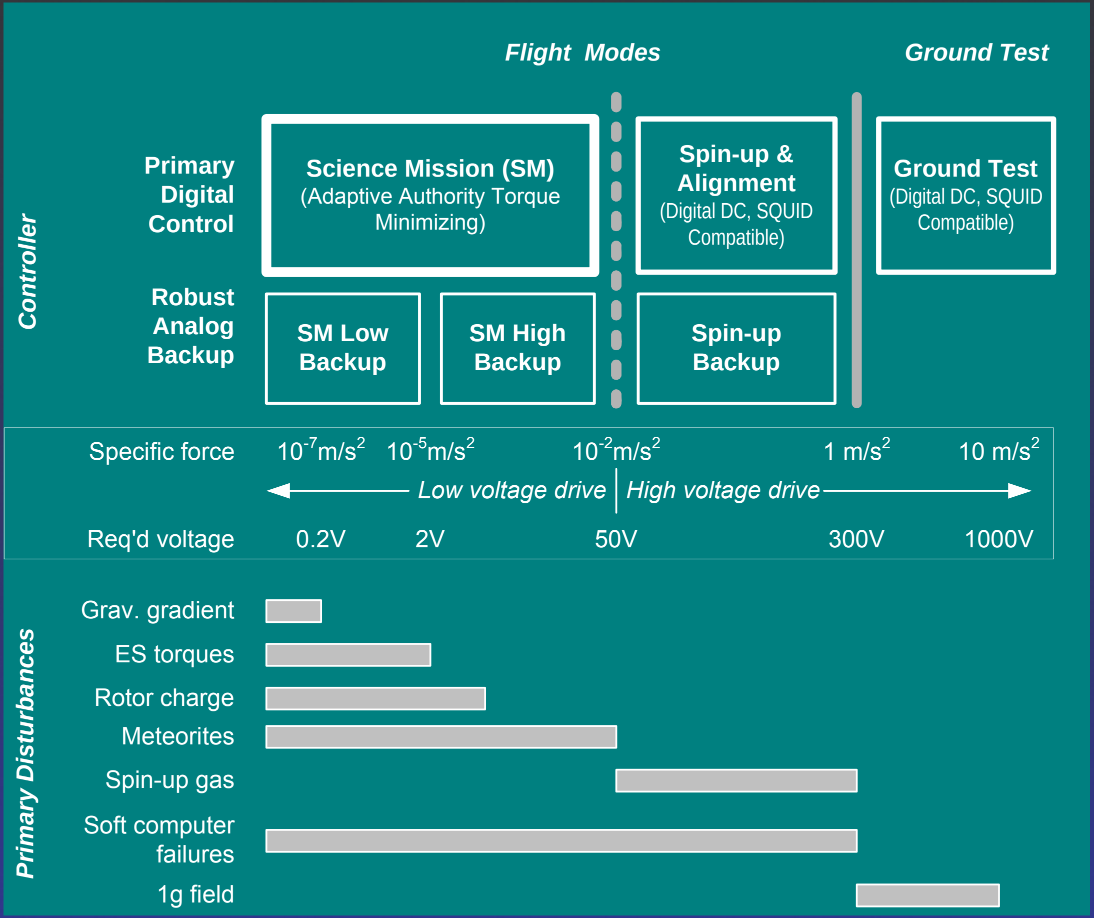
GP-B rotor $\frac{\delta r}{r} \sim 3 \times 10^{-7}$

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

Neither Near Zero alone does it

Gyro I: Suspension System

Operates over 8 orders of magnitude of g levels



Flight Modes

Ground Test

Controller

Primary Digital Control

Science Mission (SM) (Adaptive Authority Torque Minimizing)

Spin-up & Alignment (Digital DC, SQUID Compatible)

Ground Test (Digital DC, SQUID Compatible)

Robust Analog Backup

SM Low Backup

SM High Backup

Spin-up Backup

Specific force	$10^{-7} m/s^2$	$10^{-5} m/s^2$	$10^{-2} m/s^2$	$1\ m/s^2$	$10\ m/s^2$
Req'd voltage	0.2V	2V	50V	300V	1000V

← *Low voltage drive* | *High voltage drive* →

Primary Disturbances

- Grav. gradient
- ES torques
- Rotor charge
- Meteorites
- Spin-up gas
- Soft computer failures
- 1g field

DSP + Power Supply

Analog drive, Backup control

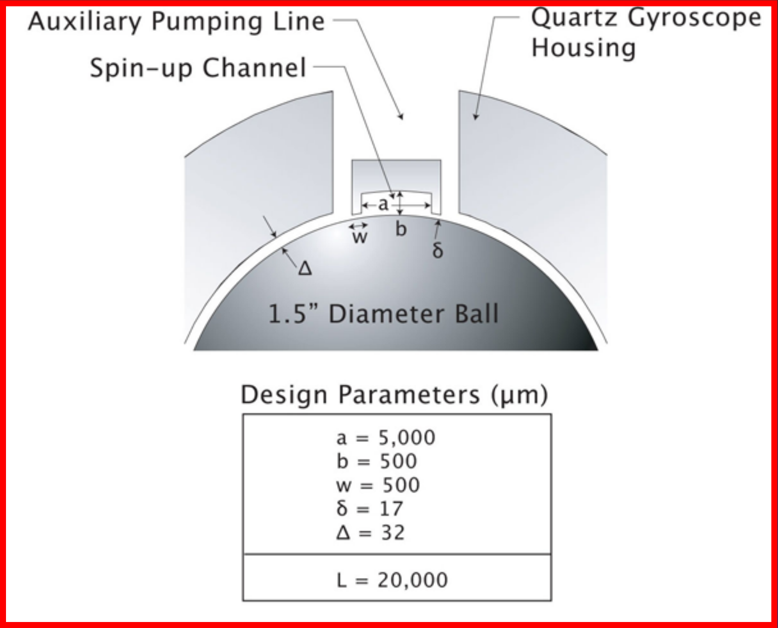
- Range of motion within cavity (15,000 nm) for:
  - science (centered in cavity)
  - spin-up (offset to spin channel ~ 11,000 nm)
  - calibration (offset, 200 nm increments)

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 region < 10^{-3} torr

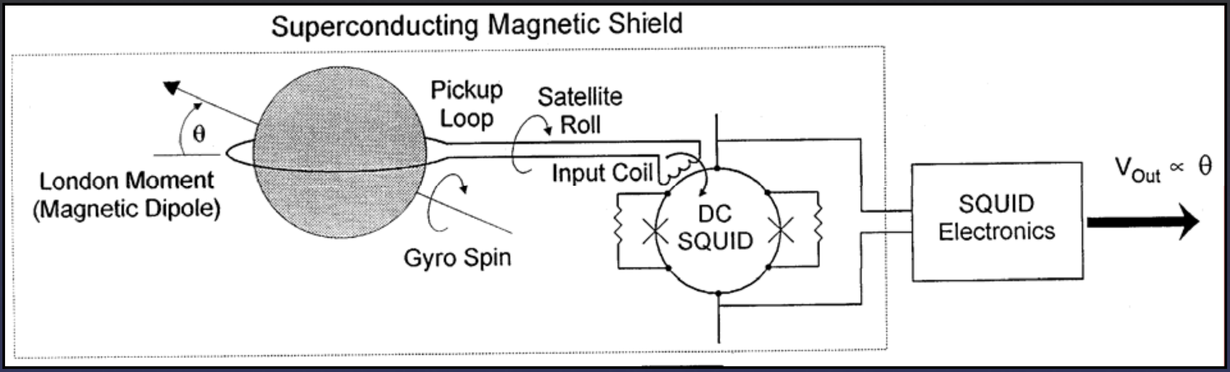
➡

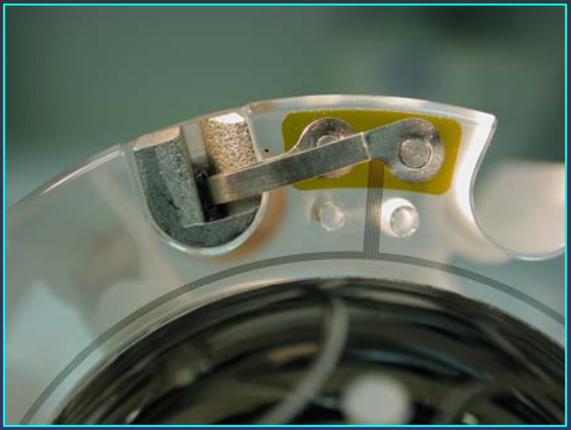
* Dan Bracken (Physics)
Don Baganoff (Aero/Astro)
\+ Gerry Karr (MSFC), John Lipa,
John Turneaure & 4 students

