Space, Cryogenics, GPS & Einstein: Preview of Gravity Probe B Results

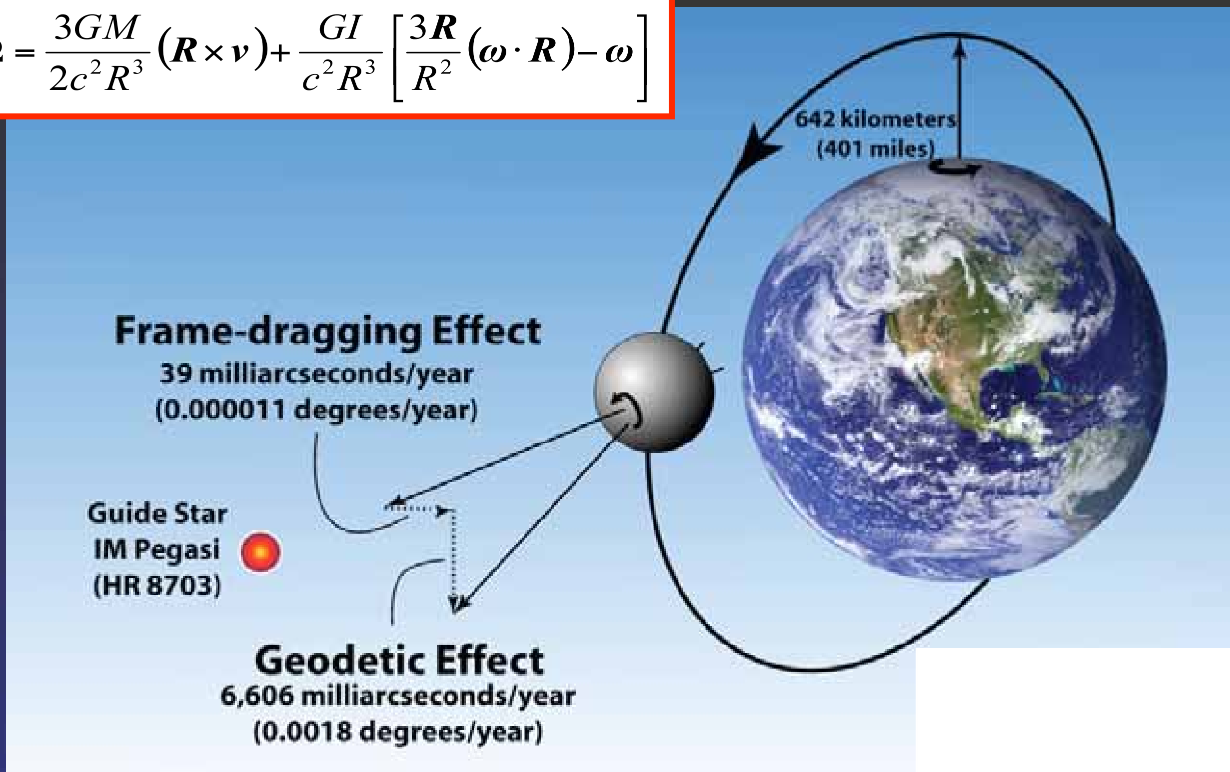
Stanford's 4th Annual PNT Symposium

November 9, 2010

Francis Everitt

Orbiting Gyroscopes & Einstein

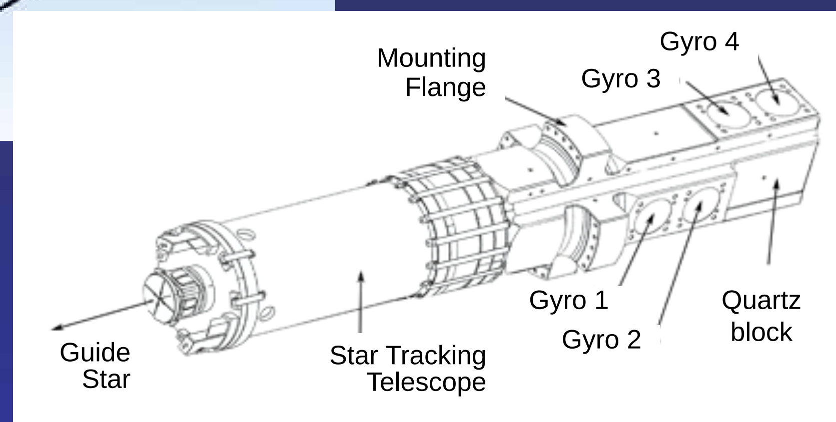
$$\boldsymbol{\Omega} = \frac{3GM}{2c^2R^3}(\boldsymbol{R}\times\boldsymbol{v}) + \frac{GI}{c^2R^3}\left[\frac{3\boldsymbol{R}}{R^2}(\boldsymbol{\omega}\cdot\boldsymbol{R}) - \boldsymbol{\omega}\right]$$



Mach

Thirring

Schiff



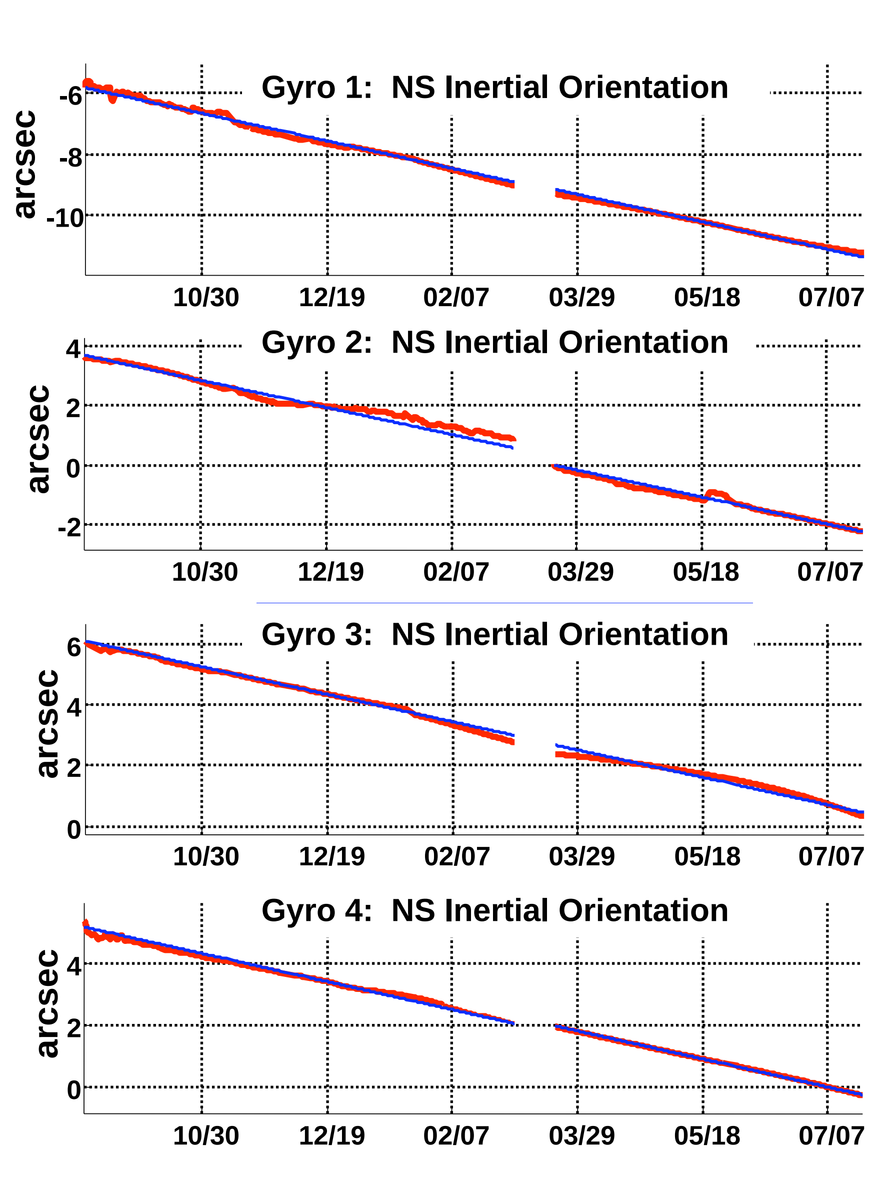
Geodetic Effect

- Space-time curvature ("the missing 3 cm")

