Effects of Patch Potentials on the GP-B Performance

Results and Lessons Learned

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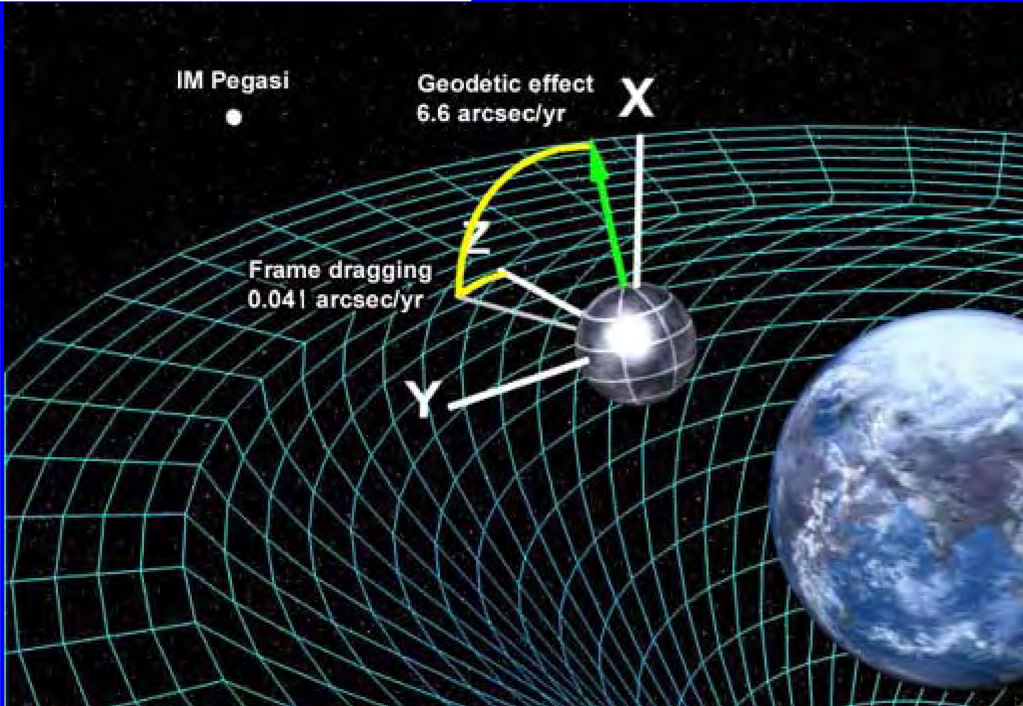
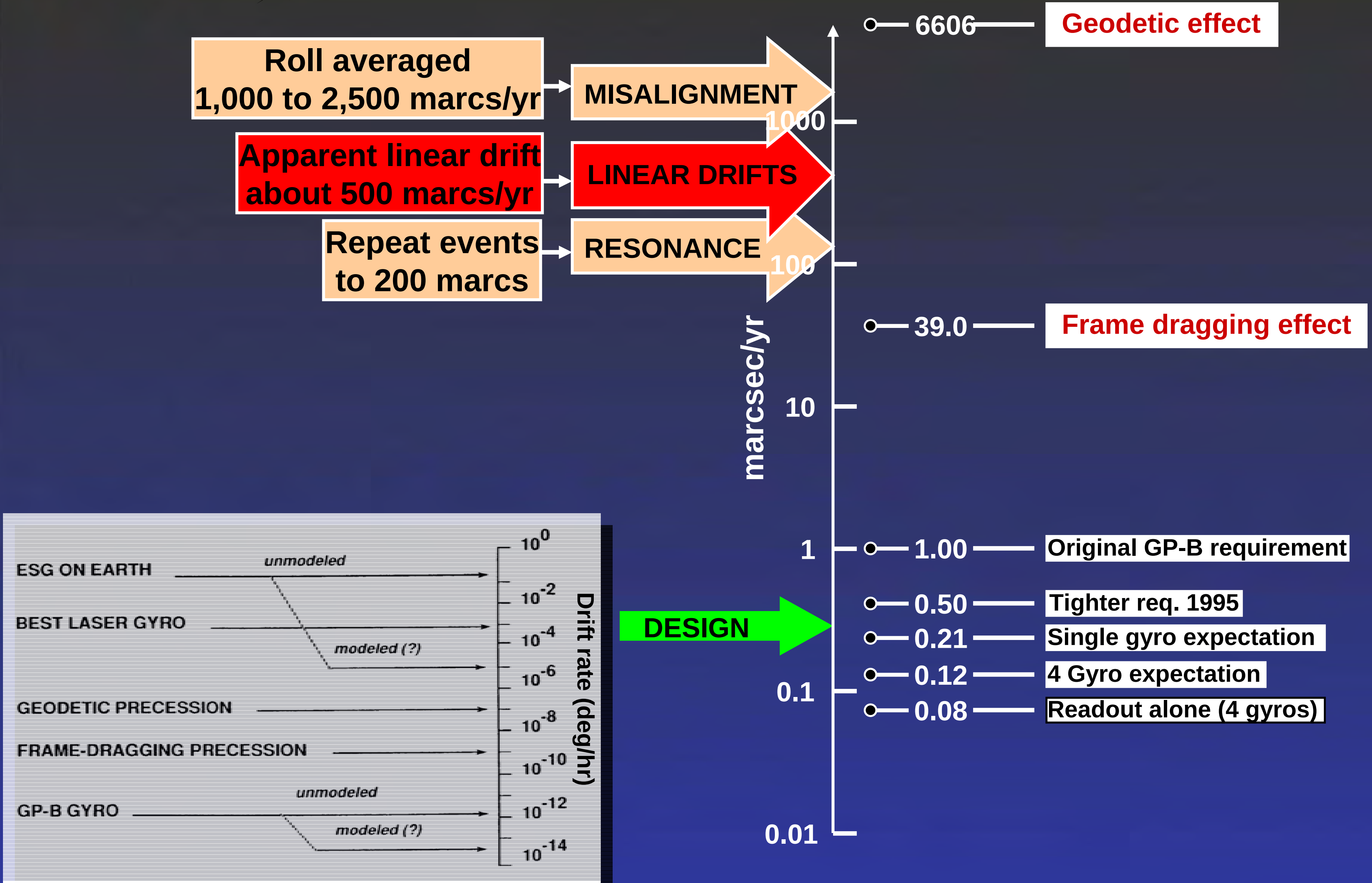


GP-B Performance



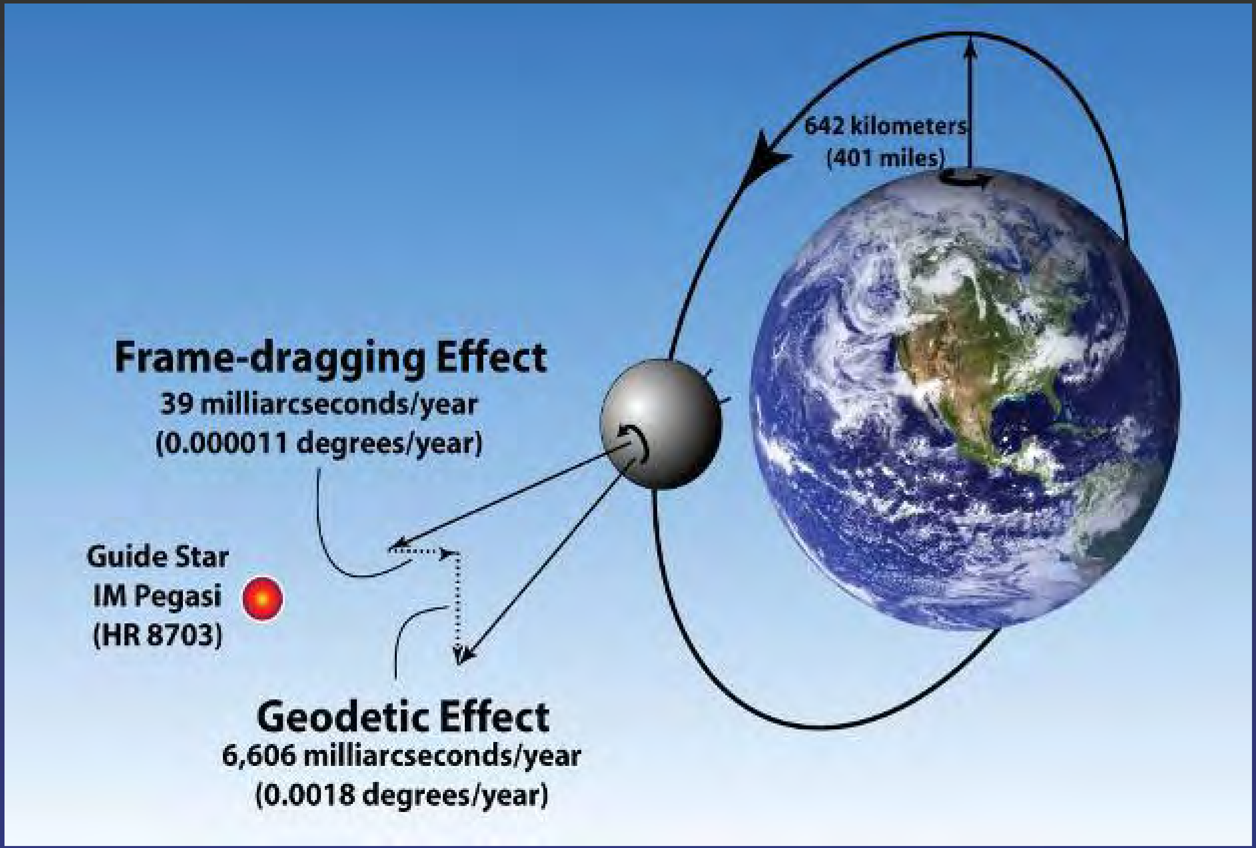
1 marcsec/yr = 3.2 × 10^{-11} deg/hr

Goals and Outline

- Identify and understand “anomalous effects” 👍
- Identify single cause of effects if possible 👍
- Establish physical base for data analysis 👍

- Experimental Observations
- Ground Measurements
- Classification of Effects on GP-B
- Discussion of Effects
- Remaining Work
- Lessons Learned

The Relativity Mission Concept



$$\overline{\Omega} = \left(\gamma + \frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\overline{R}\times\overline{v}\right) + \left(\gamma + 1 + \frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot\left(\overline{\omega}_e\cdot\overline{R}\right) - \overline{\omega}_e\right]$$

$$\frac{d\gamma}{\gamma} = \frac{3}{2}\left(\frac{d\Omega}{\Omega}\right)_{geodetic}$$

$$\frac{d\gamma}{\gamma} = 2.3\times 10^{-4}\left(\frac{\text{marcs}}{\text{yr}}\right)^{-1}$$

Geodetic Effect
Space-time curvature
de Sitter (1916)

Frame Dragging
Rotating matter drags space-time
Pugh and Schiff (1959, 1960)

