LOCKHEED MARTIN

STANFORD UNIVERSITY

Gravity Probe B Overview

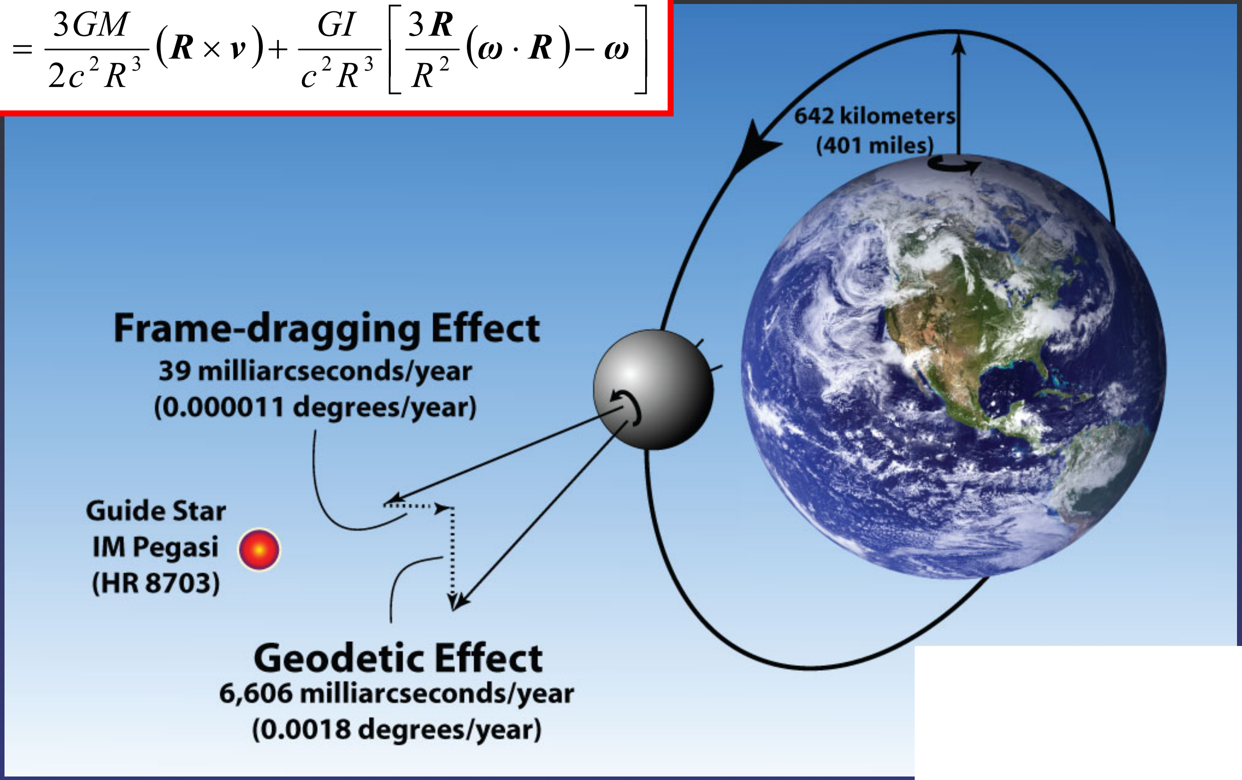
Barry Muhlfelder

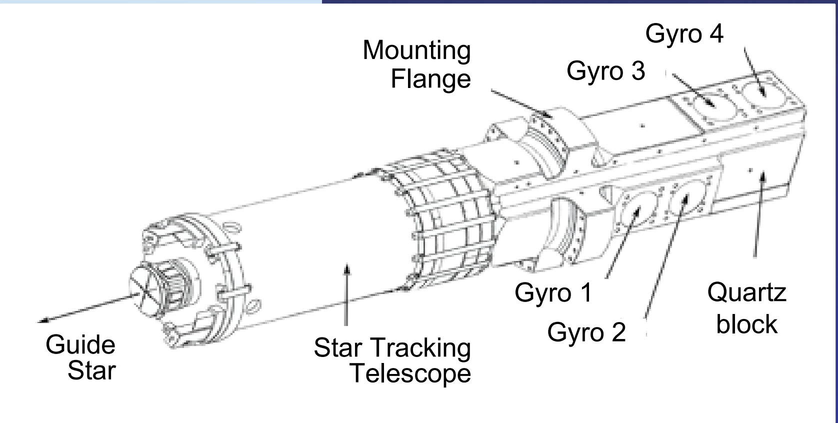
HEPL-AA Seminar

June 17, 2009

The Relativity Mission Concept

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





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

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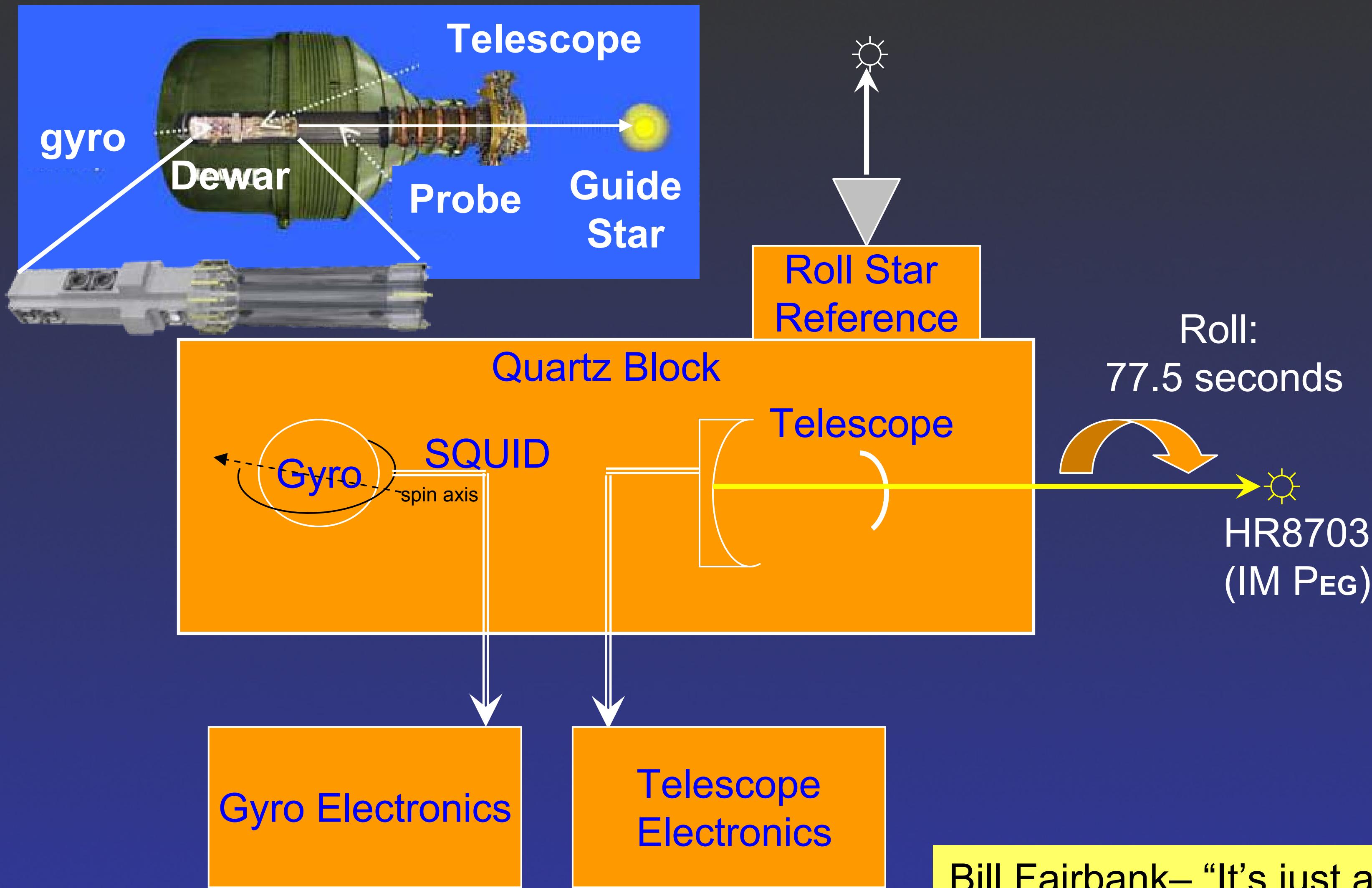
Launch: April 20, 2004 – 09:57:24

Stanford Mission Operations Center

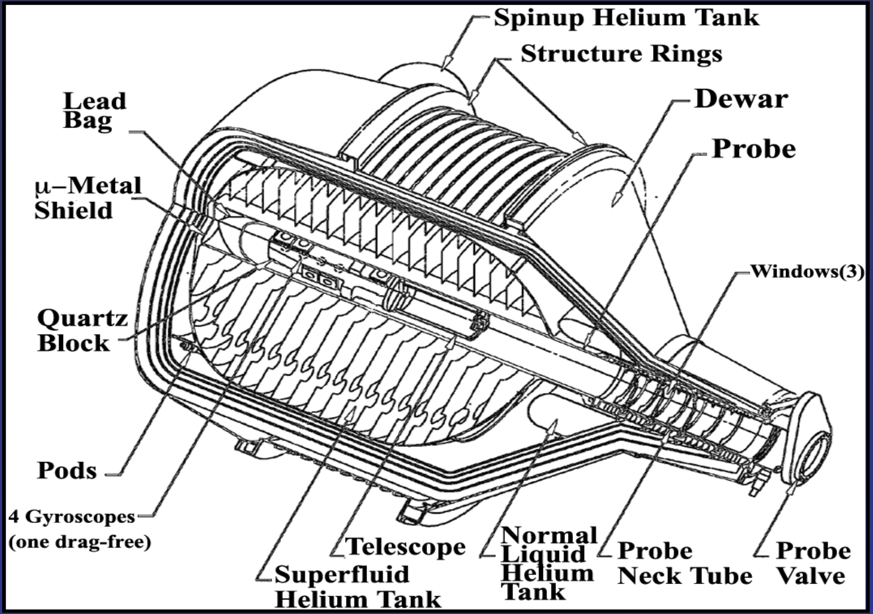
Measurement of Gyroscope Orientation Relative to Position of Guide Star



Bill Fairbank– “It’s just a star, a telescope, & a spinning sphere”

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
- Gyro Readout → calibrated to parts in 10^5
- G – T → <1 marc-s subtraction within pointing range



Basis for 10^7 advance in gyro performance

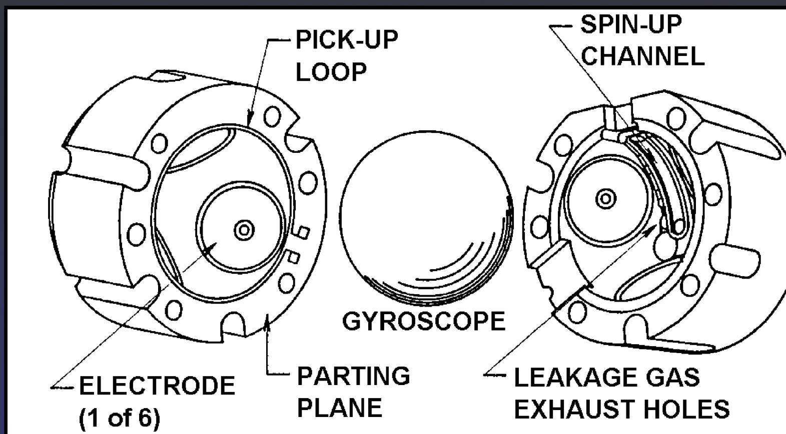
Space

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

Cryogenics

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

The GP-B Gyroscope



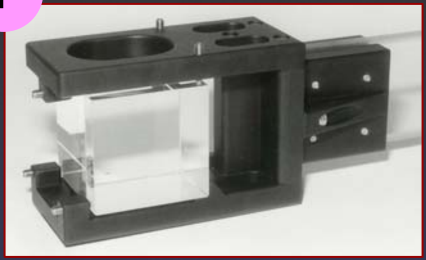
- **Electrical Suspension**
- **Gas Spin-up**
- **Magnetic Readout**
- **Cryogenic Operation**

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

Seven Near Zeros

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

1



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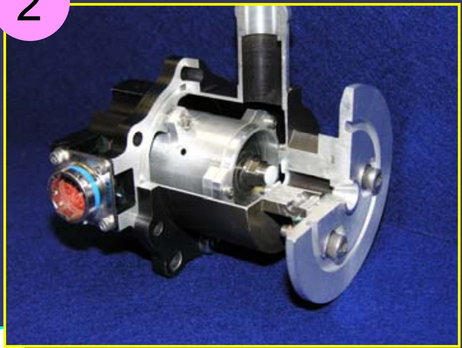