Frame-dragging Effect

- Rotating matter drags space-time ("space-time as a viscous fluid")

GR in 'Raw' Data: Early Result



Geodetic effect	marc-s/yr
Einstein expectation	- 6571 ± 1*
4-gyro mean (2007)	- 6578 ± 97

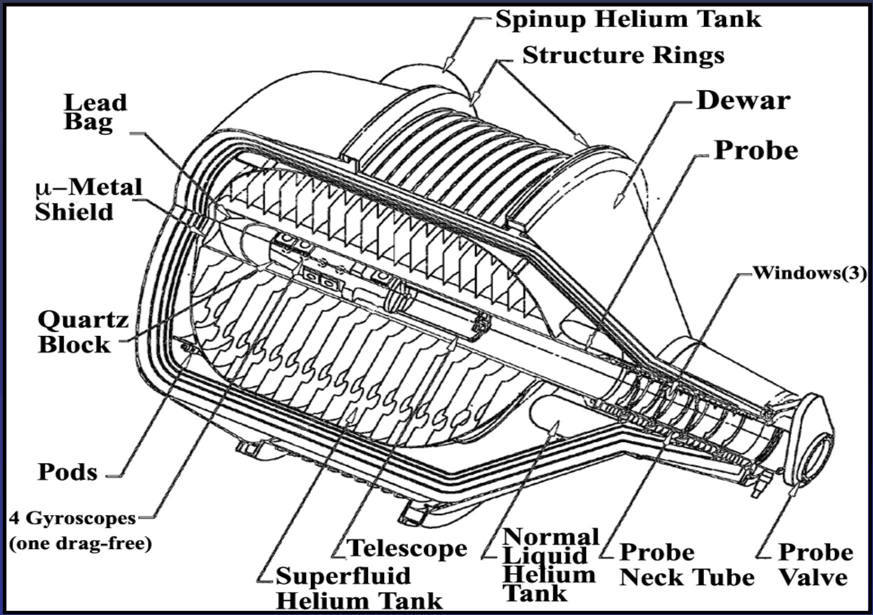
* - 6606 + 7 solar geodetic + 28 ± 1 guide star proper motion

3 Built-in Checks

- *light deflection centered on March 11*
- *aberration of starlight for scale factor*
- *24.64877 day guide star orbital motion*

4 GP-B Triumphs

- 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

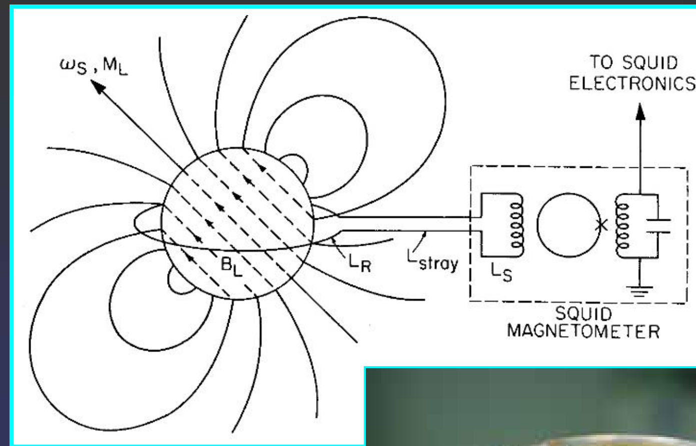
Space

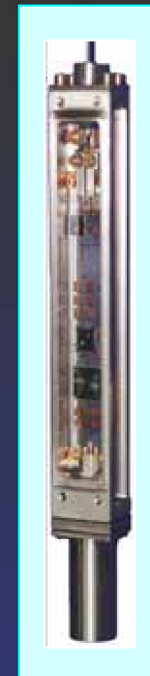
- reduced support force, "drag-free"
- S/C roll about line of sight to star

Cryogenics

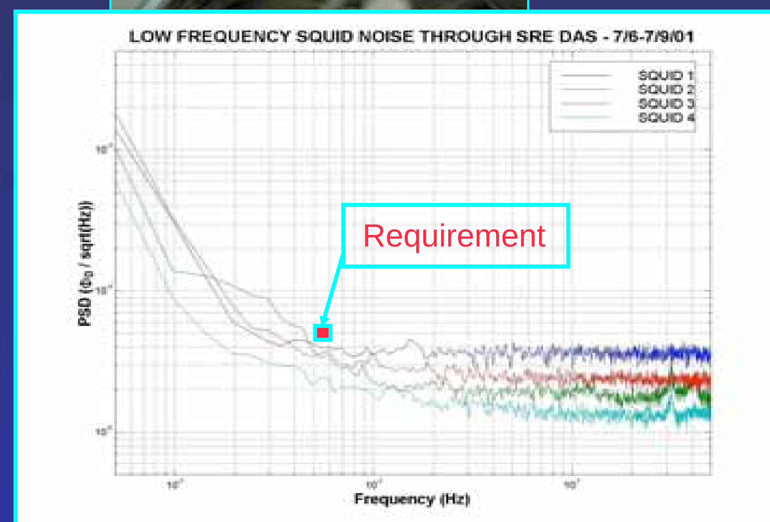
- magnetic readout & shielding
- thermal & mechanical stability
- ultra-high vacuum technology

GP-B Gyroscope



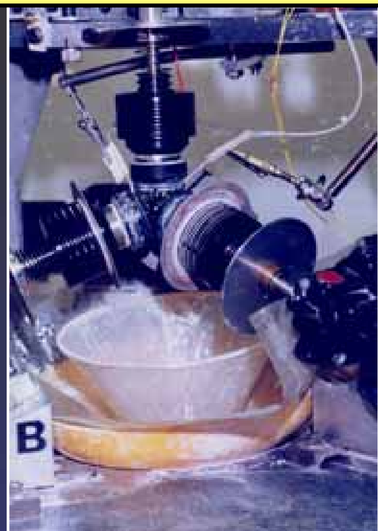


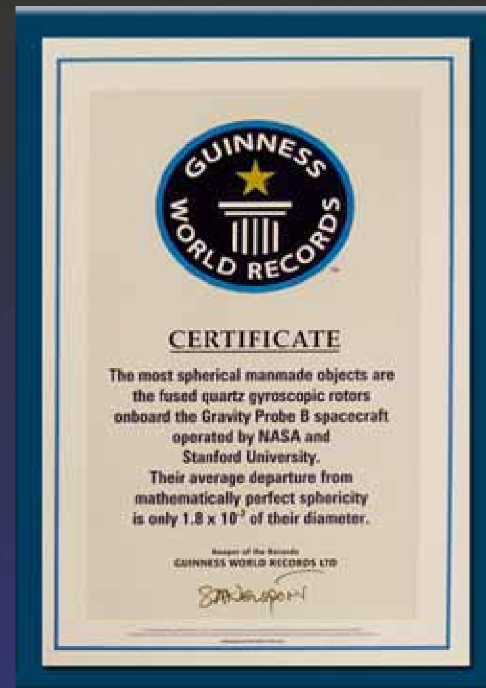
- **Electrical Suspension**
- **Gas Spin-up**
- **Magnetic Readout**
- **Cryogenic Operation**



