GP-B Charge Management

Results and Lessons Learned

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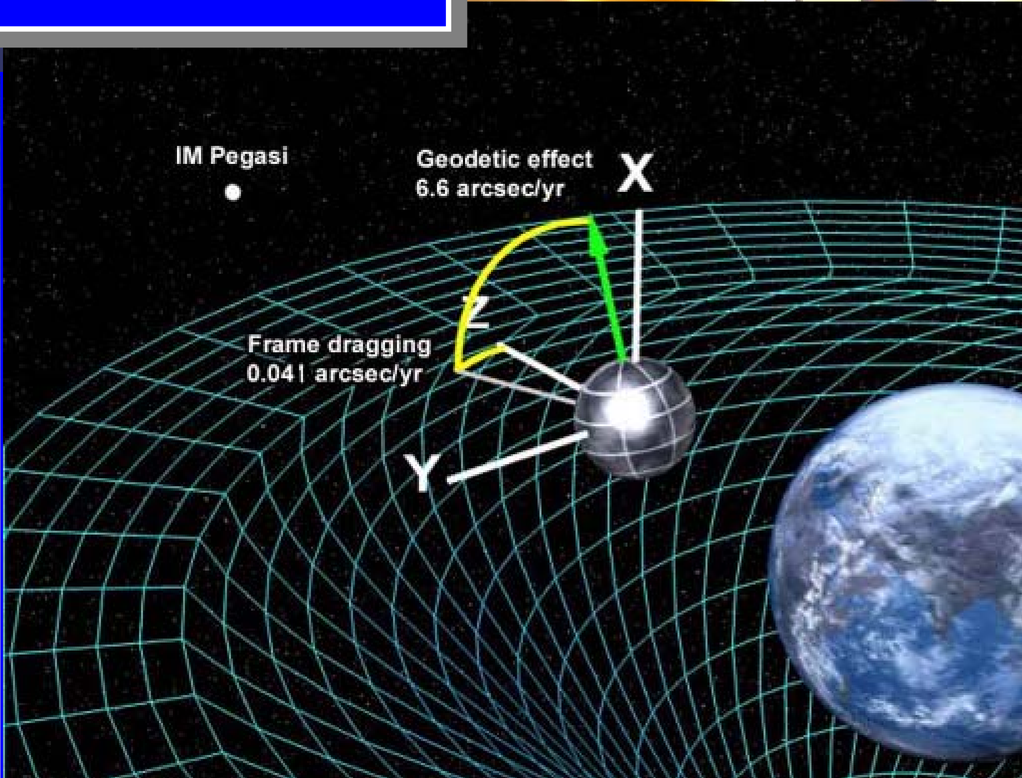