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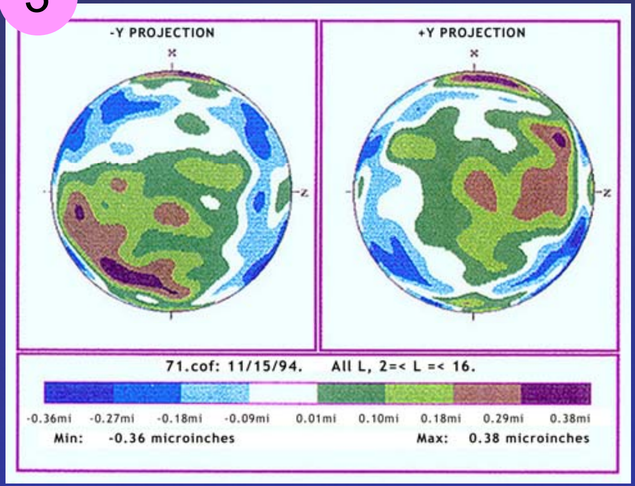

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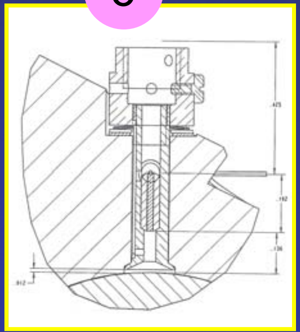
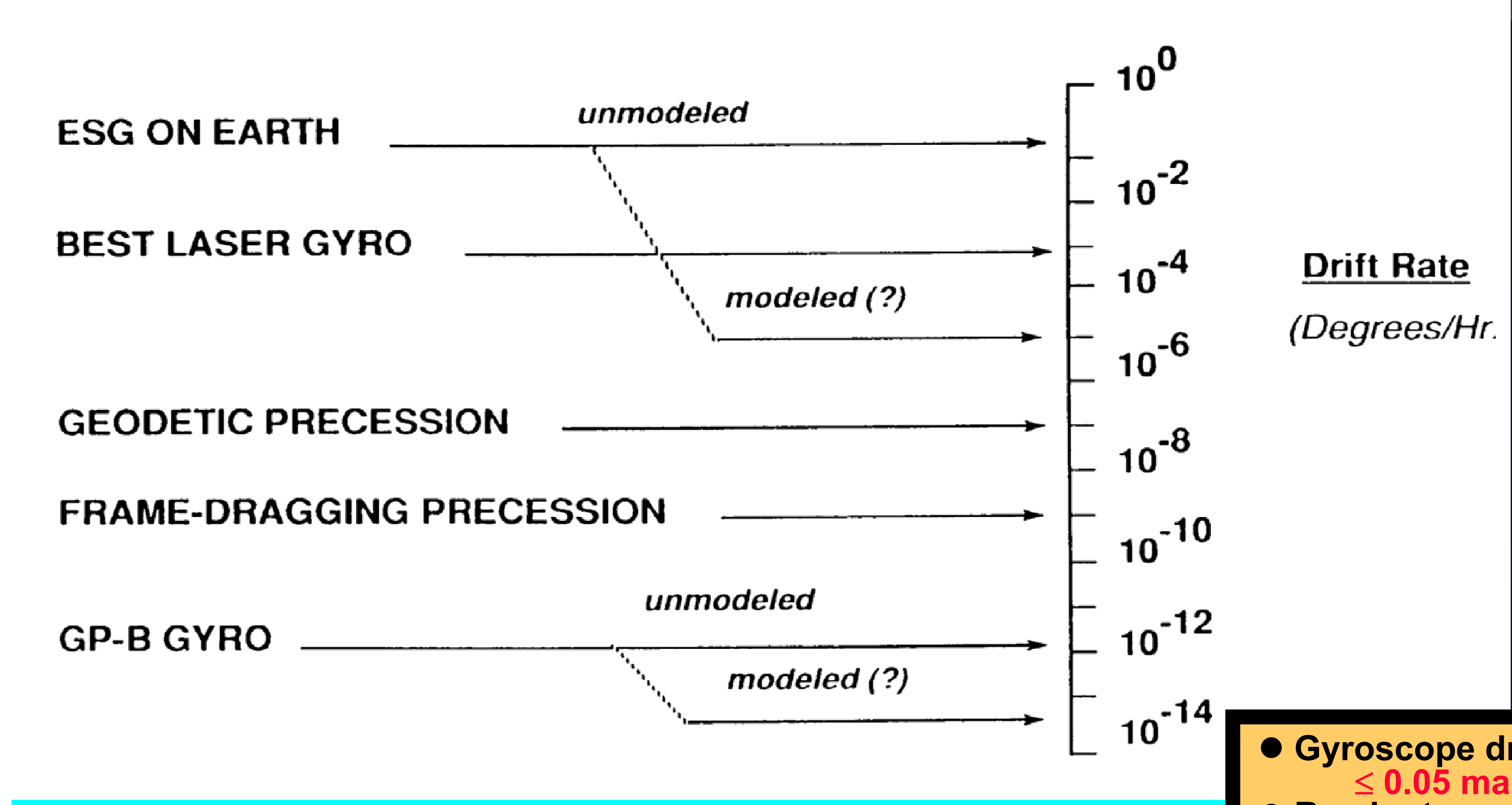


GP-B Performance

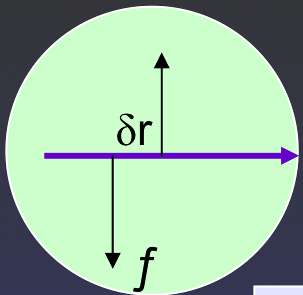
Why go to space?



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

Space improves gyro accuracy by > 50,000,000!

Mass-Unbalance & Drag-Free



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

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 ($f \sim 10^{-12}$ g cross- track average)	$\frac{\delta r}{r} < 5.8 \times 10^{-6}$ *(straightforward)*

All GP-B rotors mass unbalance < 10 nm (2 cm radius) or

$\frac{\delta r}{r}$ ~ 5×10^{-7}

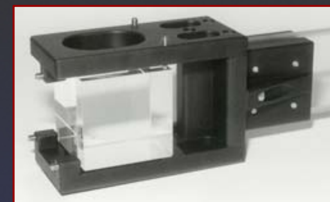
drift-rate for the drag-free GP-B < 0.01 marc-s/yr

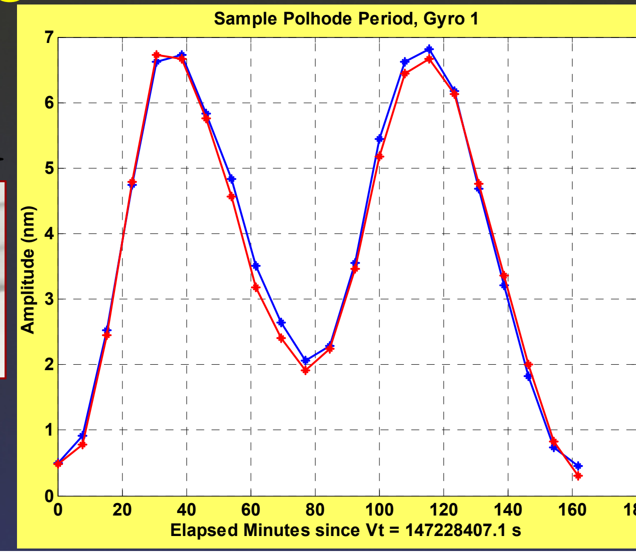
Drag-free eliminates mass-unbalance torque -- and key to understanding/quantification of other support torques

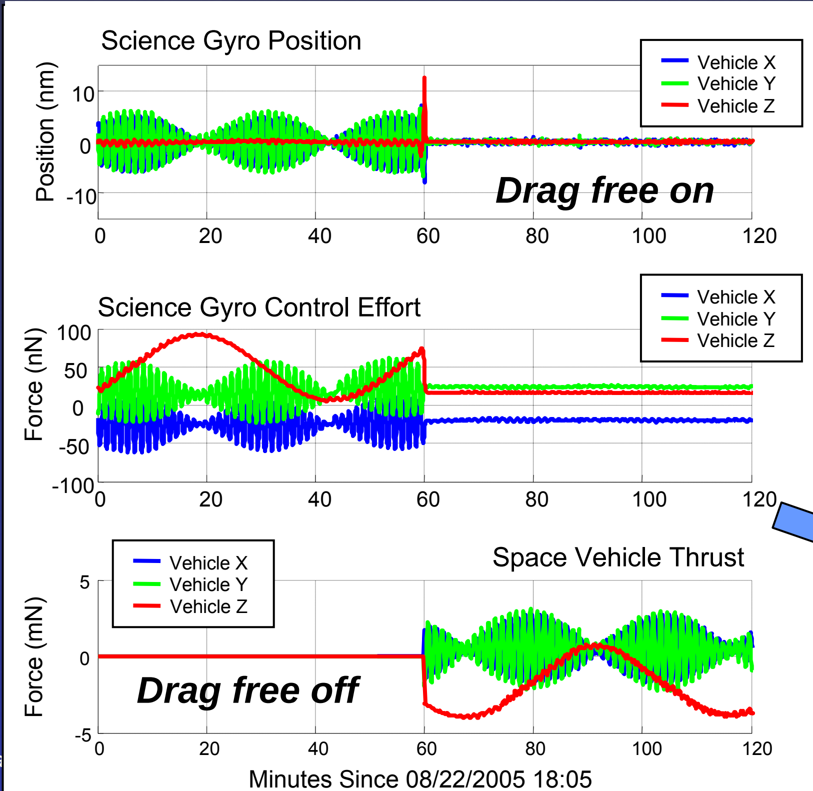
Mass Unbalance & Drag Free
On-orbit Results

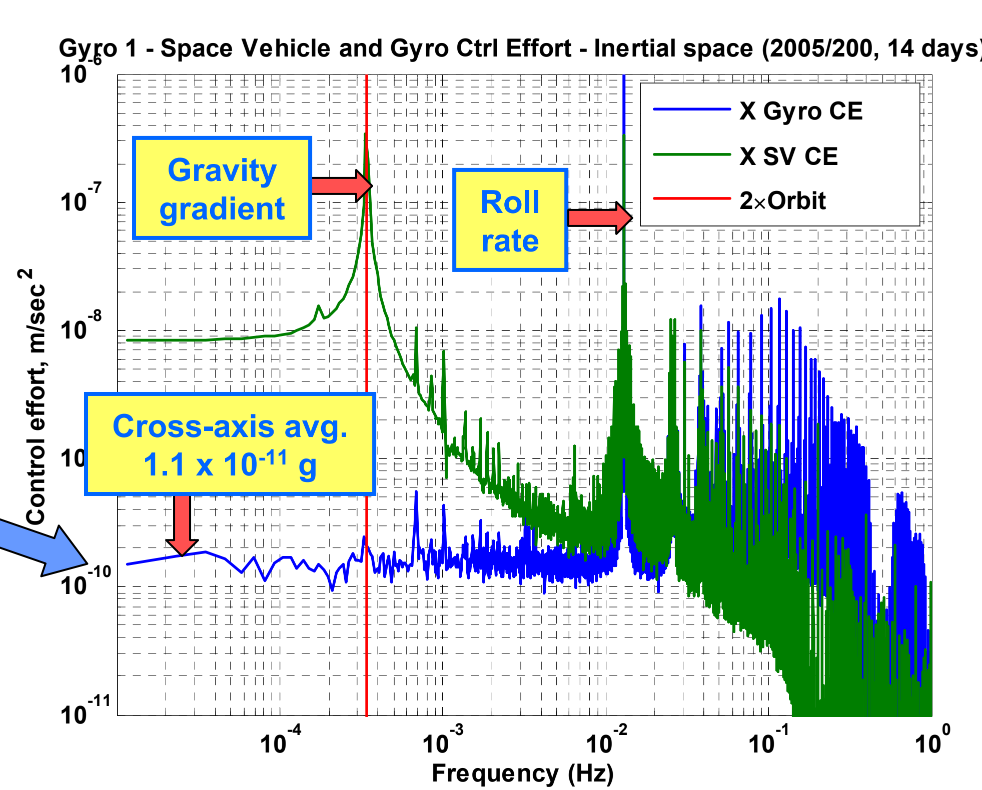
Rotor Mass Unbalance < 10 nm for all gyros

Drag Free (cross-track 10^{-11} g)