World's Roundest Sphere

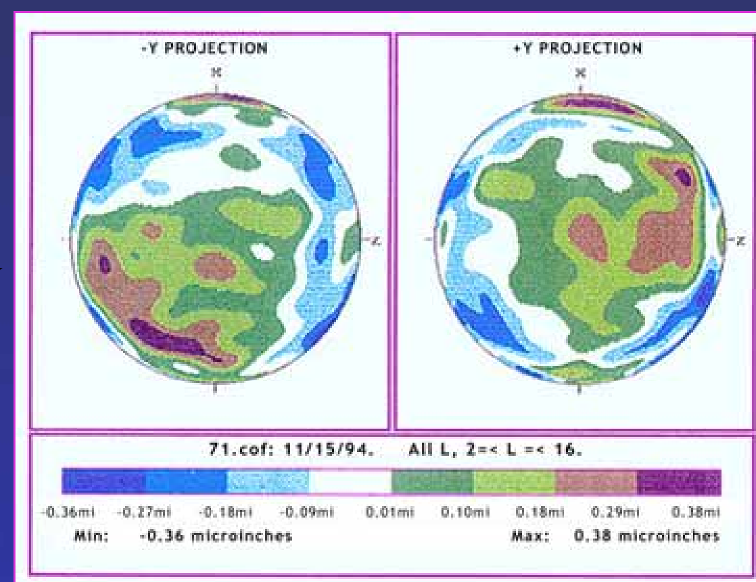
Roundness Measurement to ~ 1 nm



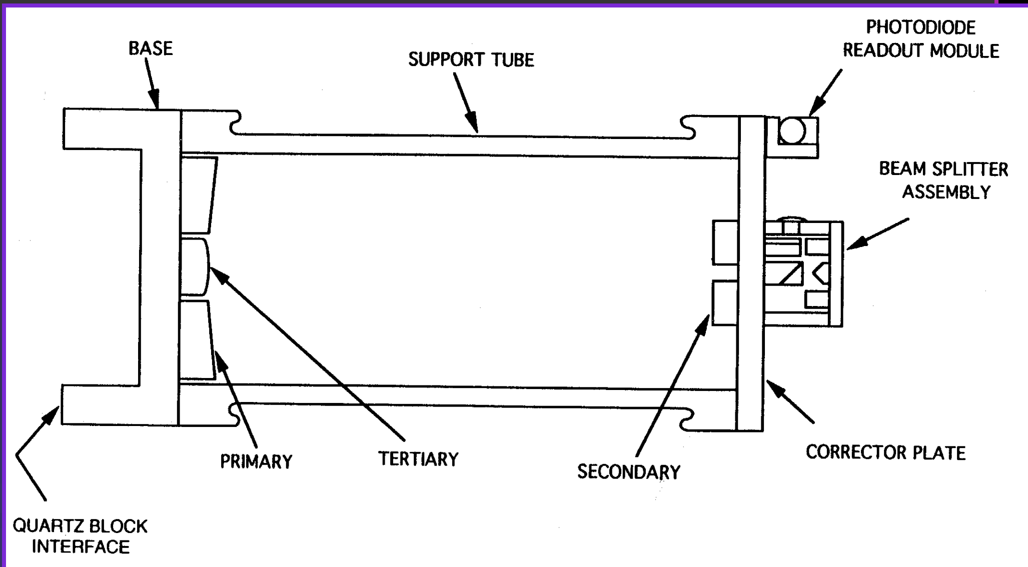


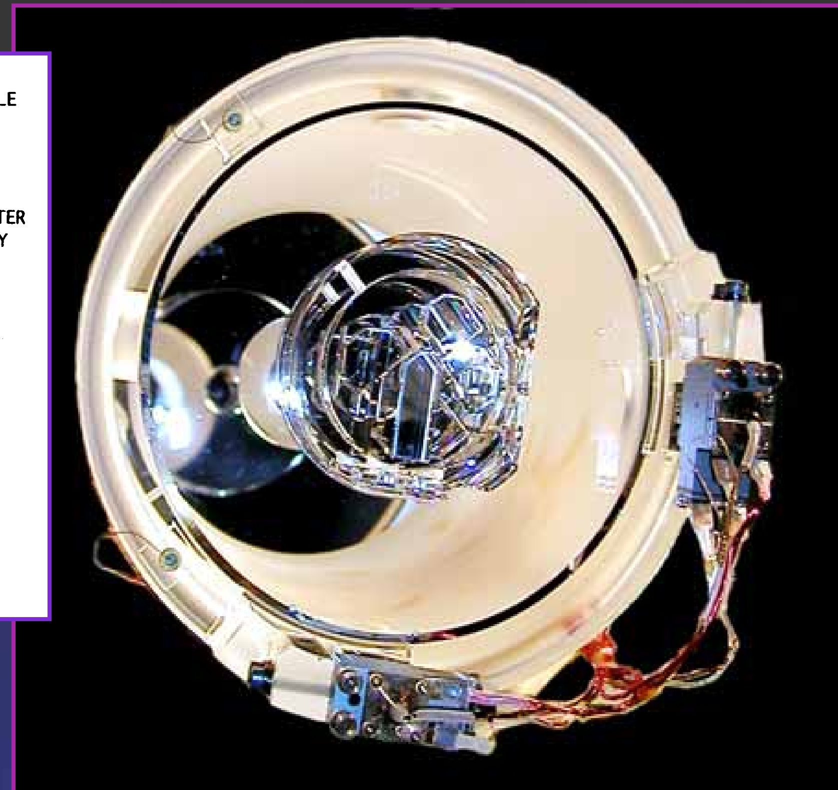
Students 1988 - 1992

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

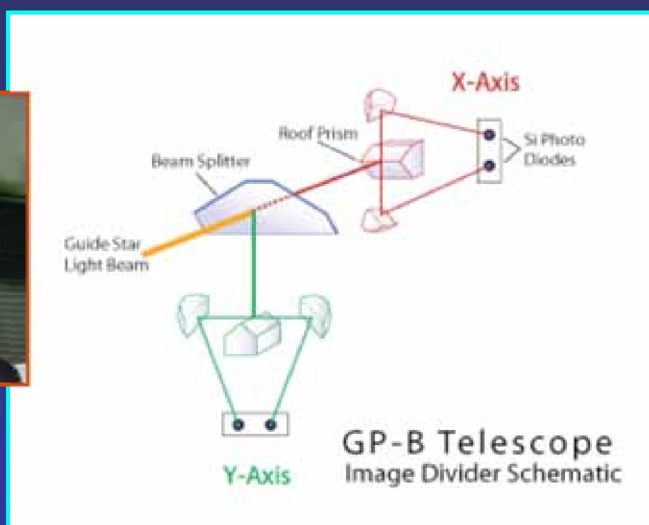


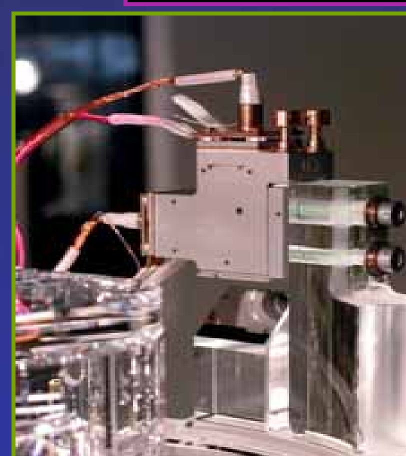
GP-B Sub-marc-s Star Tracker





Don Davidson





Detector Package

Dual Si Diode Detector

GP-B Cryogenic Payload

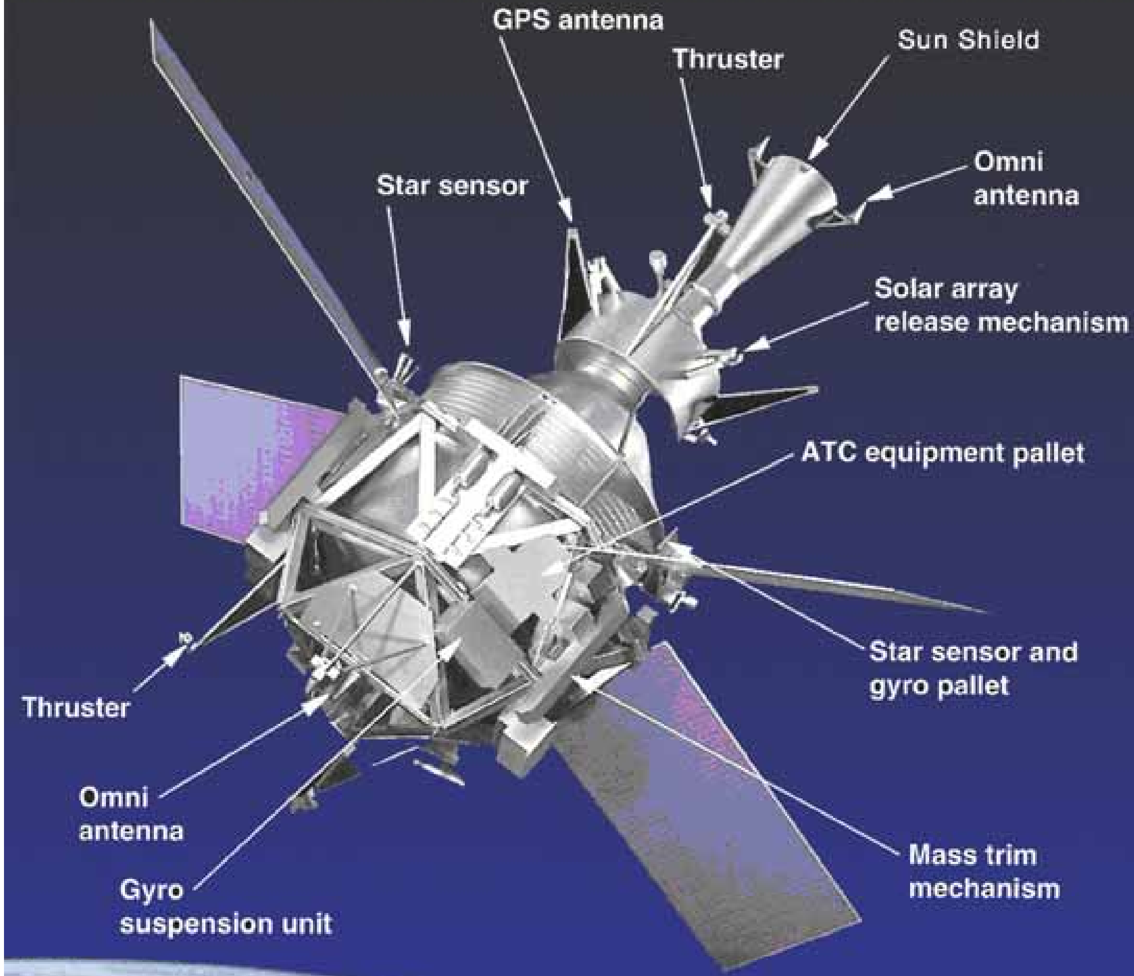
the Porous Plug: Controlling He in Space