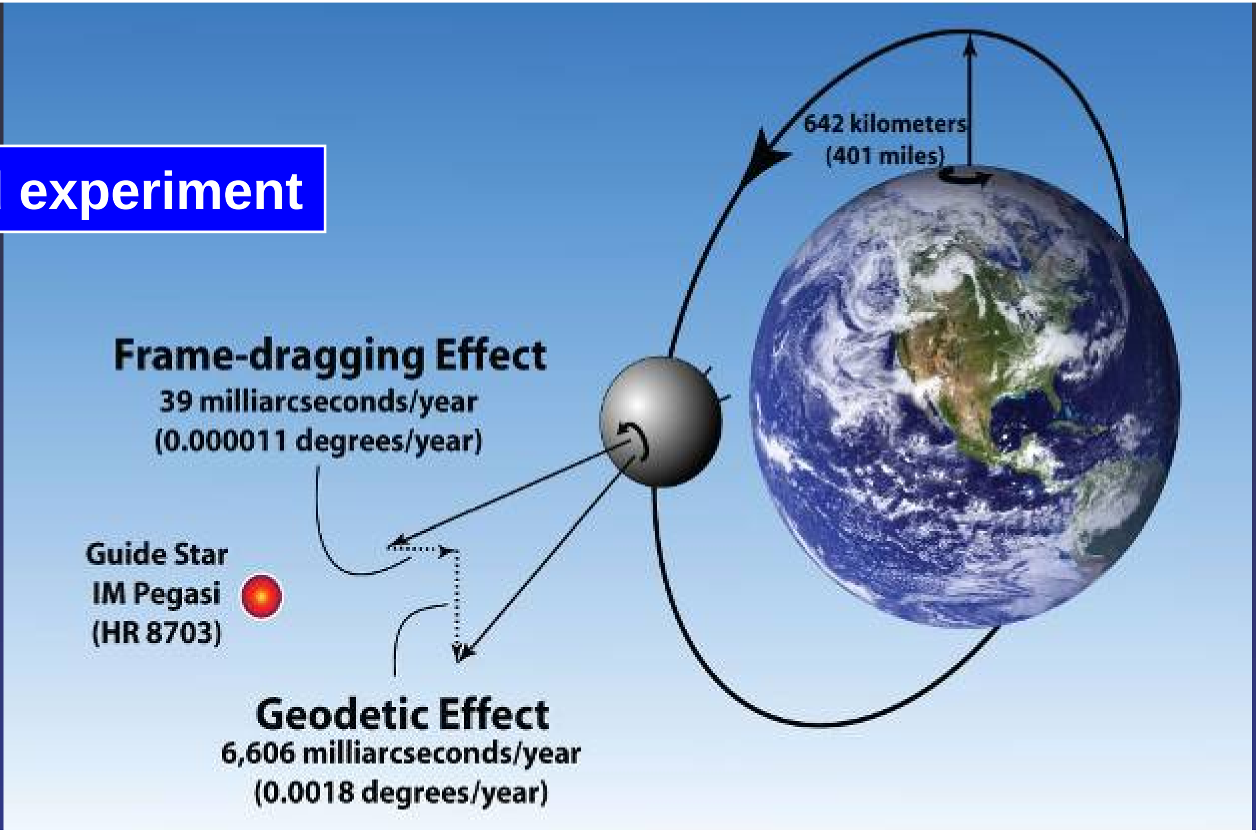
Outline

- The Relativity Mission GP-B
  - Experiment Overview
  - Results as of April 2007
- Charge Management
  - System Design
  - Results
  - Patch Effects
- Lessons Learned
  - Charge Measurement Issue
  - The Path to LISA and STEP
  - The NanoSat Program for Technology Development

The Relativity Mission Concept

**"No mission could be simpler than Gravity Probe B.
… just a star, a telescope, and a spinning sphere." — William Fairbank**