$\gamma,\ \alpha_1$

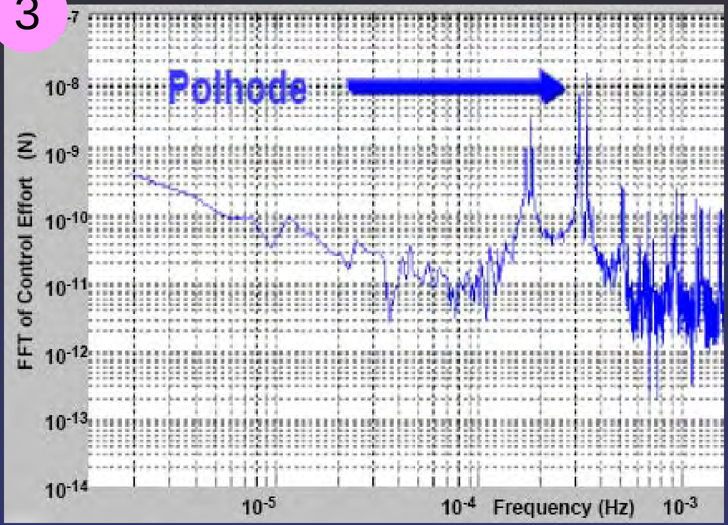
Experimental Observations

Coupling of ***rotor-fixed frame*** to the ***Gyro Suspension System (GSS)***

Modulation at low spin ω_{SL} and polhode ω_P frequency
in the ~ 1.5 Hz GSS band

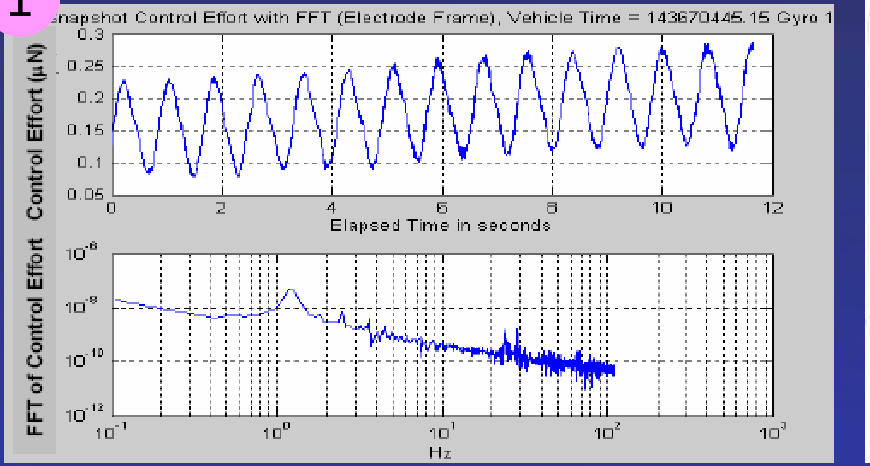
- ① ω_{SL}=1.3 Hz mod. control effort: 30% of ~1.5×10^{-7} N
- ω_{SL}=1.3Hz mod. position at : 40 nm_{pp}; ~0.1% gap
- ② ω_P mod. *z* (telescope axis) bias at 80 Hz spin : 10^{-8} N
- ③ ω_P mod. control effort at 80 Hz spin: ~10^{-8} N

③



"Triangle" = dipole + 'all' harmonics

①



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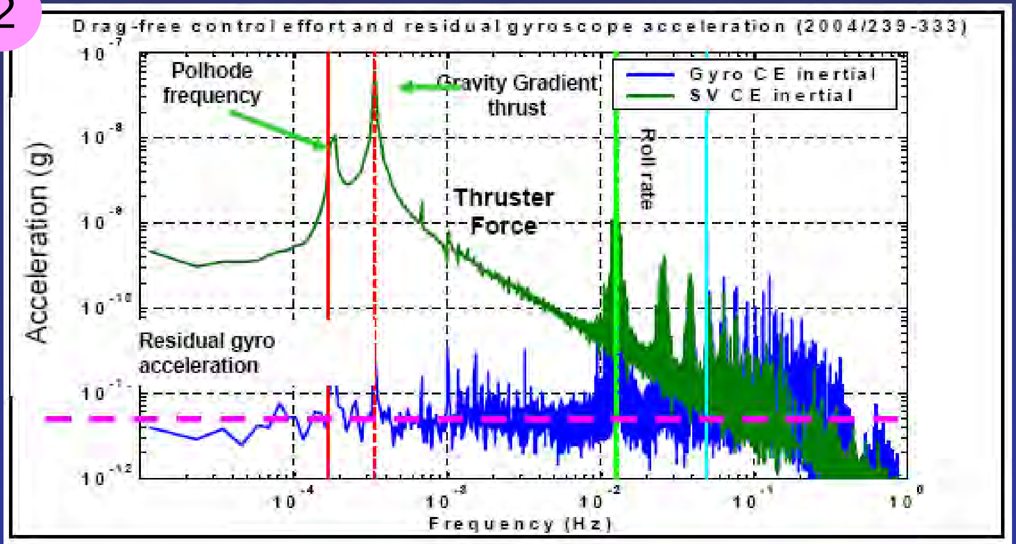


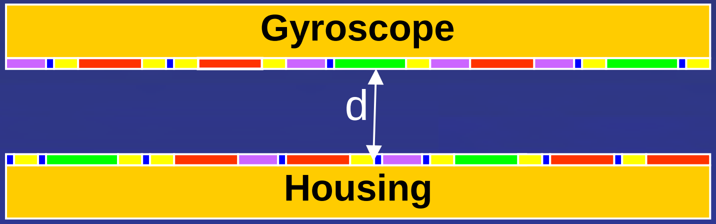
Possible Causes of Enhanced Coupling

Rotor-fixed Mechanisms

Explain “30% rotor bumps” (10^3 of expected)

1. Rotor geometry
   - a. Mass unbalance: ~10nm measured (3×10^{-4} gap)
     - ➪ Smaller than observed coupling by ~ 10^3
   - b. Surface waviness: ~10nm measured (3×10^{-4} gap)
     - ➪ Smaller than observed coupling by ~ 10^3
2. Trapped flux interacting with magnetic fields
   - Three independent calculations
     - ➪ Smaller than observed coupling by > 10^3
3. Non uniform potential of rotor surface
   - ➪ Coupling consistent with ~50 mV – 100 mV patch effect modulating $V_e \approx$ 200 mV suspension voltages

- ➢ Variation of electric potential over the surface
  - ➢ It can arise due to the polycrystalline structure
  - ➢ It can be affected by presence of contaminants
- ➢ Modeled as dipole layer
- ➢ Patch fields present on rotor and housing walls
- ➢ Cause forces and torques between surfaces

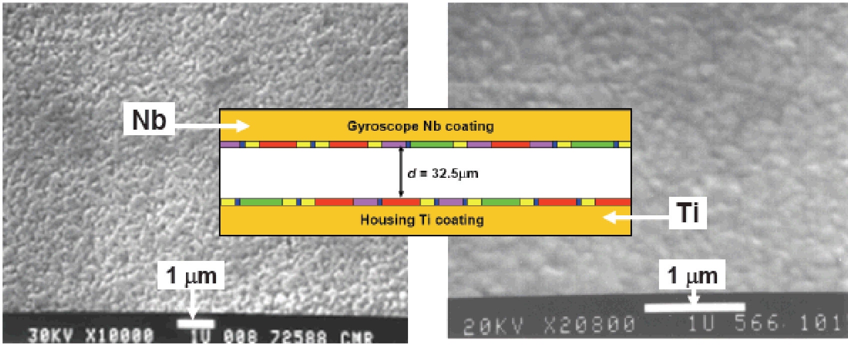


Data explained by patch potentials of ~50-100 mV on rotor and housing

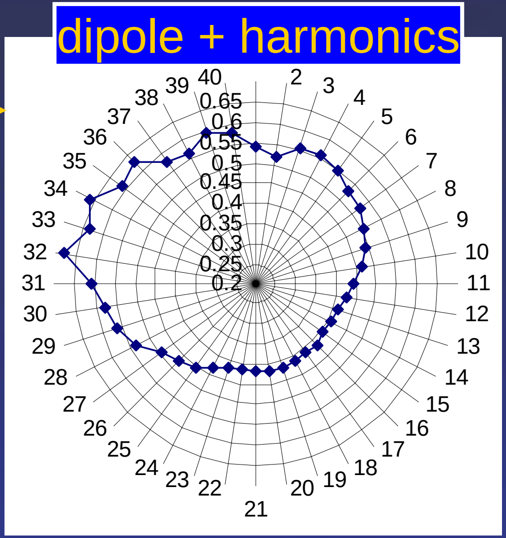
Ground Patch Effect Investigations

- Pre-launch investigation
  - Contact potential differences ~ 0.1V - 1V
  - Patches mitigated/eliminated by grain size
    0.1 μm << 32 μm rotor-electrode gap
  - Kelvin probe measurements on flat samples
- Post-launch ground investigations
  - Work function profile by UV photoemission
  - Detailed analytical modeling
  - Kelvin probe measurements

SEM images of gyro (Nb) & electrode (Ti) coatings

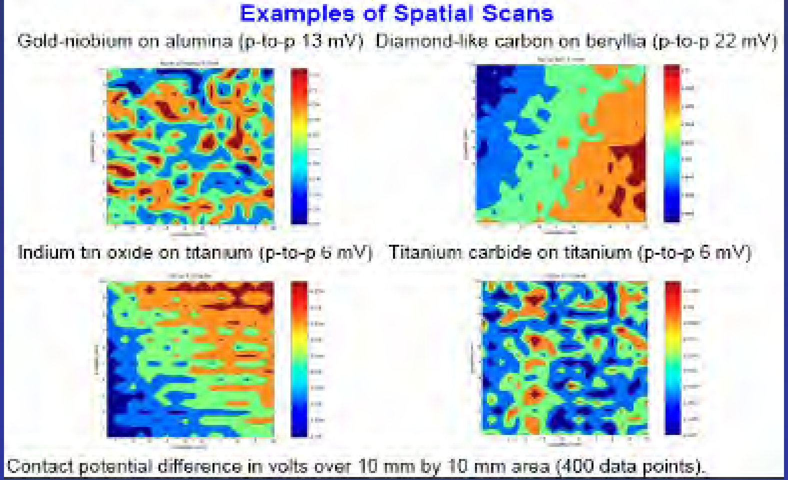


dipole + harmonics



Work function polar plot,
UV photoemission

Kelvin probe scans



Examples of Spatial Scans

Gold-niobium on alumina (p-to-p 13 mV) Diamond-like carbon on beryllia (p-to-p 22 mV)

Indium tin oxide on titanium (p-to-p 6 mV) Titanium carbide on titanium (p-to-p 6 mV)

Contact potential difference in volts over 10 mm by 10 mm area (400 data points).