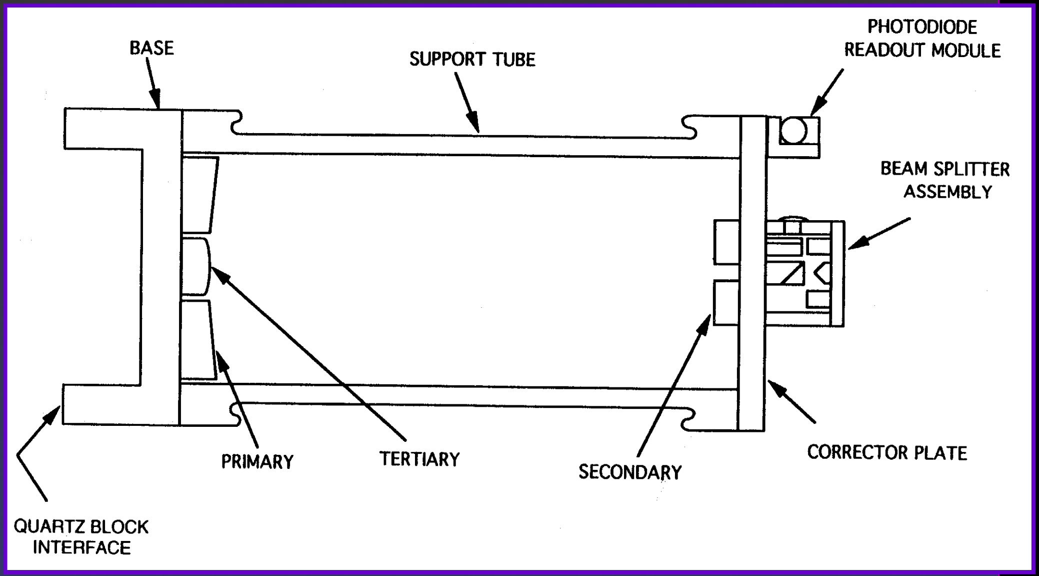


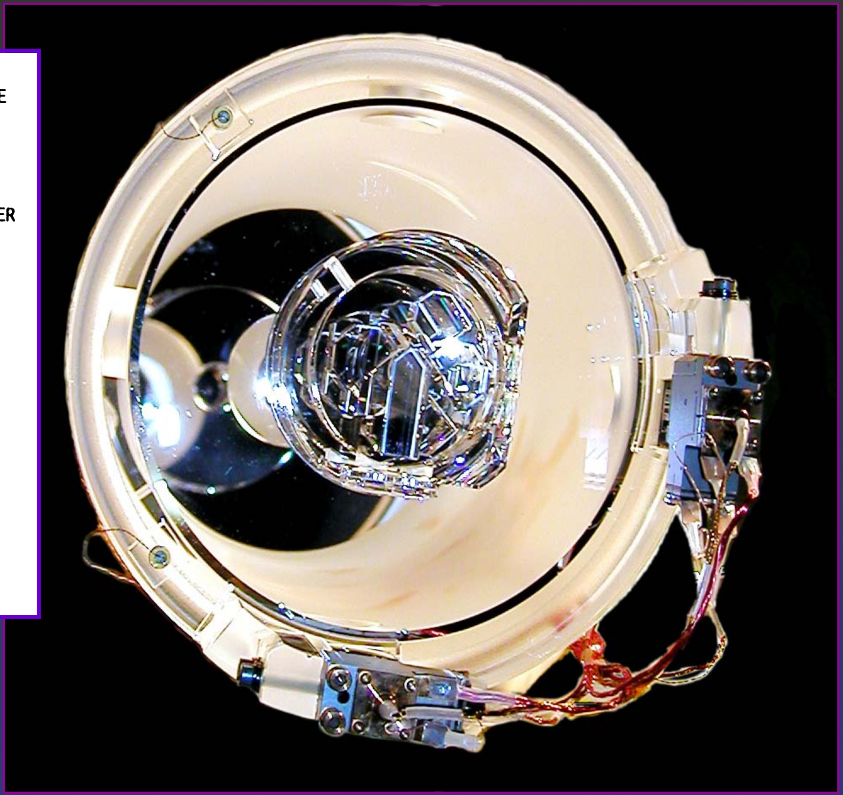


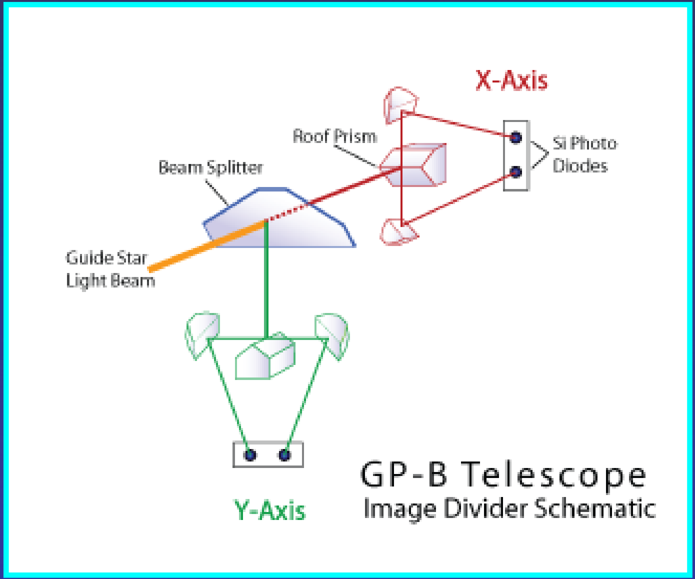


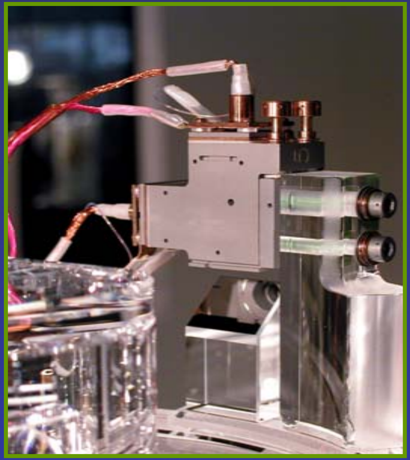


Challenge 2: Sub-milliarc-s Star Tracker





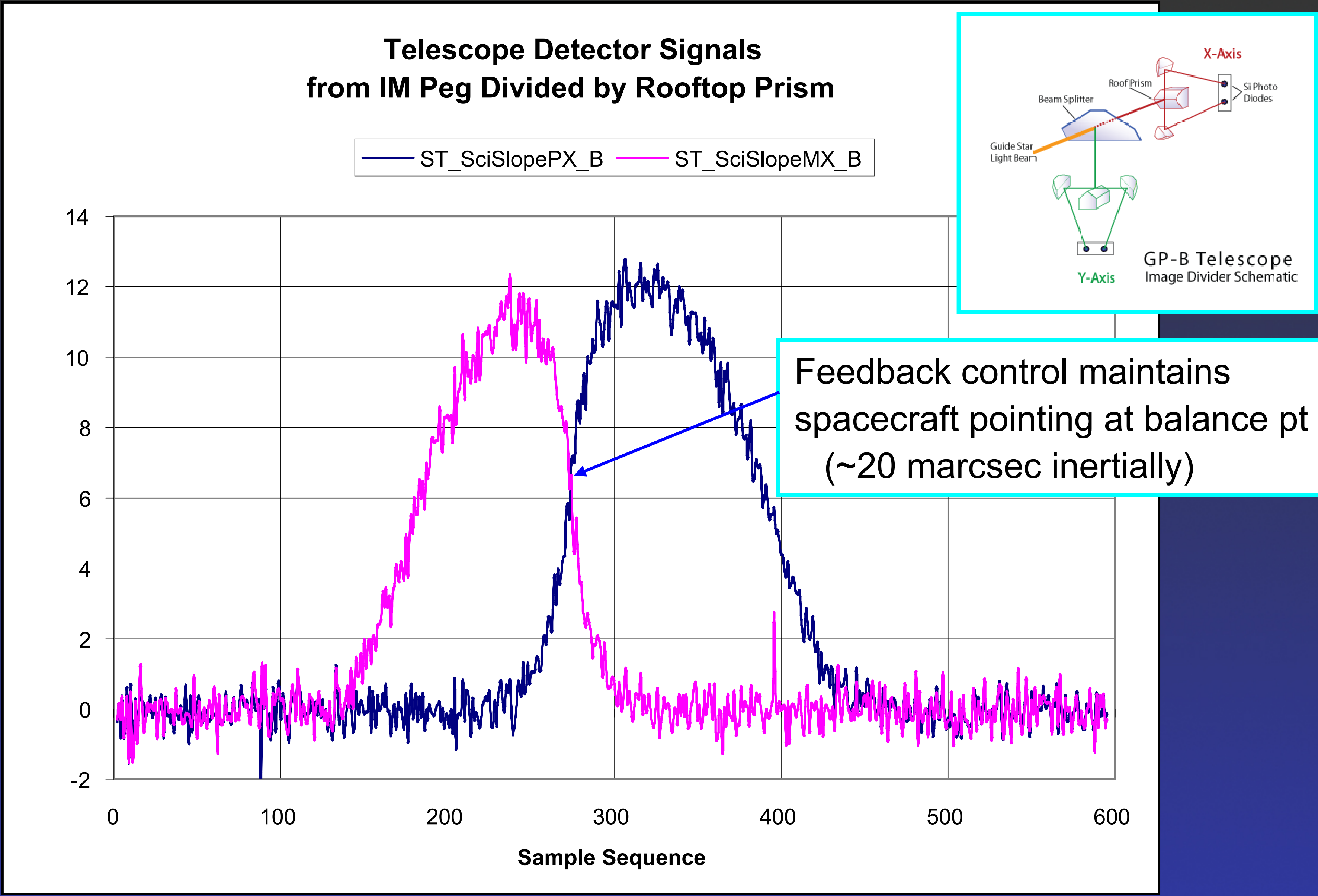




Detector Package

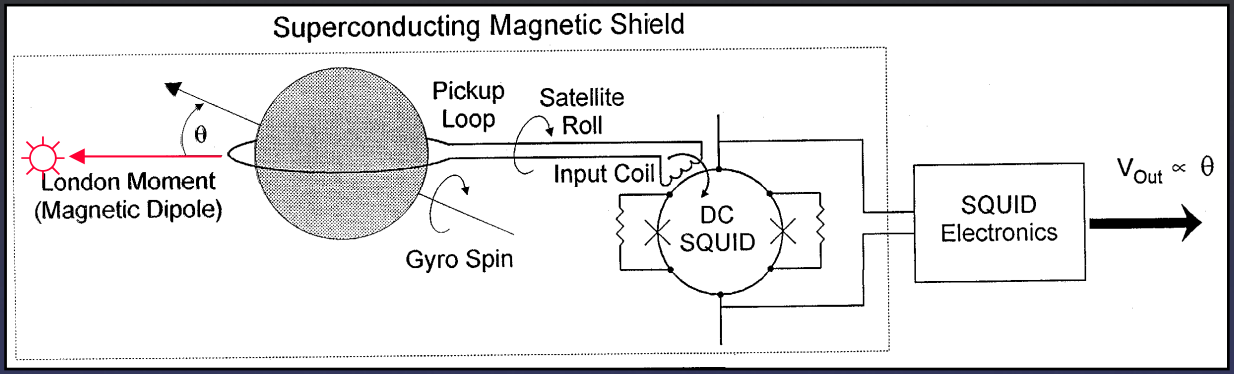
Dual Si Diode Detector

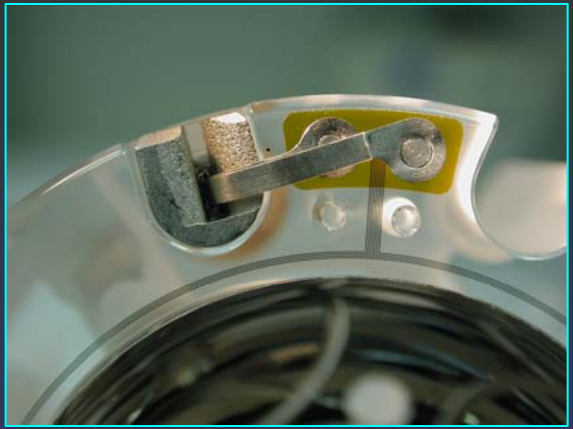
Star Tracking Telescope: On-Orbit



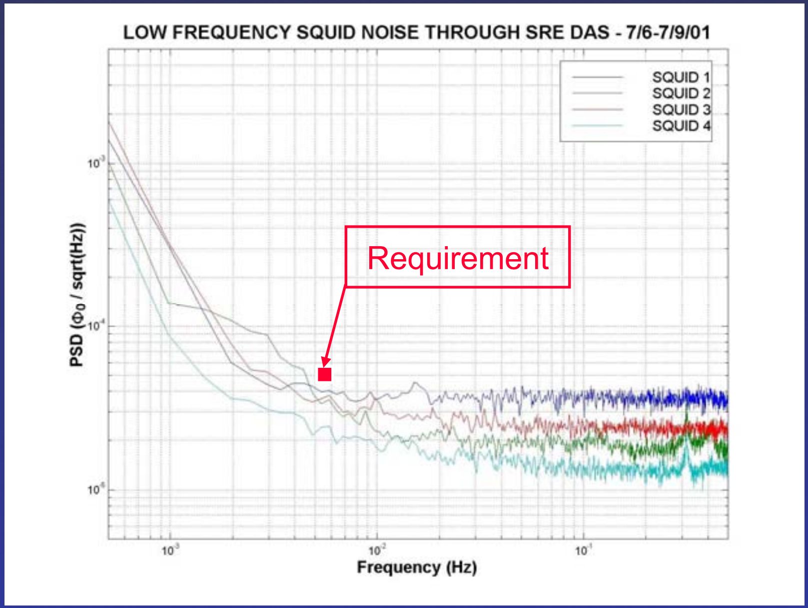
Feedback control maintains spacecraft pointing at balance pt (~20 marcsec inertially)

