Gravity Probe B:

Interim Report &

First Results

APS Meeting

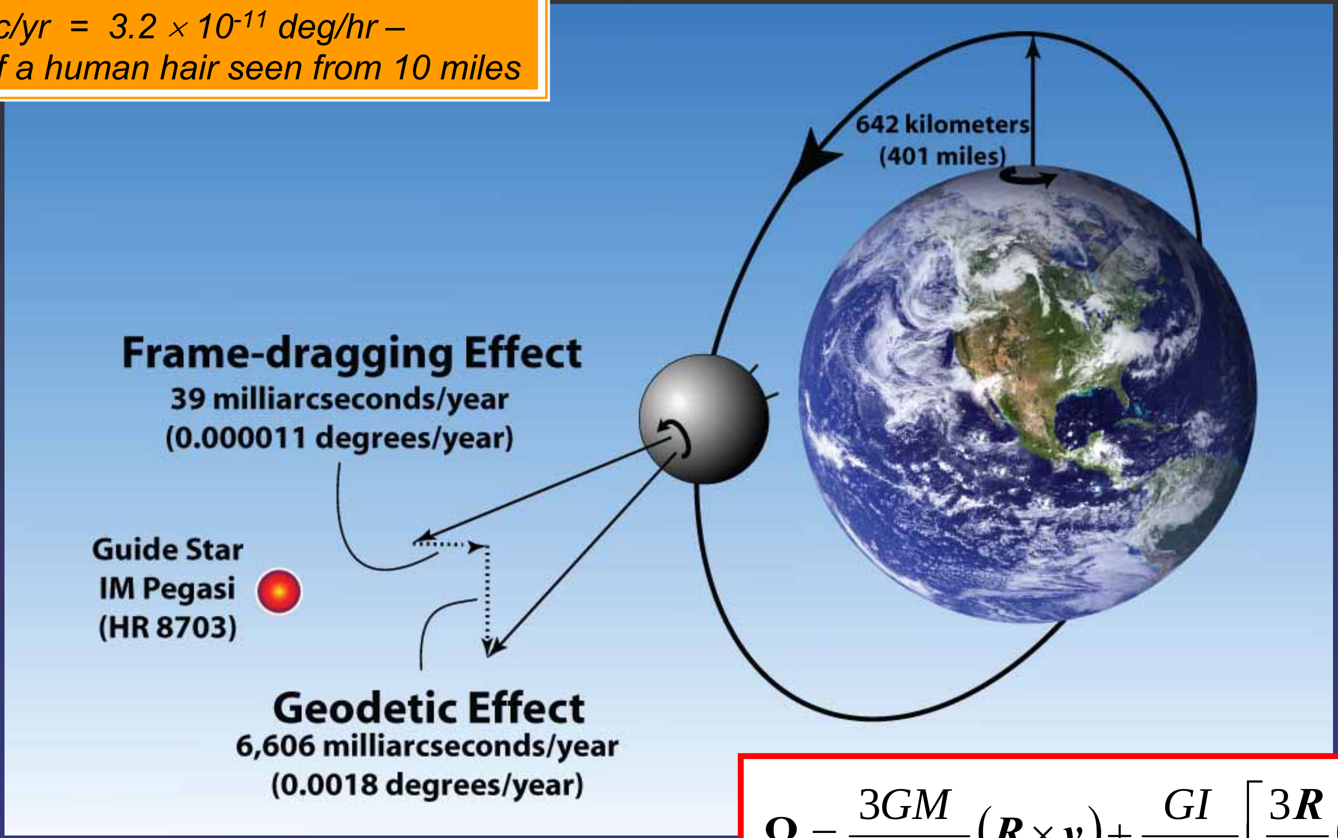
Jacksonville, FL

14 April 2007

Francis Everitt

The Relativity Mission Concept

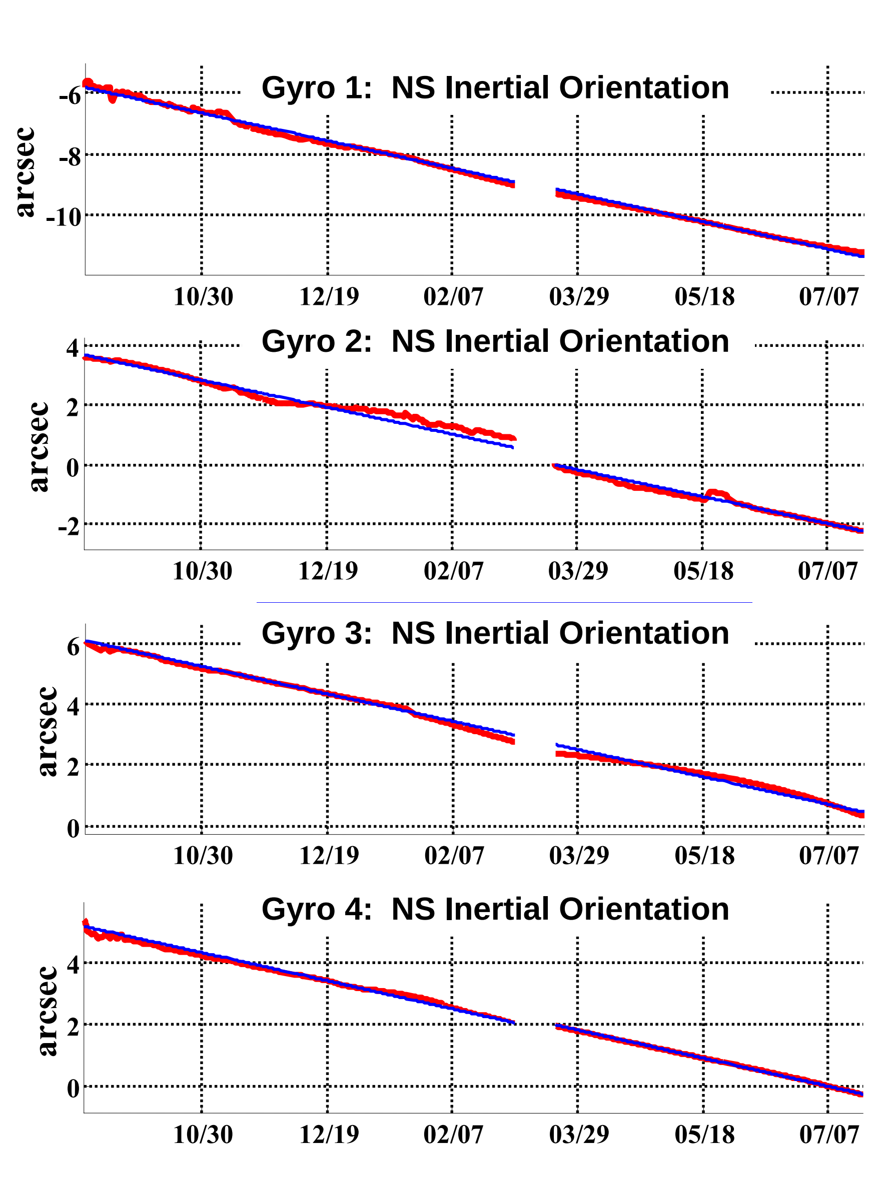
1 marc-sec/yr = 3.2 × 10^{-11} deg/hr – width of a human hair seen from 10 miles

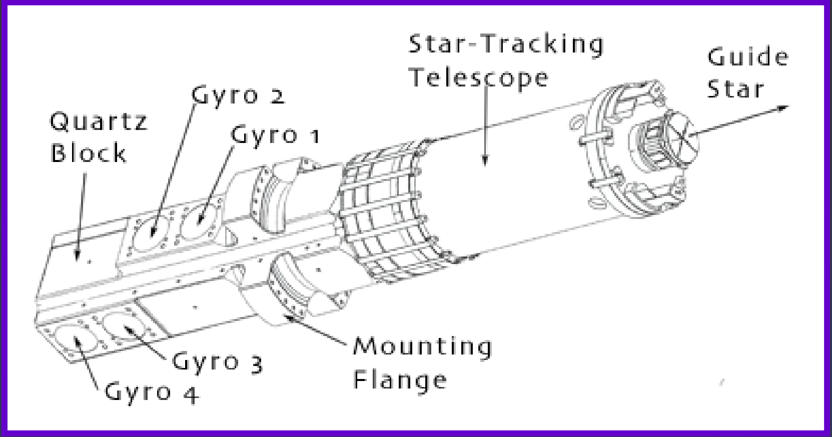


$$\mathbf{\Omega} = \frac{3GM}{2c^2R^3}(\boldsymbol{R}\times\boldsymbol{v}) + \frac{GI}{c^2R^3}\left[\frac{3\boldsymbol{R}}{R^2}(\boldsymbol{\omega}\cdot\boldsymbol{R}) - \boldsymbol{\omega}\right]$$