Controlled experiment



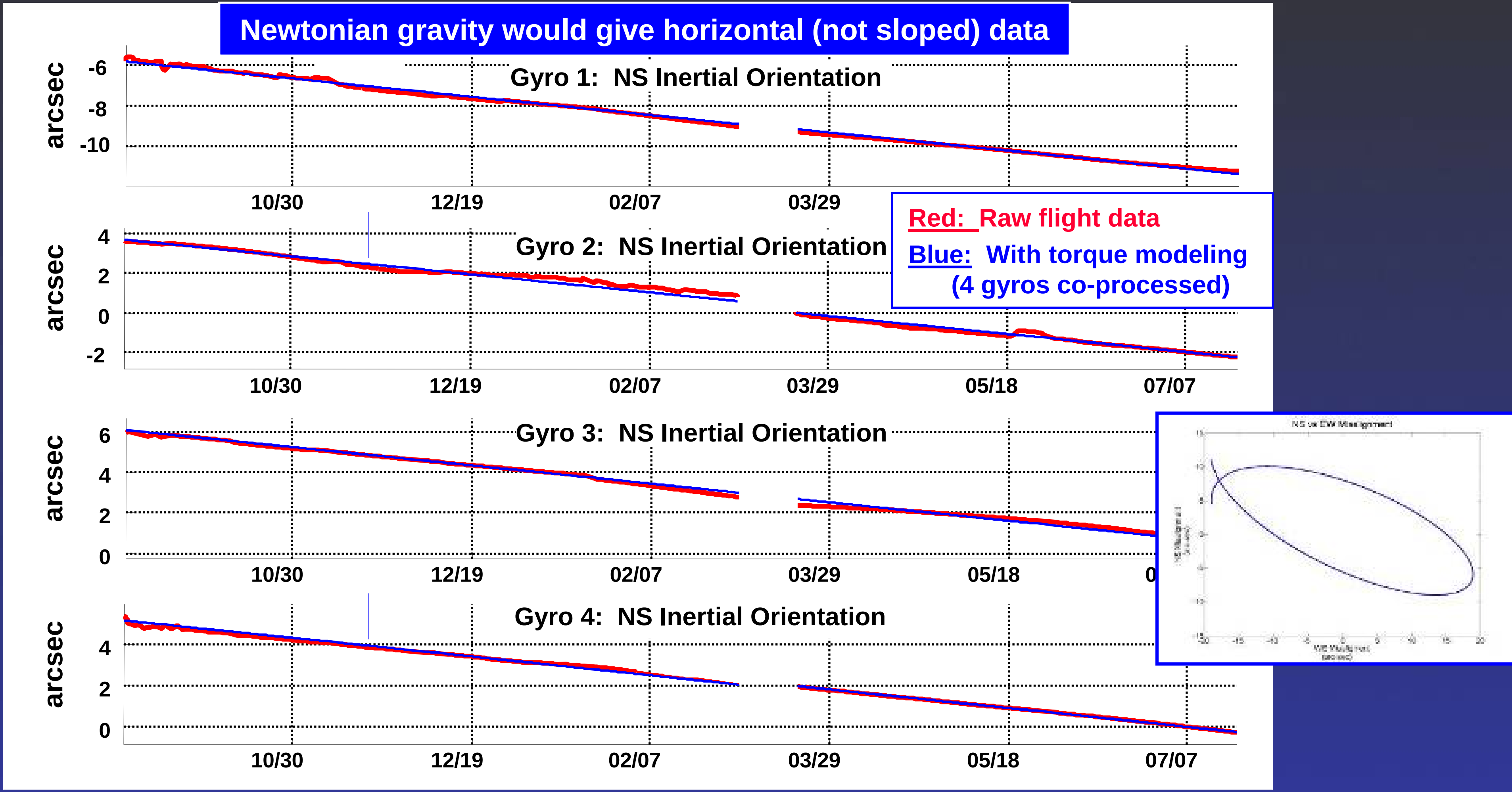
$$\overline{\Omega}=\left(\gamma+\frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\overline{R}\times\overline{v}\right)+\left(\gamma+1+\frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot\left(\overline{\omega}_e\cdot\overline{R}\right)-\overline{\omega}_e\right]$$

Geodetic Effect
Space-time curvature
de Sitter (1916)

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

Bottom Line

- GP-B has demonstrated that complex physics experiment work in space
- Seeing General Relativity Directly in a Controlled Experiment



Newtonian gravity would give horizontal (not sloped) data

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

GP-B experience is invaluable for future missions

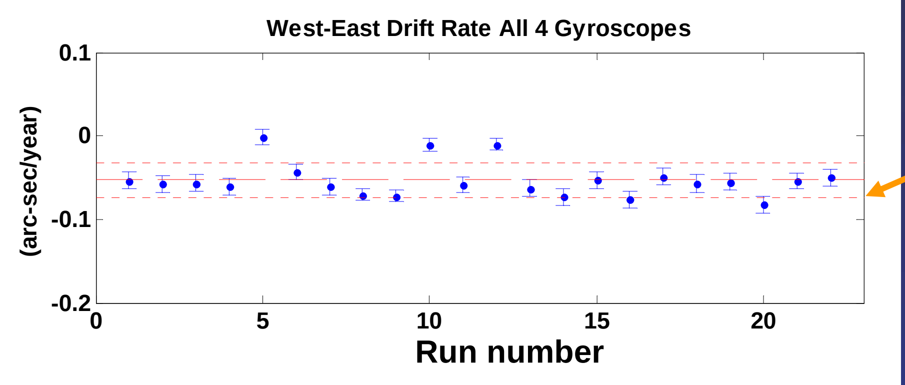
Present Statistical Error and Consistency of Rate Estimates