Challenge 3: Gyro Readout





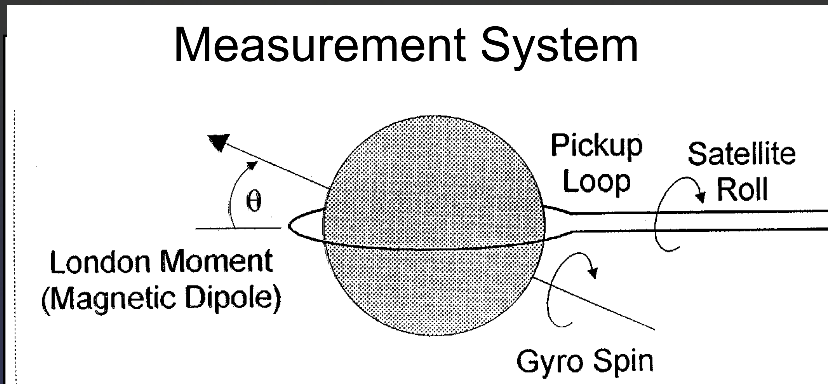
"SQUID" ⟶ 1 marc-s in 5 hours

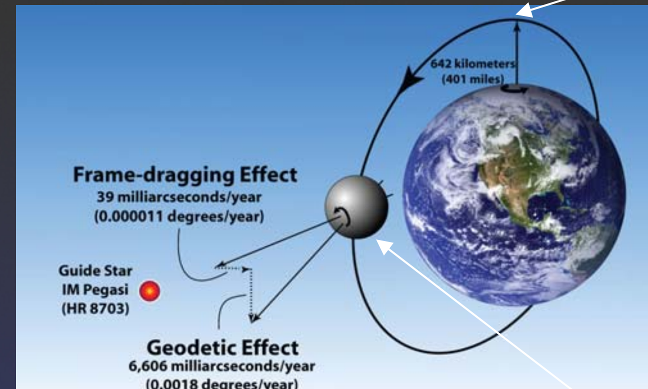


4 Requirements/Goals

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

Challenge 3: Gyro Readout Calibration

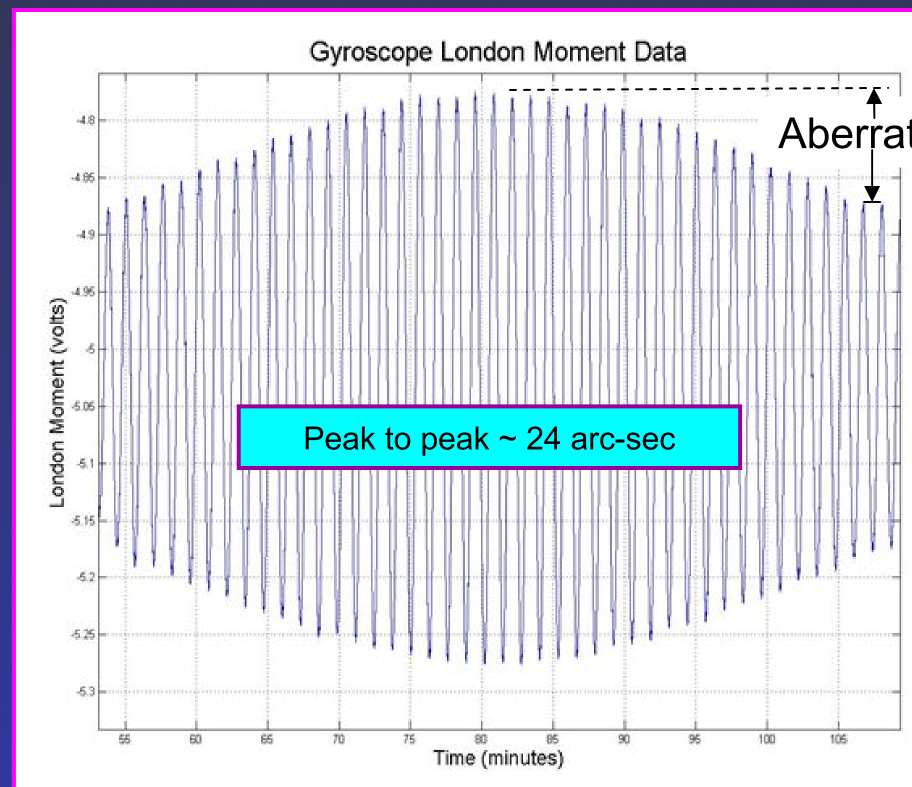




Aberration: A Natural Calibration

Orbital motion ⇒ varying apparent position of star
Cause: transverse velocity of telescope to starlight
(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



Challenge 4: Gyro-Telescope Matching

How do we subtract imperfect telescope pointing from the gyro signal?

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

scale factors matched for accurate subtraction

Scale factor matching allows G-T subtraction to < 1 marcsec

Actualities of GP-B

Good

- **gyroscopes**
  - *10^5 times better than best inertial navigation gyroscopes*
  - *SQUID noise < expected*
  - *Trapped magnetic flux meets spec*
  - *excellent charge control & centering stability*
  - *τ's ~ 7200 to 26,100 years*
- **telescope**
  - *superb overall performance*
- **dewar**
  - *beats design hold time*
- **orbit within 100 m of ideal**

Less than ideal

- *polhode rate variation*
- *misalignment torque*
- *resonance torque*

- *segmented data*
- *interference from ECU*
- *out-of-spec pointing*

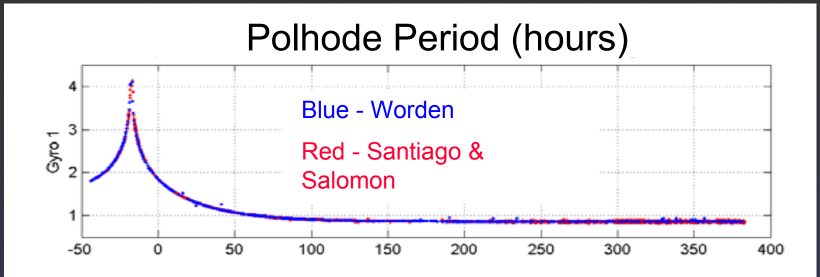
New Challenge

Systematics & data grading

Challenge 5: Data Analysis Subtleties

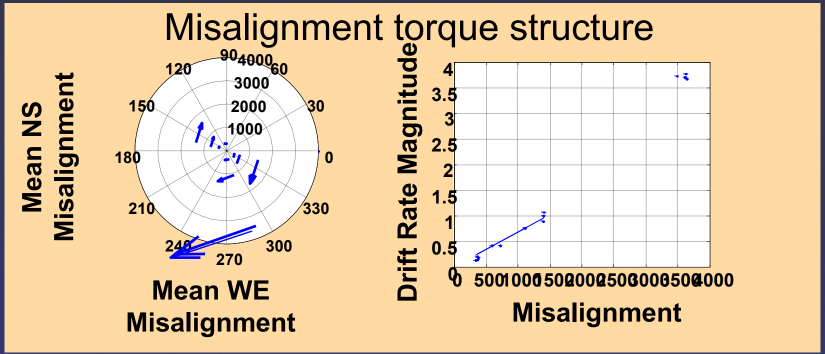
A. Polhode rate variations affect scale factor (C_g) determinations

- Discovered in early science phase
- Alex Silbergleit talk July 1



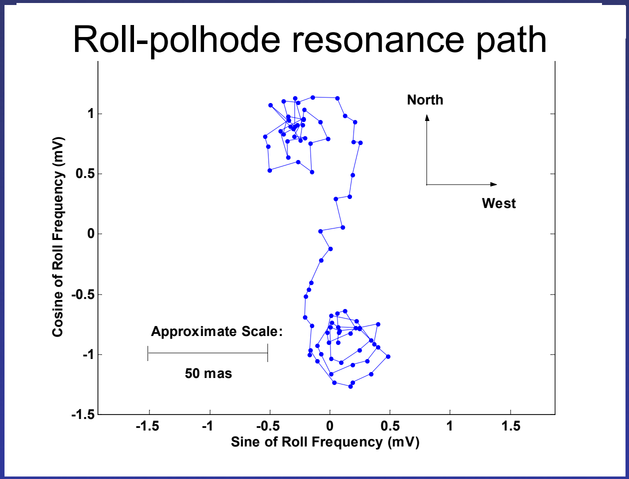
B. Misalignment torques

- Discovered in post-science calibration phase
- Mac Keiser talk next week



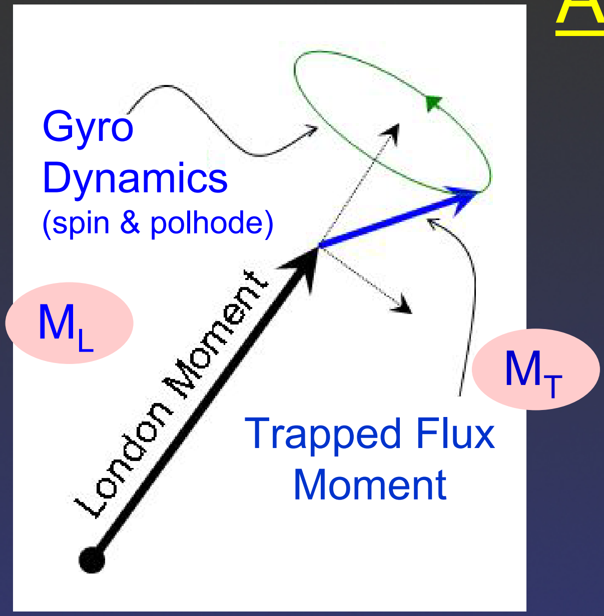
C. Roll-polhode resonance torques

- Discovered during data reduction phase
- Mac Keiser talk next week



All due to one physical cause (patch effect)

Evolving Polhode Impact on Actual London Moment Readout



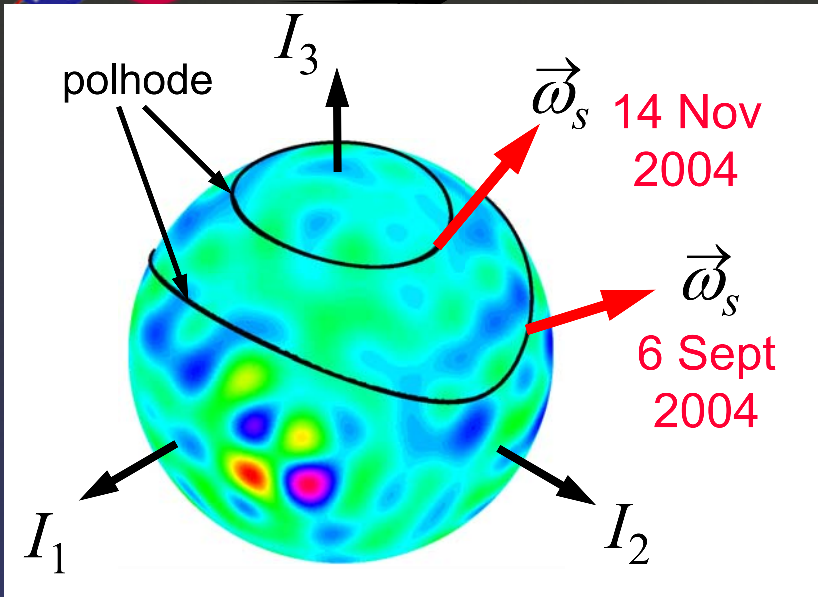
London field at 80 Hz: 57.2 μG

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

Trapped flux contributes to readout scale factor

- Expected prior to launch
- Adds to London Moment scale factor
- Trapped flux scale factor modulated by body dynamics (polhode)
- Evolving polhode prevents averaging or other simple analysis technique