- 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



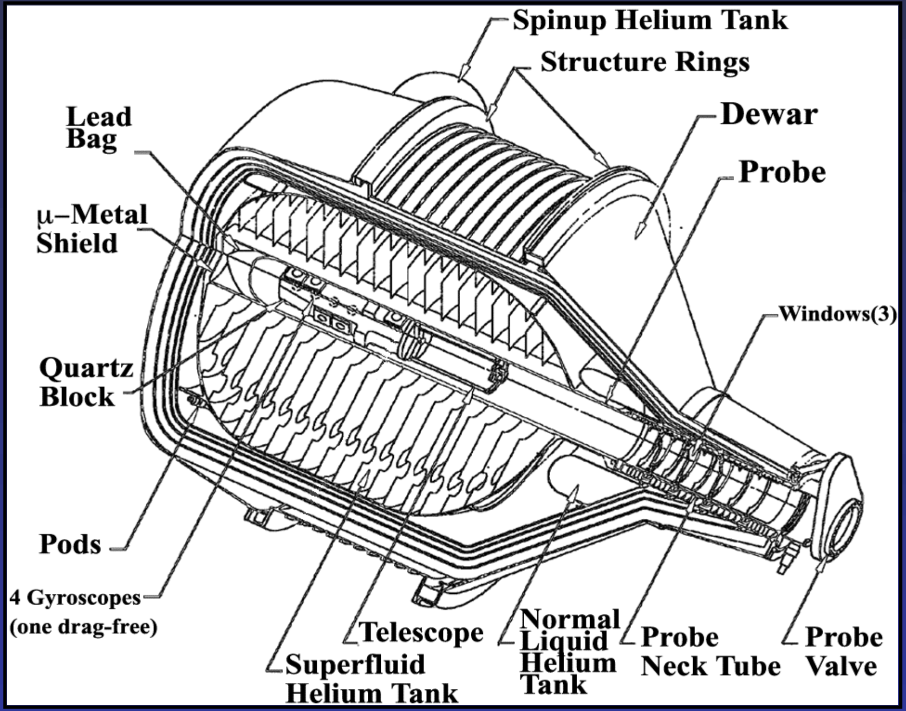


Red:
Unprocessed flight data

Blue:
After self-checking misalignment torque correction

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
- Modeling (if any) ➡ must be intrinsic, not ad hoc



Space

"Drag-free", separation of effects, elimination of "seeing“ limitations

Cryogenics

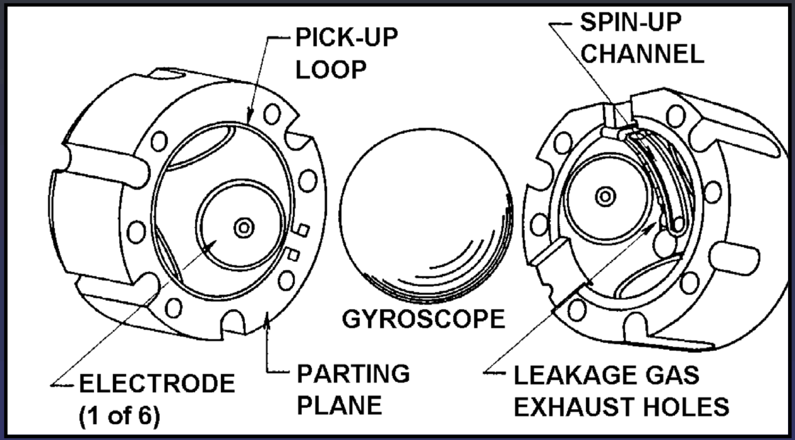
Readout, mechanical stability, low magnetic field, UHV technology

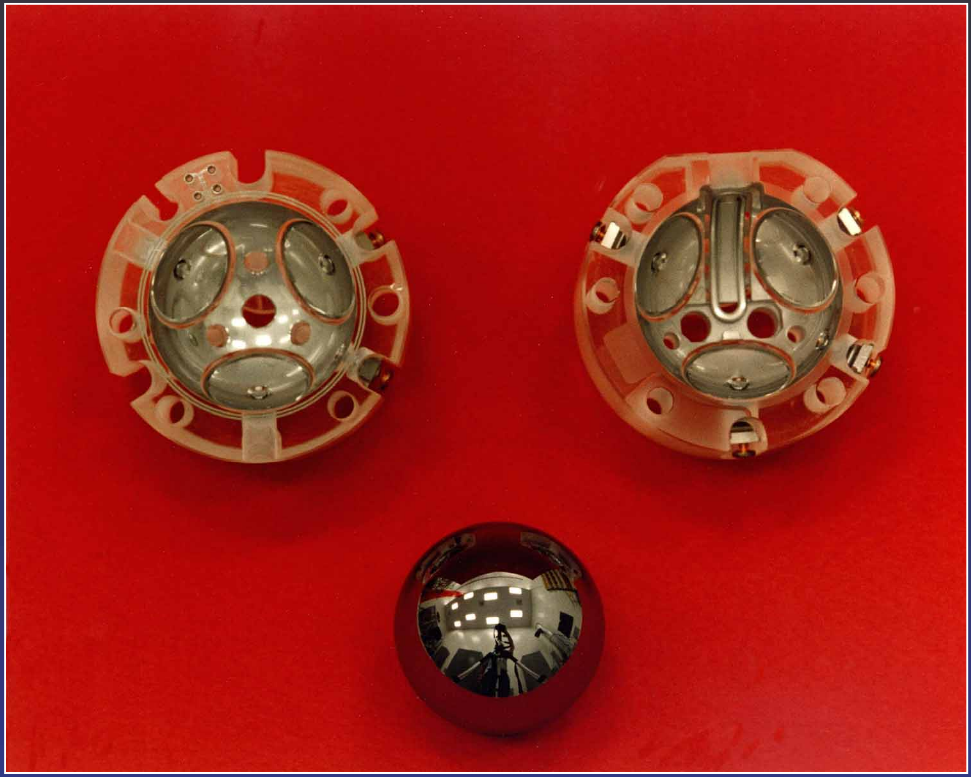
Testing General Relativity

- GM/c^{2}R & the annoying successfulness of Newton
  - Sun ~ 2 x 10^{-6} ; Earth ~ 7 x 10^{-10} ; 1 m diameter tungsten sphere ~ 10^{-21}
- Einstein's 2½ tests – Perihelion of Mercury, light deflection, redshift (½ test)
- Kinds of test enabled by new technologies since 1960
  - Clocks, electromagnetic waves, massive bodies
  - Observations vs controlled physics experiments
- New non-null tests
  - Shapiro time delay
  - Binary pulsar, especially gravitational wave damping
  - Geodetic (de Sitter) effect in Earth-Moon motion about Sun
- The Eddington PPN formalism & new null tests
  - Lunar ranging, Nordtvedt effect → restricts scalar-tensor theories
  - Earth tides, Will effect → eliminates Whitehead's preferred frame theory
- On to gravitational wave astronomy [*50 years since J. Weber detector*]