Kelvin probe

ST-7, LISA, LPF, LIGO find:

Patch potentials 30 -100 mV

Causes of Patch Potential Variations

Gyroscope

- The rotor coating process can lead to variations in the patch potential
  - Coating is the result of many layers
  - Each layer covers about 2/3 of the rotor surface
  - Coating is axi-symmetric, but varies with angle to deposition source
- Thickness variations
- Impurity variations
- Crystal structure variations
- Contaminants

Housing

- All suspension electrodes coated with same axi-symmetric process
  - Small variation from center to edge
  - 6 separate depositions
- Ground plane coating
  - Substantial variation expected due to coating process / angle
  - 2 separate depositions
- Thickness variations
- Impurity variations
- Crystal structure variations
- Contaminants

‘Eight’ Patch Potential Effects on GP-B

- Coupling to GSS → ***V_{pp}* 50-100 mV**
- *z* axis force
  - *At zero frequency*
  - *At polhode harmonics* (mentioned)
- Torques
  - *Misalignment* → *following talks*
  - *Resonance* → *following talks*
- Dissipation mechanisms
  - *Spin-down*
  - *Polhode damping*
- Charge measurement bias

Patch Potential in Spherical Harmonics

Two Approximations:

A. Dipole only

B. Harmonic expansion

- V_R: rotor potential, V_H: housing potential
- Potentials are real

$$V_R(\theta',\phi') = \frac{1}{Y_{1,0}(0,0)} \sum_{l=0}^{\infty} \sum_{m=-l}^{l} V_{R,l,m}\, Y_{l,m}(\theta',\phi')$$

$$V_H(\theta'',\phi'') = \frac{1}{Y_{1,0}(0,0)} \sum_{l=0}^{\infty} \sum_{m=-l}^{l} V_{H,l,m}\, Y_{l,m}(\theta'',\phi'')$$

$$V_{R,l,-m} = (-1)^m V_{R,l,m}^{*}$$

$$V_{H,l,-m} = (-1)^m V_{H,l,m}^{*}$$

Statistical Model

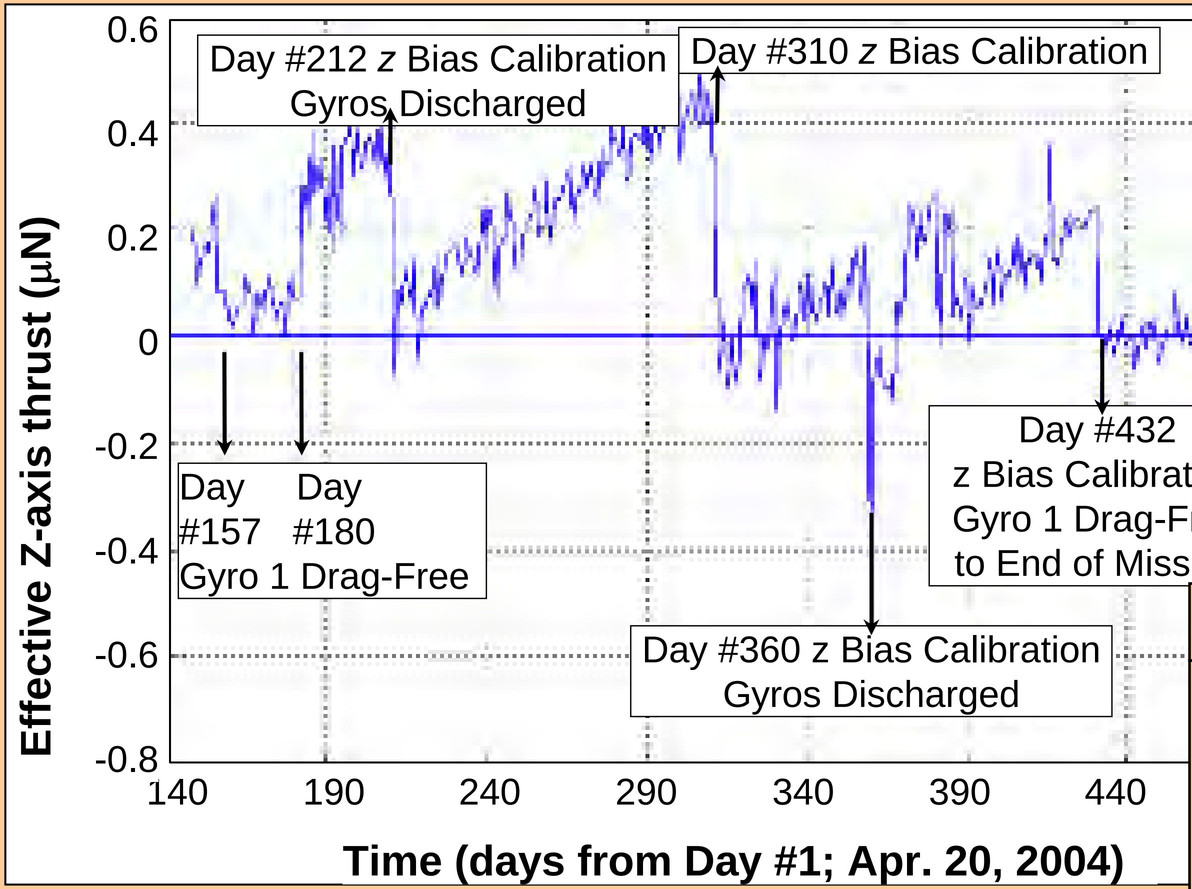
- Spherical harmonics terms are uncorrelated
- Assume a power spectrum characterized by the parameter *r*
- Assume that $V_{R,l,m}$ and $V_{H,l,m}$ are both Gaussian and have the same σ

$$V_{R,l,m} V_{R,l,m}^{*} = \frac{V_{R,1,0} V_{R,1,0}^{*}}{l^r} \qquad V_{H,l,m} V_{H,l,m}^{*} = \frac{V_{H,1,0} V_{H,1,0}^{*}}{l^r}$$

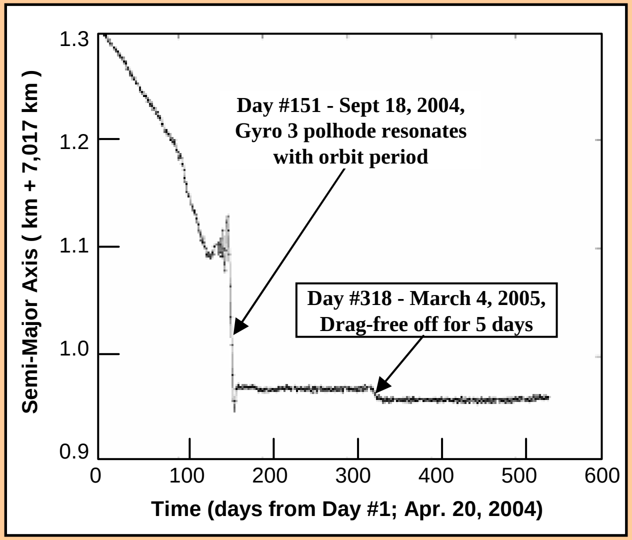
z-axis Force Effects at *f* = 0

- Average at *f* = 0
- Varying with V_R

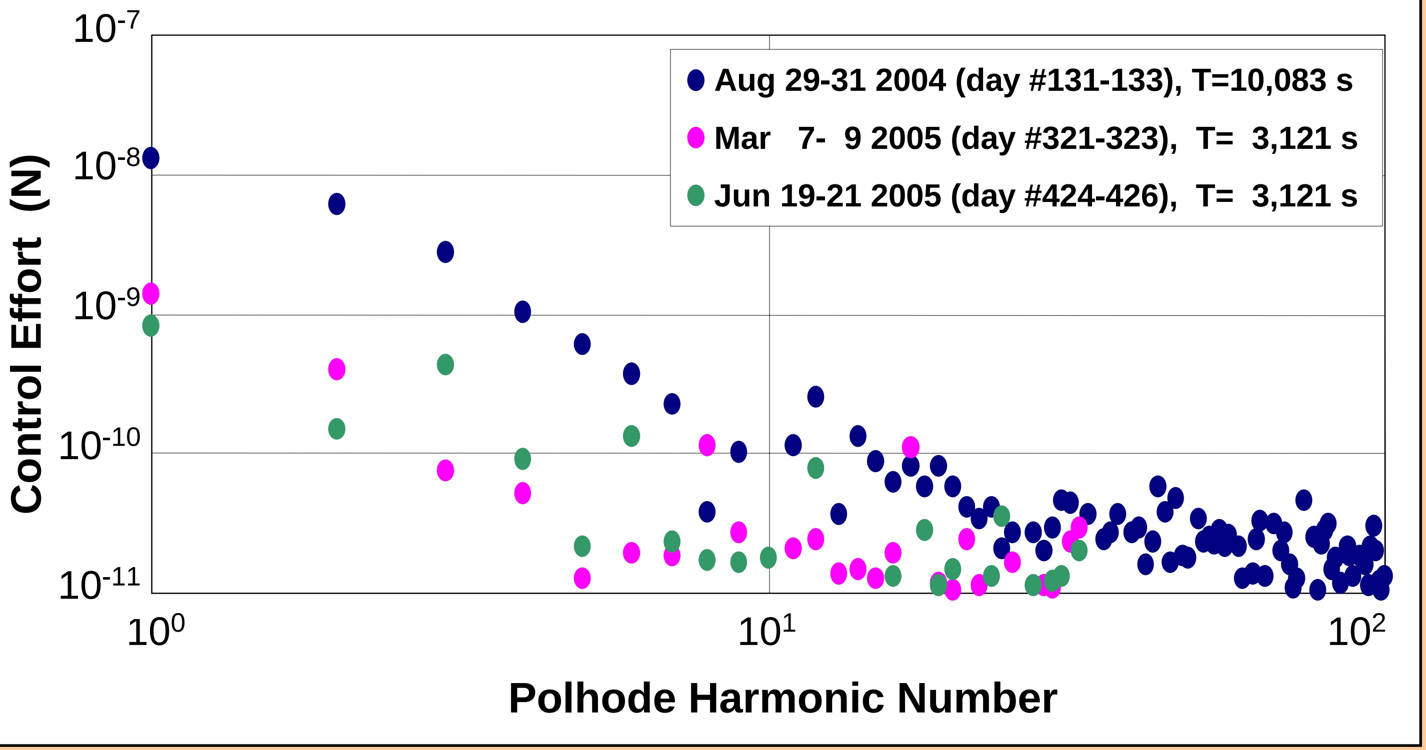
Axial thrust towards guide star (z axis) for the GP-B mission



GP-B orbit Semi-Major axis



Polhode Modulation of *z*-axis Force



Amplitude of Control Effort at Polhode Harmonics : Gyro #1 (a Axis)

Polhode Modulation

- Patch potential model gives the force for the *p*th harmonic of polhode
- Using the observations and the statistical model

$$F_{z,p} = \left(\frac{a}{d}\right)^2 \frac{4\varepsilon_0}{\left(Y_{1,0}(0,0)\right)^2} \cos(p\,\omega_P\,t) \times \sum_{l=0}^{l_{\max}} \left[\frac{V_{R,l,0}\, d^{l}_{0,0}(-\gamma) - V_{H,l,0}}{\sqrt{2l+1} \cdot \sqrt{2(l-1)+1}} \left(V_{R,l-1,0}\, d^{l-1}_{0,p}(-\gamma)\, l + V_{R,l+1,0}\, d^{l+1}_{0,p}(-\gamma) \cdot (l+1) \right) \right]$$

z-axis Forces Due to Rotor Charge

z- axis force: zero frequency average → $V_{d0} = 72\,\text{mV}$

- Model: V_{d0} rotor - housing dipole component
- Force

$$\langle F_Z \rangle = 9\,\text{nN}; \quad V_R = 10\,\text{mV}$$

$$F = \frac{8\pi}{3}\frac{\varepsilon_0 r^2}{d^2} V_R V_{d0}$$

z- axis force: variation with rotor charging → $V_{d0} = 81\,\text{mV}$

- Model: V_{d0} rotor - housing dipole component

$$\Delta F_Z = 8\,\text{nN}; \quad \Delta V_R = \frac{dV_R}{dt}\Delta t = 10\,\text{mV}; \quad \frac{dV_R}{dt} = 0.12\,\text{mV/day}$$

$$\Delta F_Z = \frac{8\pi}{3}\frac{\varepsilon_0 r^2}{d^2} \cdot \Delta V_R \cdot V_{d0}'$$