Trapped Flux Mapping: C_g Determination



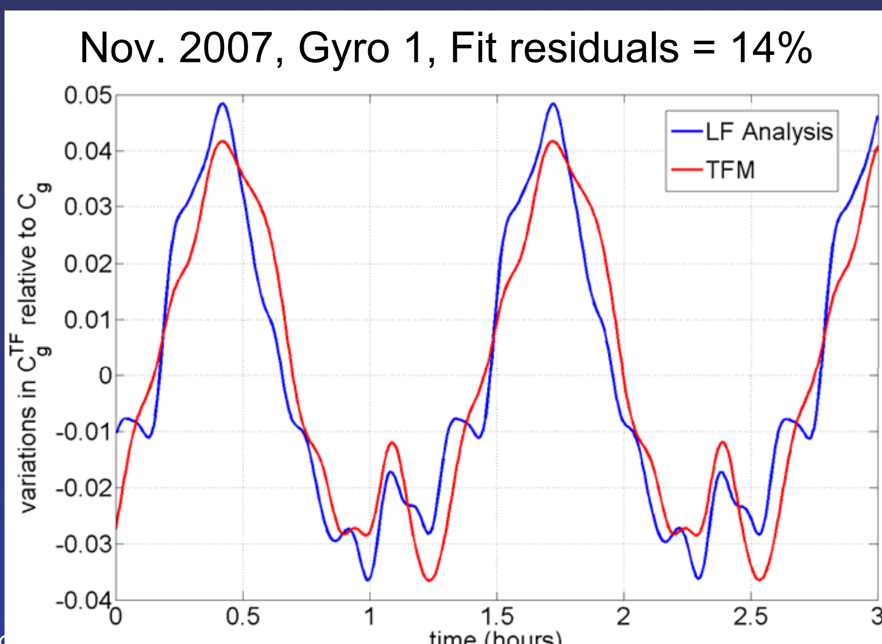
TFM determines evolving polhode phase to 1° over the full mission

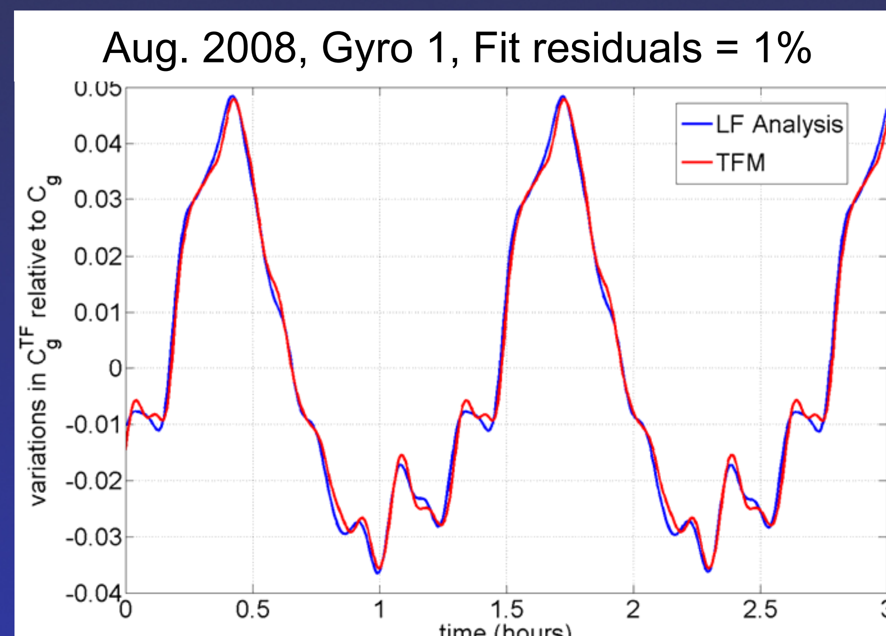
- ⇒ Fully resolves gyro scale factor
- ⇒ Crucial input for torque analysis

Alex Silbergleit

John Conklin
(Ballhaus AA award)

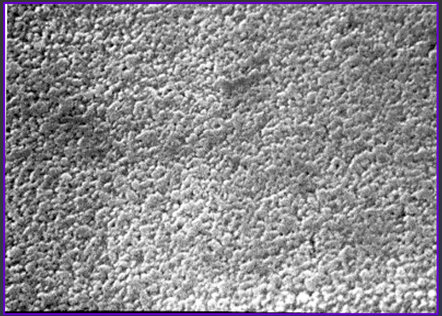
Mac Keiser





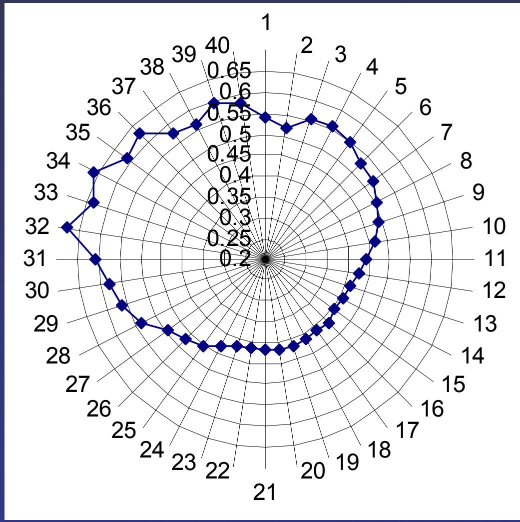
The GPB 'Patch Effect' History

- ## Pre-launch investigation
  - Rotor electric dipole moment + field gradient in housing
  - 100 mV contact potentials mitigated by minute grain size, 0.1 μm << 30 μm rotor-electrode gap
  - Kelvin probe measurements on flat samples



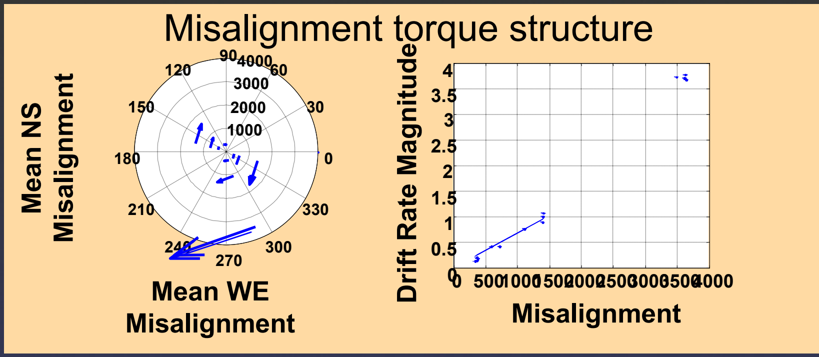
SEM image of rotor Nb film average grain size 0.1 μm

- ## On-orbit discoveries (Sasha Buchman talk next week)
  - ***Polhode damping*** (July 2004)
  - ***Drag-free z acceleration*** (Sept. 2004)
  - ***Spin down rate > gas damping*** (Feb. 2005)
  - ***Misalignment torques*** (Aug. 2005)
  - ***Roll-polhode resonance torques*** (Jan. 2007)
- ## Post-launch ground-based investigations
  - Work function profile via UV photoemission
  - Detailed analytical modeling

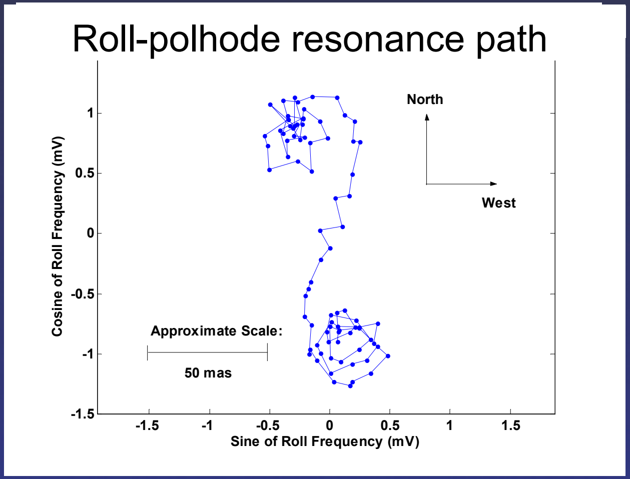


Work function polar plot

Origin of Misalignment & Resonance Torque



1. Expand rotor & housing potentials
   - Using spherical harmonics
2. Derive stored energy
   - Laplace's equation
   - Between rotor & housing
3. Find torque: Derivative of the energy
   - WRT angles defining the spin orientation
   - Spin average



→ Roll ave. torque proportional & perpendicular to misalignment

→ Non roll averaged torque when polhode harmonic = roll freq.

These torques follow directly from randomly distributed patch potentials

Treating Misalignment Torque

The 2 Methods

Algebraic: Filtering machinery to explicitly model torques

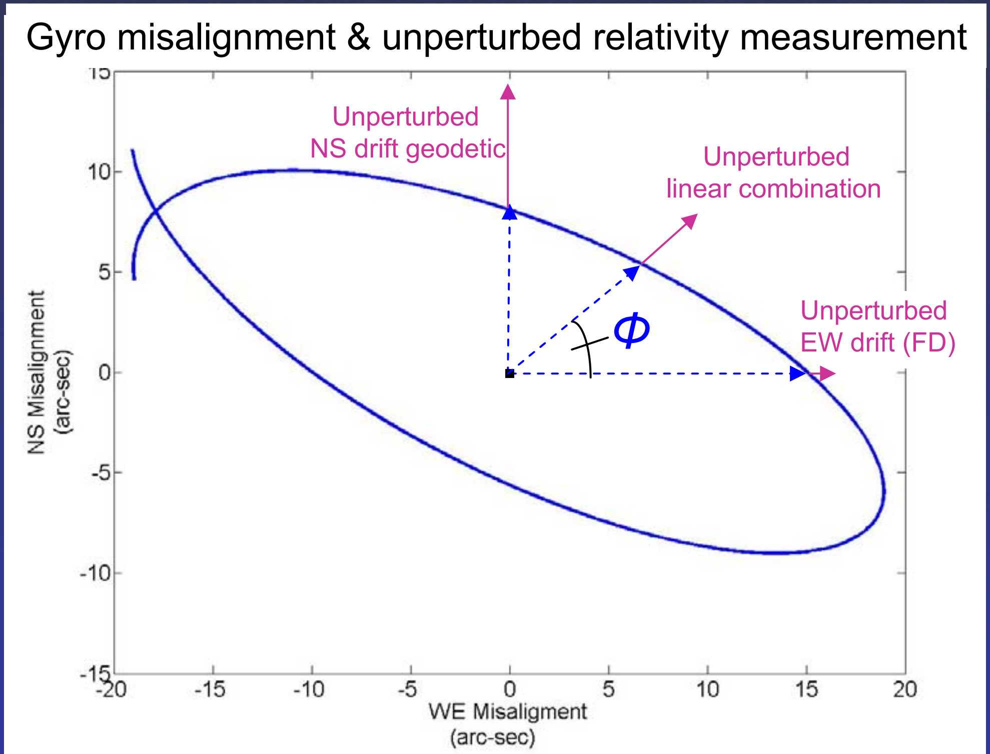
→ provides separation from relativity

Geometric: Plot rates against misalignment phase Φ

→ component of relativity free of misalignment torques

A Geometrical Insight

- Drift rate free of torque parallel to misalignment
- Annual aberration alters torque direction
  - Over time provides geodetic & FD measurement
- A truly *physical* modeling process