"Einstein's theory is a minimalist theory" - C.M. Will

The GP-B Gyroscope

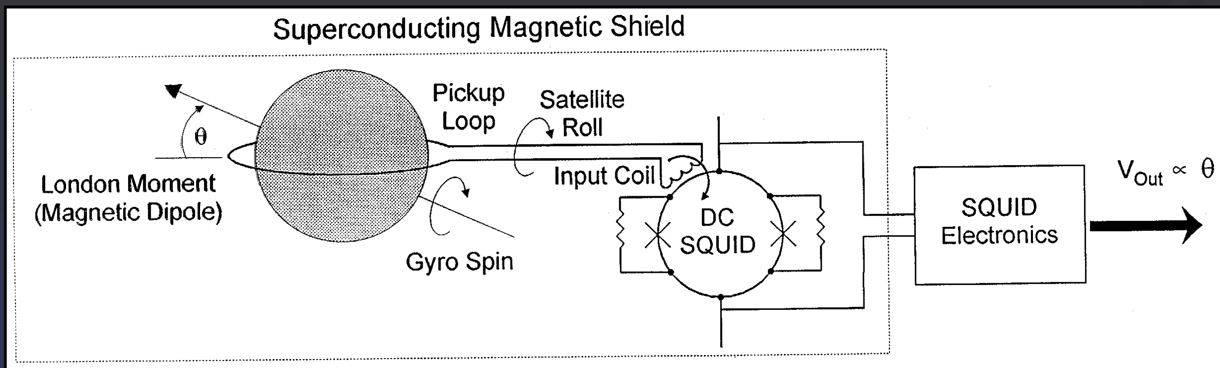


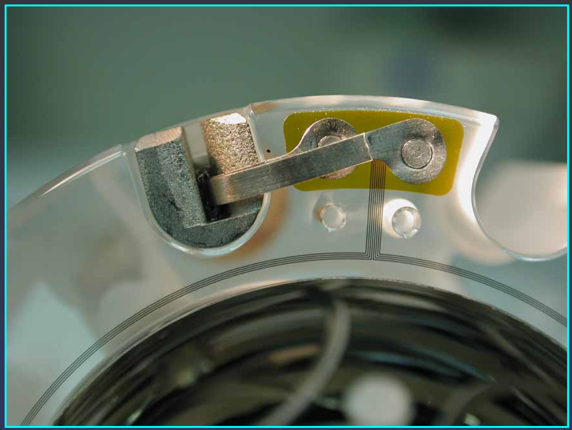


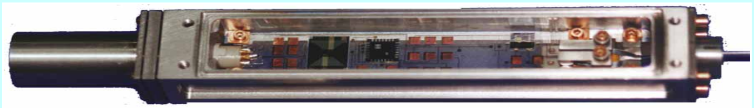
- **Electrical Suspension**
- **Gas Spin-up**
- **Magnetic Readout**
- **Cryogenic Operation**