Payload in ground testing at Stanford, August '02

First demonstration: Peter Selzer (SU Physics)
Engineered for space: Gene Urban, et al. (MSFC)
Bill Davis (Ball Aerospace), Sidney Yuan (Lockheed)

…IRAS, COBE, WMAP, Spitzer

Gravity Probe B Space Vehicle



- *Redundant spacecraft processors, transponders.*
- *16 He gas thrusters (0-10 mN) for fine 6 DOF control.*
- *Roll star sensors for fine pointing.*
- *Magnetometers for coarse attitude determination.*
- *Tertiary sun sensors for very coarse attitude determination.*
- *Magnetic torque rods for coarse orientation control.*
- *Mass trim to tune moments of inertia.*
- *Dual transponders for TDRSS & ground station communications.*
- *Stanford-modified GPS receiver for precise orbit information.*
- *Solar arrays + 70 A-hr batteries.*

GPS & GP-B

- Precise orbit determination
  - Orbit injection ~ 120m from pure polar
  - Computation of predicted GR signal
  - Gyro scale factor C_g from orbital aberration signal

Real time and post processed position and velocity requirements:

	Real Time	Post Processed
Position (rms)	100 m	25 m
Velocity (rms)	1 m/s	7.5 cm/s

Typical comparison of six hour overlaps between subsequent orbit solutions.

Overlap Comparison	Along Track	Cross Track	Radial
Position (m)	10	4	5
Velocity (mm/s)	4.5	4	6

Cross confirmed by laser ranging data

- Evaluation of drag-free performance
  - Backing out accelerometer bias to < 1mN
  - The mysterious polhode-rate dependence

- Time Transfer via PPS signal reconciling Vehicle Time with UTC
  - 2μs rms @ 77.5s spacecraft roll period

- Aeronomy (Mike Adams PhD – GP-B #100!)
  - Position & velocity from GPS
  - Acceleration & force < 10^{-10}g/√Hz from GSS

GPS Pathfinder unit with antenna array

Also Clark Cohen differential GPS attitude determination

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

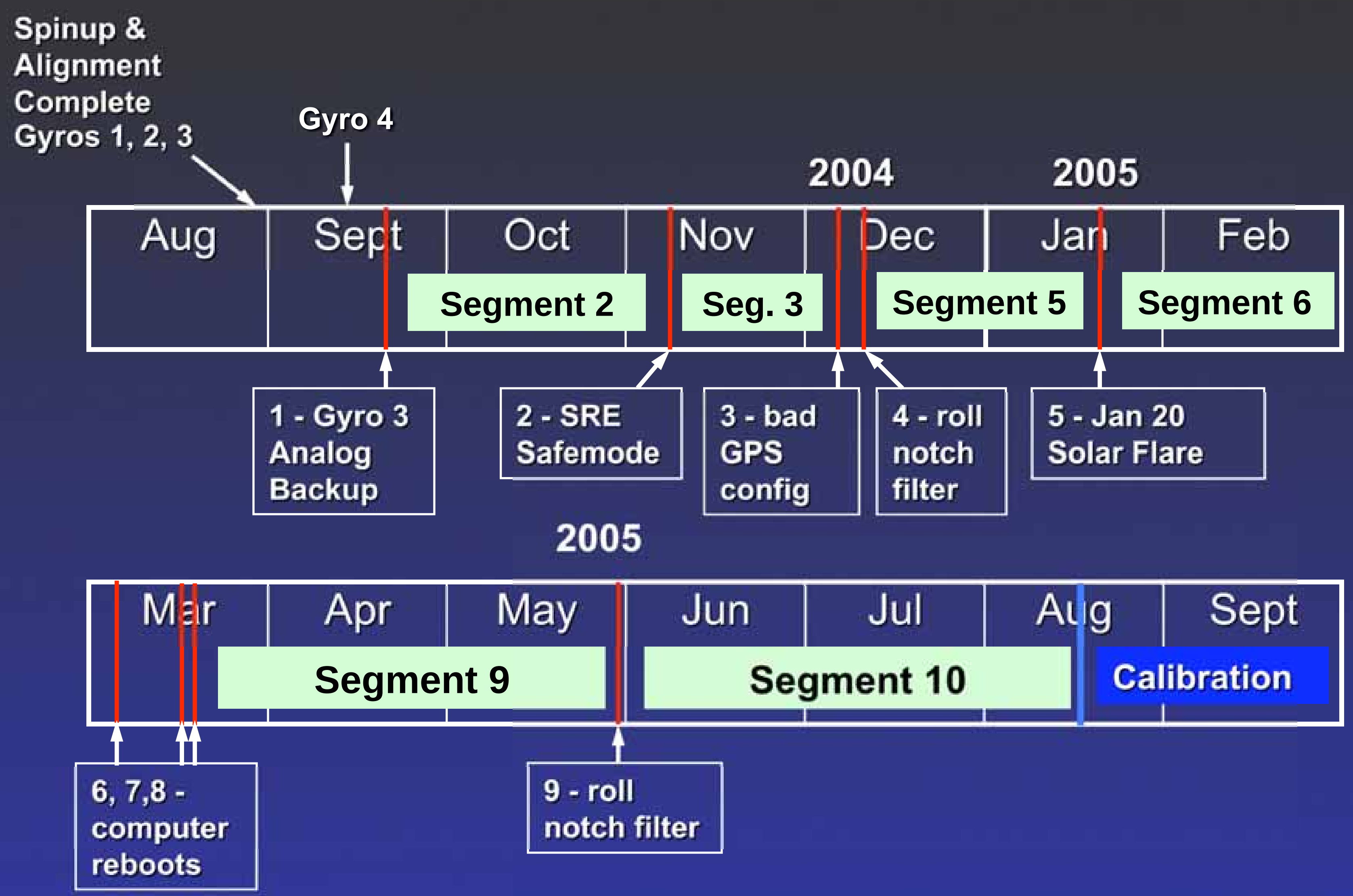
- *exploiting the built-in checks* [Nature's helpful variations]