③

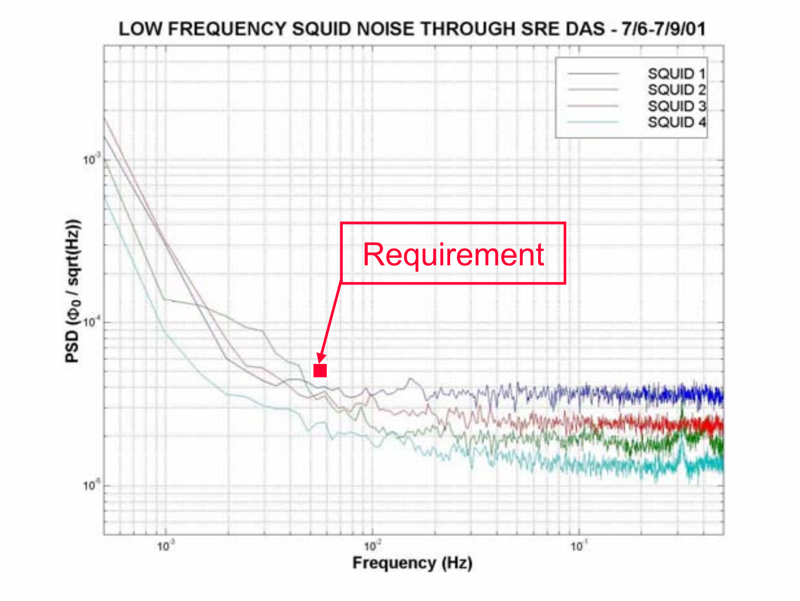
"Any fool can get the steam into the cylinders; it takes a clever man to get it out again afterwards." -- G. J. Churchward, ~ 1895

Gyro III: London Moment Readout





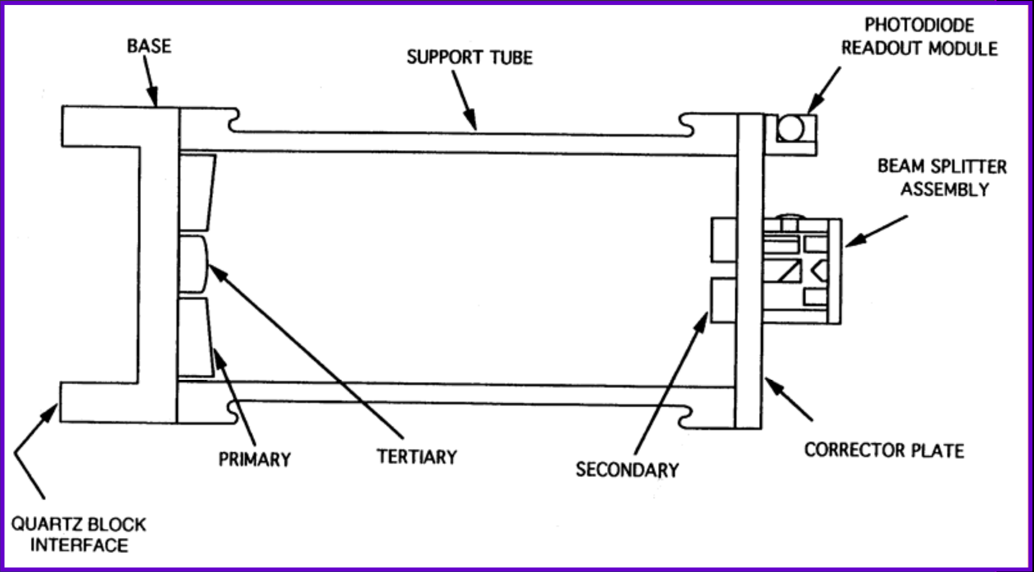
“SQUID” ⟶ 1 marc-s in 5 hours

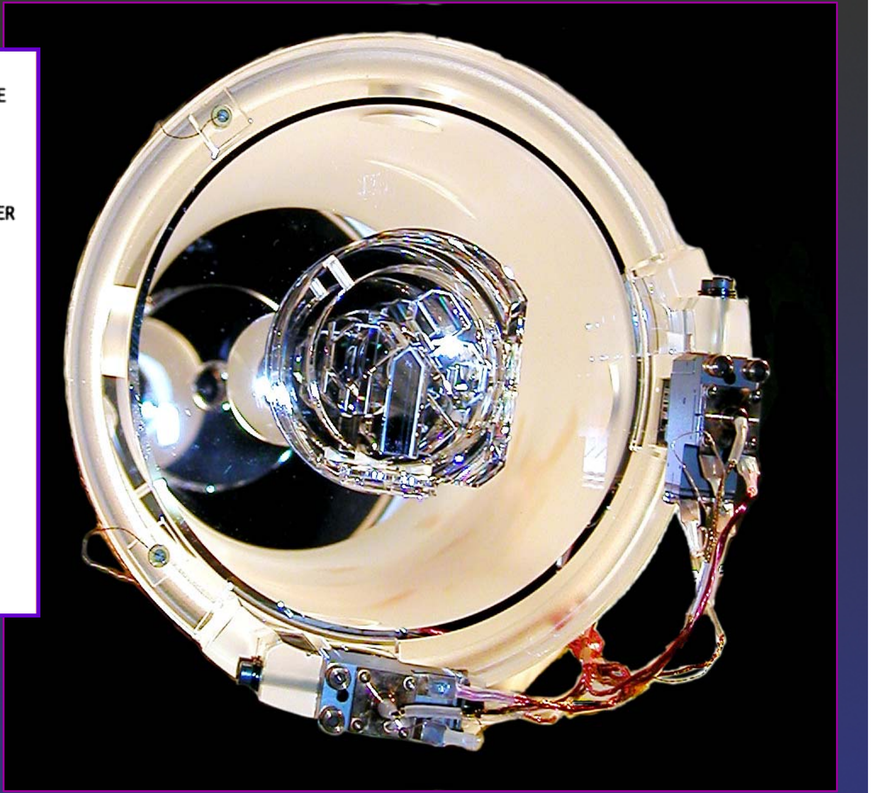


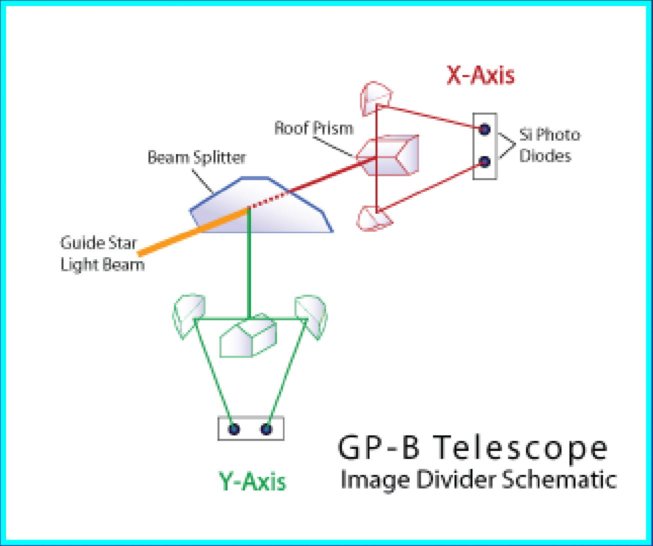
4 Requirements/Goals

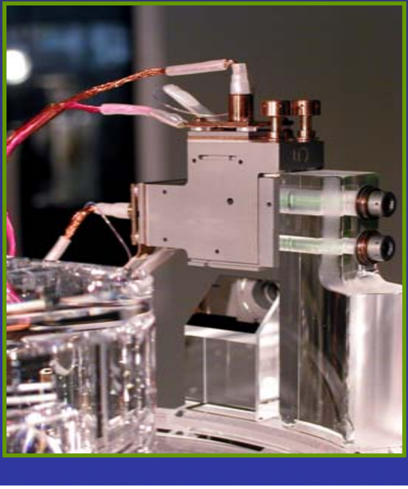
- SQUID noise 190 marc-s/√Hz
- Centering stability < 50 nm
- DC trapped flux < 10^{-6} gauss
- AC shielding > ~ 10^{12}

Challenge 2: Sub-milliarc-s Star Tracker







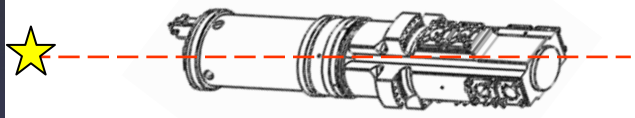


Detector Package

Dual Si Diode Detector

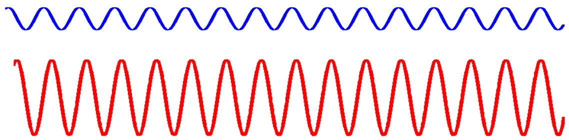
Challenges 3 & 4: Matching & Calibration

Dither -- Slow 60 marc-s oscillations injected into pointing system



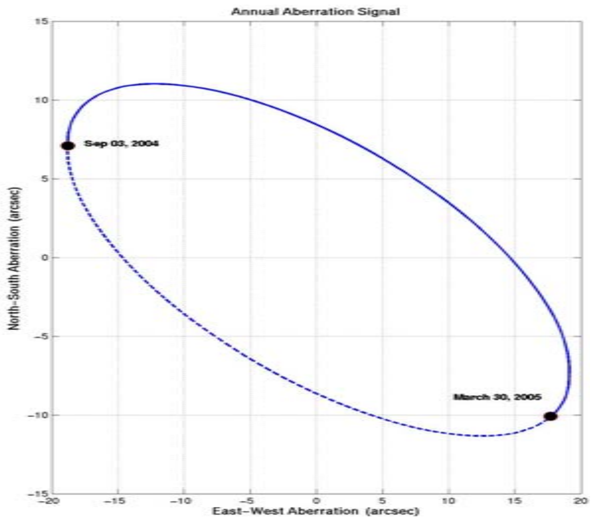
gyro output

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

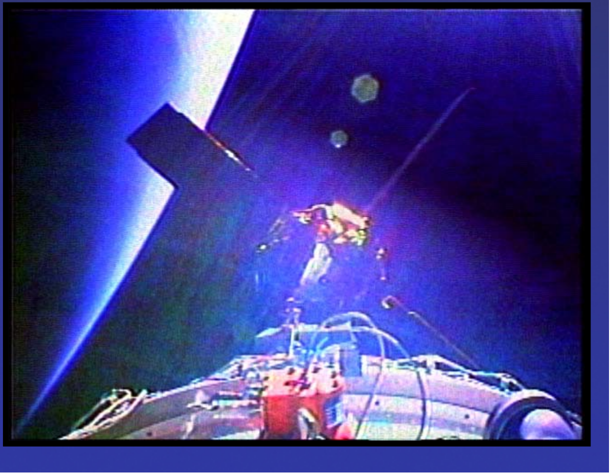
S/V around Earth -- 5.1856 arc-s @ 97.5-min period