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

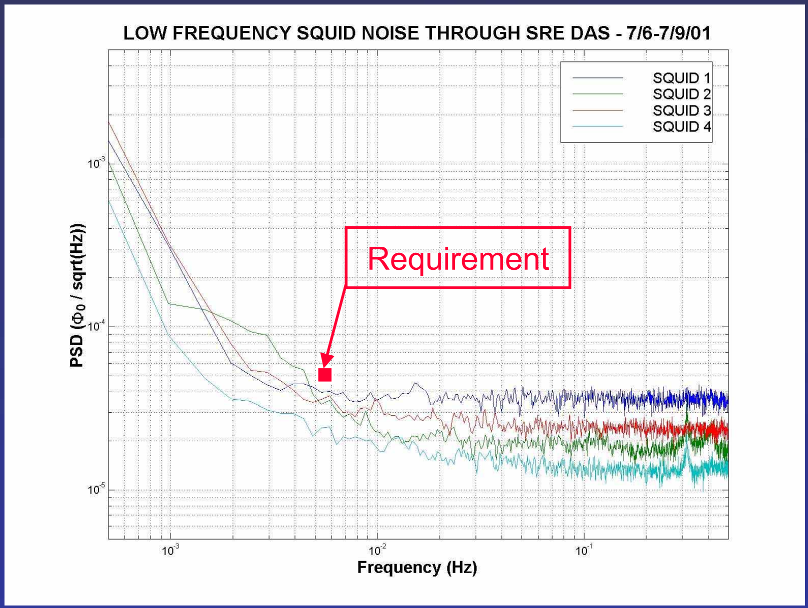
The London Moment Readout







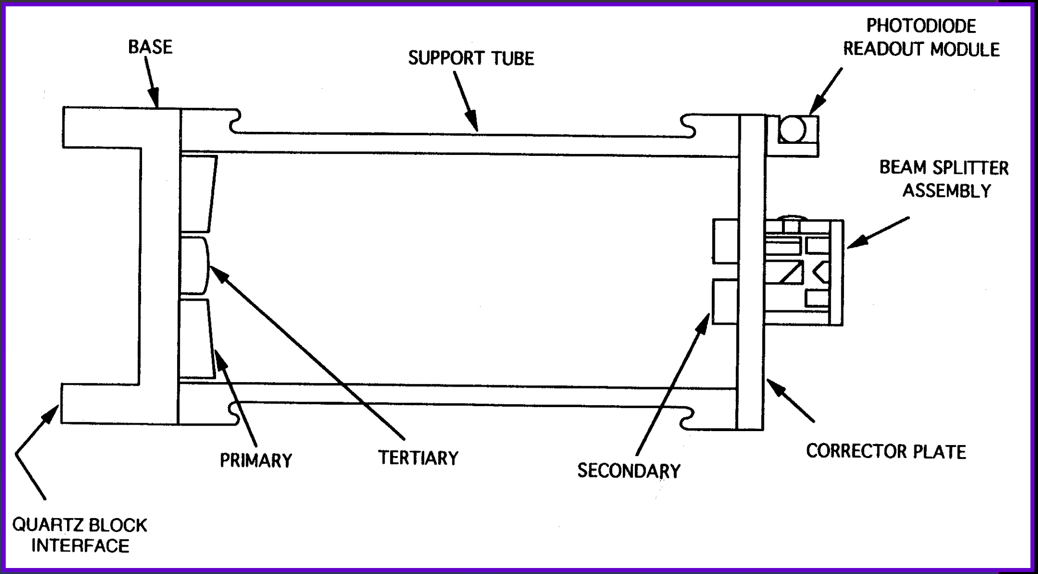
"SQUID" ⟶ 1 marc-s in 5 hours

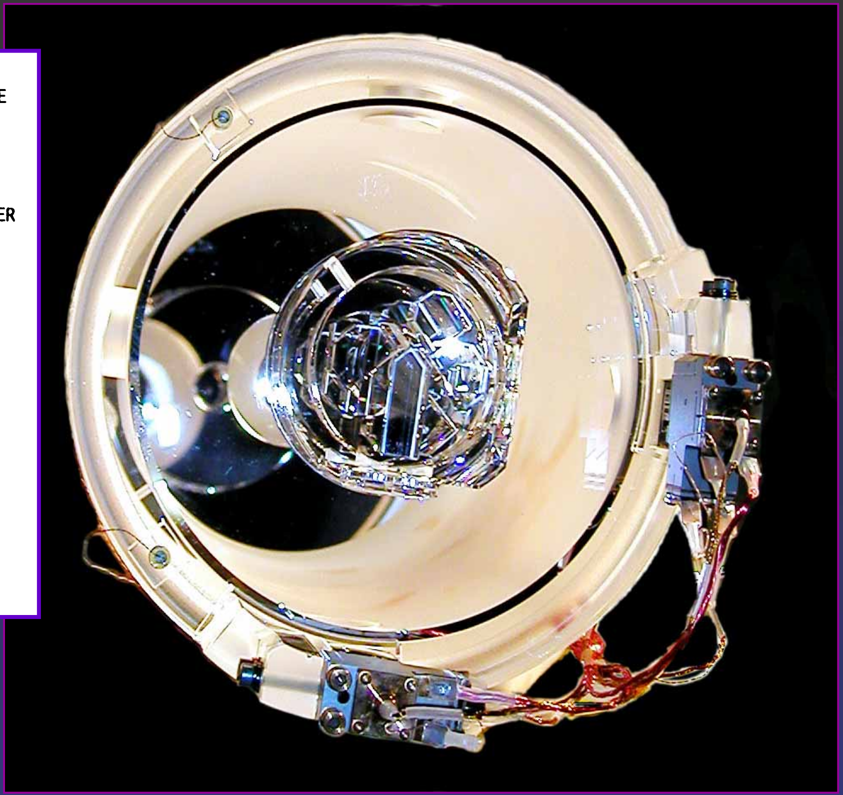


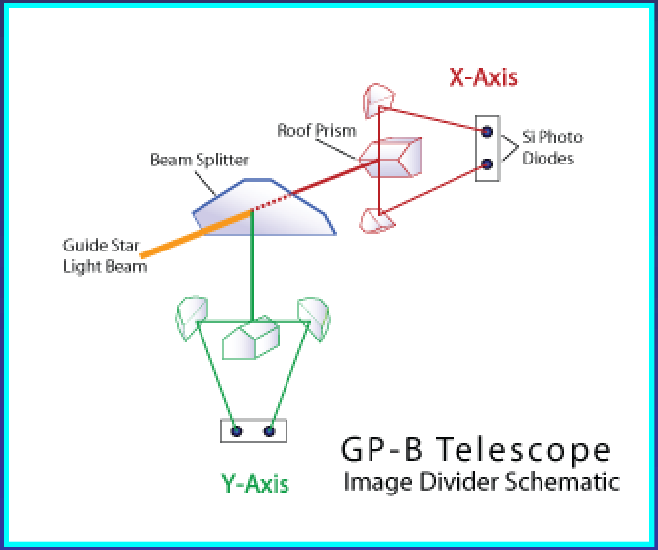
4 Requirements/Goals

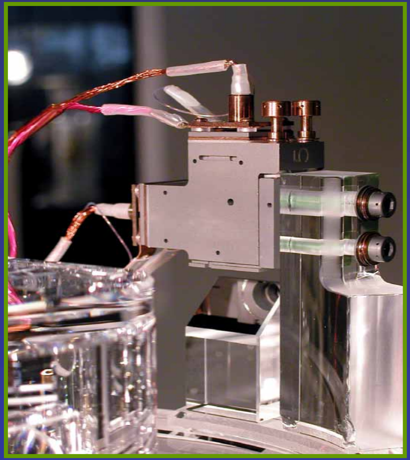
- SQUID noise 190 marc-s/√Hz
- Centering stability < 50 nm
- DC trapped flux < 10^{-6} gauss
- AC shielding > ~ 10^{12}

Sub-milliarc-s Star Tracker







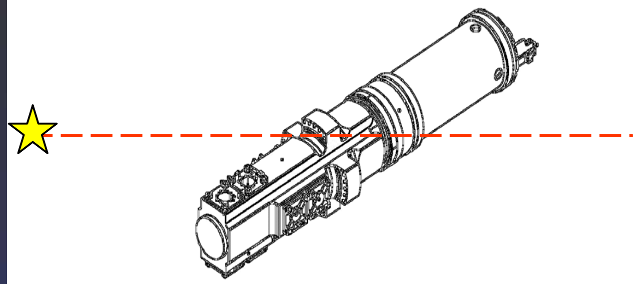


Detector Package

Dual Si Diode Detector

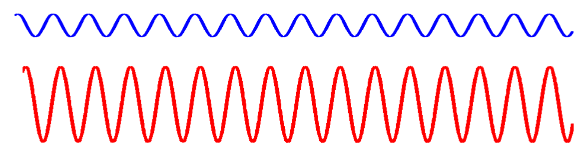
Dither & Aberration: Two Secrets of GP-B

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



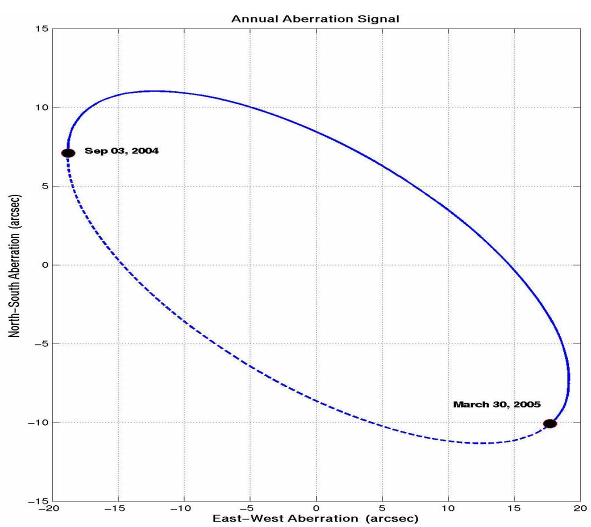
gyro output

telescope output



scale factors matched for accurate subtraction

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



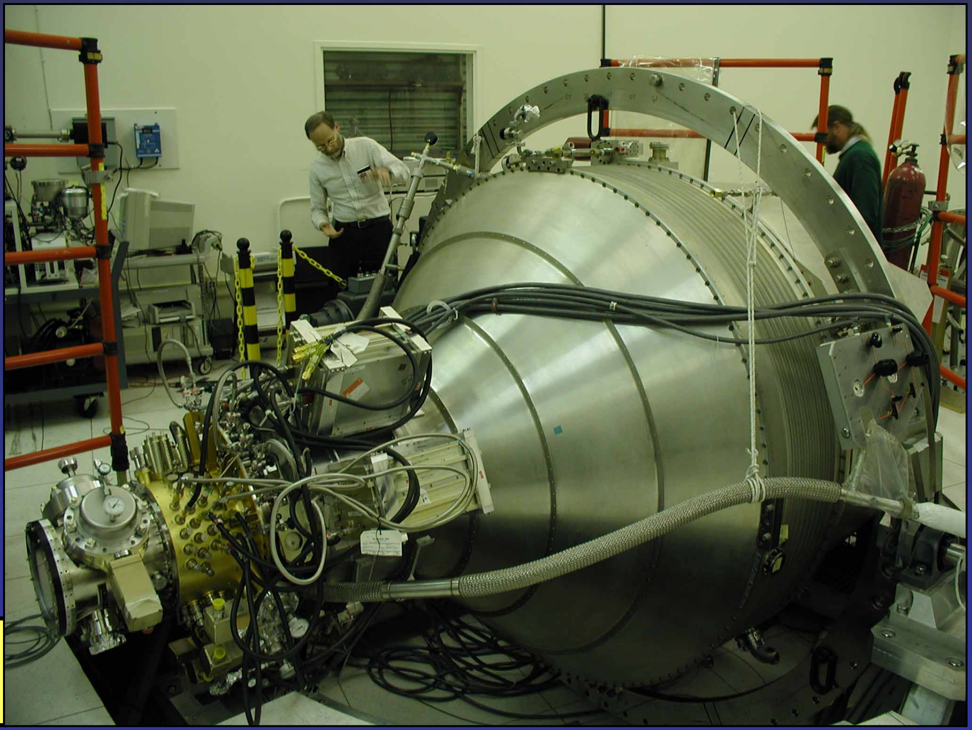
Orbital motion → varying apparent position of star (v_{orbit}/c + special relativity correction)

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



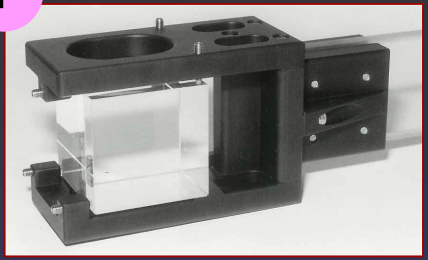
Payload in ground testing at Stanford, August 2002

Near Zeros & Their Technologies

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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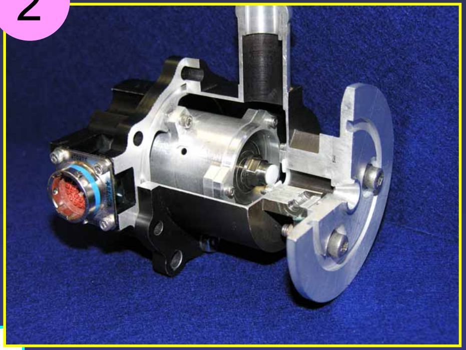

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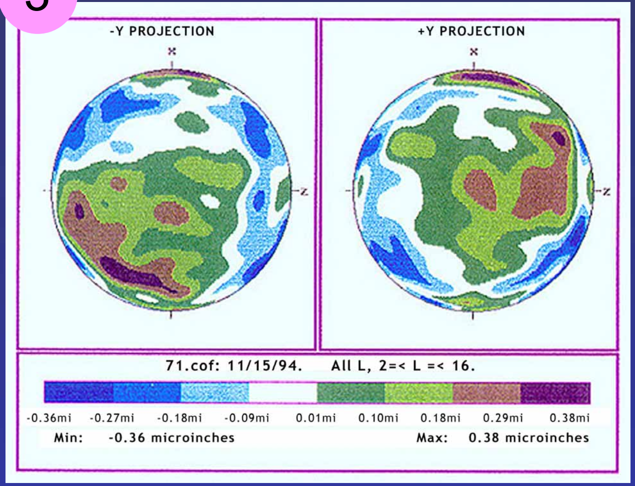