Data explained by patch potentials of **~50 - 100 mV** on rotor and housing

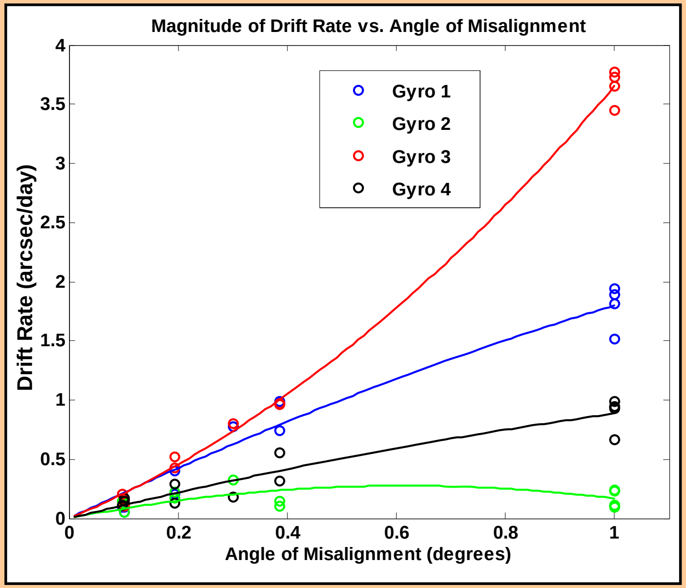
Misalignment Torque

- Torque model for given *l* and *m* = 0

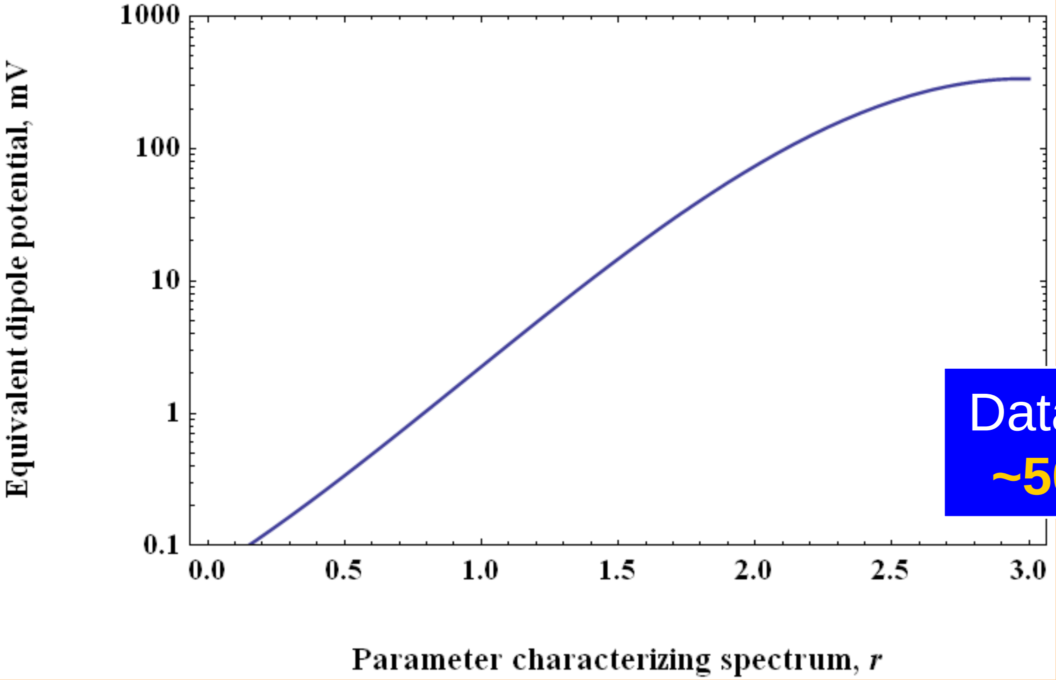
$$N_l = -\frac{C_t}{3} V_{R,l,0} V_{H,l,0} \frac{d}{d\beta}\left[d^{l}_{0,0}(\beta)\right] = \frac{C_t}{6} l\bigl(l+1)\bigr) V_{R,l,0} V_{H,l,0}\, \beta$$

- Statistical model

$$N = \frac{C_t}{6} V_{R,1,0} V_{H,1,0} \sum_{l=1}^{\sim 1800} \sqrt{\left(\frac{l(l+1)}{l^r}\right)^2}\, \beta$$



Equivalent dipole field as a function *r*



Data explained by patch potentials **~50-100 mV** on rotor and housing

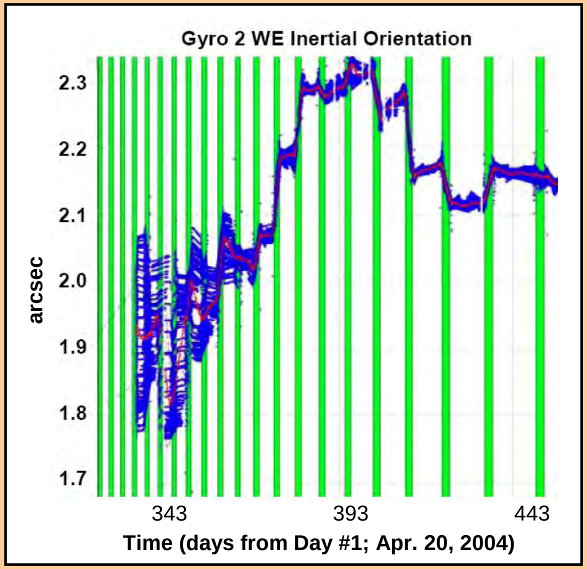
Roll – Polhode Resonance Torque

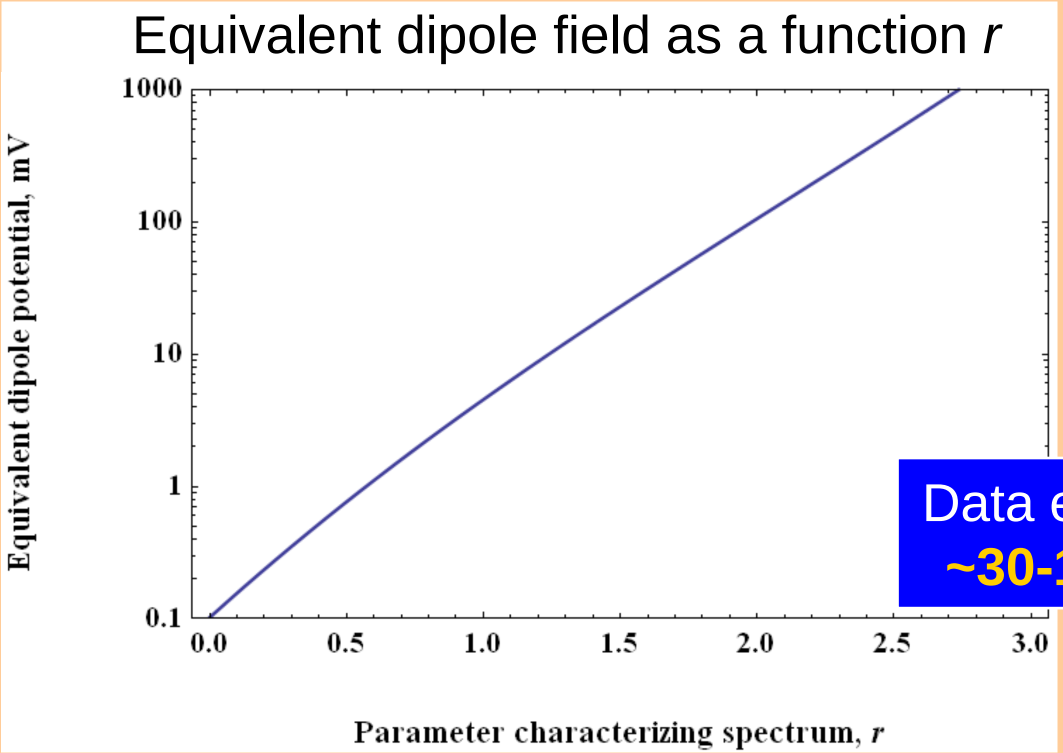
- Torque model

$$N_l = -\frac{C_t}{3} V_{R,l,1} V_{H,l,1}\, d^l_{0,m}(\gamma_P) \frac{d}{d\beta}\left[d^l_{0,1}(\beta)\right]\Big|_{\beta=0} = -\frac{C_t\sqrt{l(l+1)}}{6} V_{R,l,1} V_{H,l,1}\, d^l_{0,m}(\gamma_P)$$

- Statistical Model

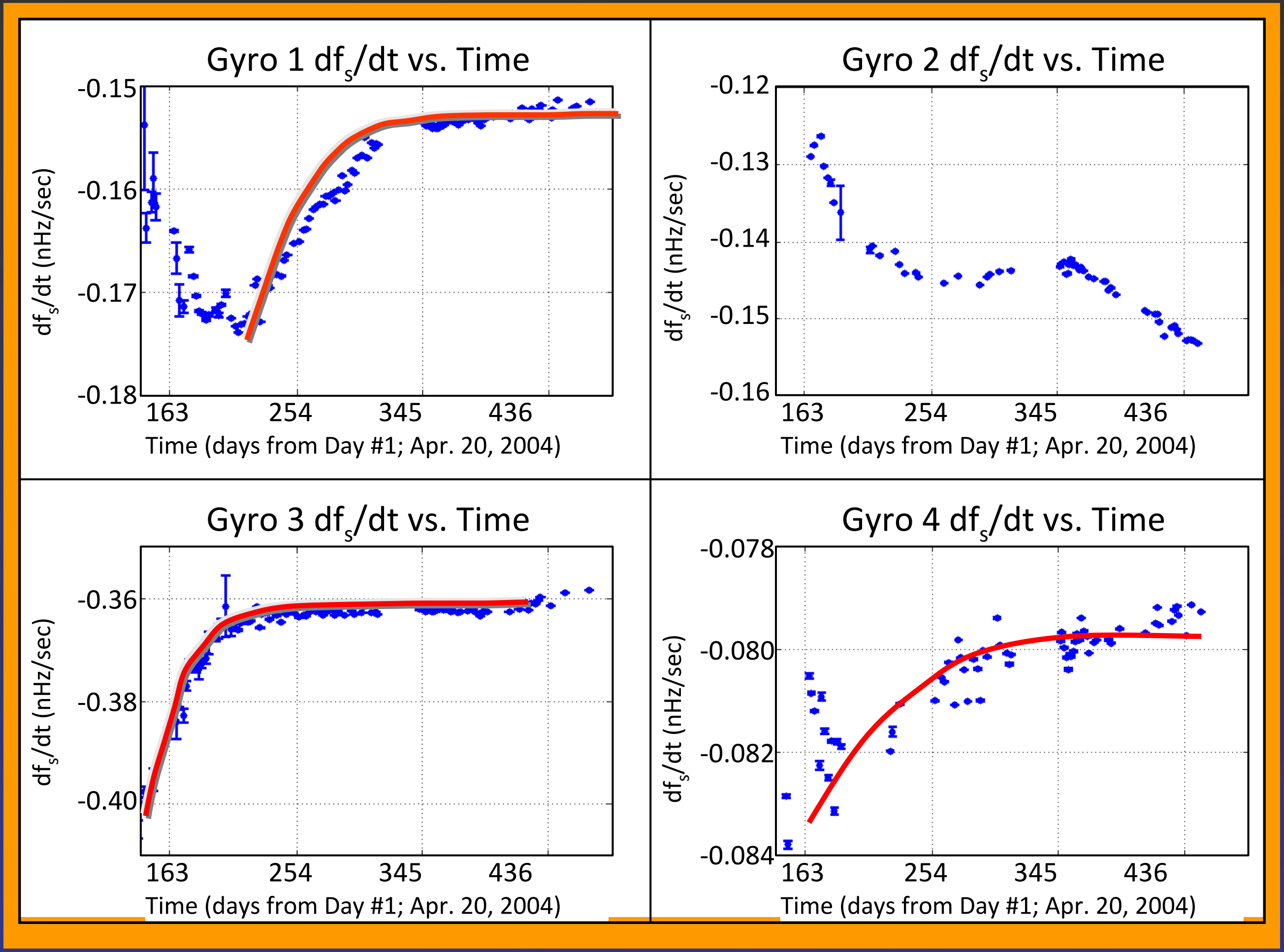
$$\boldsymbol{N = -\frac{C_t}{6} V_{R,1,0} V_{H,1,0} \sum_{l=m}^{\sim 1800} \sqrt{\left(\frac{\sqrt{l(l+1)}\, d^l_{0,m}(\gamma_P)}{l^r}\right)^2}}$$




Equivalent dipole field as a function *r*

Data explained by patch potentials **~30-150 mV** on rotor and housing

Spin-Down Measurements



- ➢ Spin-down rate decreases 5% -10% at start of mission
- ➢ Spin-down rate change is consistent with polhode damping

Spin-Down Continued

Gyroscopes spin-down and polhode parameters

Gyro	Spin-Speed Hz	df/dt μHz/hr	E_S J	P_S pW	N_S N·m·10^{-15}	τ_S yr·10^3	τ_P day	$(\Delta E_S)_{TOT}$ μJ	$(\Delta E_P)_{TOT}$ μJ	$(\Delta E_P)_{TOT}$ / $(\Delta E_S)_{TOT}$
G1	79.39	-0.57	1.25	5.0	9.9	15.9	32±2	41	3.3	8.0%
G2	61.82	-0.52	0.75	3.5	9.1	13.6	75±3	68	1.0	1.5%
G3	82.09	-1.30	1.33	11.7	22.7	7.2	31±5	93	2.5	2.7%
G4	64.85	-0.28	0.83	2.0	4.9	26.4	61±2	32	6.8	2.1%

WHY NOT GAS DAMPING?