→ Continuous accurate calibration of GP-B experiment

The GP-B Cryogenic Payload

Payload in ground testing at Stanford, August 2002

Launch: April 20, 2004 – 09:57:24



On-Orbit: GP-B Mission Operations

Anomaly Room

Gaylord Green

MOC

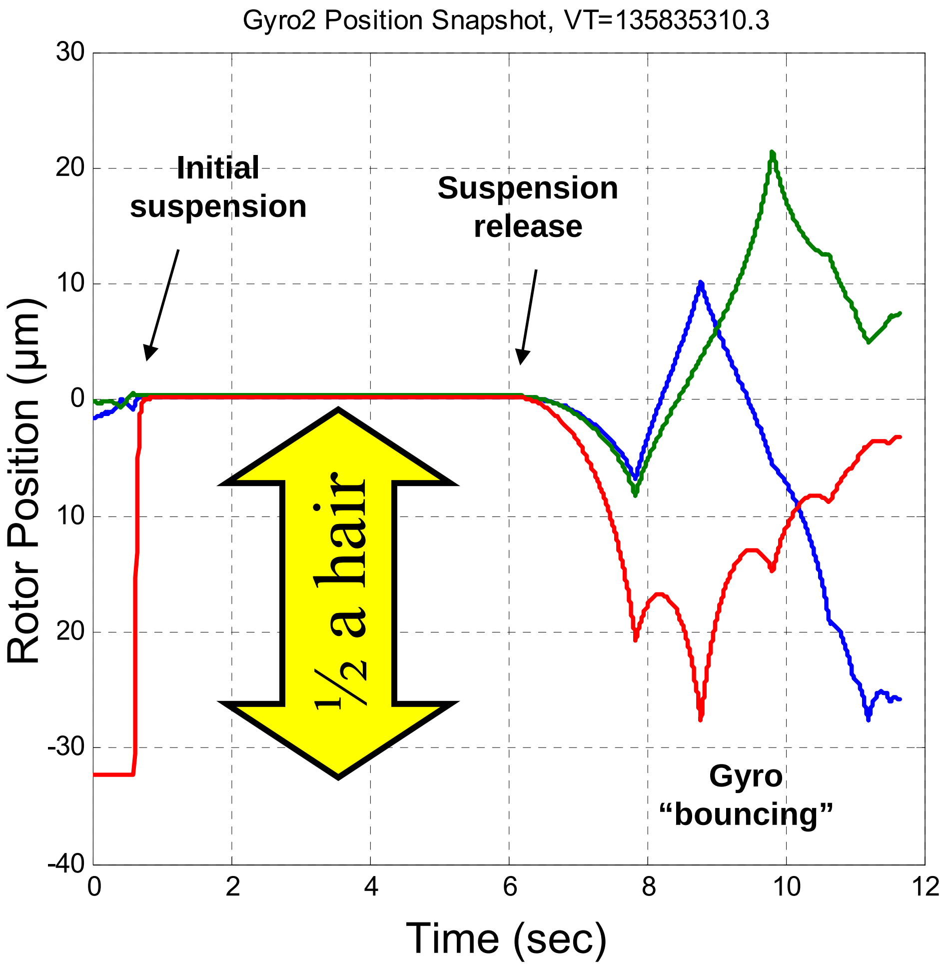
Marcie Smith

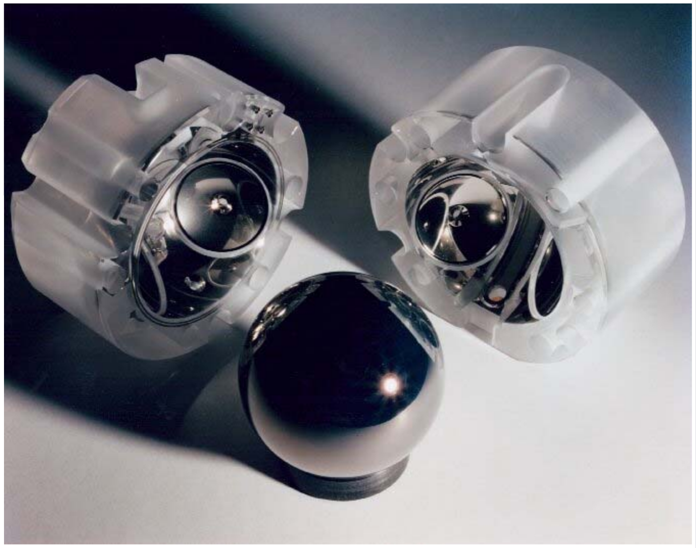
Marcie Smith (NASA Ames)
Kim Nevitt (NASA MSFC)
Rob Nevitt (NavAstro)
Brett Stroozas (NavAstro)
Lewis Wooten (NASA MSFC)
Ric Campo (Lockheed Martin)
Jerry Aguinado (LM)

+ many more

GP-B Gyro On-Orbit Initial Liftoff

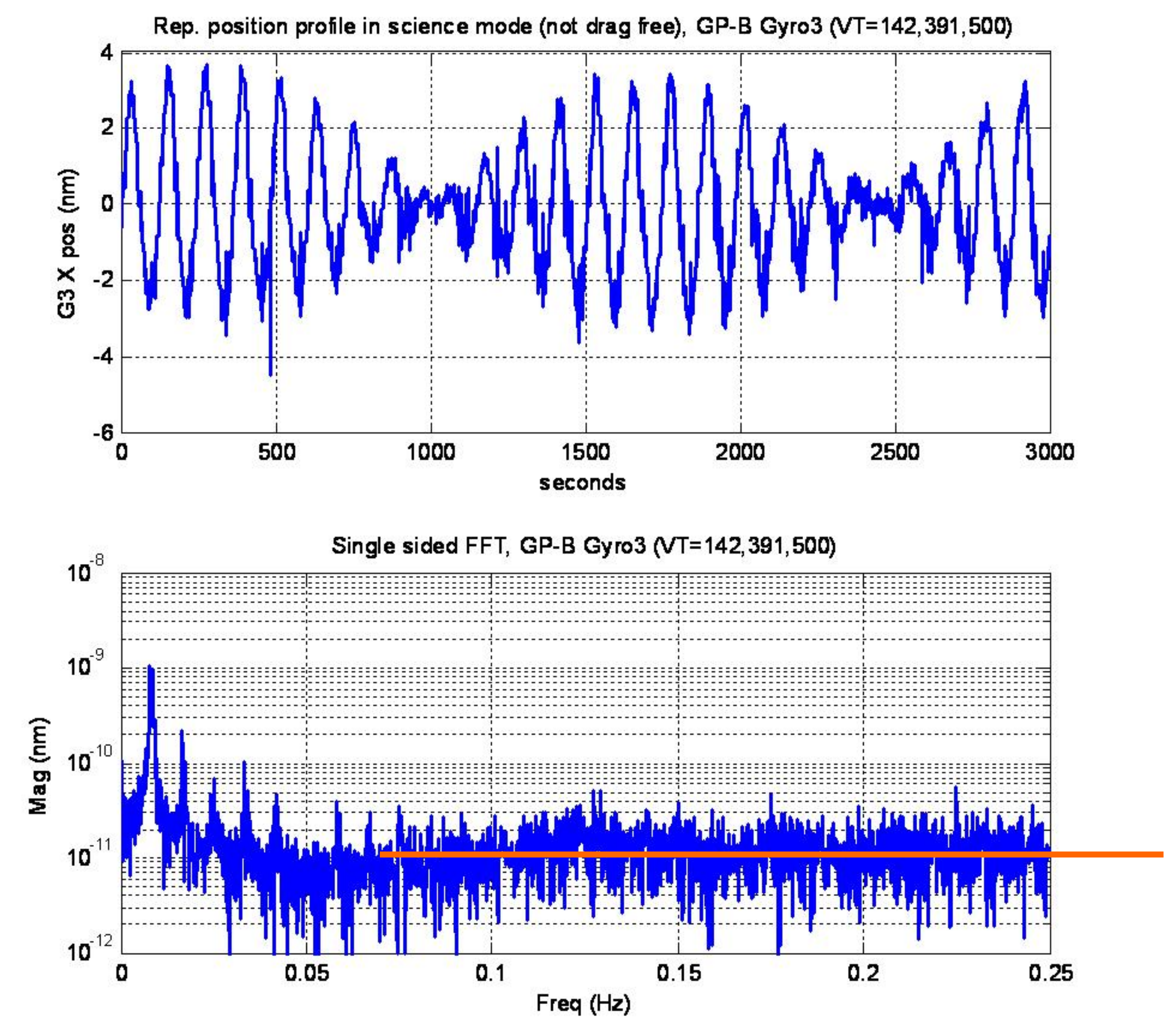
Initial gyro levitation and de-levitation using analog backup system