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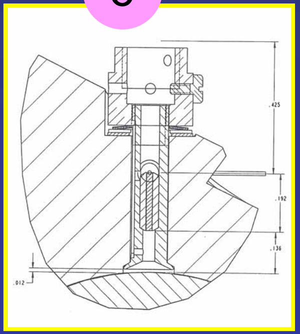
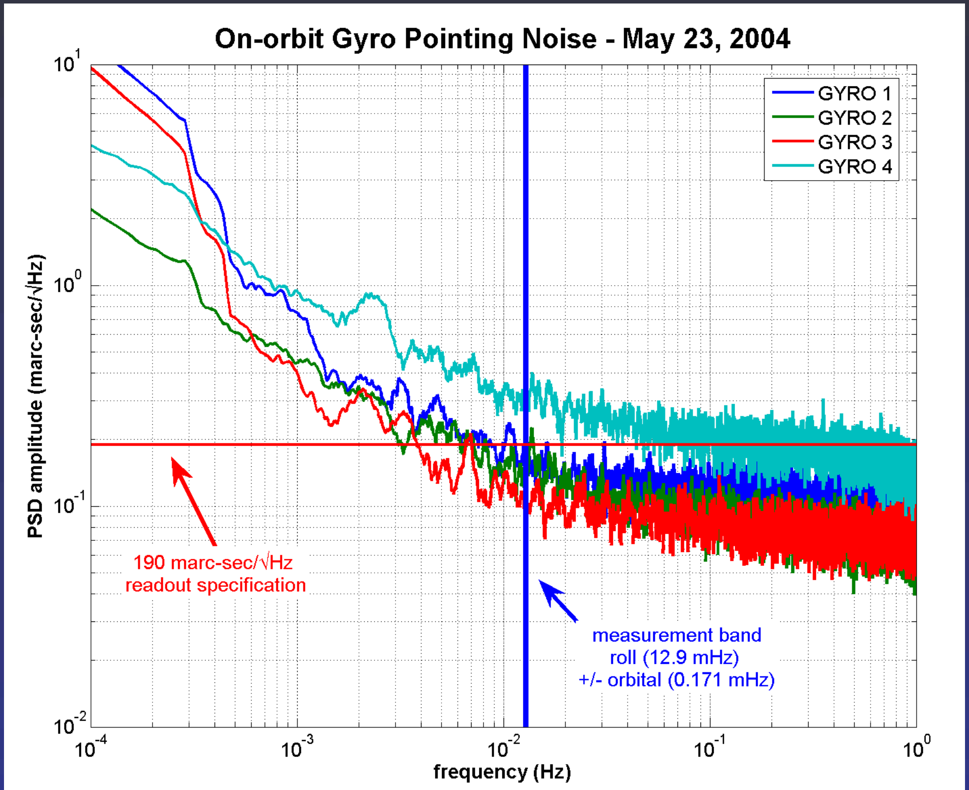
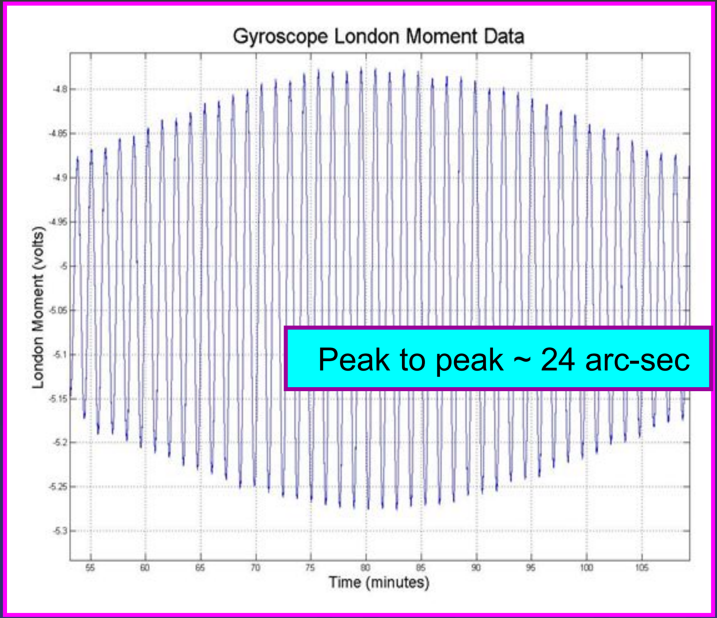