GR predictions

Geodetic (NS)
6571±1 marcs/yr

FD + other (EW)
75±1 marcs/yr

- Combined measurements of all 4 gyroscopes
  - Statistical error for single run 11 marcs/yr
  - Statistical error between runs 30 marcs/yr
- 4 Gyroscopes consistency 97 marcs/yr



EW (Lense-Thirring & other)
net expected
-75 +/- 1 marcsec/yr

	Earth FD	solar geodetic	proper motion	net expected
rate	-39	-16	-20 ± 1	-75 ± 1

- Gyroscopes are consistent with one another and with GR predictions for the frame-dragging and the geodetic effects to less than 97 marcs/yr.
- Statistical error is significantly smaller than the differences between gyroscopes or between data runs: clear room for improvement!!

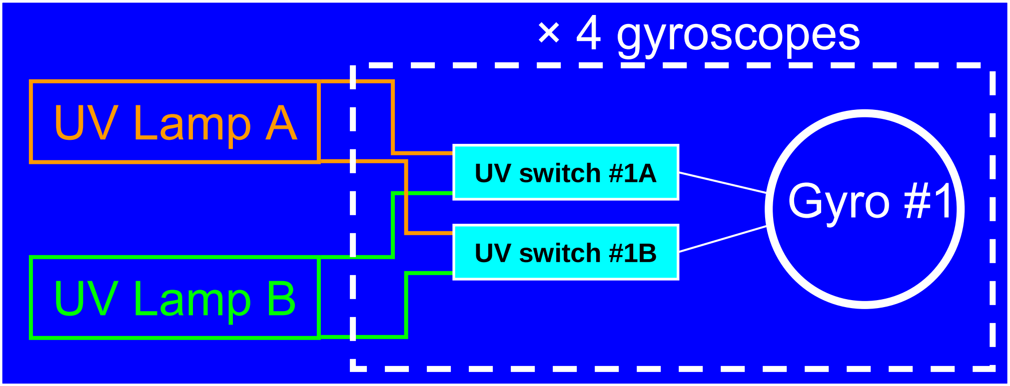
Charge Management

Charging Sources	Ground Test/Analysis	SM Results
Levitation	< 1V test	200 – 500 mV
He gas spin-up	< 1V test	Not observed: < 20 mV
Cosmic radiation	~ 0.1 -1 mV/day (GEANT)	0.1 – 1 mV/day

- *Variation in cosmic radiation charging*
  - *Shielding: Decreasing from Gyro #1 to Gyro # 4*
  - *Solar flares*

- **Rotor charge controlled with UV excited electrons**
  - **2 UV Hg lamps (254 nm line)**
  - **8 UV switches**
  - **2 UV fibers per gyroscope**

Schematic of GP-B UV architecture



- **Continuous measurement at the 0.1 mV precision**
- **Control to 5 mV meets requirement of 15 mV**

Charge Measurement by Force Modulation
NO PATCH EFFECT

$$V_R = \frac{Q_R + \sum_{e\pm=1}^{3} \langle V_{e\pm} \rangle \cdot C_{e\pm} + \langle V_g \rangle \cdot C_g}{C_T} \qquad C_T \equiv \sum_{e\pm=1}^{3} C_{e\pm} + C_g$$

Nominally $\langle V_{e\pm} \rangle = \langle V_g \rangle = 0 \quad \Rightarrow \quad V_R(\omega = 0) = \frac{Q_R}{C_T}$

$$F \equiv F_+ - F_- = \frac{A_+ \varepsilon_0}{2d_+^2}(V_{e+} - V_R)^2 - \frac{A_- \varepsilon_0}{2d_-^2}(V_{e-} - V_R)^2$$

$$V_{e\pm}(\omega_C) = \pm V_C \cos(\omega_C t) \qquad A_+ = A_- \equiv A \qquad d_\pm \equiv d \pm \Delta d$$

$$F(\omega_C) = \frac{2A\varepsilon_0}{d^2} V_R V_C \cos(\omega_C t) \quad \text{to} \quad \mathrm{O}(\Delta d)$$

$R \Rightarrow$ rotor
$e\pm \Rightarrow$ electrode pair
$g \Rightarrow$ ground plane
$A\pm / d\pm \Rightarrow$ electrode pair area/spacing
$C \Rightarrow$ charge measurement
$\omega_C \Rightarrow$ in control band ☜