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

Suspension Performance On-Orbit



Noise floor

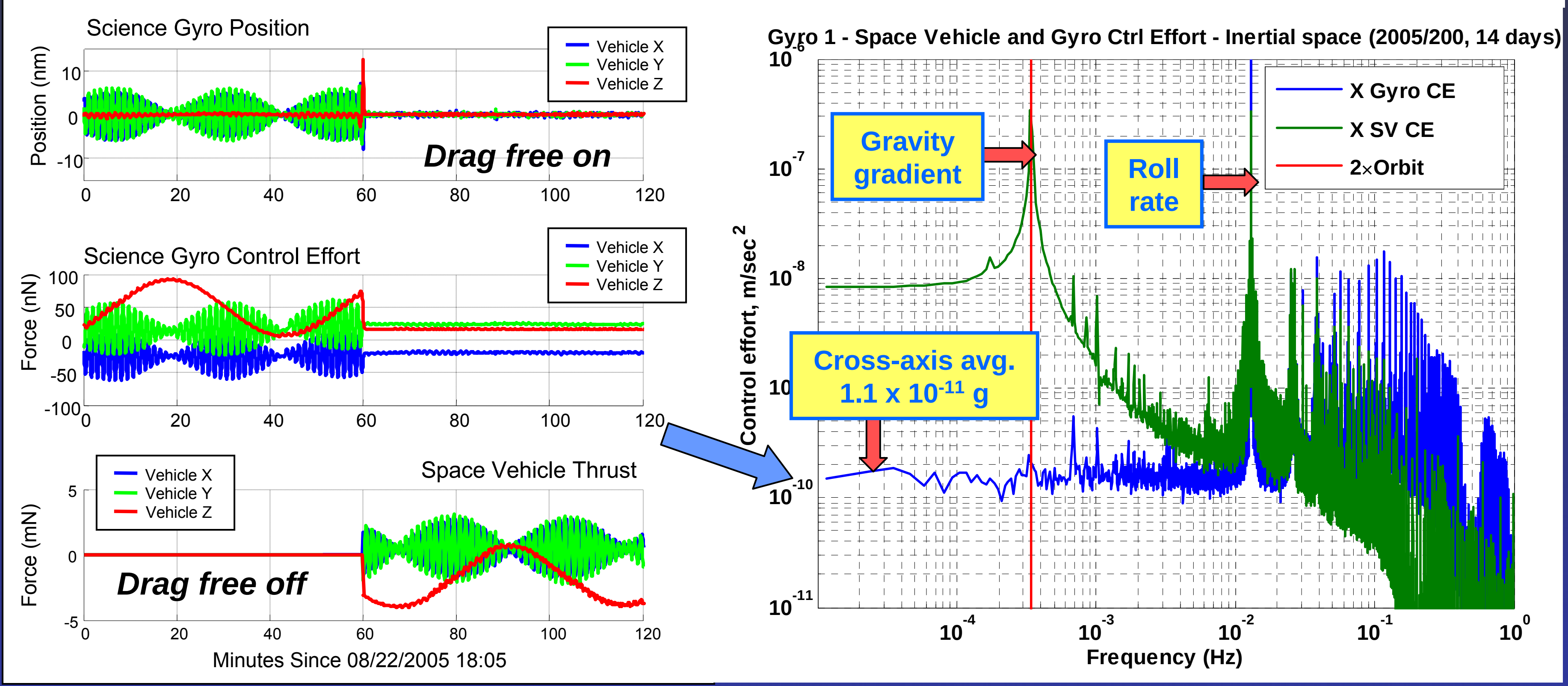
Gyro position – non drag-free gravity gradient effects in Science Mission Mode

Measurement noise – 0.45 nm rms

Drag-Free: 2nd 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)



Science Gyro Position

Drag free on

Science Gyro Control Effort

Space Vehicle Thrust

Drag free off

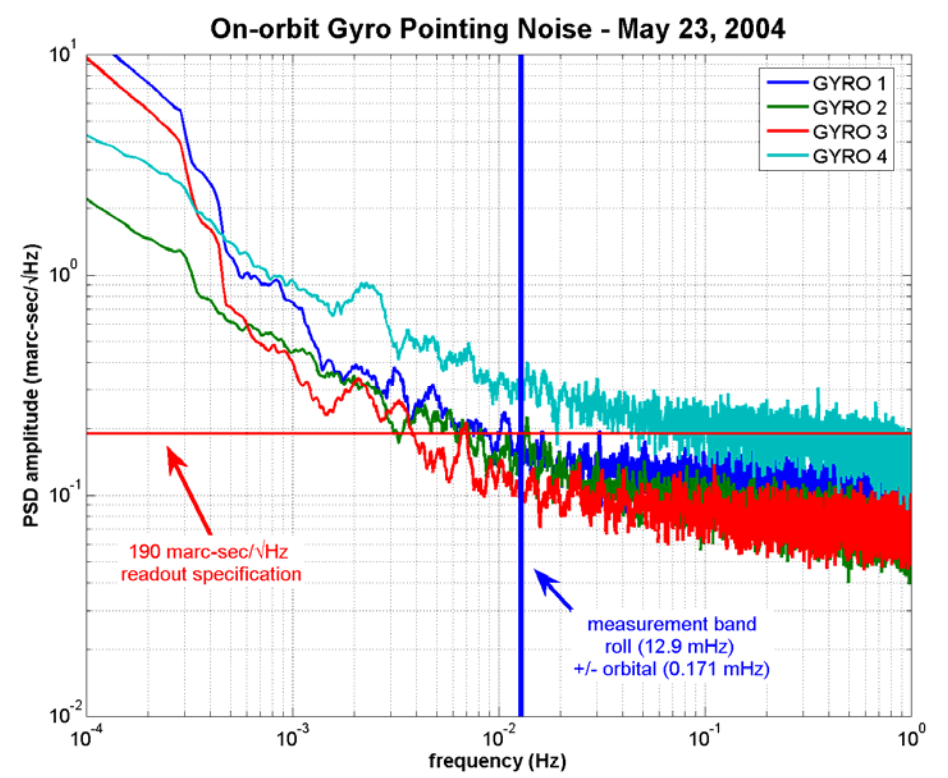
Gyro 1 - Space Vehicle and Gyro Ctrl Effort - Inertial space (2005/200, 14 days)

Gravity gradient

Roll rate

Cross-axis avg. 1.1×10^{-11} g

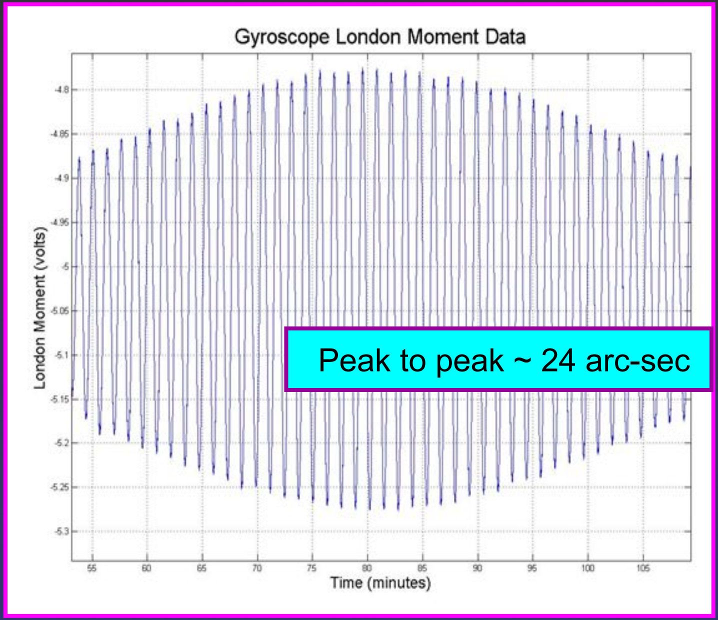
Gyro Readout Performance On-Orbit



On-orbit Gyro Pointing Noise - May 23, 2004

190 marc-sec/√Hz
readout specification

measurement band
roll (12.9 mHz)
+/- orbital (0.171 mHz)