- No change in df/dt observed for 75 mK temperature increase
- df/dt = 6 μHz/hr at 4 K (from about 1 μHz/hr at 1.8 K)
- **Inconsistent with gas damping by more than 10^3**

$$\tau = \frac{1}{5}\frac{r_0 \cdot \rho}{P_G}\sqrt{\frac{2\pi \cdot k_B T}{m_G}}$$

$$\sigma = n\lambda \exp\left(\frac{E_B}{k_B T}\right); \qquad \lambda \equiv \sqrt{\frac{h^2}{2\pi \cdot m_{He} k_B T}}; \qquad 70\,\mathrm{K} \le E_B / k_B \le 150\,\mathrm{K}$$

$$\frac{P_2}{P_1} = \exp\left(\frac{E_B}{k_B T}\frac{\Delta T}{T}\right); \qquad \frac{d\omega_2/dt}{d\omega_1/dt} = \exp\left(\frac{E_B}{k_B T}\frac{\Delta T}{T}\right); \qquad \frac{d\omega_2/dt - d\omega_1/dt}{d\omega_1/dt} = \left[\exp\left(\frac{E_B}{k_B T}\frac{\Delta T}{T}\right)\right] - 1$$

$$2\times10^{-17}\ \mathrm{Pa} \le \langle P\rangle_{He} \le 3\times10^{-12}\ \mathrm{Pa}\ \ \text{"Calculated"}$$

$$2\times10^{-9}\ \mathrm{Pa} \le \langle P\rangle_{He} \le 6\times10^{-9}\ \mathrm{Pa}\ \ \text{"Actual"}$$

Spin-Down Modeling

- Model
  - Electrodes and ground plane are grounded through resistors
  - R_G=300 MΩ, C_G = 500 pF; R_E = 20 kΩ, C_E = 78 pF
  - Voltage induced at spin and harmonics on electrodes and ground plane
- Calculate induced voltage on each electrode for each *l* and *m*
  - $X_{l,m}(\theta,\phi)$ is a real function combining $Y_{l,m}(\theta,\phi)$ and $Y_{l,-m}(\theta,\phi)$

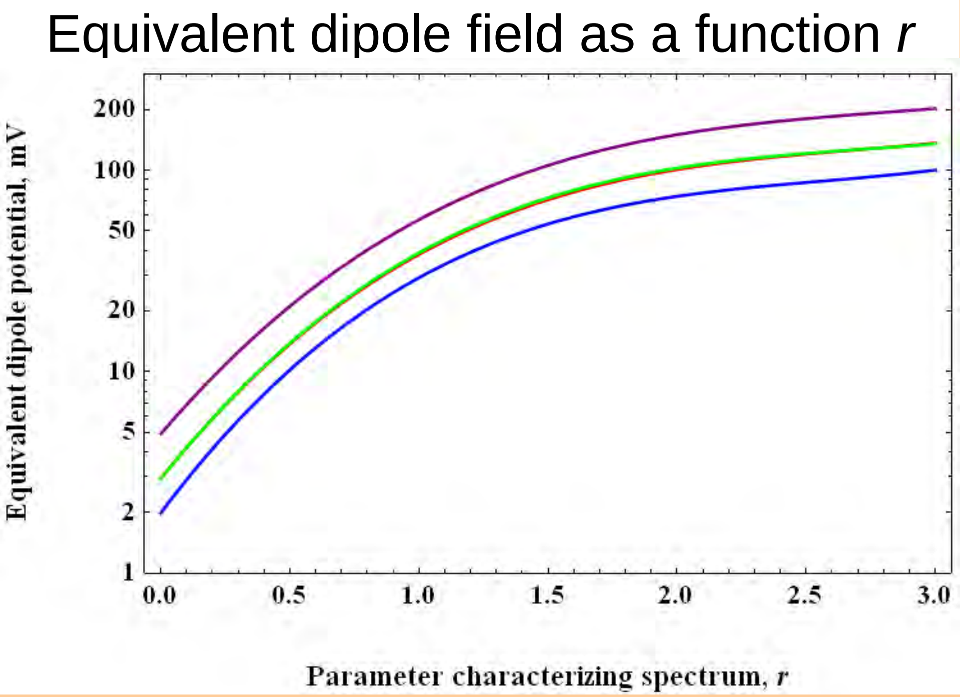
$$v_{i,l,m} = \frac{1}{V_0}\int_{i^{th}\ Suface} X_{l,m}(\theta,\phi)\,dS$$

- Calculate electrode power loss *l* and *m*

$$P_{i,l,m} = \frac{\left(v_{i,l,m}V_0\right)^2}{R}\,\frac{\left(m\,\omega_S\,RC\right)^2}{1+\left(m\,\omega_S\,RC\right)^2}$$

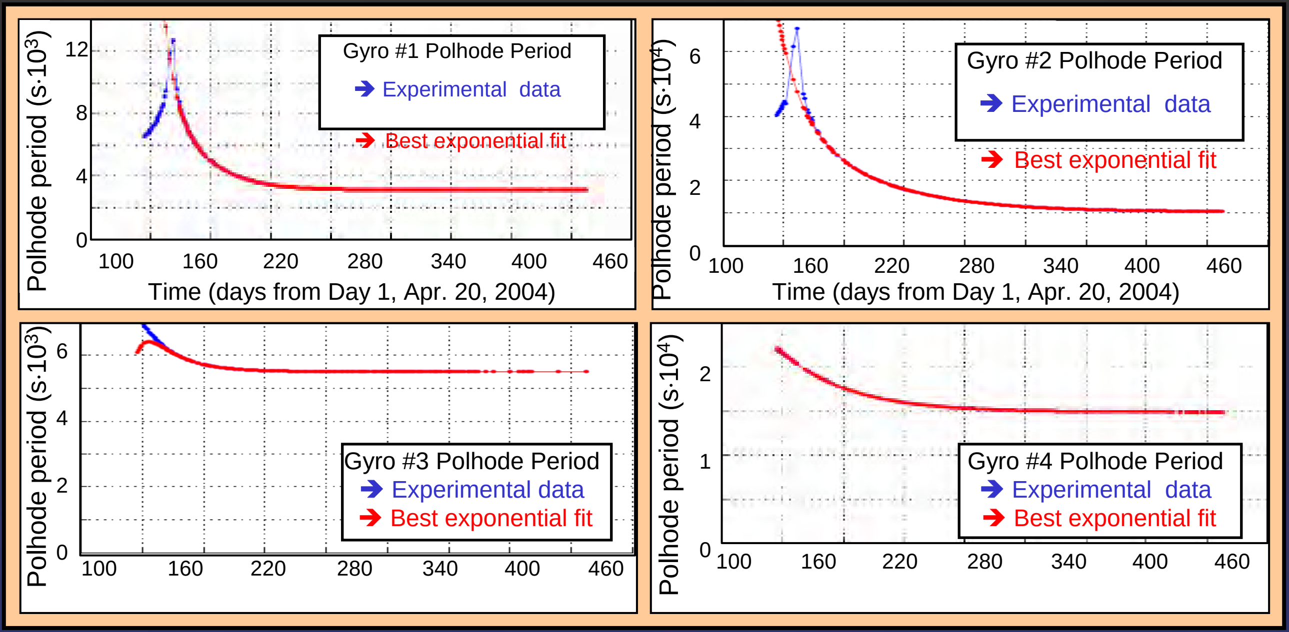
$$\left(\omega_S\,RC\right)_E^2 << 1; \qquad \left(\omega_S\,C\right)_E^2 R_E \le \left[\frac{P_{i,l,m}}{\left(v_{i,l,m}V_0\right)^2}\right]_E \le R_E^{-1}$$

$$\left(\omega_S\,RC\right)_{GP}^2 >> 1: \quad \left[\frac{P_{i,l,m}}{\left(v_{i,l,m}V_0\right)^2}\right]_{GP} = R_{GP}^{-1}$$


Equivalent dipole field as a function *r*

Data explained by patch potentials **~50-150 mV** on rotor and housing

Polhode Damping Data

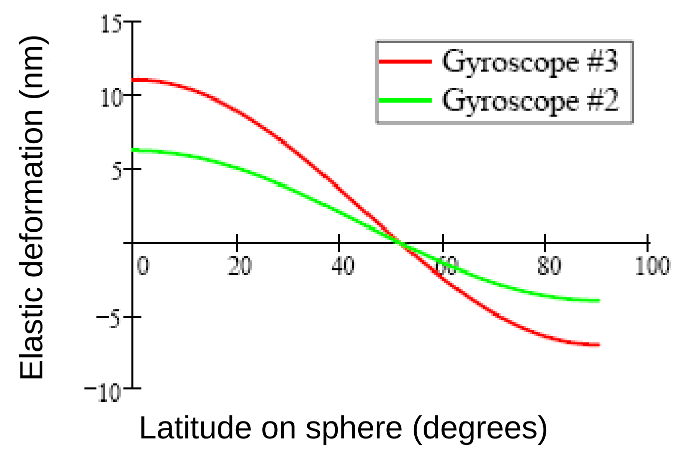


Polhode damping periods calculated from spin-down power dissipation

Gyro	k_1 ×10^6	ω (s^{-1})	$\langle d\omega_{SP}/dt\rangle_0$ (s^{-2}) ×10^{10}	$\langle\tau_{dis}\rangle_{SD}$ (day)	τ_{dis} (day)
G1	**3.36**	**499**	**2.2**	**44**	**31**
G3	**2.07**	**516**	**1.9**	**33**	**30**
G4	**0.93**	**407**	**0.3**	**70**	**64**

Polhode Damping by Plastic Dissipation?