C. Post-experiment tests - 46 days

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

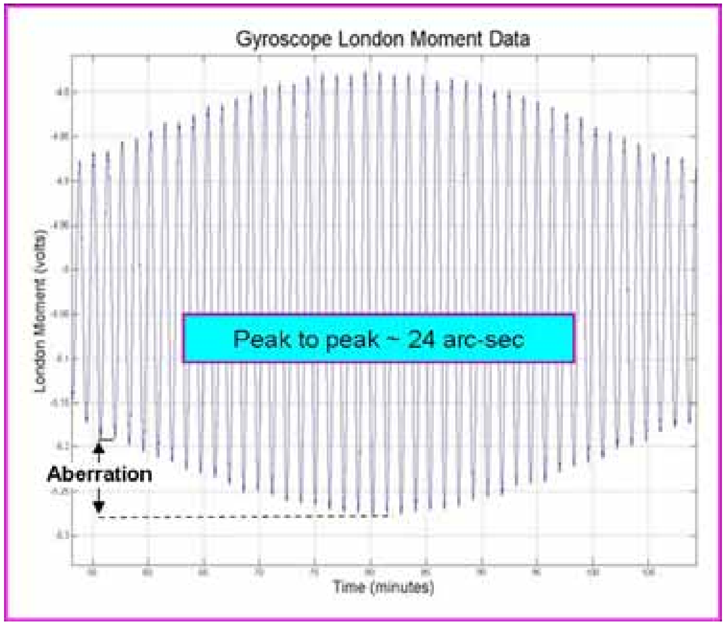
"Always be suspicious of the news you want to hear"

In-Orbit Science Operation



Nature's Calibrating Signal

Aberration -- *Nature's calibrating signal for gyro scale factor* C_g



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

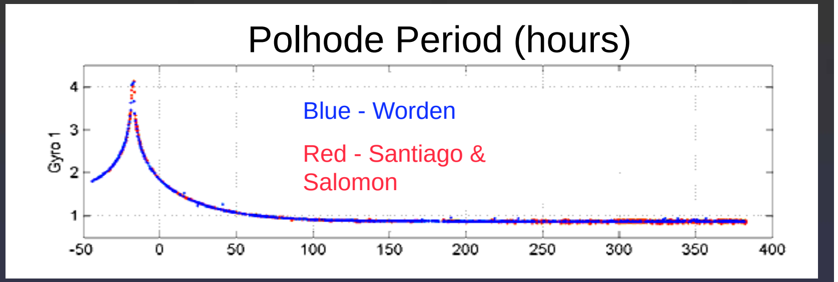
S/V around Earth -- 5.1856 arc-s @ 97.5-min period
Earth around Sun -- 20.4958 arc-s @ 1-year period

⇨ Continuous accurate calibration of GP-B experiment

The 3 'Patch Effect' Gremlins

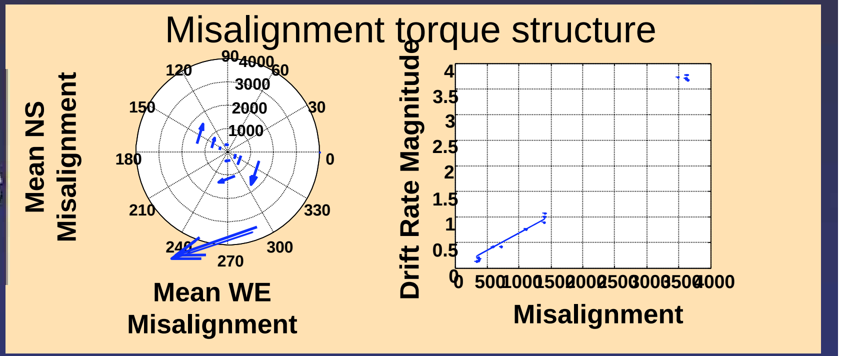
A. Polhode-rate variation

- *complicates C_g calibration*
- *connects to gremlin C*



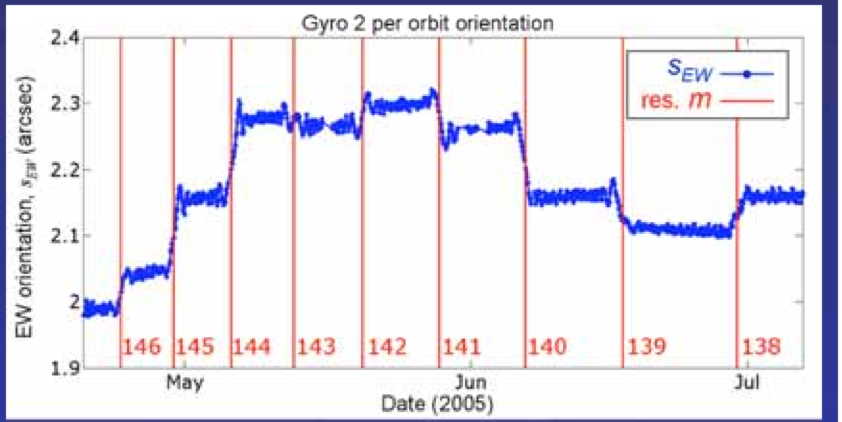
B. Misalignment torques

- *>100x bigger-than-expected gyro drifts discovered on pointing to other stars*



C. Roll-polhode resonance torques

- *mysterious shifts over 1-3 days in individual gyro orientations*



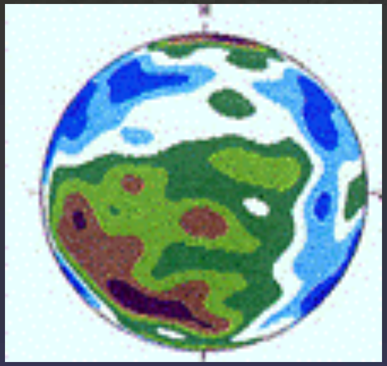
All due to one cause (patch effect)

Roundness & Out-of-Roundness

1 Mechanical – *Good & Essential*

Rotor ~ 5 x 10^{-7} Housing ~ 4 x 10^{-6}

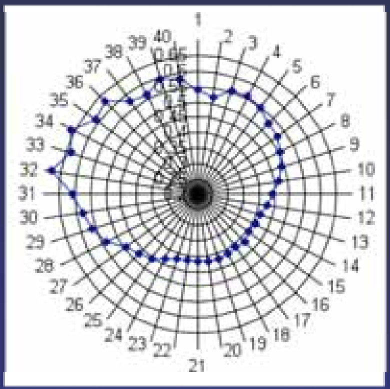
Gyro Mapping



2 Electrical – *Bad & Very Unexpected*

Large sideways forces from 'patch effect' voltages

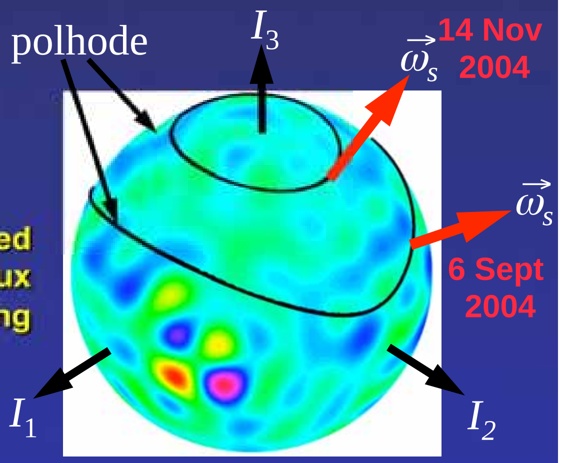
Work function polar plot



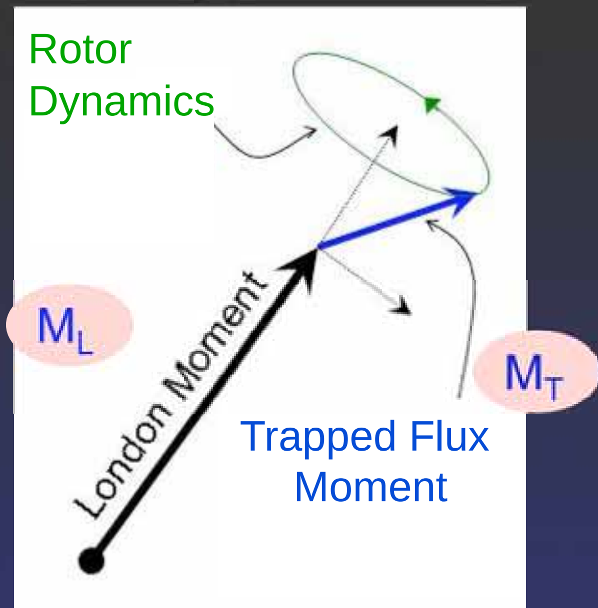
3 Magnetic – *Seemingly Bad, Miraculously Good!*