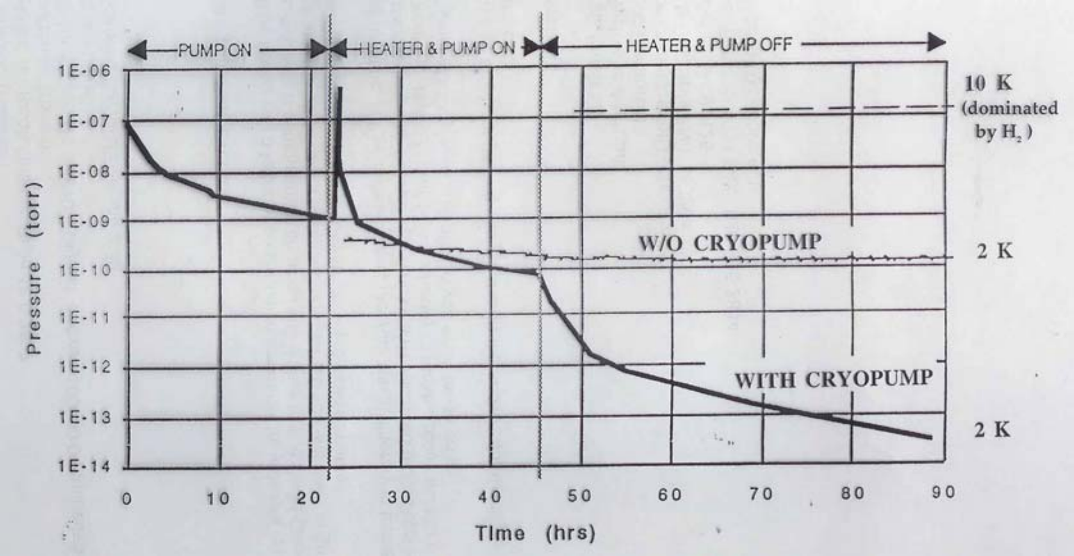
Gyroscope London Moment Data

Peak to peak ~ 24 arc-sec

Gyro	Experiment Duration (days)	SQUID Readout Limit (marc-s/yr)
1	353	0.198
2	353	0.176
3	353	0.144
4	340	0.348

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 ~ 10^{-14} torr
(+ minute patch-effect dampings)

In-flight Verification, 3 Phases

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 Harrison & Cavendish]

Detailed calibration & data consistency checks eliminated many potential error sources & confirmed many pre-launch predictions, but…

Surprise 1 (Phase A, B) – Polhode-rate variations ⟹ affect C_g determinations

Surprise 2 (Phase B, C) – Larger than expected misalignment torques

The GP-B Data Analysis Team


John Turneaure

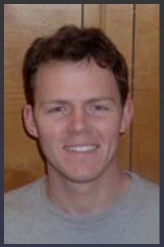

John Lipa

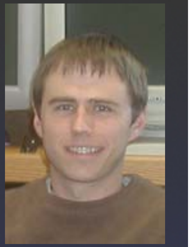

Dan DeBra


Bill Bencze


Michael Heifetz


Sasha Buchman


Karl Stahl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Bruce Clarke


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Matthew Tran, Gregor Hanuschak, Ed Fei, Michael Salomon, Sara Smoot


Suwen Wang

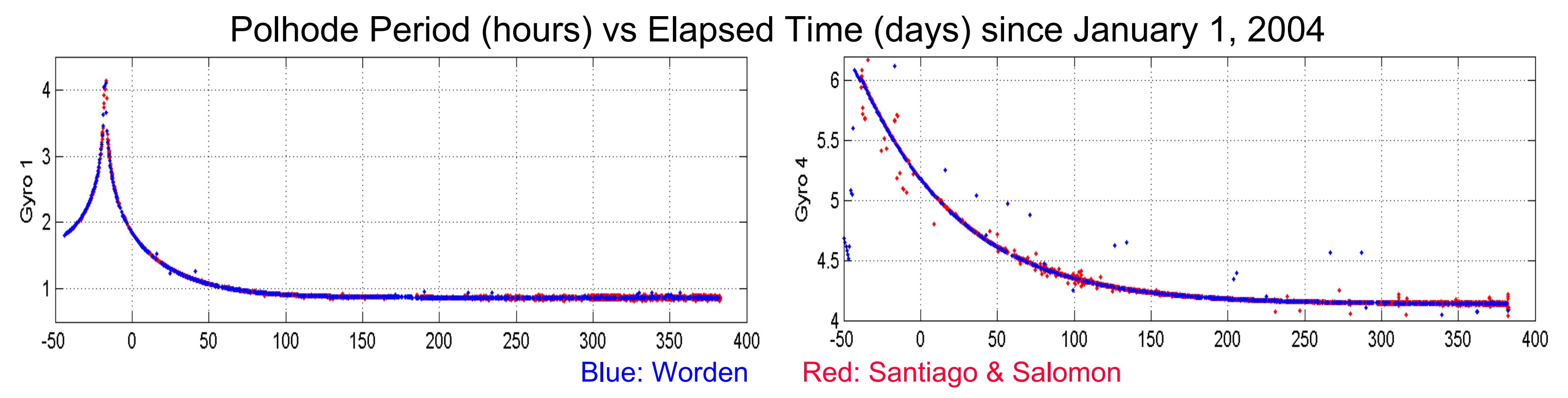

Peter Boretsky


David Santiago


John Goebel

Surprise 1: Polhode Rate Variations

Observed rate variation: 2 analyses in close agreement


Polhode Period (hours) vs Elapsed Time (days) since January 1, 2004

Blue: Worden Red: Santiago & Salomon

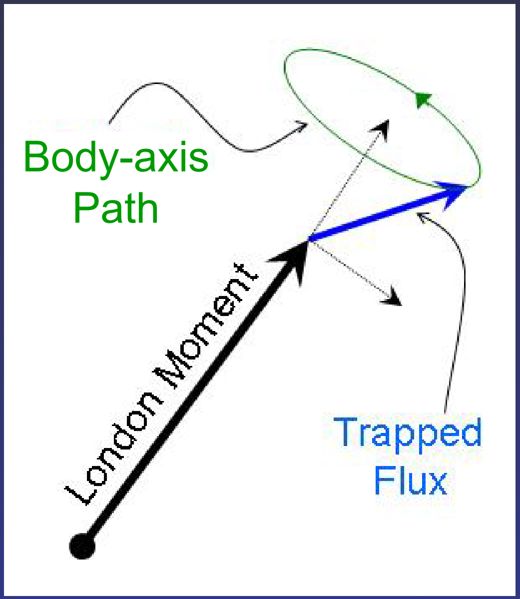
- 10^{-13} W energy dissipation → spin axis motion from I_1 (min) to I_3 (max) in one year [D. DeBra]
- Detailed model adding dissipation term to Euler equations
  - No change in angular momentum alignment
  - True energy dissipation with excellent fit to observed dissipation curves
  - Rotor asymmetry parameter determinations [A. Silbergleit]

$$Q^2 = (I_3 - I_2) / (I_3 - I_1) \leq 1$$

→ affects C_g determinations

Polhoding & C_g Determination

- C_g approaching 10^{-5} ⟹ linking data from many orbits
- The actual 'London moment' readout:



London field at 80 Hz: 57.2 μG

Trapped fields

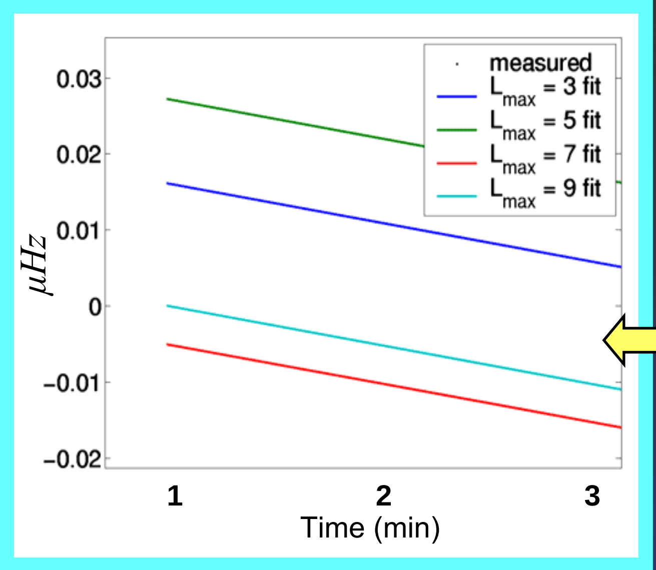
Trapped fields	Gyro 1	3.0 μG
	Gyro 2	1.3 μG
	Gyro 3	0.8 μG
	Gyro 4	0.2 μG

- Orbit-to-orbit fit of 4 to 6 polhode harmonics ⟹ net $M_L + M_T$ history

More advanced method: utilize Trapped Flux Mapping data

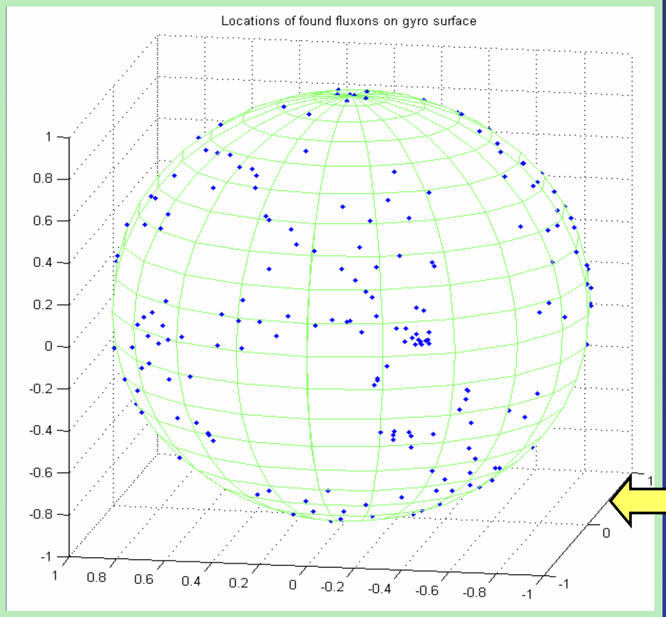
Trapped Flux Mapping & Polhode Phase

- Gyro Motion:
  - Spin speed precision: ~30 nHz
  - 10 X improvement in polhode phase & angle determination
    (phase known now to 0.1 radian over whole mission)