- Why not plastic dissipation in gyroscope
  - Nb to Quartz interface: **No credible mechanism**
  - Quartz ≤ **2×10^{-18} W**
  - Nb Coating ≤ **2×10^{-18} W**



Elastic deformation of spinning gyros

$$\Delta r(\theta) = \frac{2\rho\omega^2 r_0^3}{3Y}\left[-P_2(\cos\theta)\frac{(1+\nu)(2+\nu)}{(7+5\nu)} + \frac{(1-2\nu)}{5}\right] \qquad \left\{P_2(\cos\theta) \equiv \frac{3}{2}\left(\frac{1+\cos(2\theta)}{2}\right) - \frac{1}{2}\right\}$$

$$\boldsymbol{E_S = \frac{Y\delta^2}{2}V} \text{ and } \boldsymbol{\langle P_P\rangle = \frac{E_S}{Q\langle T_P\rangle}} \qquad \left\{\boldsymbol{\delta \equiv \frac{\langle \Delta r\rangle}{r};\quad \nu = 0.16}\right\}$$

Material	Q (quality factor)	Y ($\mathrm{N{\cdot}m^{-2}}$) (elastic modulus)	V ($\mathrm{m^3}$) (volume)	ρ $\langle r\rangle / r$	E_S (J) (strain energy)	$\langle P_P\rangle$ (W) (power loss)
Quartz	10^7	7.17×10^{10}	3×10^{-5}	2.4×10^{-7}	6×10^{-8}	**≤ 1.9×10^{-18}**
Nb	10^4	12×10^{10}	5×10^{-9}	4×10^{-7}	5×10^{-11}	**≤ 1.6×10^{-18}**

Polhode Damping Observations

- Dissipation to ground at $\omega_{Sp} = n\omega_p \pm m\Omega_p$ can reduce polhode energy exponentially
- Polhode maximum power dissipation 0.1 - 1 pW
  - 10 -40% of average spin-down power
- Polhode average power dissipation 40 – 400 fW
  - 1.5 – 8.0% of average spin-down power
- Polhode power dissipation is consistent with patch induced dissipation to ground
- Complete derivation NOT yet successful

Continuing work

- DeBra
- Silbergleit
- Keiser
- Turneaure
- Buchman

Gyro	**P_S (pW)**	**$(P_P)_{max}$ (pW)**	**$(P_P)_{max}$ / P_S**	**$\langle P_P \rangle$ (fW)**	**$(\Delta E_P)_{TOT}$ (μJ)**	**$\langle P_P \rangle$ / P_S**
G1	5.0	1.09	32%	400	3.3	8.0%
G2	3.5	0.14	10%	54	1.0	1.5%
G3	11.7	0.87	42%	316	2.5	2.7%
G4	2.0	0.12	13%	42	6.8	2.1%

Data consistent with patch potentials **~30-150 mV** on rotor and housing

Force-Modulation Charge Measurement

with Patch Effects

Rotor Patches $\Delta d = 0$

$$V_{Ra} = V_R + 1/2(V_1 + V_2)$$
$$V_{Rb} = V_R + 1/2(V_1 + V_2)$$
$$V_{Rc} = V_R + V_3$$

→

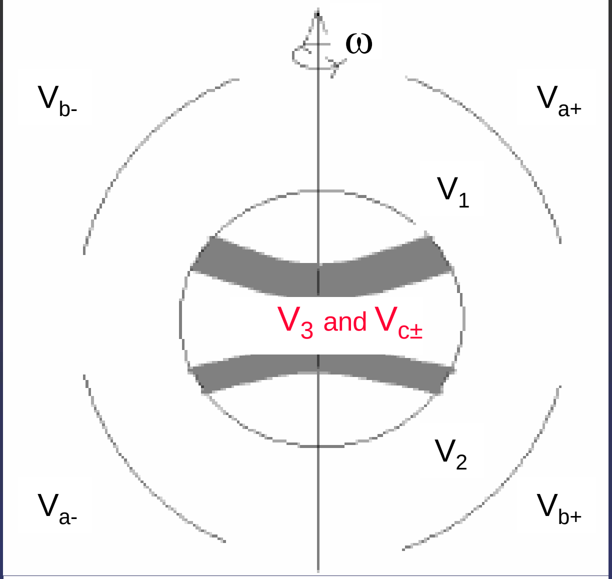
$$V_{Ra} = V_{Rb} \neq V_{Rc}$$
$$V_{R(a,b,c)} \neq f(\Delta d_{(a,b,c)})$$

Rotor Patches $\Delta d \neq 0$

$$V_{Ra} = V_R + 1/2(V_1 + V_2) + \Delta d_a(V_1 - V_2)$$
$$V_{Rb} = V_R + 1/2(V_1 + V_2) - \Delta d_b(V_1 - V_2)$$
$$V_{Rc} = V_R + V_3$$

→

$$V_{Ra} \neq V_{Rb} \neq V_{Rc}$$
$$V_{R(a,b)} = f(\Delta d_{(a,b)})$$
$$V_{Rc} \neq f(\Delta d_c)$$



The Spin Averaging GP-B Gyroscopes

Rotor and Housing Patches $\Delta d \neq 0$

$$V_{Ra} = V_R + 1/2[(V_1 - V_{a+}) - (V_2 - V_{a-})] + \Delta d_a[(V_1 - V_{a+}) - (V_2 - V_{a-})]$$
$$V_{Rb} = V_R + 1/2[(V_1 - V_{b+}) - (V_2 - V_{b-})] - \Delta d_b[(V_1 - V_{b+}) - (V_2 - V_{b-})]$$
$$V_{Rc} = V_R + V_3 - 1/2(V_{c+} - V_{c-}) - \Delta d_c(V_{c+} - V_{c-})$$

→

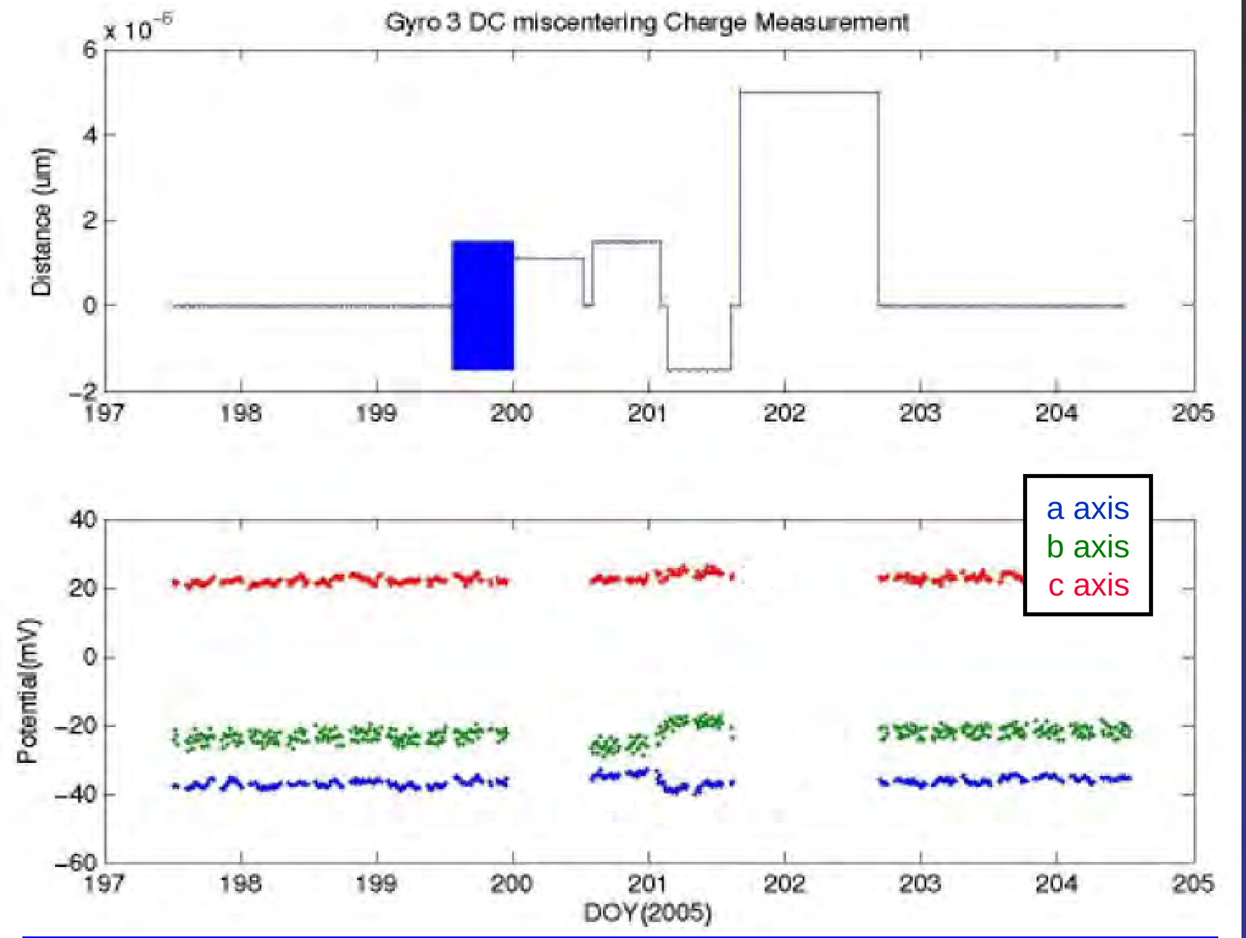
$$V_{Ra} \neq V_{Rb} \neq V_{Rc}$$
$$V_{R(a,b,c)} = f(\Delta d_{(a,b,c)})$$

- ➢ Rotor and Housing patches required for data modeling
- ➢ GP-B data is insufficient for unique solution

Ed Fei senior thesis

Charge Measurement with Patch Effects

Relative position of gyroscope #3; same for all three axes



Gyroscope #3 potentials and their shifts due to miscentering

$$V_{Ra} \neq V_{Rb} \neq V_{Rc}$$

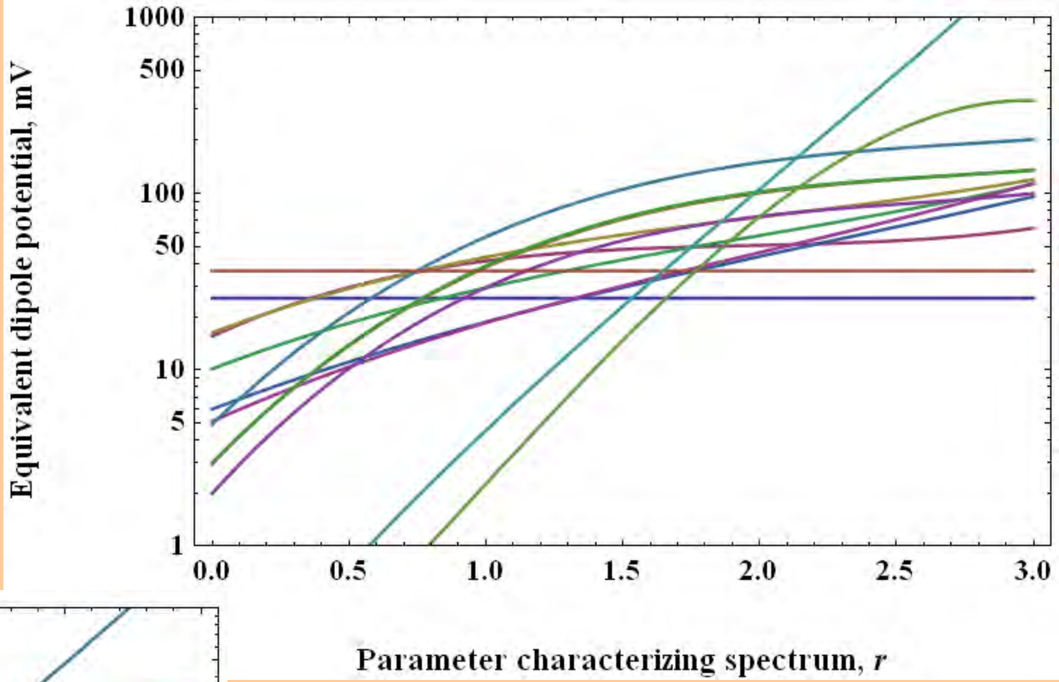
$$V_{R(a,b,c)} = f\left(\Delta d_{(a,b,c)}\right)$$