Gyro Readout Performance On-Orbit

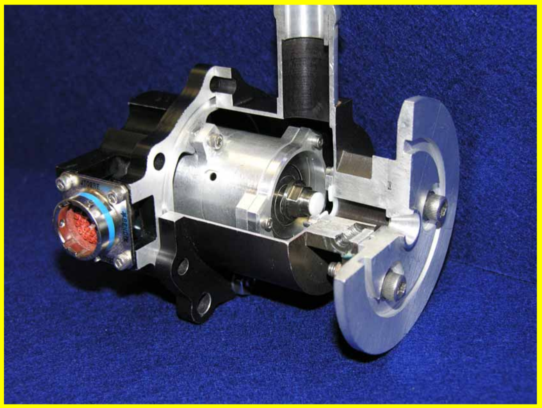


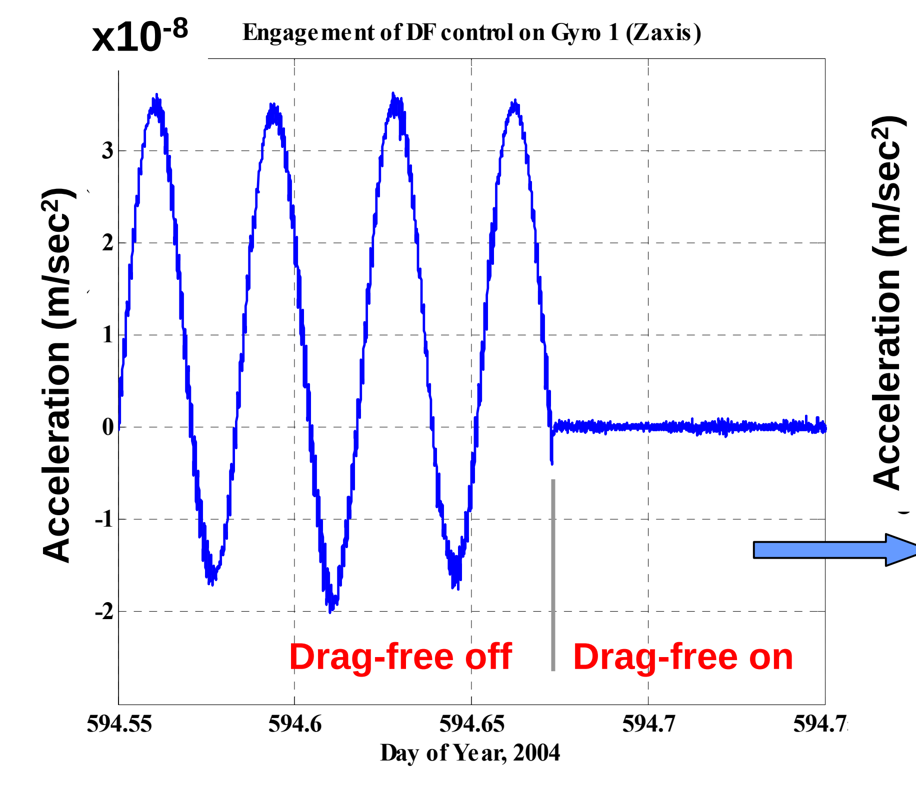


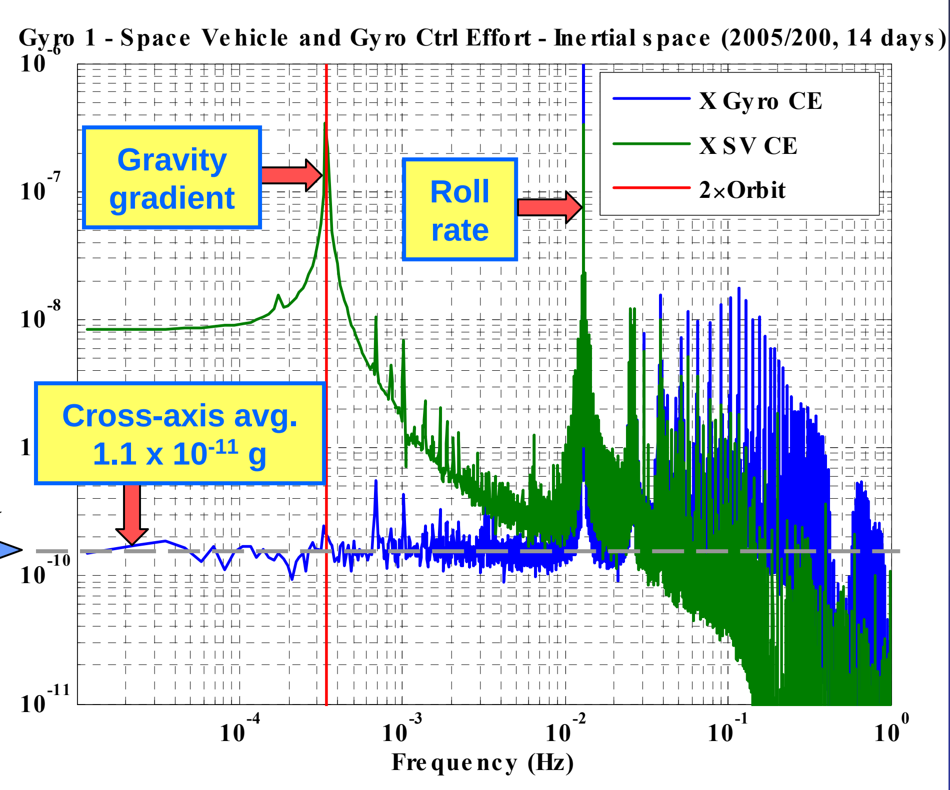
Gyro	Experiment Duration (days)	SQUID Readout Limit (marc-s/yr)
1	353	0.198
2	353	0.176
3	353	0.144
4	340	0.348

Drag-Free: 2^{nd} Near Zero

Boil off gas from Dewar vented continuously through 16 Proportional Thrusters provides spacecraft attitude and translational control







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 Cavendish]

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

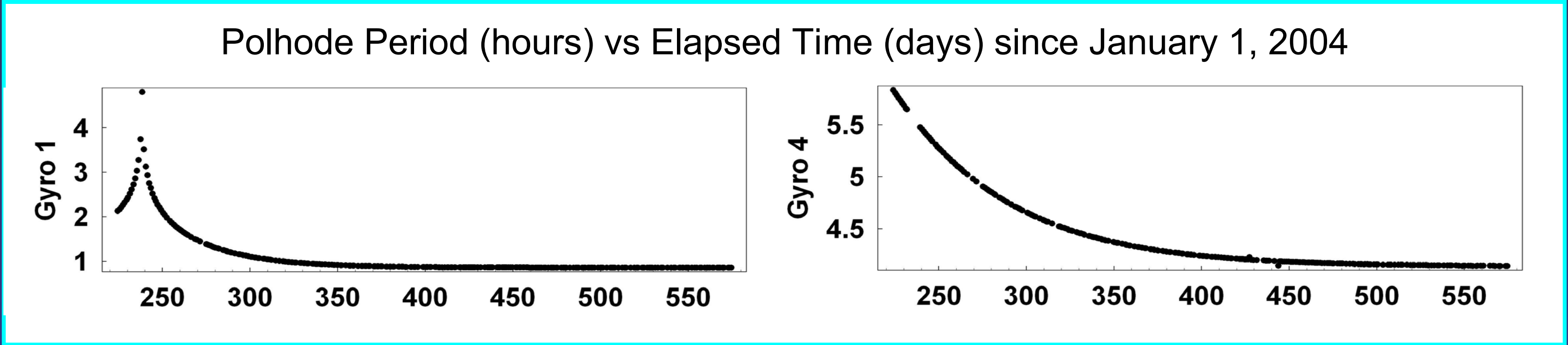
Observation (Phase B) – Segmented data (solar flare events, etc.)

Discovery 1 (Phase A, B) – Polhode-rate variations ⇒ affect C_g determinations

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

Discovery 1: Polhoding & C_g

- Issue: *C_g better than 10^{-4} ⇒ linking data from 6 or more orbits*
- The actual 'London moment' readout:
  - M_L + dipole component of trapped flux along spin axis $M_T \sim 1\%\ M_L$
  - Total trapped flux fixed in rotor but M_T modulated by polhoding
  - Orbit-to-orbit fit ⇒ complicated by varying polhode rate



- Current: Fit 4 to 6 polhode harmonics to get mean M_T
- Refinement: Utilize Trapped Flux Mapping data

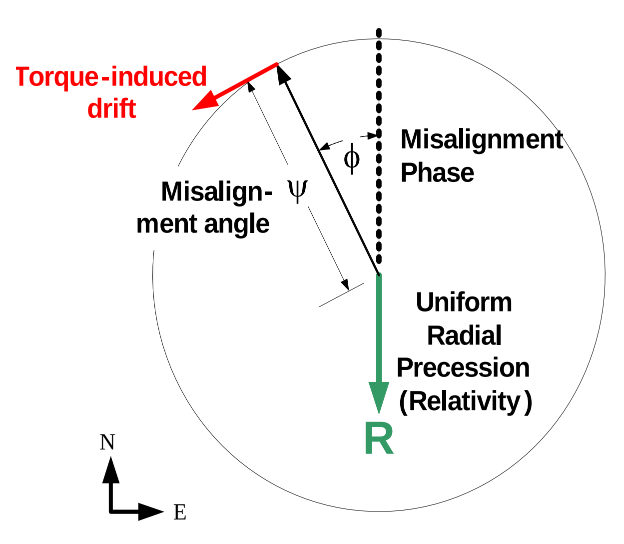
Discovery 2: Misalignment Torques

- Torque & misalignment angle ϕ, ψ ⇨ 0.1 to 1.0 arc-s/yr drift rates
- Probable cause – Electrostatic 'patch effect' on rotor *and* housing
- Relativity

  Fixed direction in inertial frame

- Misalignment Torque/Drift

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



- M. Keiser observation
  - Component of R $\parallel$ ϕ free of misalignment torques
  - ϕ modulated over year by annual aberration

Eliminating Misalignment Drift

- Two Complementary Approaches, 'Geometric' & 'Algebraic'

- 'Geometric', *rate-based*

  (i) Torque-free component of *R* determined from e.g. 5-day batch-averaging

  (ii) BONUS: torque-coefficient *k* found in separate measure of component ⊥ to (i)

- 'Algebraic', *orientation-based*

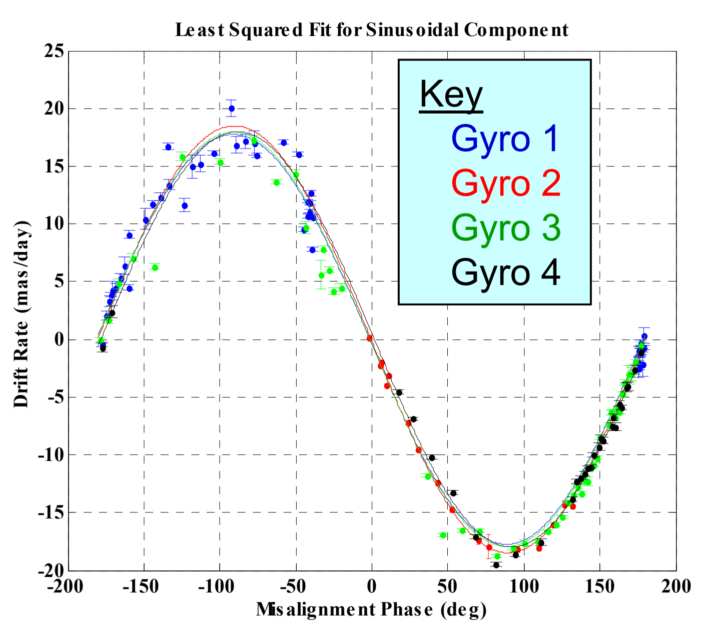
  (i) Also utilizes geometrical relationships, BUT with

  (ii) Explicit torque models & continuous estimation & filtering

- Complementarity
  - e.g., separate *k*-profile determinations from the two methods can be cross-checked against each other