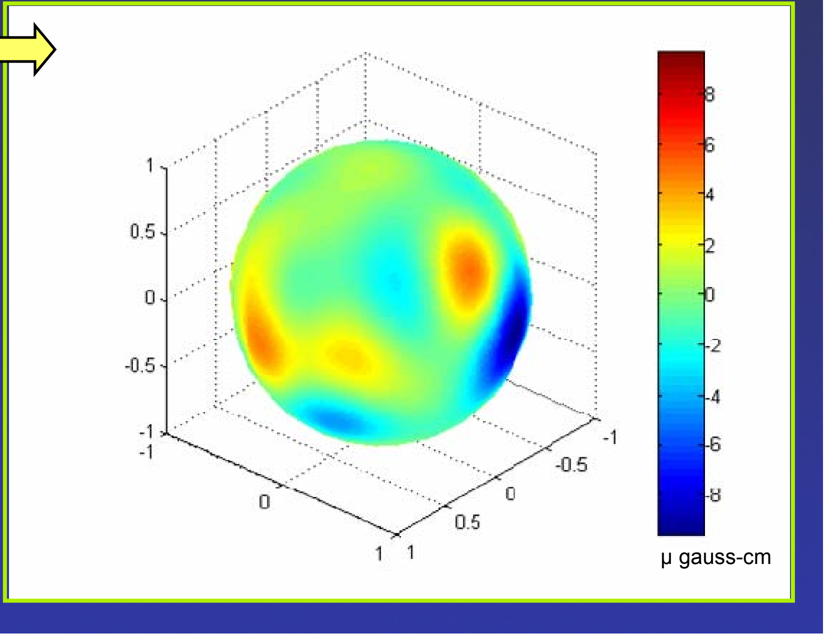
nHz gyro spin speed

- Trapped Flux Distribution



Magnetic potential map

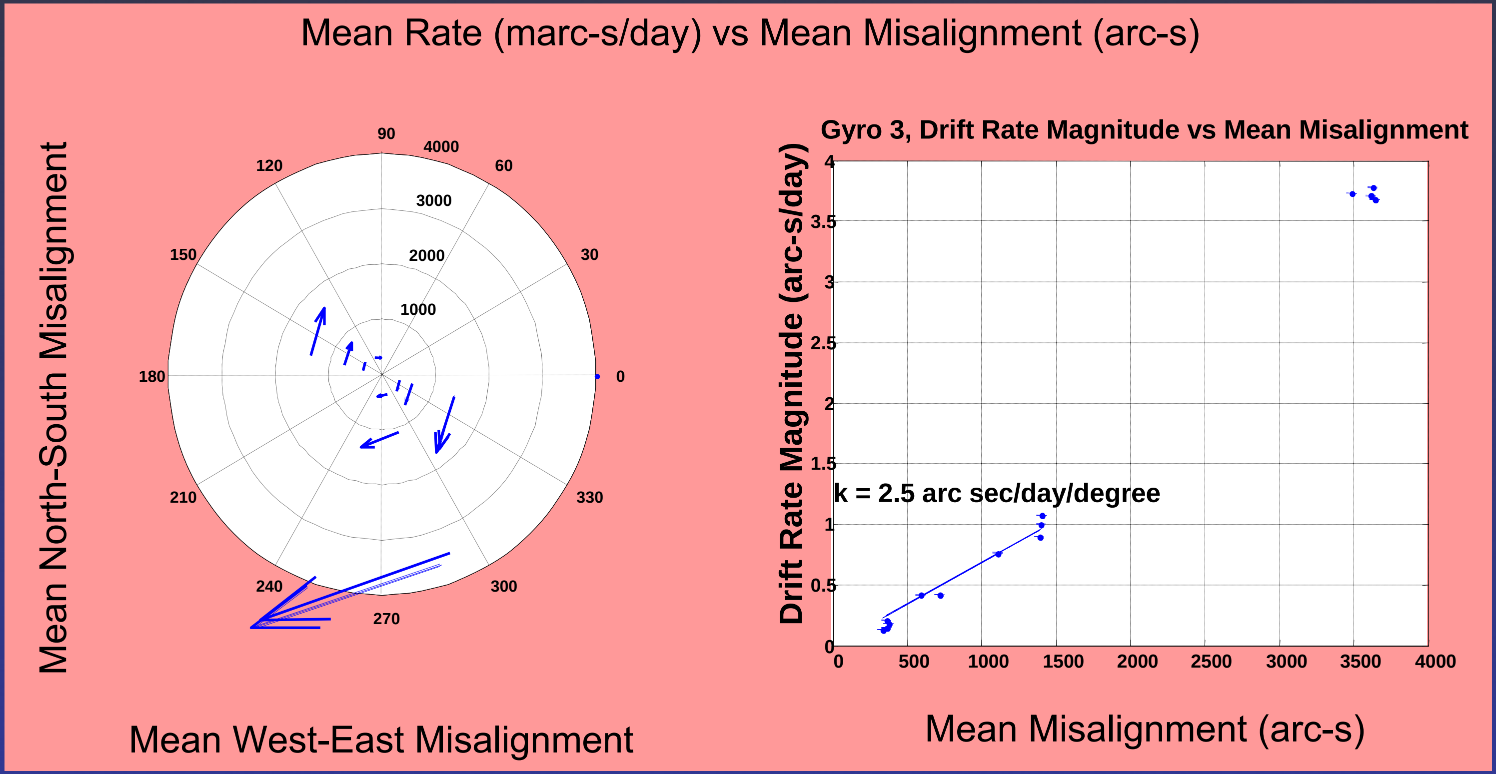
Fluxon map



Surprise 2: Larger than Expected Misalignment Torques

Pointing to a succession of real & virtual guide stars

- duration – 12 hours to 2 days
- misalignment range 0.1 to 7 degrees



Mean Rate (marc-s/day) vs Mean Misalignment (arc-s)

Drift-rate azimuthal & linear to < 2% up to 1500 arc-s misalignment

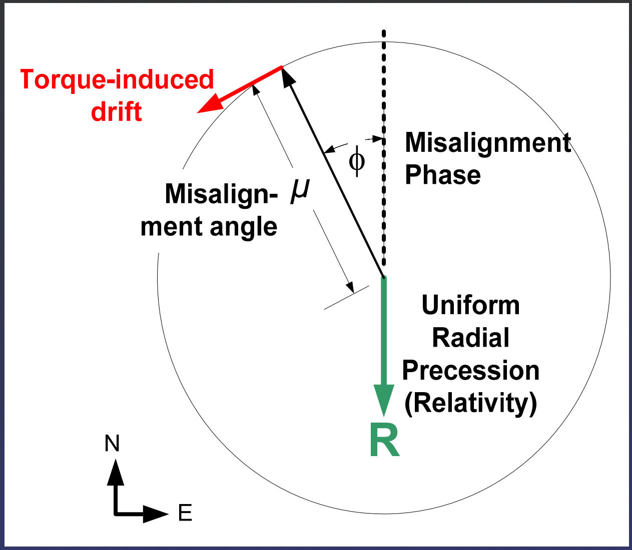
Geometric Separation of *R* & μ Drifts

- Relativity (*R*)

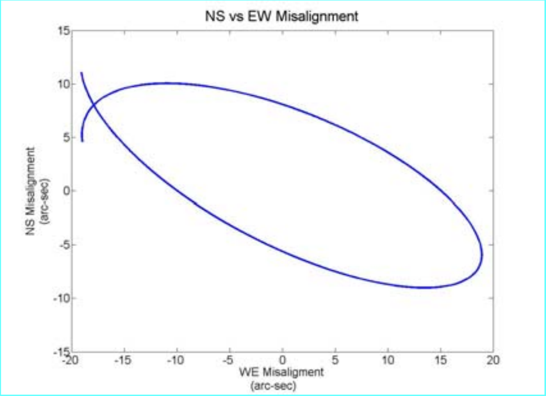
  Fixed direction in inertial frame

- Misalignment Drift (μ)

  Torque $\propto$ to μ
  Drift $\perp$ misalignment vector

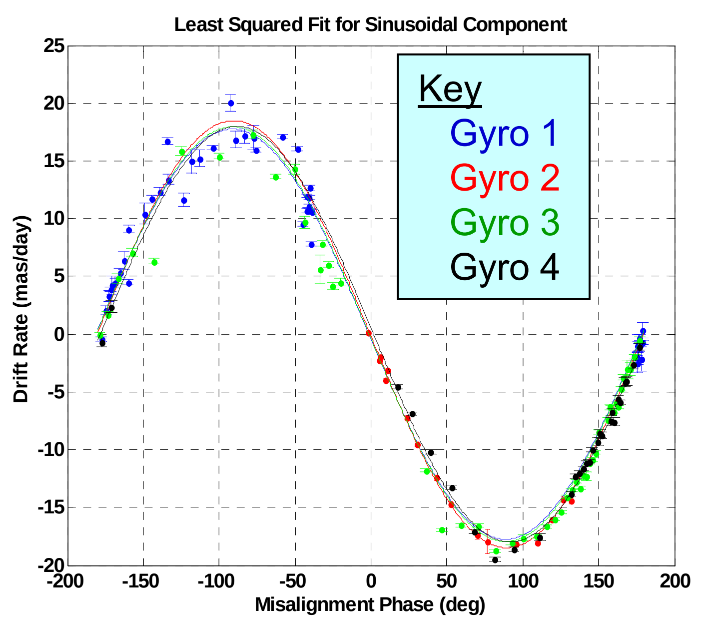


- M. Keiser Observation
  - Component of R ∥ Φ free of misalignment torques
  - Component of R $\perp$ Φ → complete history of torque coefficient *k*
    - Φ modulated over year by annual aberration