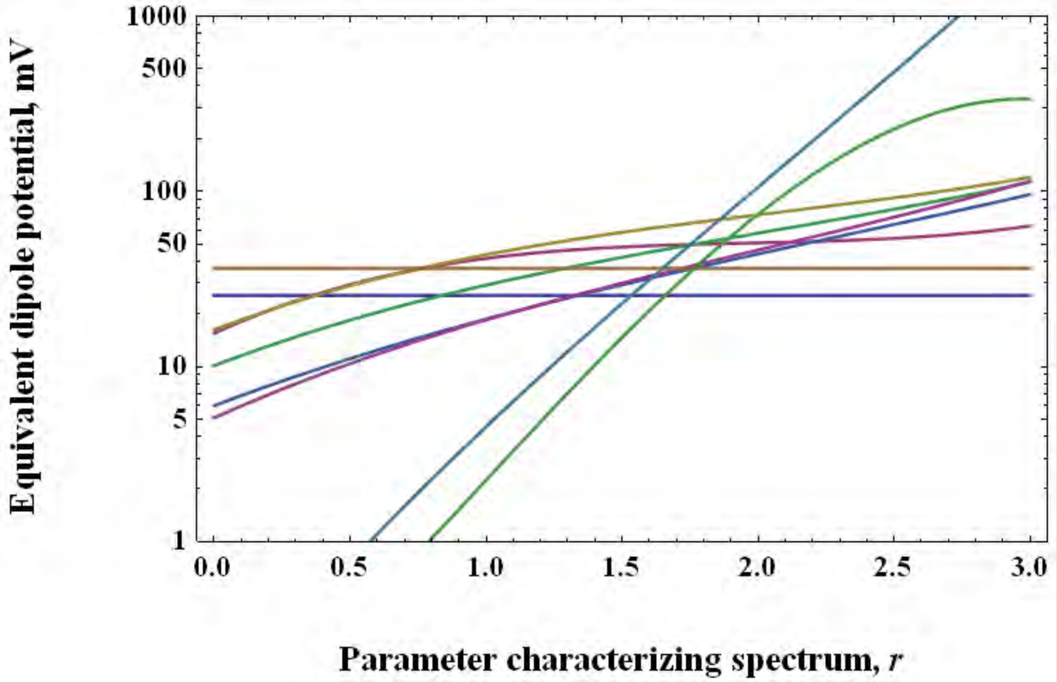
$$\max\left|V_{Ri} - V_{Rj}\right| \approx 60\,\text{mV}$$

Data explained by patch potentials of **~50-100 mV** on rotor and housing

Patch Effects Summary- I

Equivalent dipole field as a function of ***r*** with all results





Equivalent dipole field as function of ***r*** without spin-down results

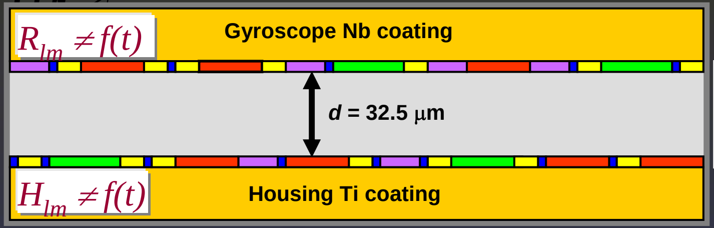
Patch Effects Summary- II

Dependence of effects on V_R, V_H and l

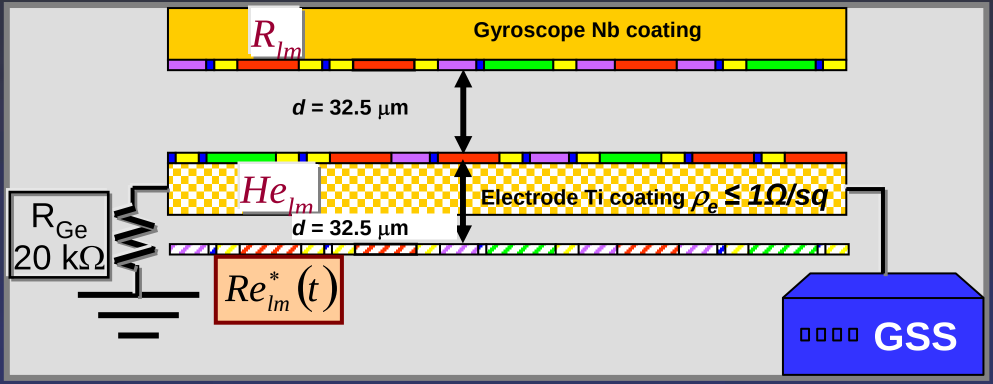
Effect due to patch potentials	Dependence on V_R and V_H	Dependence on l
Zero-frequency z-axis force due to change in rotor charge	$V_Q (V_R - V_H)$	Only for combination of $l = 1$ and rotor charge Q
Zero-frequency z-axis force modulated by polhode	$V_R \times (V_R - V_H)$	No dependence on l for $l \leq p$
Gyro acceleration at spin speed	V_R (rotor charge > 200 mV)	Principally for $l \leq 3$
Gyro spin-down	V_R	Independent of l up to 1
Rotor charge measurement	$V_R - V_H$	Principally for $l \leq 3$
Misalignment torque	$V_R \times V_H$	Proportional to $l(l+1)$ for $l <$ ~1700
Roll-polhode resonance torque	$V_R \times V_H$	Proportional to $[l(l+1)]^{1/2}$ for $l \geq$ polhode harm. res. # and $l <$ ~1300

All Data explained by patch effects **~30-150 mV** on rotor and housing

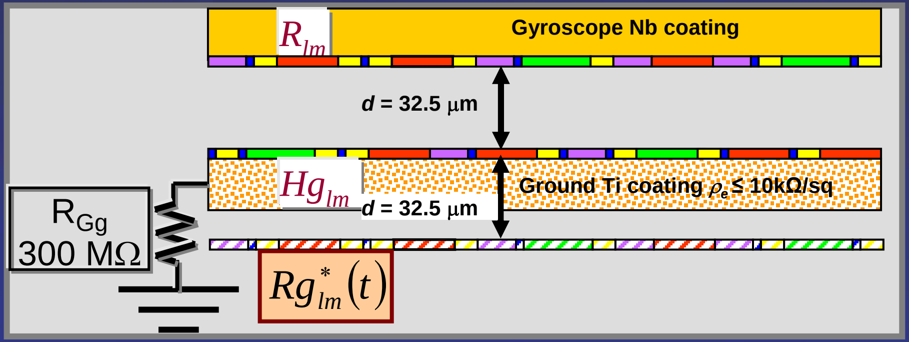
Remaining Work *Is Model Complete?*



Time Independent
Present Model



With time dependence
of electrodes



With time dependence
of ground plane

Characteristic time scales of the gyroscope system

Source	τ_e	**Spin/*m***	τ_g	**Roll**	**Orbit**	**Polhode/*p***
Time constant (s)	1.6×10^{-6}	1.5×10^{-2}	1.5×10^{-1}	77.5	5.9×10^{3}	$2.4 \times 10^{3} – 1.4 \times 10^{4}$

Remaining Work *Observations on Systematic Errors from Patch Effect*

- Include time dependence ?
- Estimates of presently understood effects

  Vary between < 0.1marcs to > 5 marcs
  - Roll averaging efficiency
  - Other symmetries: electrodes, ground-plane
- Polhode damping torques ?
- Other patch effect torques & resonances ?
- Approach to estimating the GP-B error
  - **Statistical versus systematic**
  - **Achievable accuracy**
  - **HS guide star data**

Lessons Learned – I

Mitigate patch potential effects (PPE)

- Reduce patch potentials
  - **Improve materials**
  - **Improve cleaning and assembly processes**
- Compensate patch potential effects
  - **Bias electrodes to compensate PPE average**
- Increase gaps (d^{-3} force variation dependence)
  - **Make gap and test mass sizes comparable**
- Shift spectrally
  - **High: above measurement band**
  - **Low: as close to $f = 0$ as possible**
- Minimize electric fields
  - **Eliminate electrostatic forcing (spheres)**
  - **Eliminate electrostatic sensing (optical)**

Will work !

Might work

Will work ?

For:
LISA, STEP
LIGO, other

Lessons Learned – II

- Optimize charge management system
  - Eliminate charge measurement (passive)
  - Make charge generation continuous
  - Eliminate control loop
- Simulate control system
  - Extensive with hardware in the loop
  - Analytical simulations
- Data acquisition rates
  - Measurement band × 2 to 10
  - Plus highest electronics frequency snapshots

Will work !

Might work

Will work ?

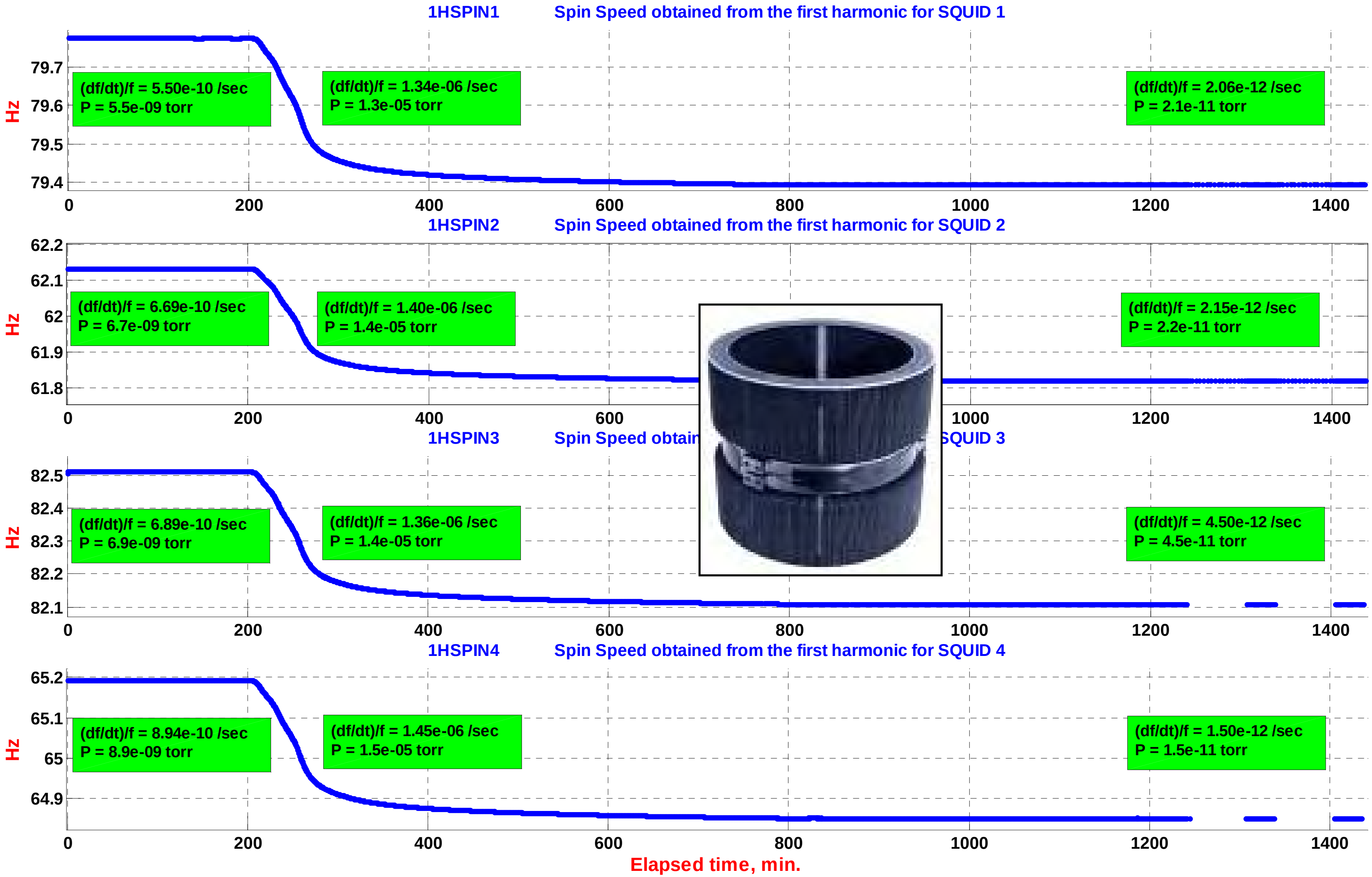
For:
LISA, STEP
LIGO, other

Conclusions

- All known effects (eight) can be accounted for by patch potentials on the rotor and housing in a quantitatively consistent way (polhode damping not completed)
- Limits on patch effect sources of systematic errors not a problem above 5 marcs and probably better (time dependence, misalignment and resonance not included)
- Work remaining in torque modeling, error estimation, polhode damping
- **Complex experiments in space work**
  - **All GP-B systems worked beyond expectations**
  - **Surprises can be overcome: GP-B patch effects modeling**