For details: M. Keiser lecture & M. Heifetz poster, April 15

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

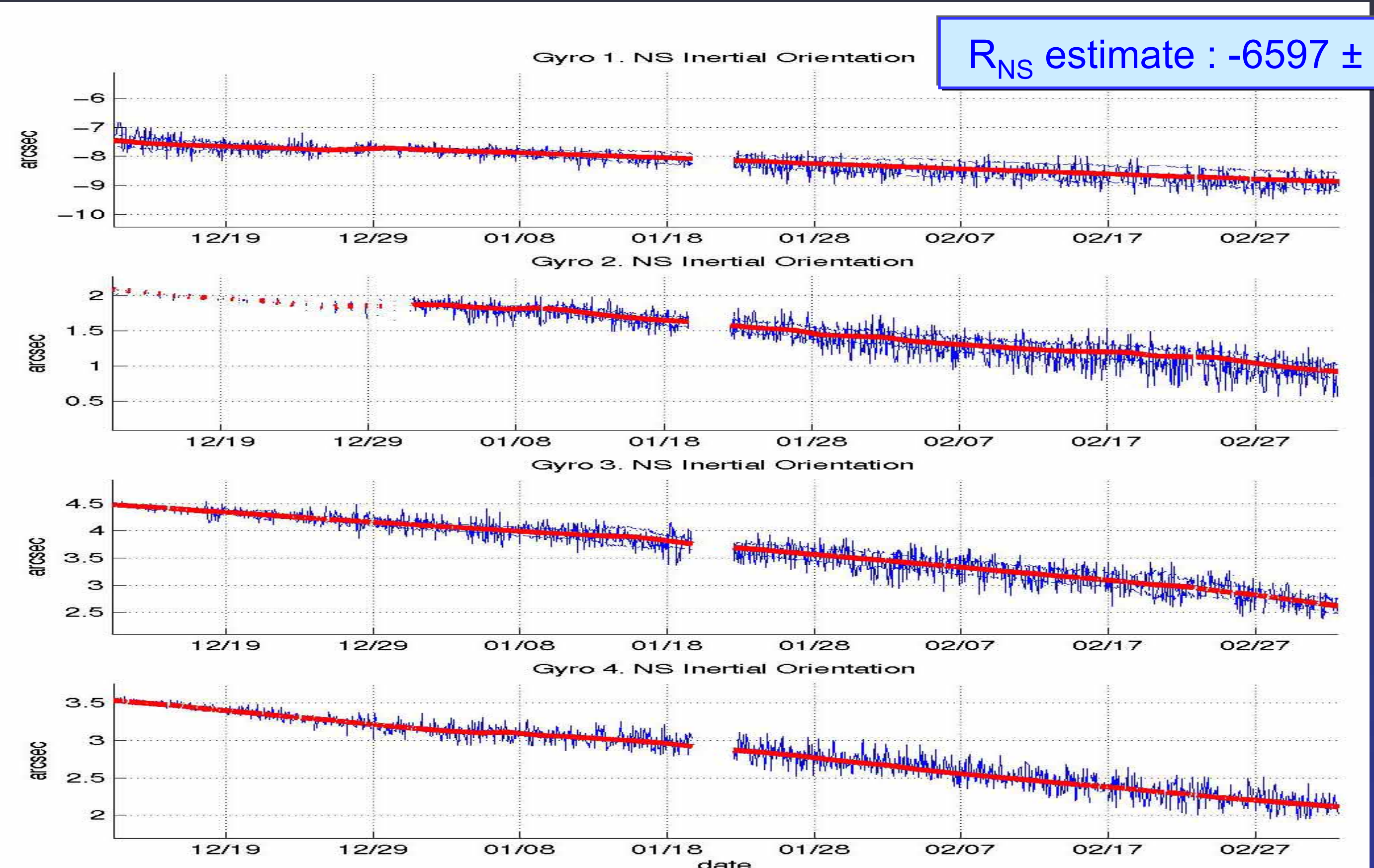
- Power of Geometric Approach
  - Clear proof of relativity separation
  - Diagnostic tool for other potential disturbances
- Requirement for Final GP-B Result
  - Recover $t^{-3/2}$ dependence by Algebraic or Enhanced Geometric Method

Algebraic Method Example

85 Days with Solar Flare Segmentation

[December 10, 2004 – March 5, 2005]

R_{NS} estimate : -6597 ± 20 marc-s/yr



2nd floor analysis from December 2006

Initial Geodetic Effect Results

	'Geometric'	'Algebraic'			
		glimpse 1	glimpse 2	glimpse 3	glimpse 4
	Full Year	158 days	85 days	82 days	41 days
1σ statistical error only	-6638 ± 11	-6584 ± 52	-6597 ± 20	-6595 ± 10	-6604 ± 7
	Separate gyro, ~ 5-day batches	Combined gyro processing, continuous filtering			

Progress in modeling with algebraic approach evident

SQUID noise limit

Net expected

-6571 ± 1 *

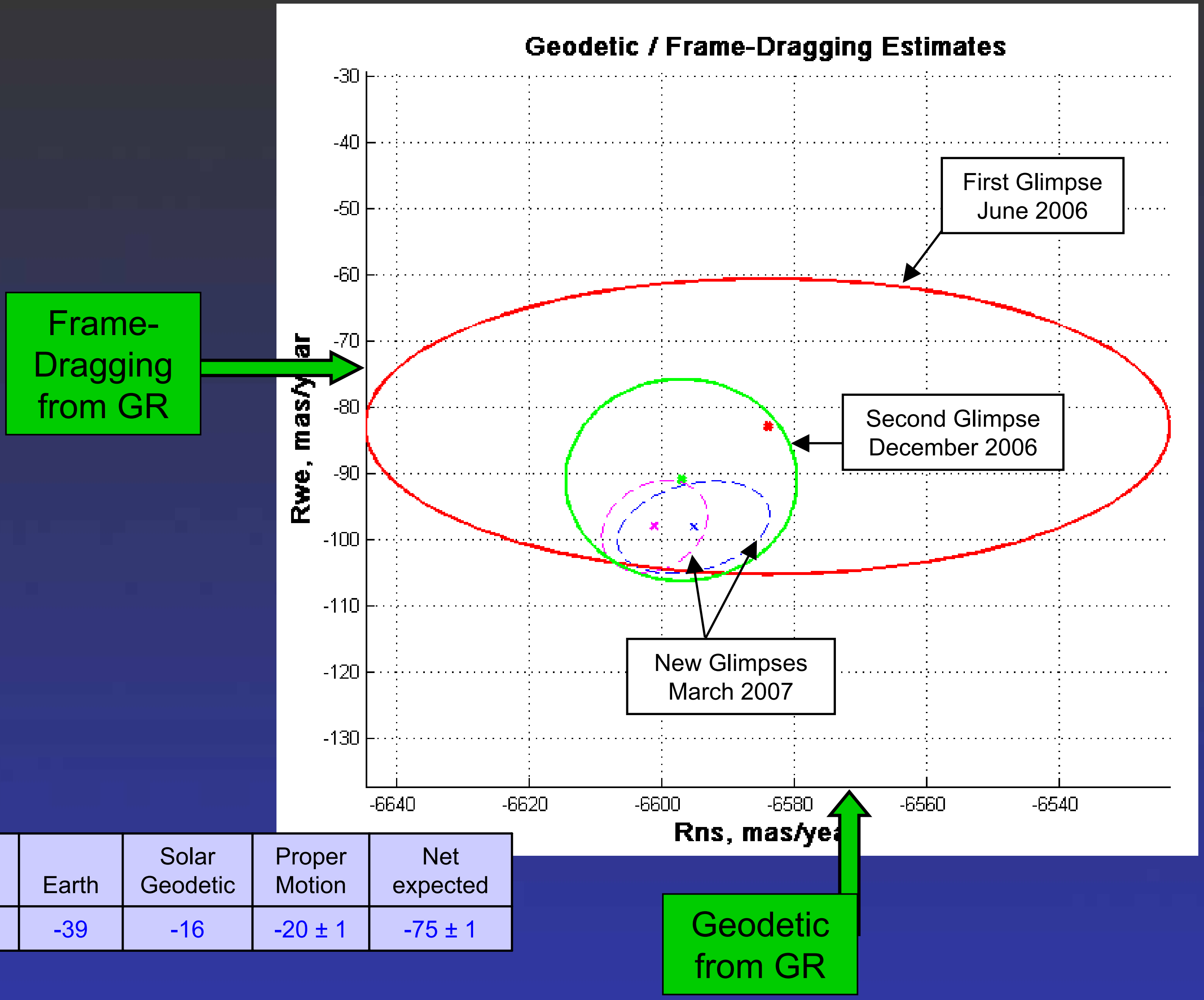
[marc-s/yr]