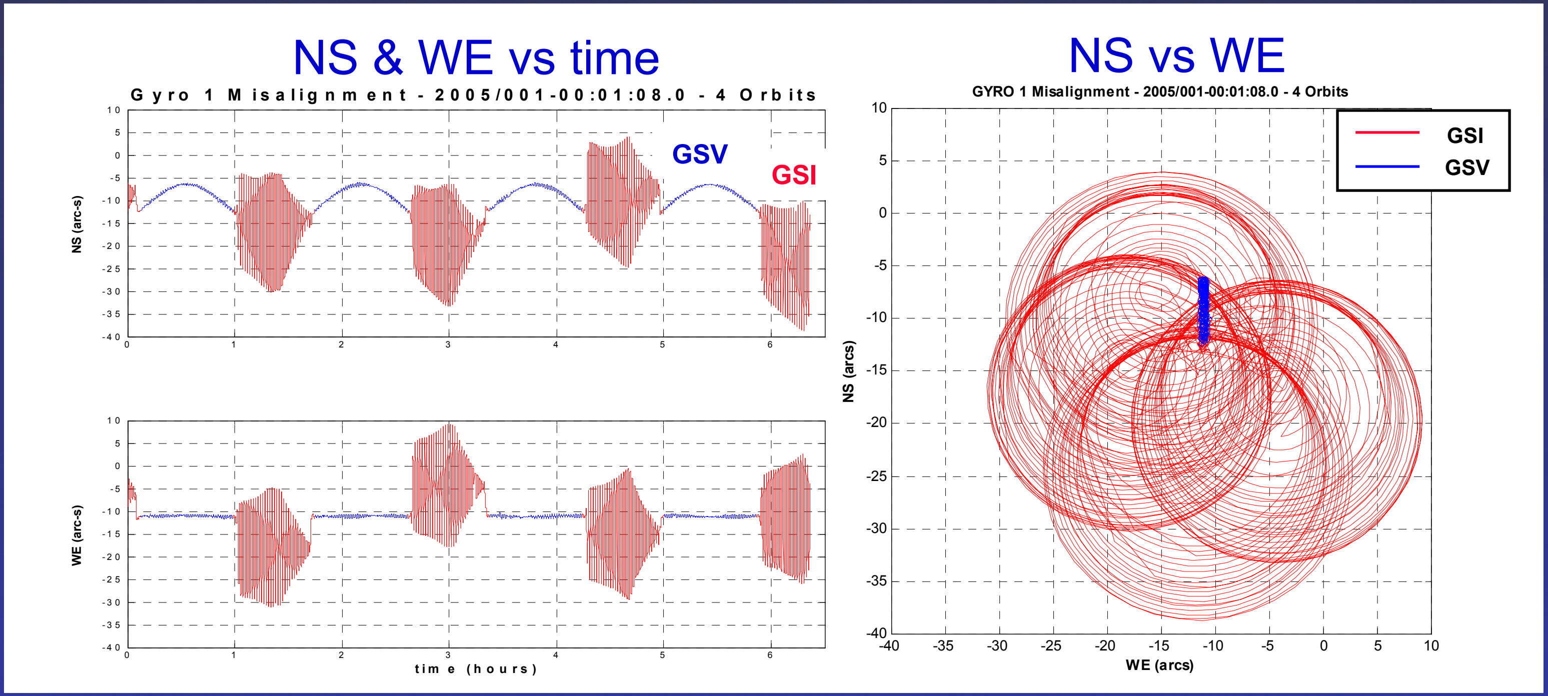


Mac Keiser

Obtaining Continuous Misalignment History

- Required to remove effect of misalignment torque
- Science gyroscopes provide precision misalignment information when guide star occulted

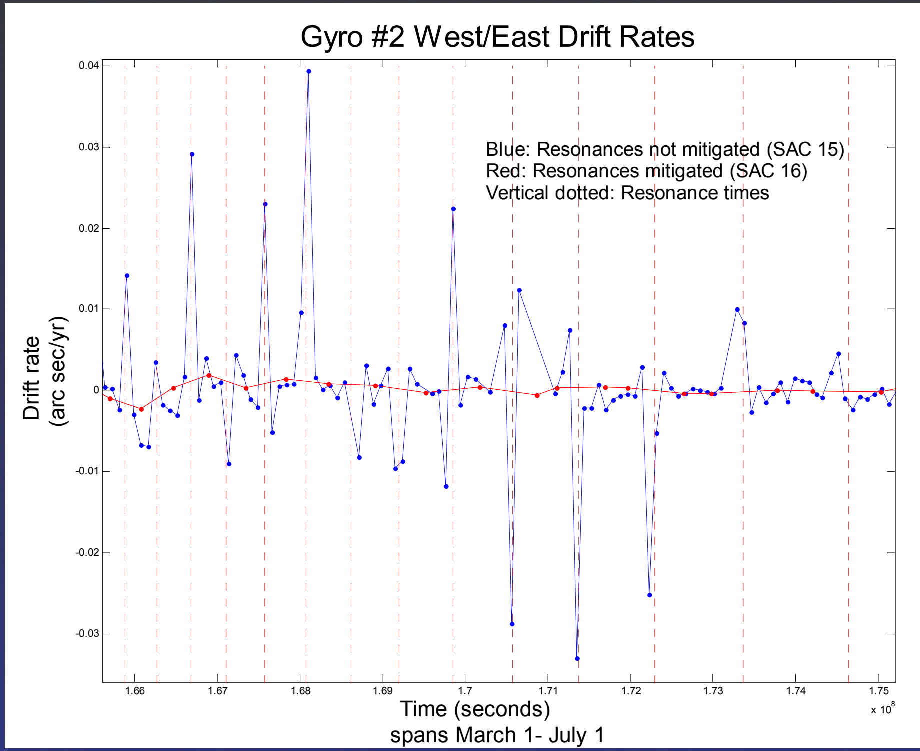
Continuous Guide-Star Valid / Guide-Star Invalid misalignment history



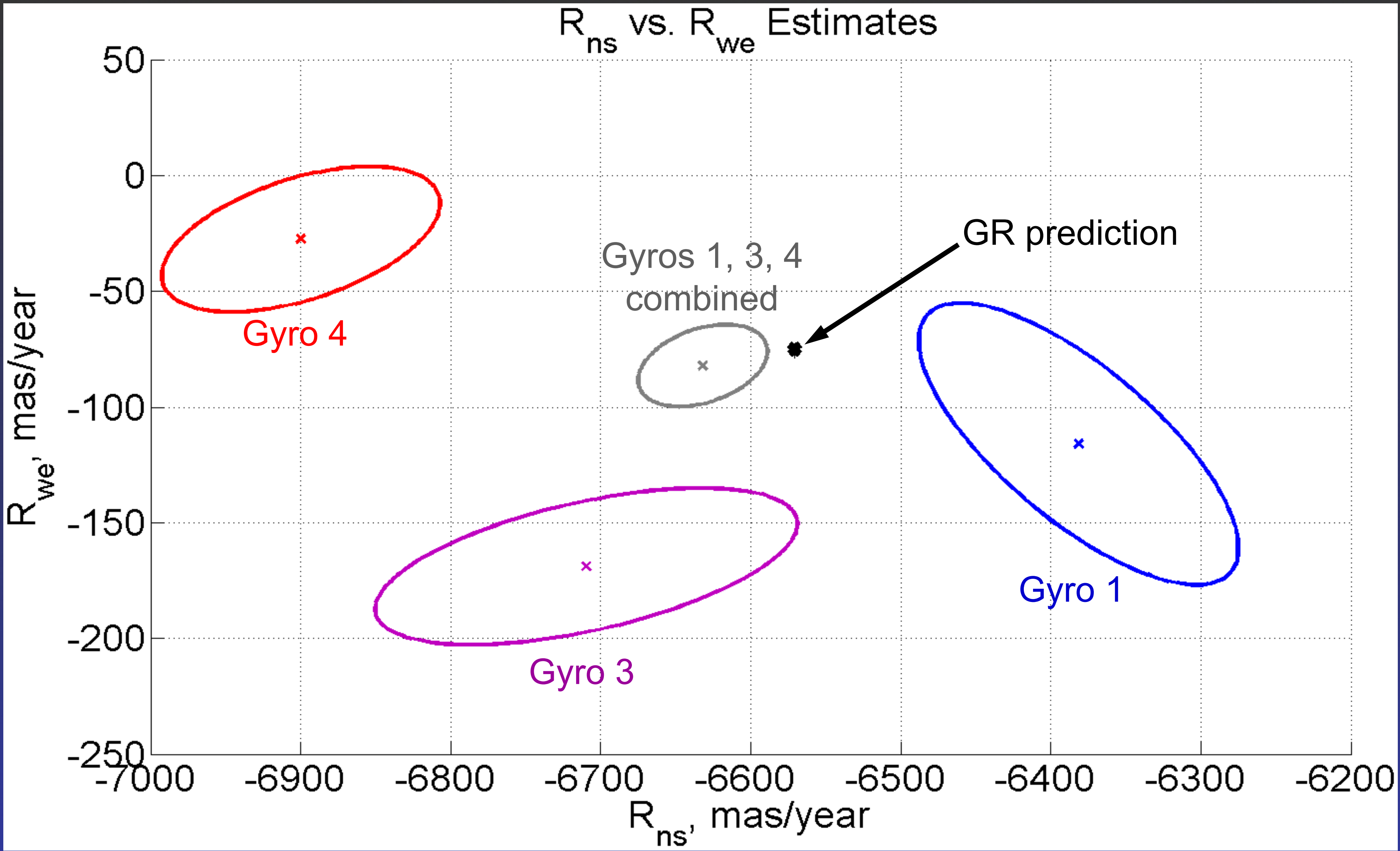
Early Methods for treating Resonance Torque

1. Excise data during resonances
   - Blue curve shows large drift during resonances
   - Red curve eliminates spikes by excising data

2. Model drift during resonances
   - A unique drift rate during each
   - A separate drift rate elsewhere

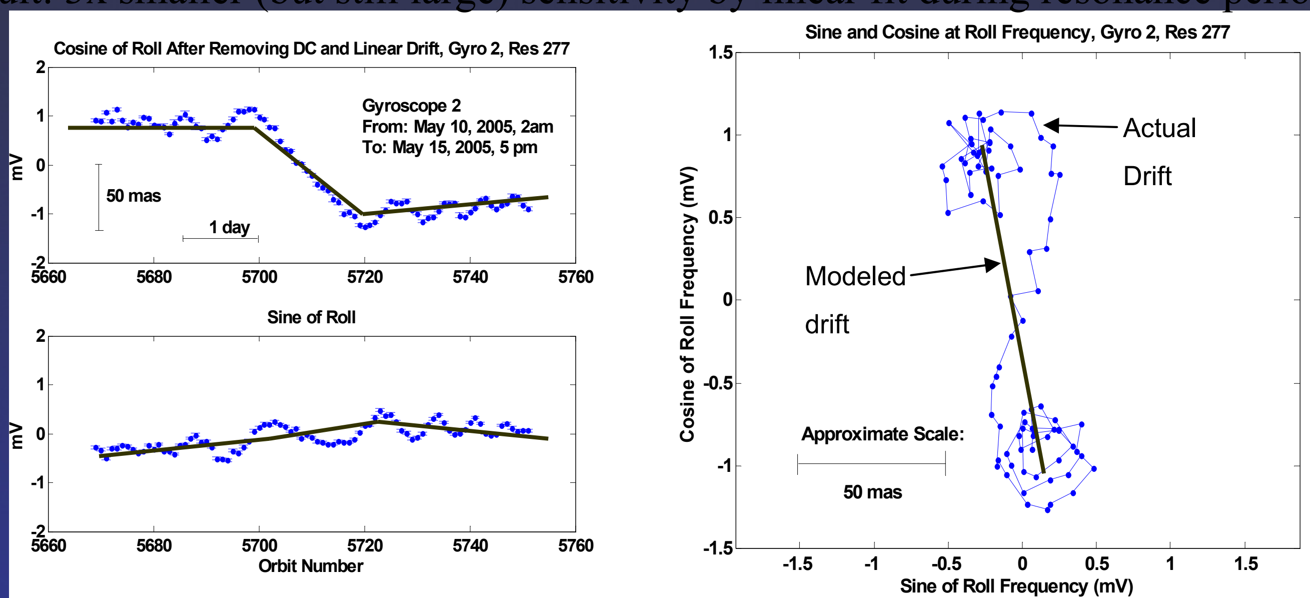


Early Results [Nov '07]



Resonance Torque Modeling Limitations

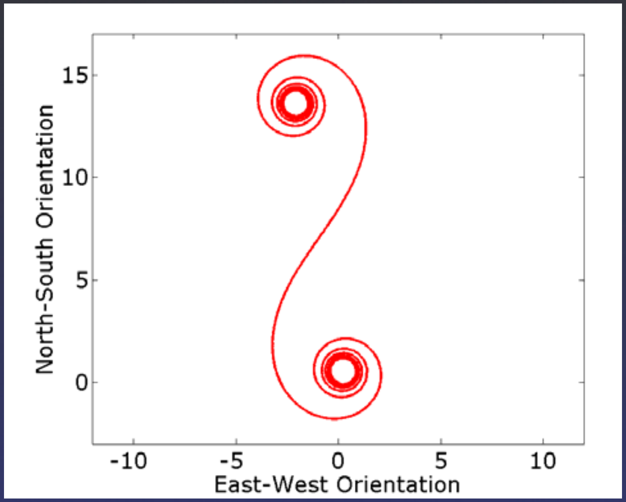
- **Issue: High sensitivity for resonance torque modeling (2007)**
  - Leading term in experiment error (relativity rate scatter)
    - ➢ First result based upon excluding data within resonance periods
    - ➢ Second result: 3x smaller (but still large) sensitivity by linear fit during resonance periods