Back-up slides

Spin-Down Rates



SQUID 1:

(df/dt)/f = 5.50e-10 /sec
P = 5.5e-09 torr

(df/dt)/f = 1.34e-06 /sec
P = 1.3e-05 torr

(df/dt)/f = 2.06e-12 /sec
P = 2.1e-11 torr

SQUID 2:

(df/dt)/f = 6.69e-10 /sec
P = 6.7e-09 torr

(df/dt)/f = 1.40e-06 /sec
P = 1.4e-05 torr

(df/dt)/f = 2.15e-12 /sec
P = 2.2e-11 torr

SQUID 3:

(df/dt)/f = 6.89e-10 /sec
P = 6.9e-09 torr

(df/dt)/f = 1.36e-06 /sec
P = 1.4e-05 torr

(df/dt)/f = 4.50e-12 /sec
P = 4.5e-11 torr

SQUID 4:

(df/dt)/f = 8.94e-10 /sec
P = 8.9e-09 torr

(df/dt)/f = 1.45e-06 /sec
P = 1.5e-05 torr

(df/dt)/f = 1.50e-12 /sec
P = 1.5e-11 torr

Spherical Harmonic Transformation

- Transformation from Rose

$$Y_{l,m'}(\theta',\phi') = \sum_{m=-l}^{l} e^{-i\,m\,\alpha} d^{l}_{m,m'}(\beta)\, e^{-i\,m'\,\gamma}\, Y_{l,m}(\theta,\phi)$$

- From SV roll axis to rotor frame
  - To spin axis: {α, β, 0}

    ← β (misalignment), α (misalignment phase)
  - To rotor frame: {$-\omega_S\, t$, $-\gamma_P$, $-\omega_P\, t$}

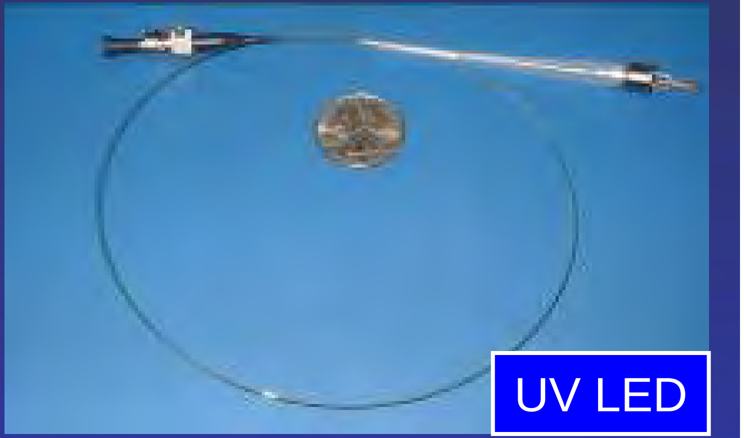
    ← ω_S (spin freq.), γ_P (polhode angle), ω_P (polhode freq.)
- From SV roll axis to housing frame {$\omega_R\, t$, 0, 0}

  ← ω_R (roll frequency)

The Path to Future Experiments I
UV Sources

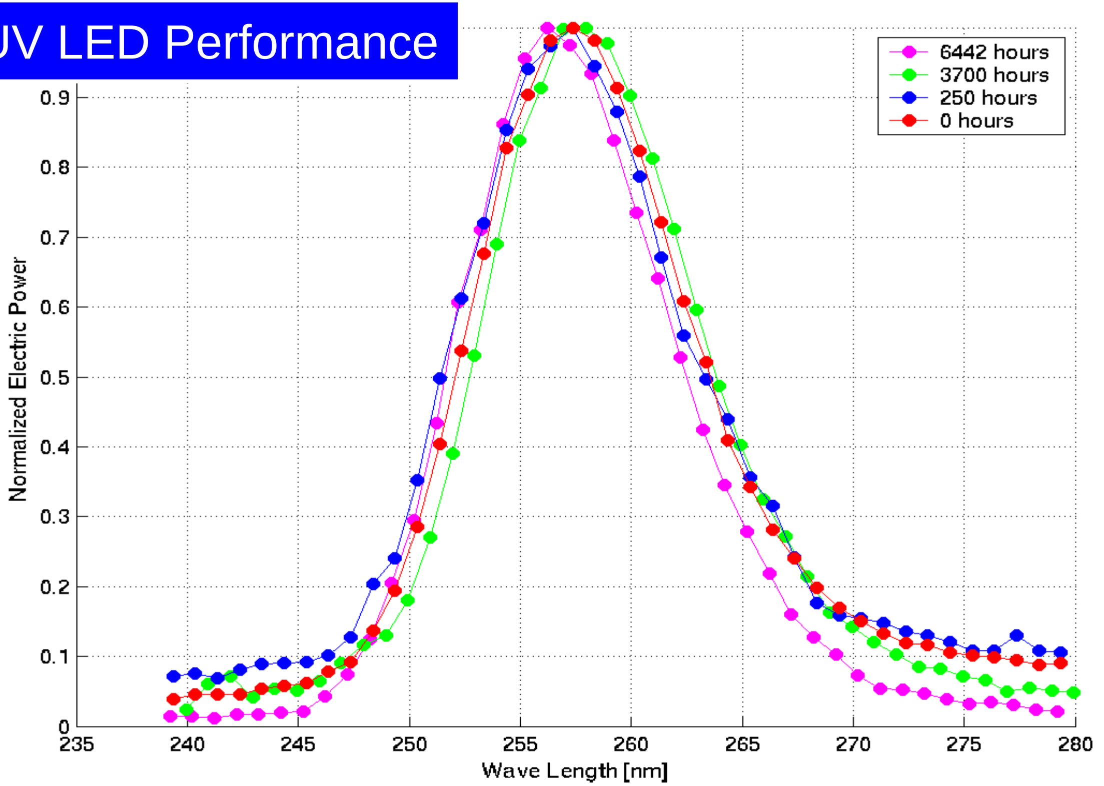
- Better UV source: **UV LED**
  - Long lifetime >10,000 hours to date
  - Lower power consumption
  - Lower mass
  - AC modulation up to 1 GHz

Talk by Ke-Xun Sun



UV LED

UV LED Performance



The Path to Future Experiments II Charging Requirements

$Q_{LISA} \leq 10^{-13}$ C $\tau_{LISA} \cong 3$ hours
$Q_{GPB} \leq 10^{-11}$ C $\tau_{GPB} \cong 4$ months

Q requirement drivers
a) Laurence force, b) $k \propto Q^2/d$

1. Reduce the LISA frequency of discharging requirement **by 10 from 10^{-4} Hz to 10^{-5} Hz**

   Now $(10^{-17}$C/s$) / (10^{-13}$C$) = 10^{-4}$Hz

   - Improve radiation shielding by 10 ⇒ **10^{-17} C/s to 10^{-18} C/s**
   - Improve EMI shielding by 10 ⇒ **10^{-13} C to 10^{-12} C**
   - Increase gap by 10 ⇒ **3 mm to 30 mm**
   - Minimize patch effects on TM and housing
   - Combinations of above

2. Reduce the LISA test mass potential requirement **by 50-100 from 2 mV to 100 - 200 mV**

   Now $(10^{-13}$C$) / (50\times10^{-12}$F$) = 2\times10^{-3}$V

   - Improve EMI shielding by 10 ⇒ **10^{-17} C/s to 10^{-18} C/s**
   - Increase gap by 10 ⇒ **50 pF to 5 pF**
   - Combinations of above

The Path to Future Experiments III
Improved Technology and Operations

3. Control magnitude and time dependence of patch effects

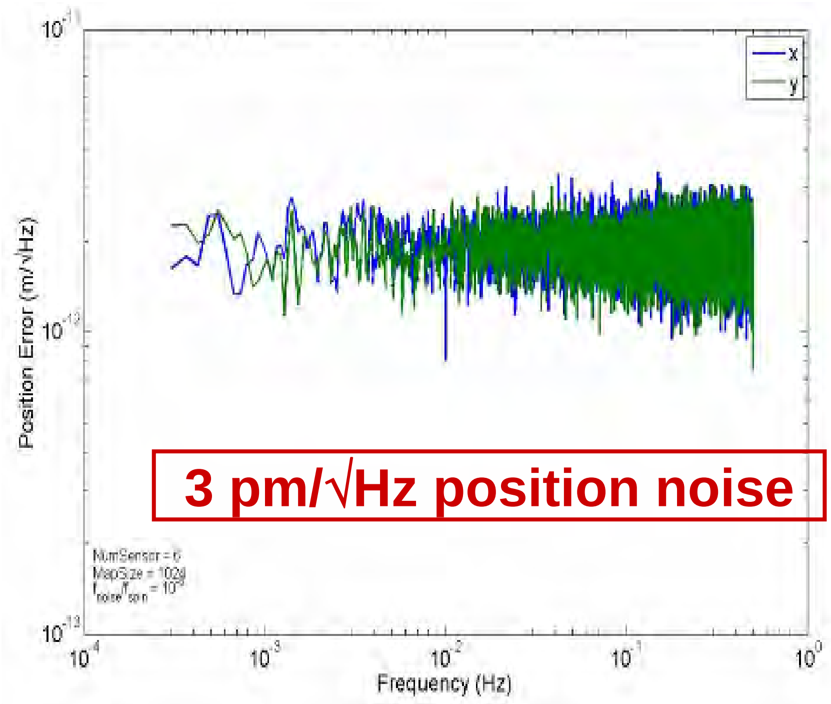
- Materials development
- Ground testing

4. Extensive charge measurements and calibrations

- Measurement frequencies must be different for different sensors
- Single electrodes
- Variable TM positions
- Particle monitoring

5. Use improved position measurement and control of TM

- 3 pm/√Hz with optical read-out
- Control position to <10 pm/√Hz with micro-thrusters



3 pm/√Hz position noise

The Path to Future Experiments IV
The Improved Charge Management System

Best

A. Charge measurement

- **Not required**
- Frequency of measurement below SM band
- Continuous measurement

B. Charge generation (use UV LED)

- **Continuous**
- Frequency of discharging below SM band

C. Charge control loop

- **Not required**
- Frequency of discharging below SM band
- Continuous control