Trapped flux ~ 0.4% - 5% of London Moment

Trapped Flux Mapping



Ideal vs. Actual M_L Readout



London field at 80 Hz: 57.2 μG

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

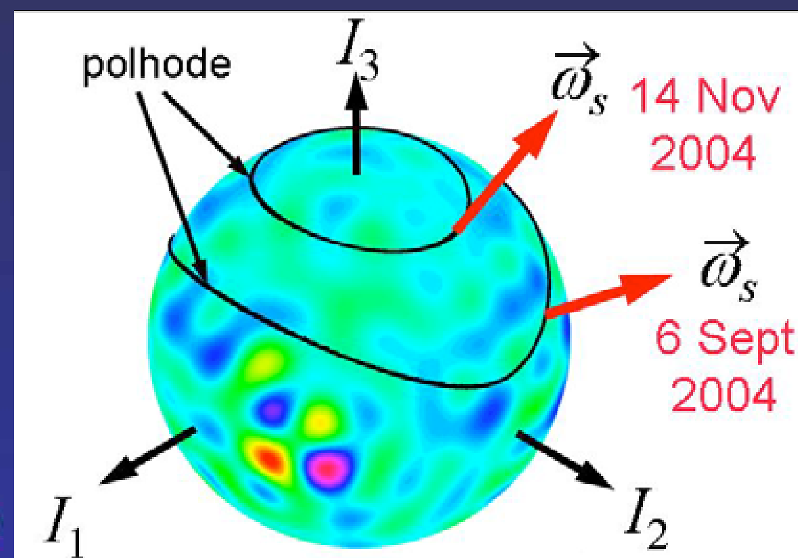
Detailed Trapped Flux Mapping (TFM) ➡

3 Key Students

John Conklin

Michael Dolphin

Michael Salomon

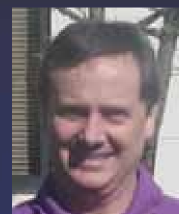


Gyro Scale Factor Calibration

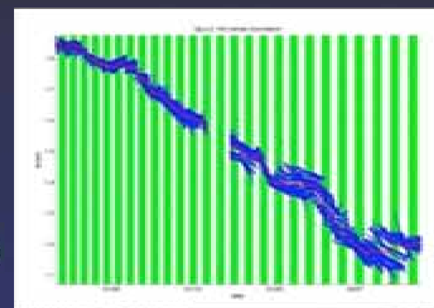
Issue: Must link data from many successive half orbits to calibrate C_g. Exact knowledge of polhode phase ϕ_p required.

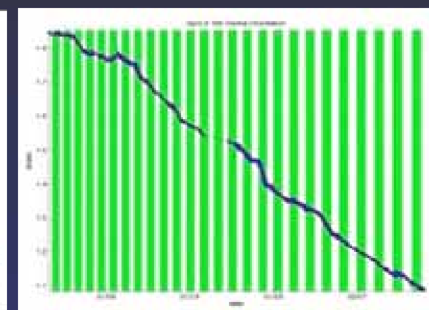
Resolution: TFM determines ϕ_p to 1° throughout mission

1. Initial TFM treatment
   → 100σ to 6σ to 2σ

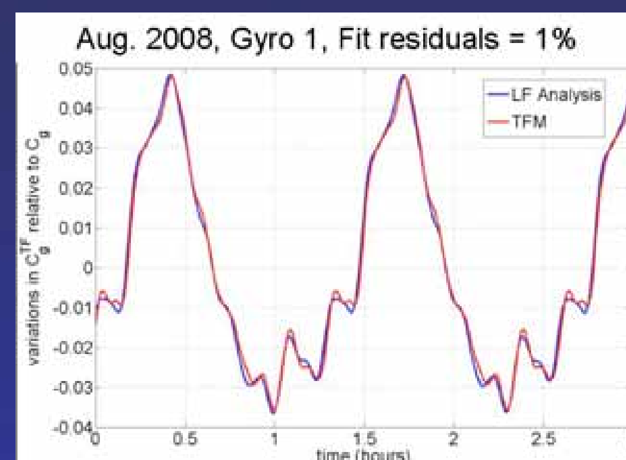


Tom Holmes





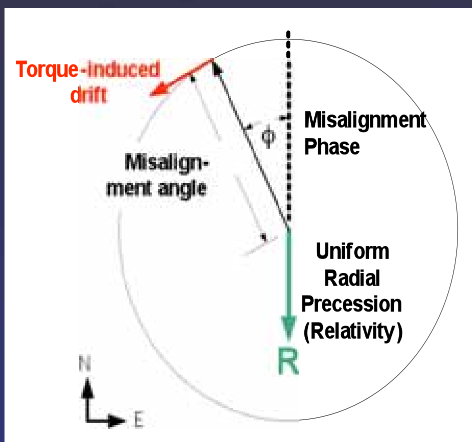
2. ~ 10^{-4} calibration of polhode variation in C_g due to trapped flux

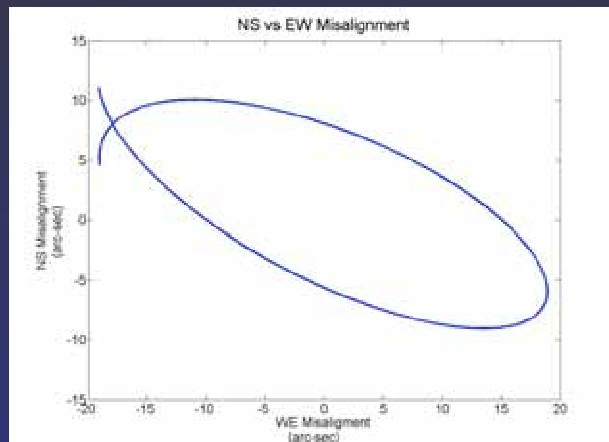


3. use of aberration signal to calibrate ~ 10^{-3} C_g variation over mission

Misalignment Torque Geometry

- GR signal in fixed inertial direction
- Torque direction varies due to annual aberration
- *Uncorrupted relativity signal parallel to misalignment*

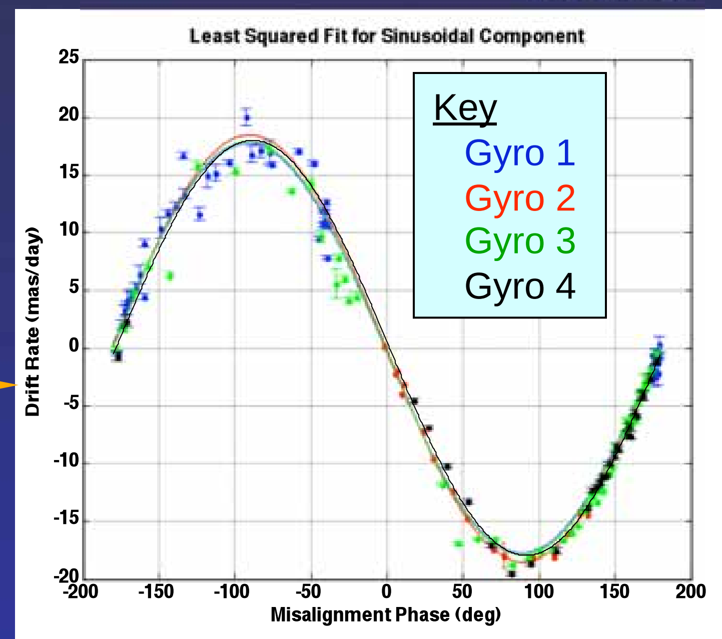




Mac Keiser

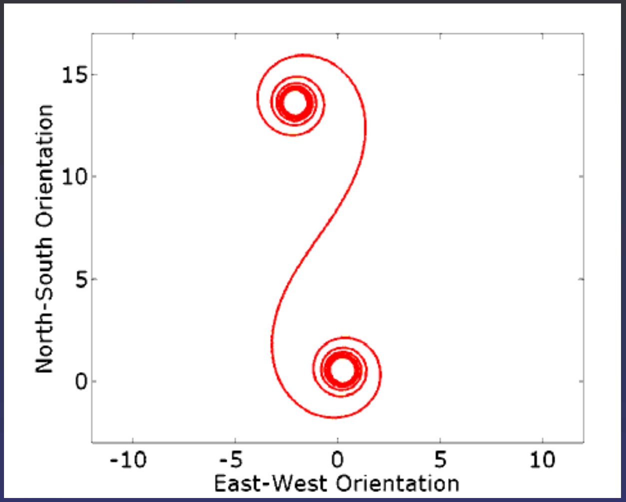
Replot data against misalignment phase

- *Amplitude gives combined relativity signals*
- *Phase separates the two effects*