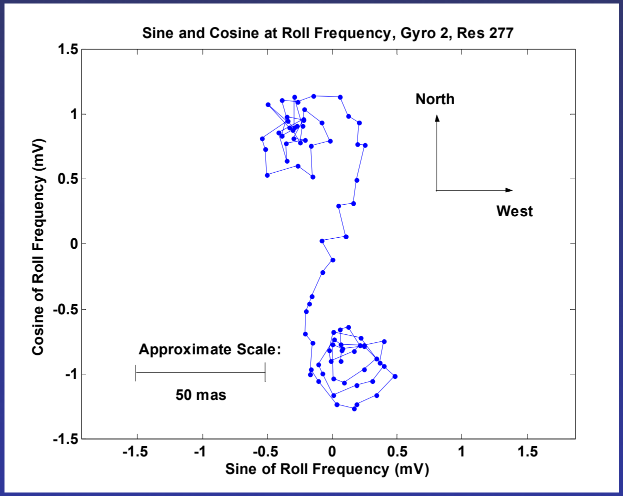
Next step: Once per orbit model improves sensitivity & experiment error

Improved Resonance Torque Modeling

- 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

The Science Equations [Aug 2008]

- Add resonance torque model to equations of motion
  - Follows directly from randomly distributed patch potentials

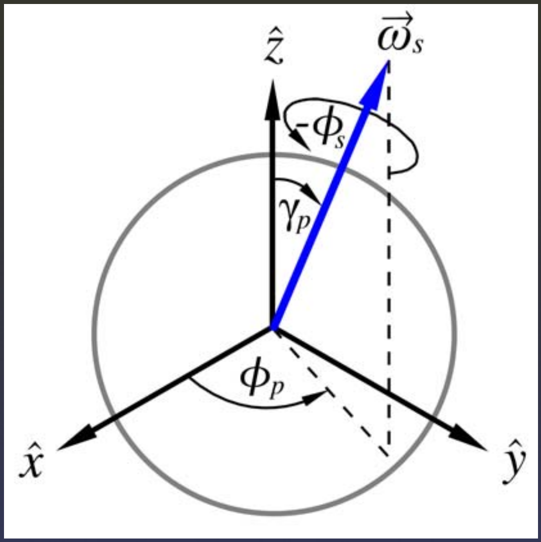
$$\frac{ds_{NS}}{dt} = r_{NS} + k(t)\mu_{EW} + \sum A_m(t)\cos\Delta\phi_m - B_m(t)\sin\Delta\phi_m$$
$$\frac{ds_{EW}}{dt} = r_{EW} - k(t)\mu_{NS} + \sum A_m(t)\sin\Delta\phi_m + B_m(t)\cos\Delta\phi_m$$

Relativity — Misalignment torque — Resonance torque

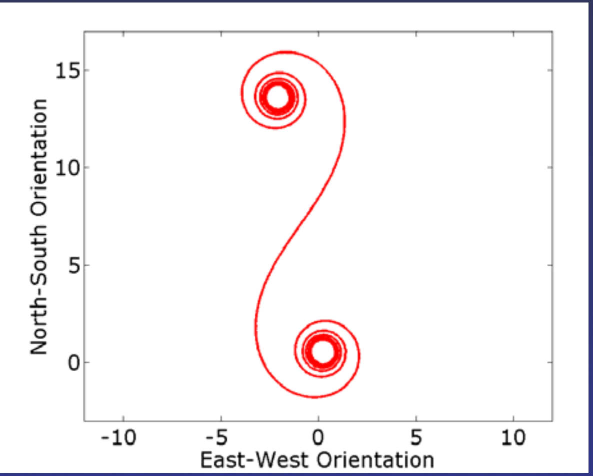
- Resonance condition → $\Delta\phi_m = \phi_{\mathrm{roll}} - m\phi_p$

→ Treatment of roll-polhode term hinges on TFM

Resonance Torque Modeling Implementation



- Torque coefficients tied to gyro body
- TFM provides accurate body dynamics profile
  - γ_p ϕ_p (in addition to readout scale factor)
  - TFM: body fixed trapped flux as marker

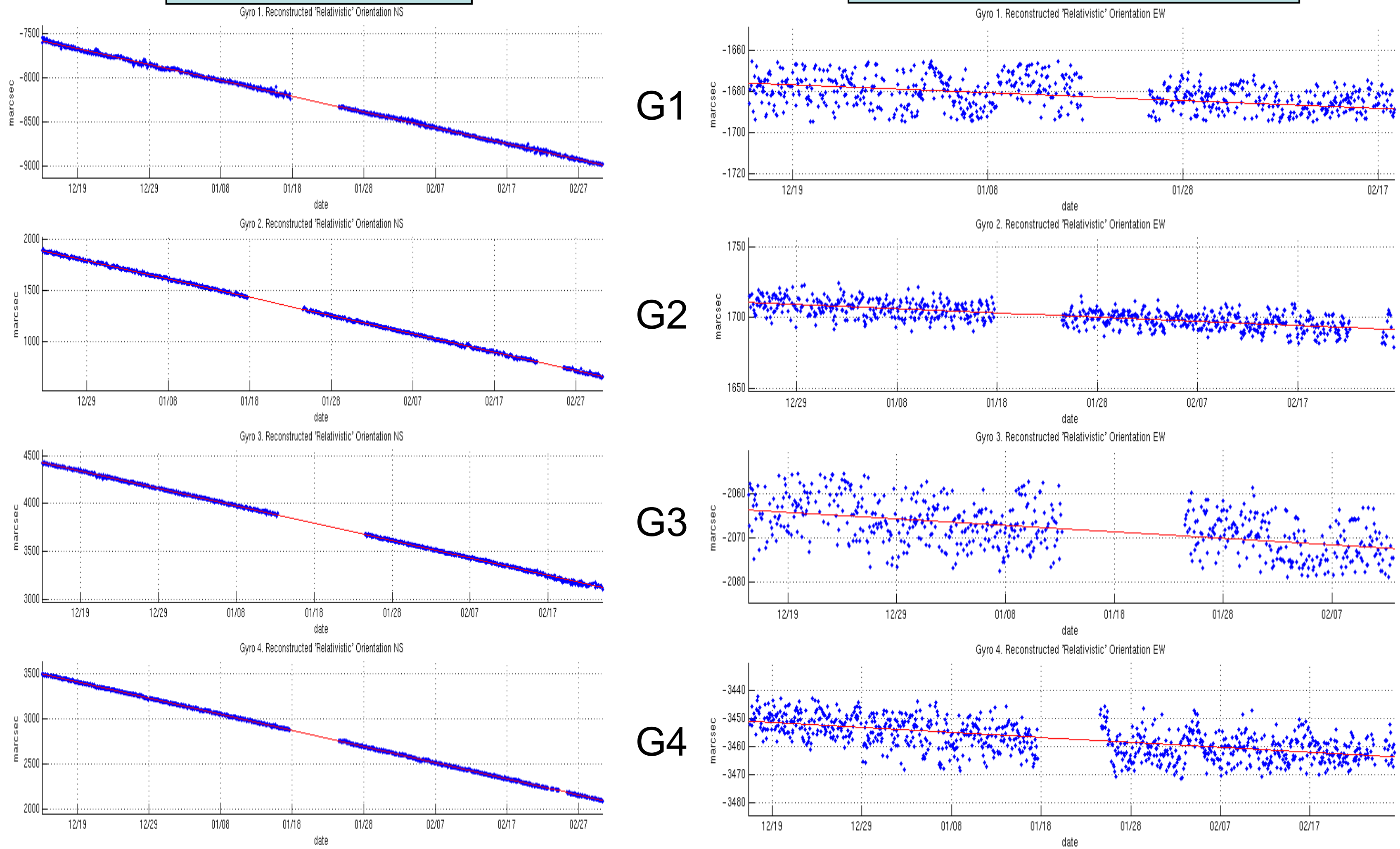


- Torque model uses TFM polhode
- Requires accuracy for tracking high order polhode harmonics

Body dynamics determined from TFM is KEY

Full Model Results as of Dec '08

N-S (Geodetic) | E-W (Frame-dragging)

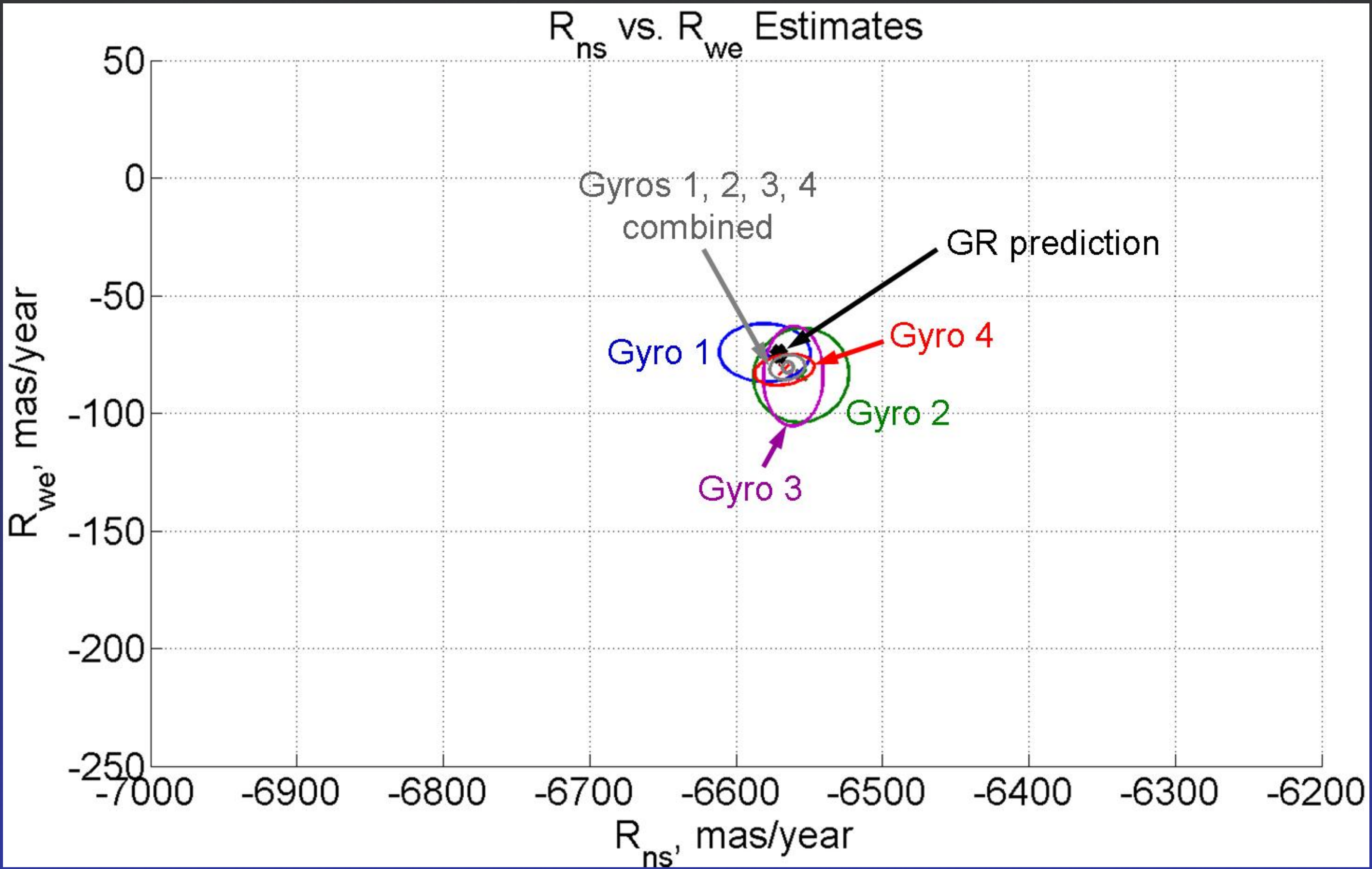


(note: different y-axis scale for N-S vs. E-W)