← defines a truly *physical* modeling process

Geometric Method Results



- Original Mission Concept
  - $\delta\Omega = Lt^{-3/2}$, t ~ mission length
- Simple Geometric Approach
  - $\delta\Omega_G = \sqrt{2}\, LT^{-1}t^{-1/2}$, T - batch length

SQUID Readout Limit (marc-s/yr)

	Gyro 1	**Gyro 2**	**Gyro 3**	**Gyro 4**
Original	0.198	0.176	0.144	0.348
Simple Geometric (5-day batch)	19.8	17.6	14.4	33.5

- Power of Geometric Approach
  - Clear proof of relativity separation
  - Diagnostic tool for other potential disturbances
- Path to Final GP-B Result

Recover $t^{-3/2}$ dependence by *Integral* Geometric Method

Initial Year-Long 4 Gyro Average

Integral Method at Floor 2, but no Floor 2-Floor 1 iterative corrections

	Net expected *	4 gyro average, full year
NS	-6571 ± 1	-6578 ± 9 (1σ)
EW	-75 ± 1	-87 ± 9 (1σ)

- Caveat: *current bound (worst case) on systematic error ≤ 97 marc-s/yr*
- Encouraging features
  - method effectively removes misalignment torque error
  - path to dramatically smaller experimental uncertainty

*

	Earth	Solar Geodetic	Proper Motion	Net Expected
NS	-6606	+7	+28 ± 1	-6571 ± 1
EW	-39	-16	-20 ± 1	-75 ± 1

rigorous treatment of systematics in process

The Way Forward

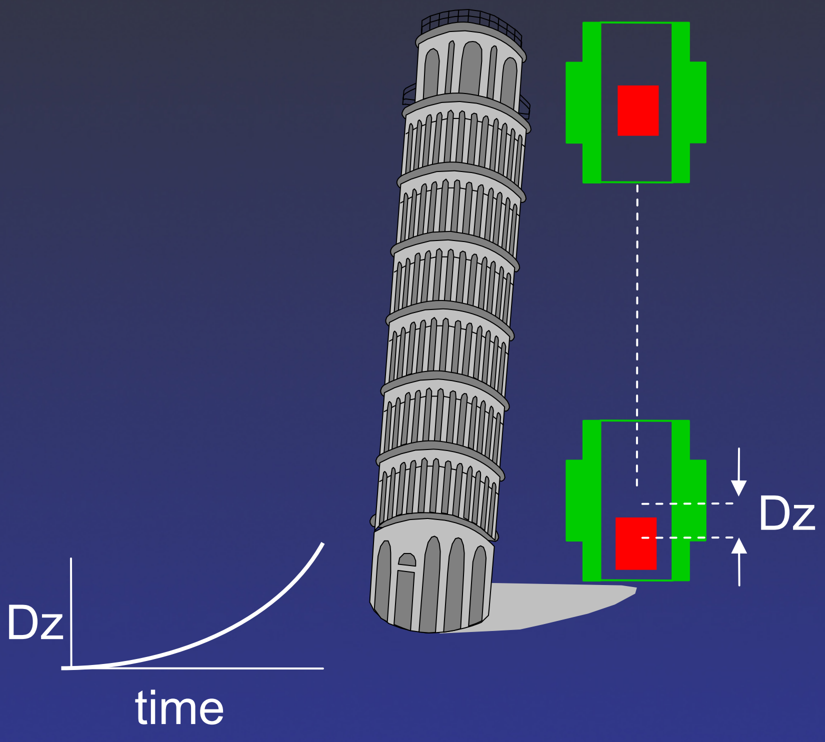
- A fully-physical Torque Model
  - Effectively realized through Integral Geometric approach
- Elimination of C_g scale factor issue by TFM
  - Known now to 3 x 10^{-4}; with TFM ~ 10^{-5}
- Limit & goal of final analysis through December 2007
  - ⇨ SQUID limit 0.144 to 0.343 marc-s/yr
  - ⇨ segmented data raises these to ~ 0.5 to 1 marc-s/yr (Duhamel)
- Final 'double blind' comparison with HR8703 proper motion data