-6638 ± 97

Residual gyro-to-gyro inconsistencies due to incomplete modeling ~ 100 marc-s/yr

* Earth -6606, solar geodetic +7, proper motion +28 ± 1 ⟹ net expected -6571 ± 1

Glimpses of Frame-Dragging



	Earth	Solar Geodetic	Proper Motion	Net expected
EW	-39	-16	-20 ± 1	-75 ± 1

Assessment of 4 Frame-Dragging Glimpses

- Modeling of scale factor & torques improved substantially since June 2006
- Filtering technique more robust; can estimate many more parameters
- CAVEATS
  - Excessive sensitivity to modeling of torque coefficients
    - ⇒ occasional worrying outliers
  - Inconsistencies between 4 gyros are real
    - ⇒ long-term modeling with detailed torque coefficient history in work
  - Combined gyro processing eliminates some error sources
    - ⇒ may miss others

Requires cross-checking with geometric method
essential to understand physical processes

The Story So Far

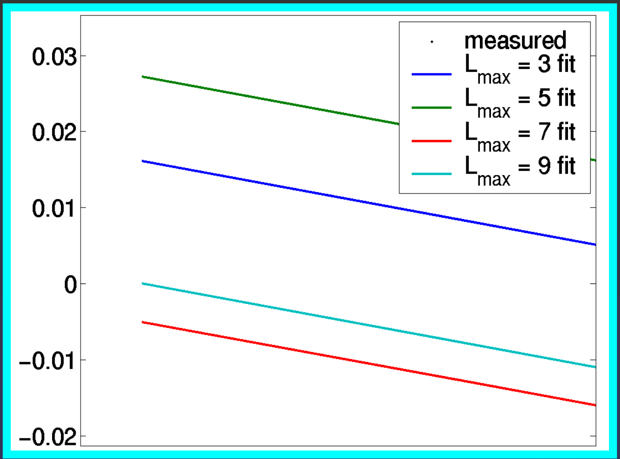
- Geodetic effect clearly seen in unprocessed science data
- Gyro orientation data have reached SQUID readout limit in each gyro
- Results of In-Flight Verification/Calibration process
  - Most pre-launch estimates confirmed, eliminating many potential error sources
  - Discovery 1: polhode damping & its effect on C_g
  - Discovery 2: 'patch effect' misalignment torques

Need to be completely separated in final analysis

- Complementary 'geometric' & 'algebraic' approaches to misalignment torques
  - Encouraging agreement between torque-coefficient determination
- 'Glimpses' of Frame-Dragging effect
  - Probably authentic but strong caveat needed due to outliers which reveal model sensitivity

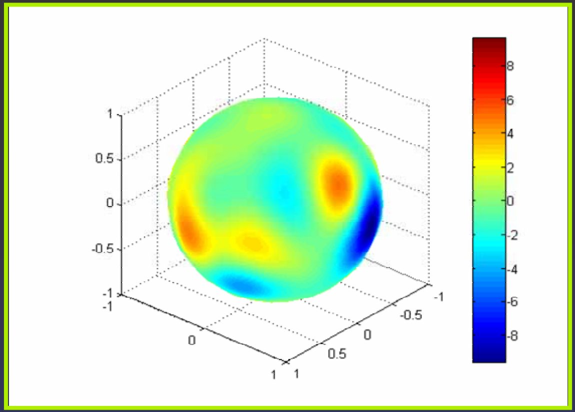
C_g & Trapped Flux Mapping

μHz

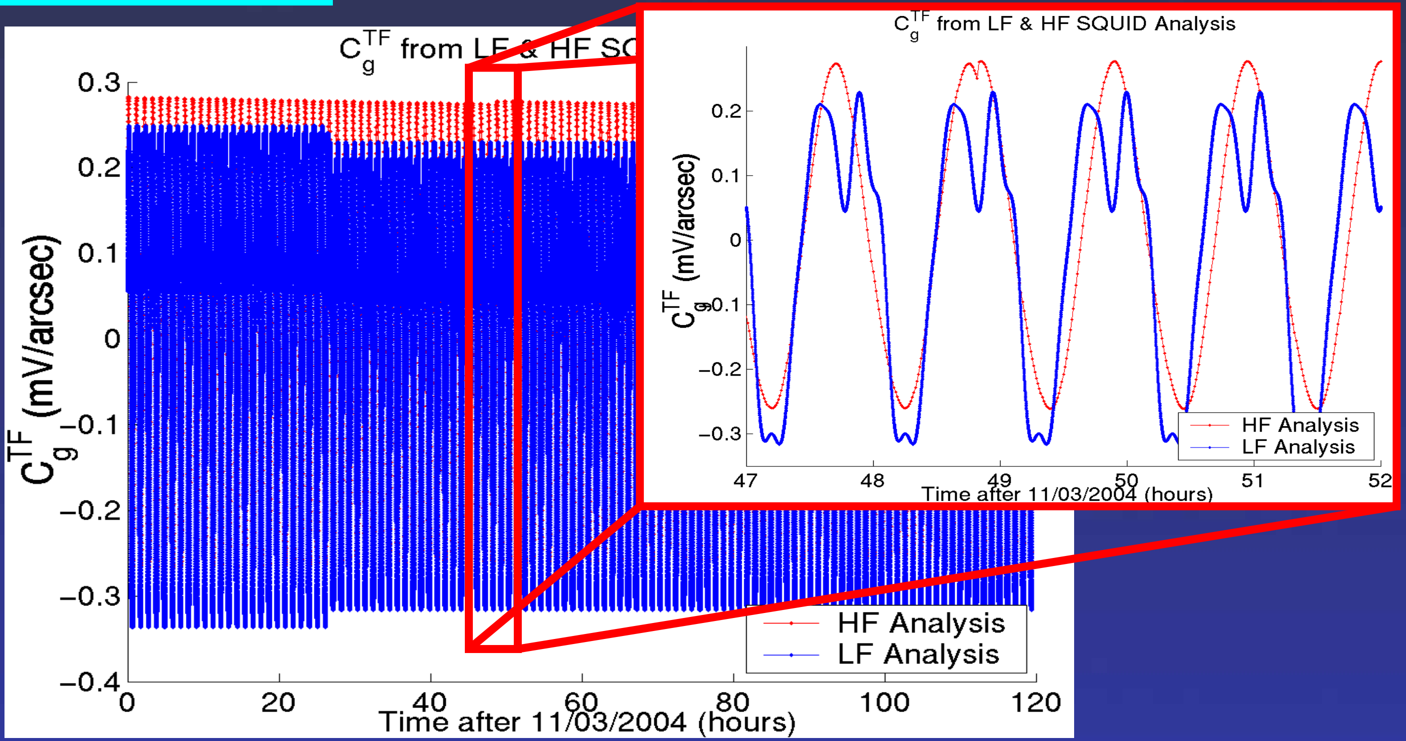


nHz gyro spin speed

Fluxon map



C_g variation from Trapped Flux Mapping



The Way Forward

(1) Many issues completely solved, meet full accuracy

(2) Elimination of C_g Scale Factor Issue by Trapped Flux Mapping Data

(3) Completing of Misalignment Torque Modeling & Exploration of Other Potential Torque effects

(4) Limit & Goal of Final Analysis through December 2007

- ⇨ SQUID readout limit 0.144 to 0.343 marc-s/yr depending on gyro
- ⇨ segmented data raises these limits to ~ 0.5 to 1 marc-s/yr (Duhamel effect)

(5) Final 'Double Blind' Comparison with HR8703 Proper Motion Data

- Irwin Shapiro talk this afternoon

GP-B Science Advisory Committee

C. Will, Chair	J. Ries
D. Bartlett	P. Saulson
R. Reasenberg	E. Wright
R. Richardson	

The GP-B Data Analysis Team

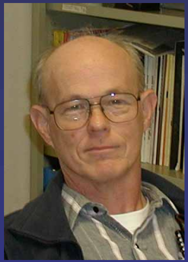

John Turneaure


John Lipa


John Goebel


Yoshimi Ohshima


Paul Shestople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Bill Bencze


Michael Heifetz


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Jeff Kolodziejczak


Jie Li


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