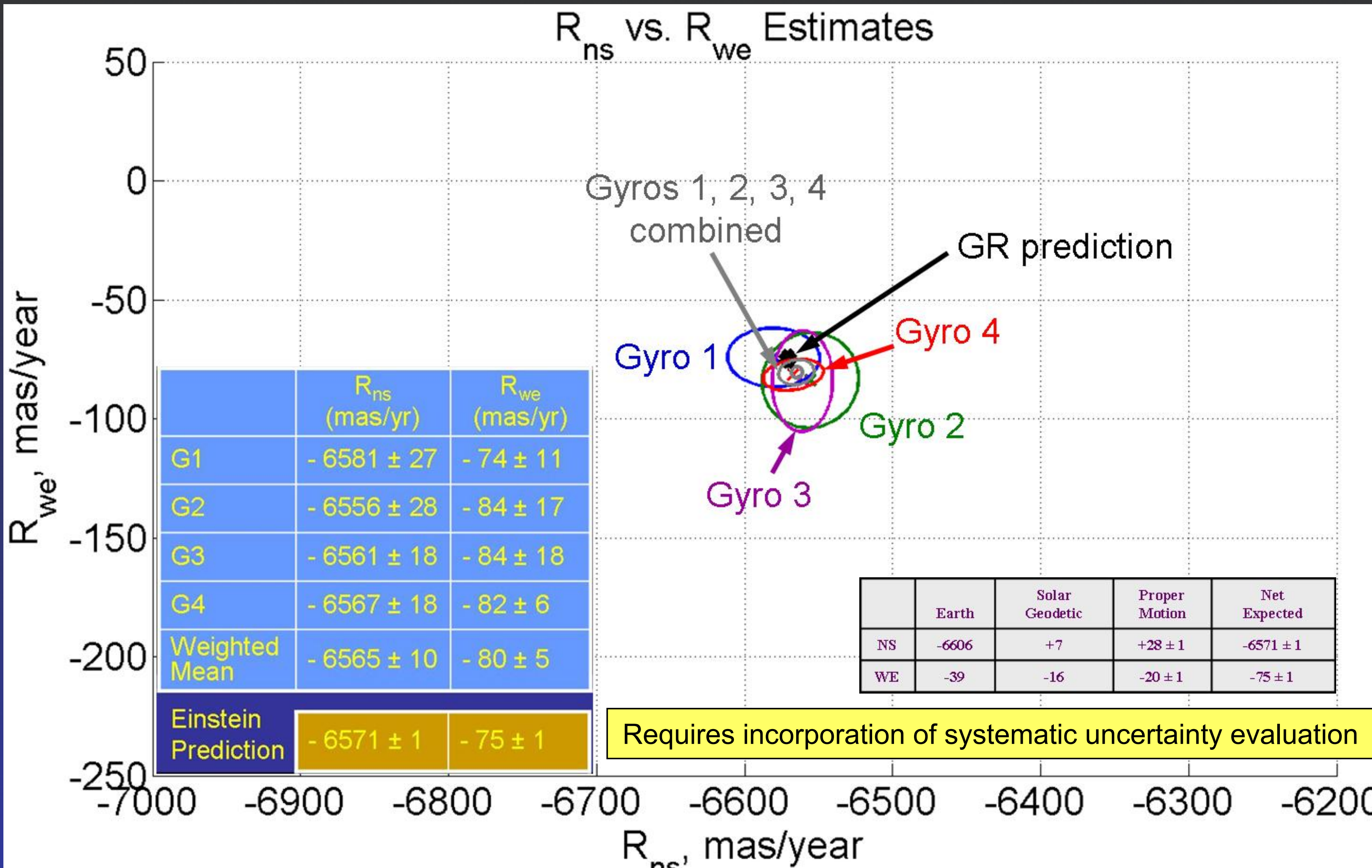
Geodetic1-4

ragging

Full Model Results as of Dec ’08



Full Model Results as of Dec ’08 - II



	R_{ns} (mas/yr)	R_{we} (mas/yr)
G1	- 6581 ± 27	- 74 ± 11
G2	- 6556 ± 28	- 84 ± 17
G3	- 6561 ± 18	- 84 ± 18
G4	- 6567 ± 18	- 82 ± 6
Weighted Mean	- 6565 ± 10	- 80 ± 5
Einstein Prediction	- 6571 ± 1	- 75 ± 1

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

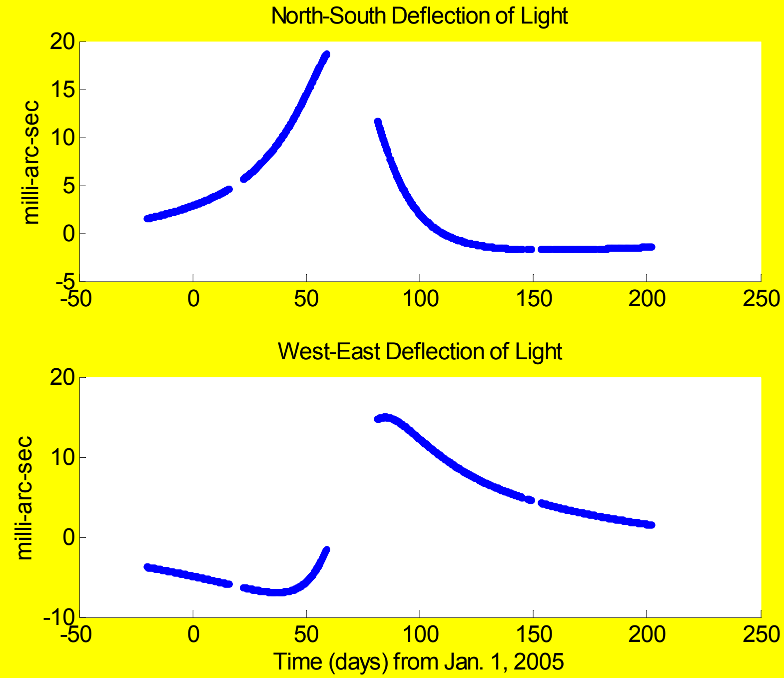
Requires incorporation of systematic uncertainty evaluation

Independent SuperGeometric Results

1 R_{NS} & R_{WE} – Gyro #4

$$R_{NS} = -663 \pm 16\, mas/y$$
$$R_{WE} = -77 \pm 14\, mas/yr$$

2 Gravitational deflection of light



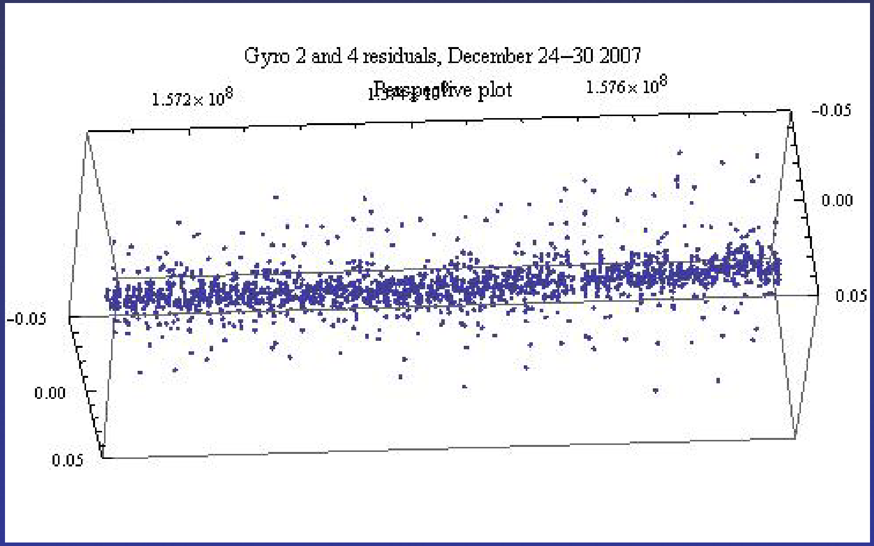
Result to date $\lambda = 1.20 \pm 0.17$

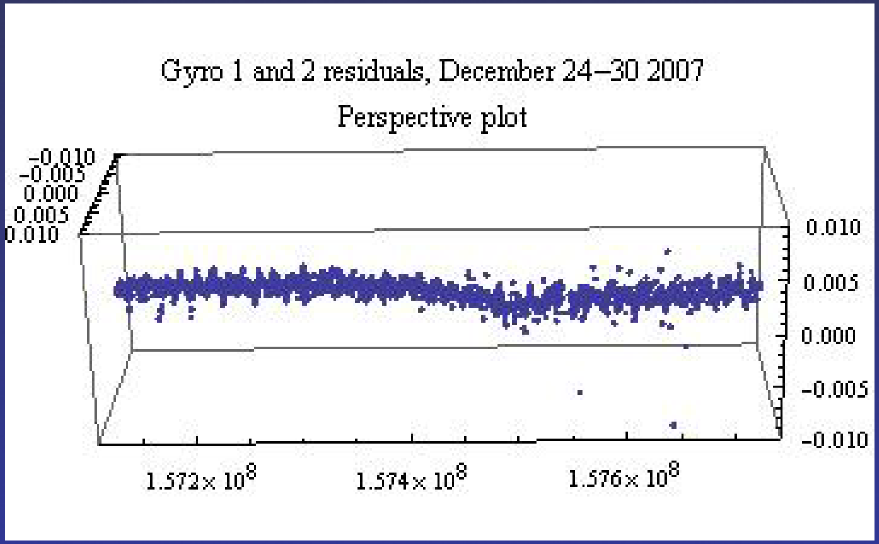
3 24.6487-day guide star orbital motion

$$a_{NS} = -1.65 \pm 0.14 mas \quad b_{NS} = -0.36 \pm 0.14 mas$$
$$a_{WE} = -0.11 \pm 0.12 mas \quad b_{WE} = -0.61 \pm 0.13 mas$$

Advanced Investigations of Systematics

- Improved science modeling
  - Exact treatment of readout nonlinearities
  - Thermal correlations
  - 2-sec processing
- Detailed gyro-to-gyro comparisons





Are we done?

- **Current '2 floor' 4-gyro result ~ 5 marcs/yr (statistical uncertainty)**
  - limited by ⟶ { once-per-orbit time step; 3 out of 10 segments (158 days vs. 333 days)

- **Fundamental & operational limits**
  - SQUID noise 0.14 – 0.35 marcs/yr (gyro dependent)
  - Covariance ~ 1-2 marcs/yr (4 gyros combined)

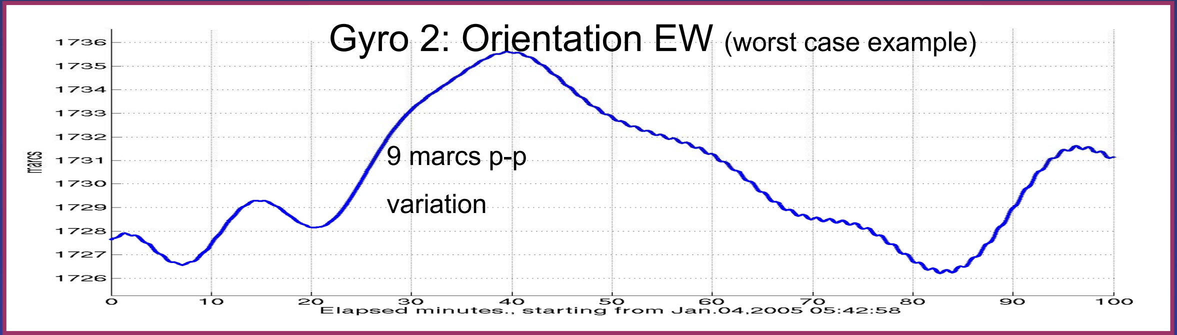
$$\frac{ds_{NS}}{dt} = r_{NS} + k(t)\mu_{EW} + \sum A_m(t)\cos\Delta\phi_m - B_m(t)\sin\Delta\phi_m$$

$$\frac{ds_{EW}}{dt} = r_{EW} - k(t)\mu_{NS} + \sum A_m(t)\sin\Delta\phi_m + B_m(t)\cos\Delta\phi_m$$

$$\Delta\phi_m = \phi_{\text{roll}} - m\phi_p$$

Note: noiseless trajectory shown. ⟶

Noise must be added for complete evaluation



Accurate integration requires time step << 1 orbit ⟶ *parallel processing*

Advanced (2-sec) Filter Development

Two simultaneous development activities

Co-PI Charbel Farhat

1. Serial processing ⟶ ***accuracy***
   - built on 4-years' experience with 2-floor (once per orbit) filter
   - accurately models the physical phenomena
   - has passed truth test

2. Parallel processing ⟶ ***speed***
   - ~ 10x faster (3 day analysis → overnight)
   - requires computer cluster
   - ~ 10% modified/additional code

Talk by Michael Heifetz July 29

Michael Heifetz

Badr Alsuwaidan

Majid Almeshari

John Conklin

Vladimir Solomonik

Upcoming GPB Talks

• June 24	Sasha Buchman Mac Keiser	Evidence for patch effect Torques & analysis treatment
• July 1	Alex Silbergleit	Trapped flux mapping
• July 29	Michael Heifetz	Data Analysis Past, Journey

Path to Completion

- Serial 2-sec processing (applied to data subset) *Aug '09*
- Complete transition to parallel processing *Oct '09*
- Extension from 5, 6, 9 (applied to full data set) *Dec '09*
- Complete treatment of systematics *Jan '10*
- Blind test against SAO guide star orbital motion *Feb '10*
- Grand synthesis of Geometric & Algebraic results
  ⇨ approach ~ 1-2 marcs/yr 4-gyro limit *Jun '10*

Final results to be announced at Fairbank Workshop on Fundamental Physics & Innovative Engineering in Space *Aug '10*