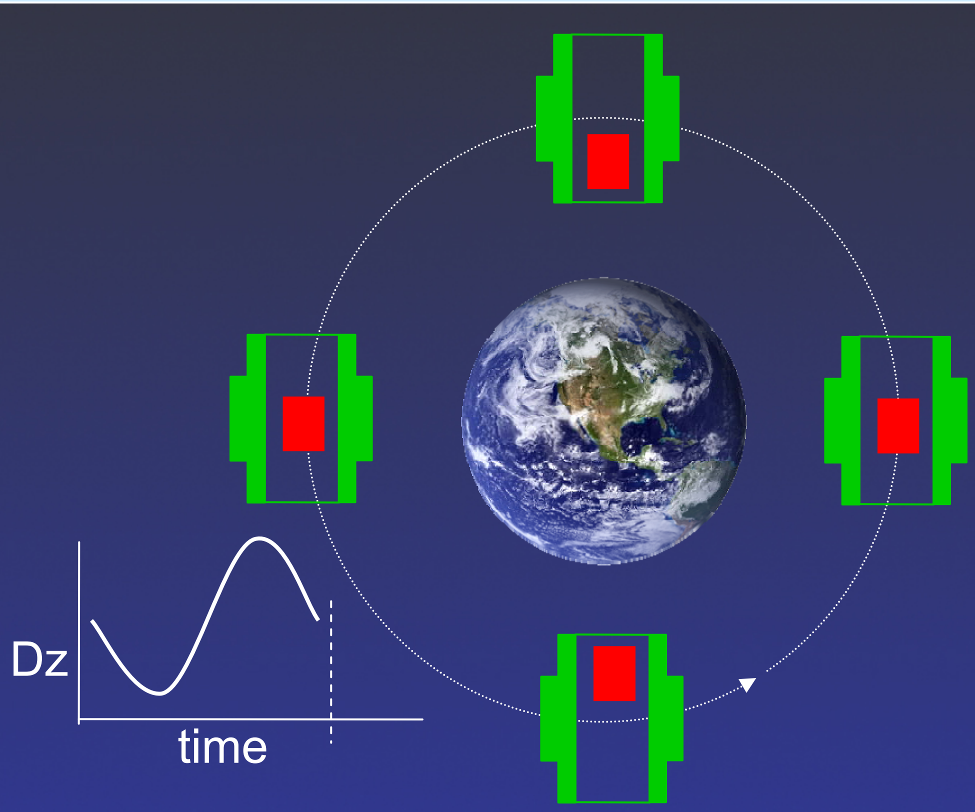
Next major announcement – December 2007

⇨ on to STEP

Satellite Test of the Equivalence Principle

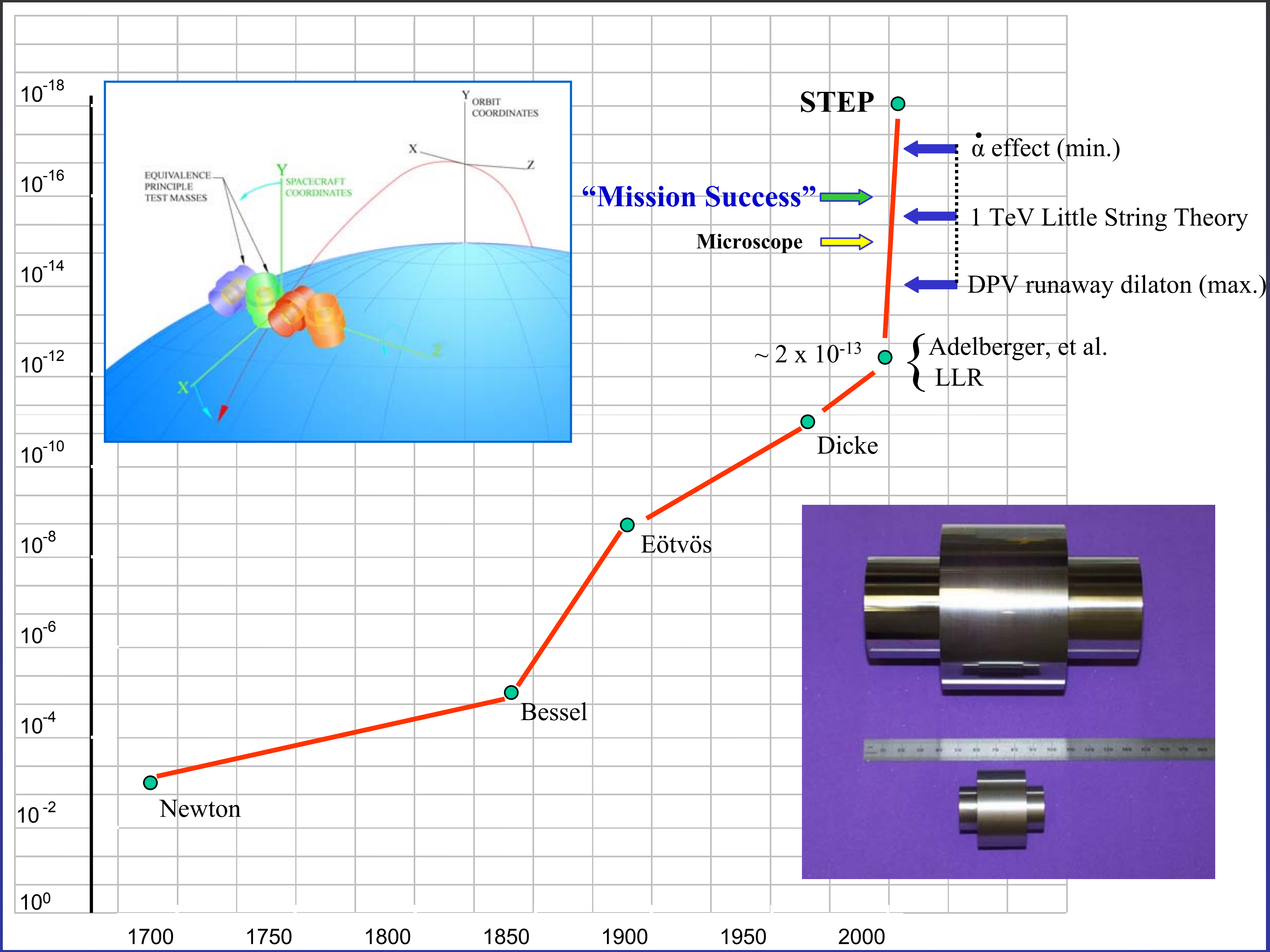
Newton's Mystery {
$F = ma$ mass - the receptacle of inertia
$F = GMm/r^2$ mass - the source of gravitation



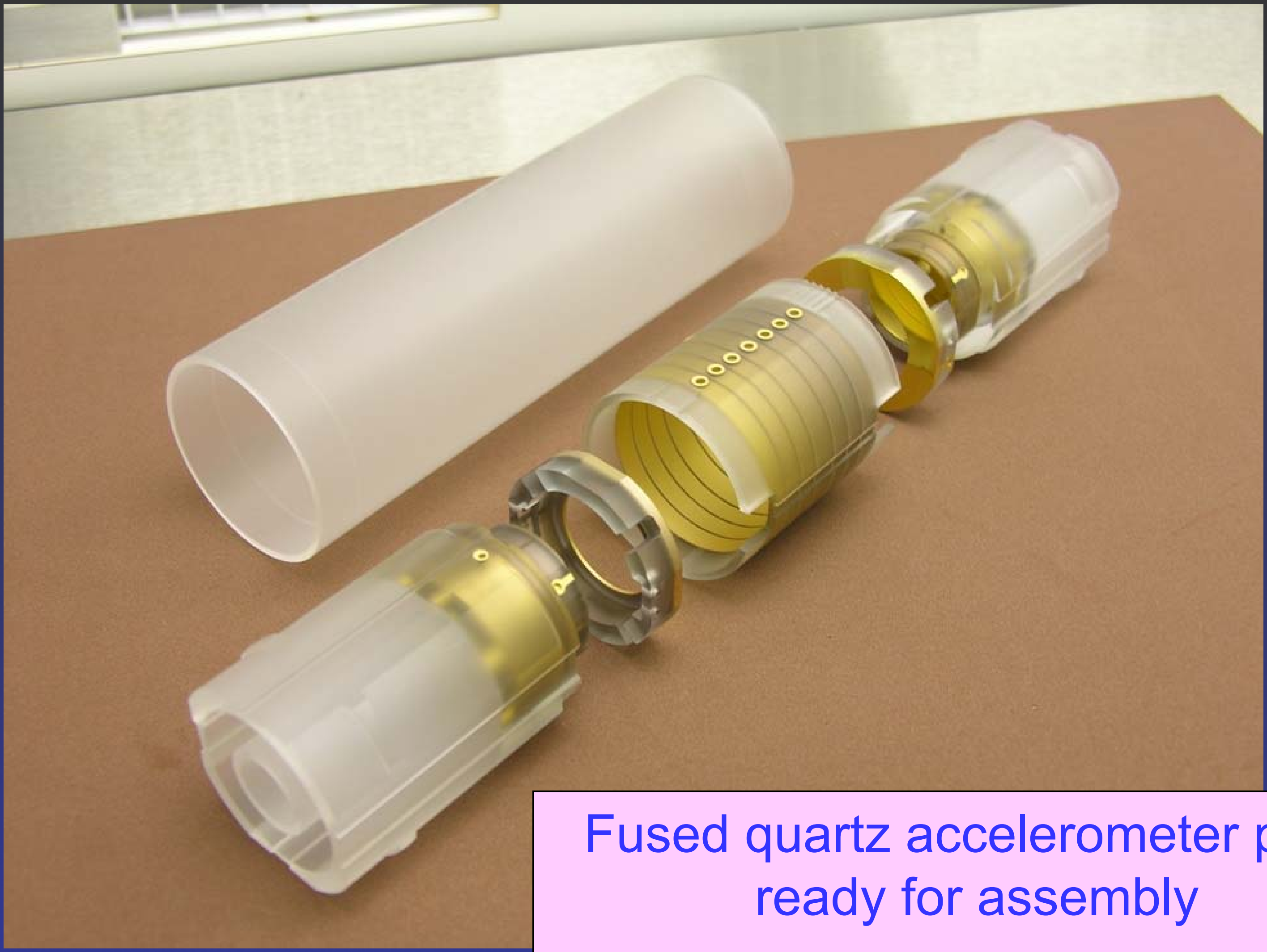


Orbiting drop tower experiment {
* More time for separation to build
* Periodic signal

Space > 5 Orders of Magnitude Leap



Flight Inner Accelerometer

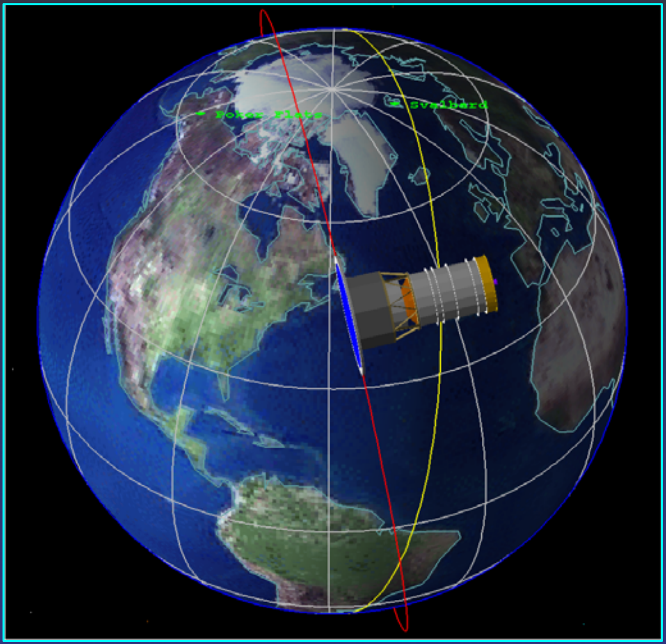


Fused quartz accelerometer parts ready for assembly

Quartz machining by Axsys, Inc.
Coatings by Dr. Ping Zhou

STEP: Credibility & Impact

- Robust Equivalence Principle data
    - 4 accelerometers, each ⟹ η to 10^{-18} in 20 orbits
- Positive result (violation of EP)
    - Discovery of new interaction in Nature
    - Strong marker for unified theories
    - Implications for dark energy
- Negative result (no violation)
    - Severely limits approaches to problems of unification & dark energy
    - Strongly constrains supersymmetric & quintessence theories



> "Improvement by a factor of around 10^5 could come from an equivalence principle test in space . … at these levels, null experimental results provide important constraints on existing theories, and a positive signal would make for a scientific revolution." (p. 162)
> *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (2003)*
> -- National Academies Press, the National Academy of Sciences

Interdisciplinary Invention & Students

- The power of interdisciplinary invention
  - Physics-Engineering collaboration
  - Establishing creative industrial connections
- Student contributions
  - 85 Stanford PhDs to-date (29 physics, 55 engineering, 1 math)
  - 16 PhDs at other universities (4 at UAH)
  - 4 PhDs in progress (2 GP-B, 2 STEP)
  - 31 Master’s & Engineer’s degrees (20 GP-B, 11 STEP)
  - 364 Undergraduates (11 Departments), 55 High School students

cryogenic porous plug

TRIAD drag-free satellite, 1972

GP-B/GPS airplane landing

silicate bonding

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BRAINSTORM
THE NEWSLETTER OF STANFORD UNIVERSITY'S OFFICE OF TECHNOLOGY LICENSING (OTL)

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OptoBond™: The industry-bound bonding technology from Gravity Probe B

by Rich Scholes

GPB's Stringent Requirements

Bound to Succeed

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