Resonance Torque

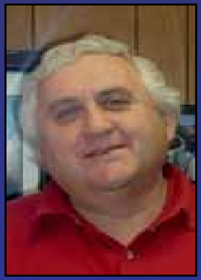
- Spin axis path predicted from rotor & housing potentials
  - Roll averaging fails when $\omega_r = n\omega_p$
  - Orientations follow Cornu spiral
  - Magnitude & direction depend on patch distribution, roll & polhode phases at resonance



- Example: Gyro 2, Resonance 277 – Oct 25, '04

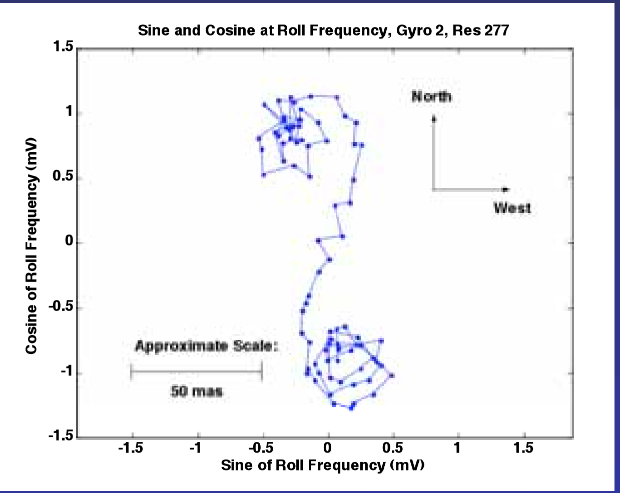

Jeff Kolodziejczak


Mac Keiser


Alex Silbergleit


Michael Heifetz


Vladimir Solomonik



Adding in the Resonance Torque

Misalignment torque

Roll-polhode resonance torque

Relativity

$$\frac{ds_{NS}}{dt} = \boxed{r_{NS}} + \boxed{k(\phi_p, \gamma_p)\mu_{EW}} + \boxed{\sum_m A_m(\gamma_p)\cos\Delta\phi_m - B_m(\gamma_p)\sin\Delta\phi_m}$$

$$\frac{ds_{EW}}{dt} = \boxed{r_{EW}} - \boxed{k(\phi_p, \gamma_p)\mu_{NS}} + \boxed{\sum_m A_m(\gamma_p)\sin\Delta\phi_m + B_m(\gamma_p)\cos\Delta\phi_m}$$

$$\Delta\phi_m = \phi_{\rm roll} - m\phi_p \longrightarrow \text{Resonance condition}$$

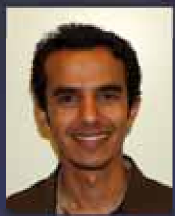
From once-per-orbit averaging to 2-sec processing ⇒

2-sec Filter Development

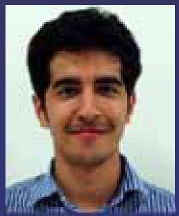
24 month effort {
- reworking 4 years experience w/ 2 floor model
- parallel processing for 14x increase in speed

KACST Team Members

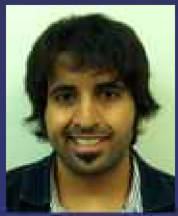
Badr Alsuwaidan
(residuals analysis, truth modeling)



Majid Almeshari
(efficient parallel processing)



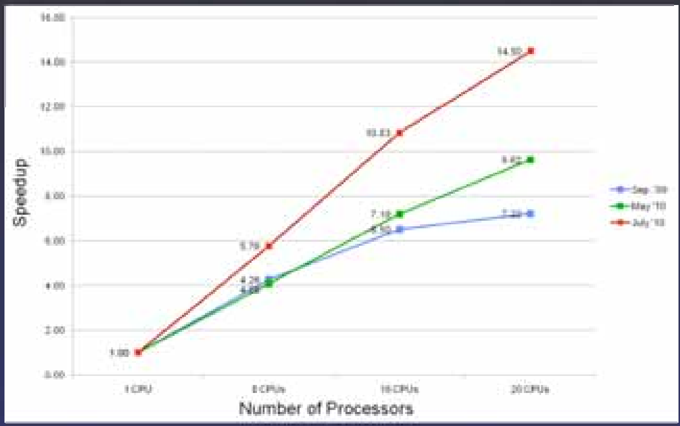
Homoud Aljabreen
(non-linearity, thermal sensitivities)

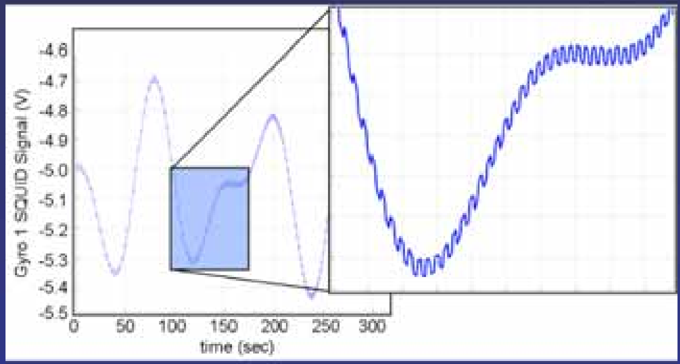


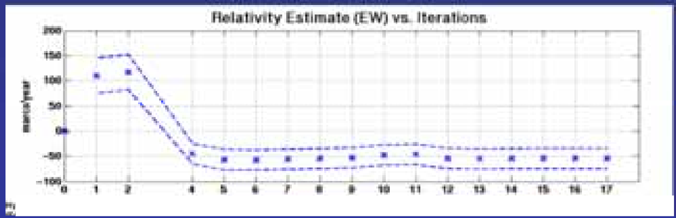
Ahmad Aljadaan
(results viewer, submission process)

Rashed Al Yousef
(dSPACE spacecraft simulator)

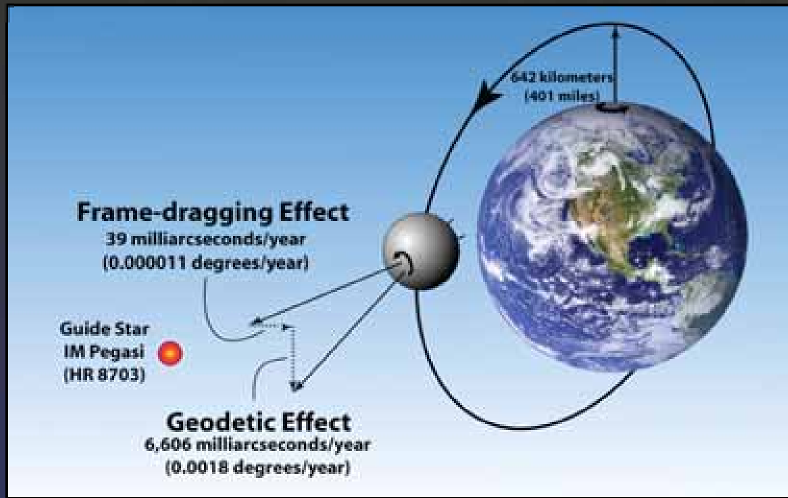
Muflih Alrufaydah
(telescope research)



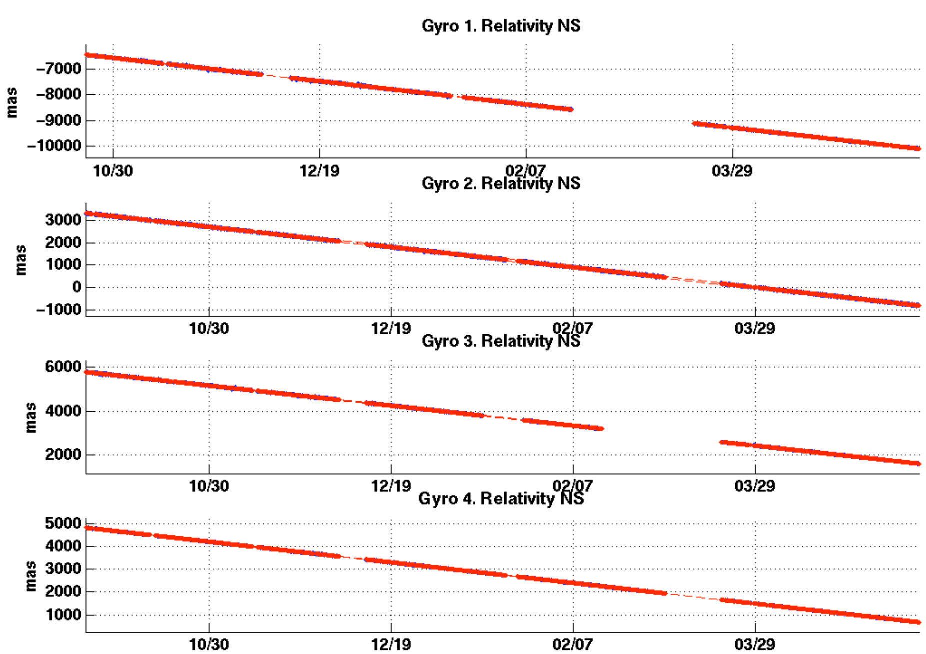




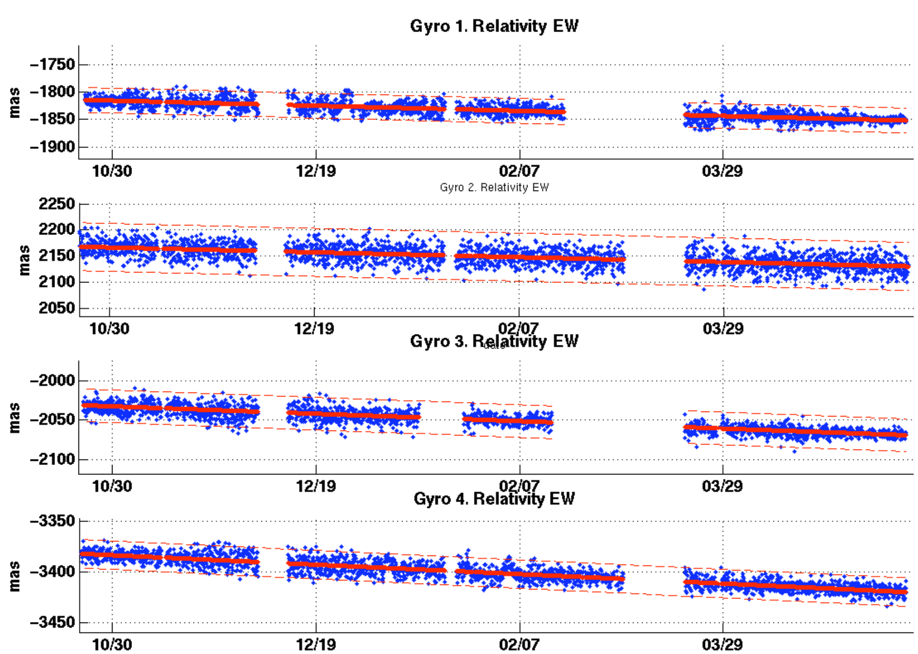
Preview of Gravity Probe B Result



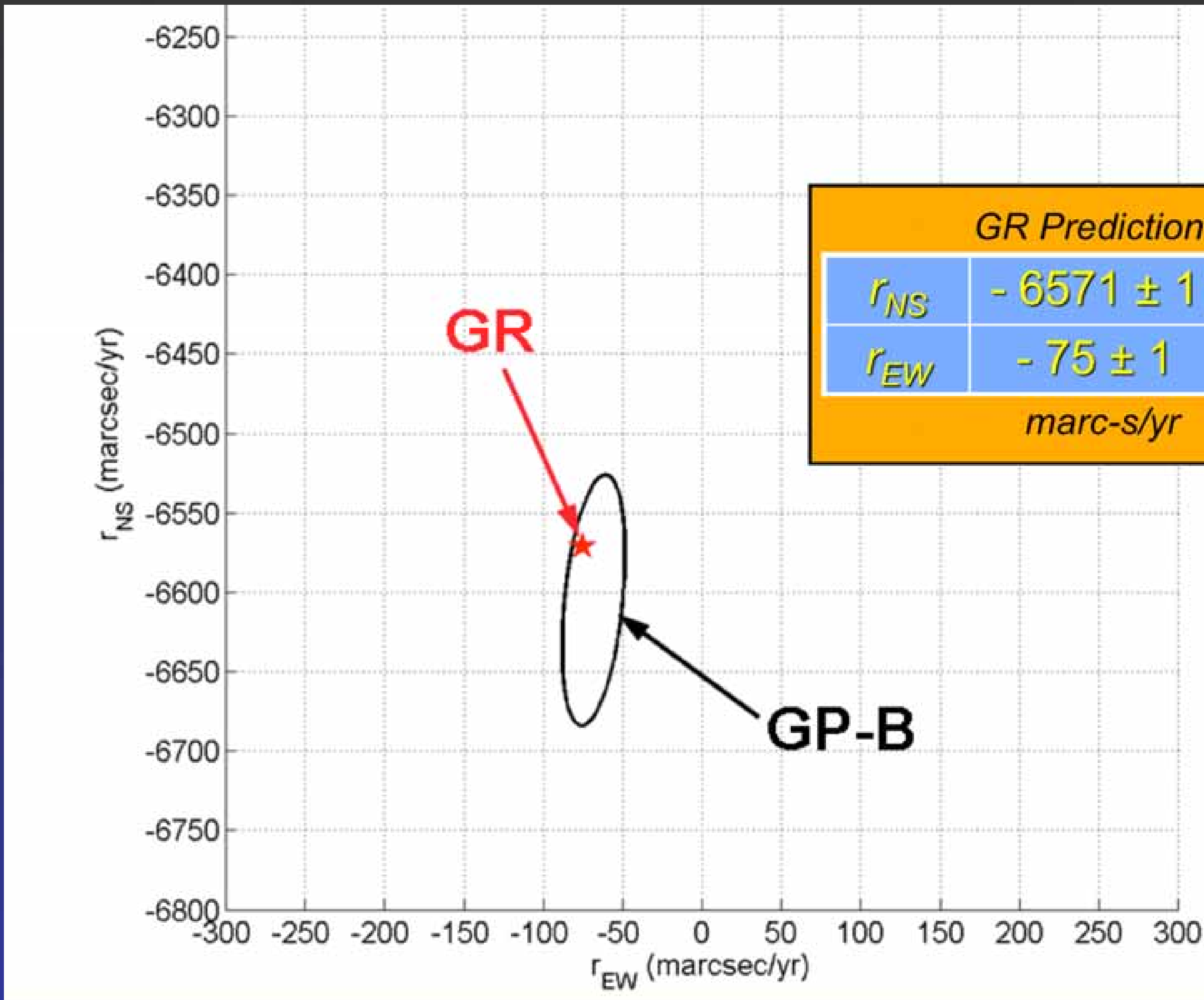
r_{NS} (geodetic)



r_{EW} (frame-dragging)



Comparison with General Relativity



	GR Prediction	*GP-B Result*
r_{NS}	- 6571 ± 1	- 6605.0 ± 32.4
r_{EW}	- 75 ± 1	- 68.3 ± 8.2
	marc-s/yr	*marc-s/yr*

Frame-dragging & Mach's Principle

- H. Thirring 1918
- Gyroscope @ center of hollow rotating sphere
- Extension to closed universe
- Einstein's *The Meaning of Relativity* (1953, pp. 100-107)
  - *"…these effects, which are to be expected in accordance with Mach's ideas, are actually present according to our theory, although their magnitude is so small that confirmation of them by laboratory experiments is not to be thought of."*
- The 12-step argument in Misner-Thorne-Wheeler (1973)
  - *"…Einstein's theory identifies gravitation as the mechanism by which matter there influences inertia here."*
- Frame-dragging & dark energy?

Students & Development of GP-B

86 Doctorates (29 Physics; 56 A/A, ME, EE; 1 Math.)

15 Master's Degrees, 5 Engineer's Degrees

14 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

cryogenic porous plug

TRIAD drag-free satellite, 1972

GP-B/GPS airplane landing

silicate bonding