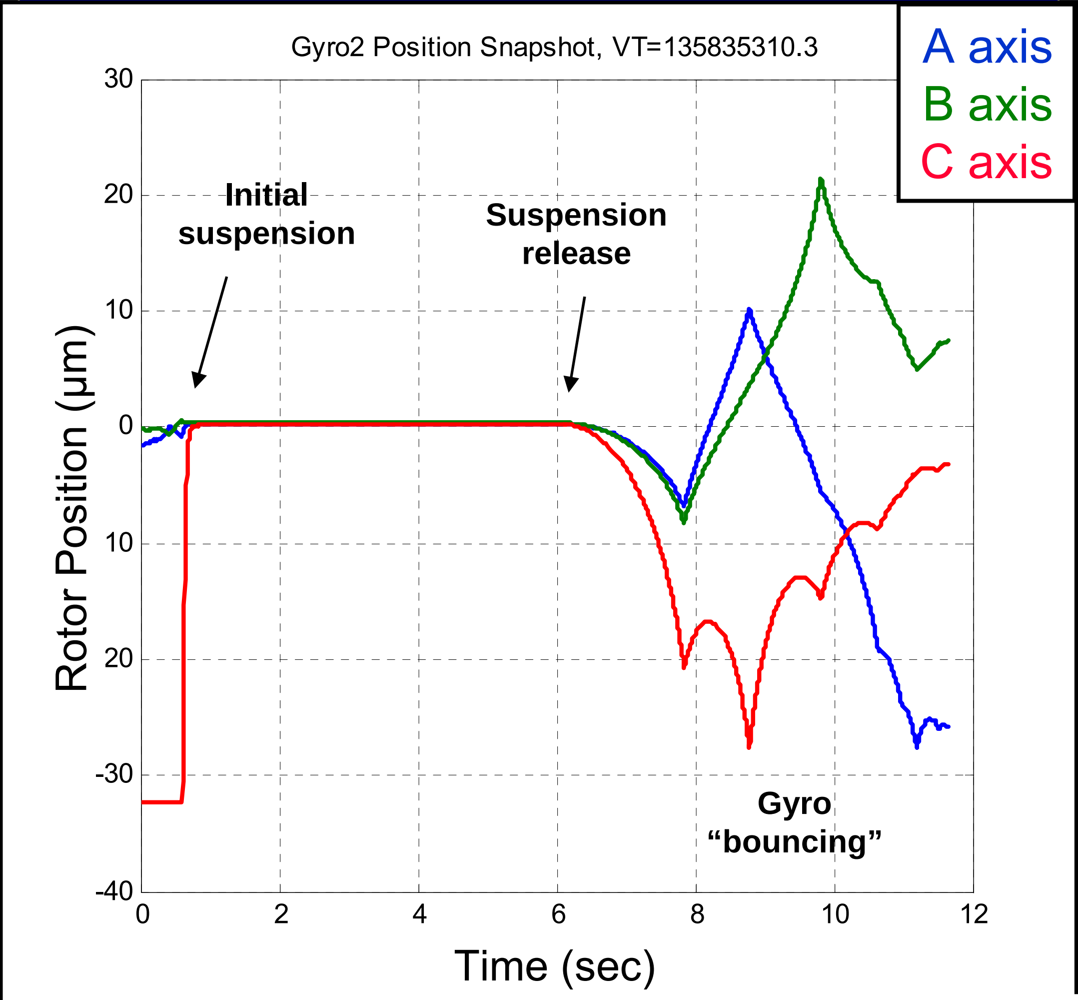
1) $\omega_C < \omega_{Suspension} < \omega_{Draf-free} \Rightarrow d(\omega_C) = 0$ measure $F(\omega_C)$
2) $\omega_C > \omega_{Draf-free} > \omega_{Suspension} \Rightarrow F(\omega_C) = 0$ measure $d(\omega_C)$
3) $\omega_C < \omega_{Draf-free} \Rightarrow d(\omega_C) = 0$ measure $F_{Drag-free}(\omega_C)$

$F(\omega_C)$ proportional to V_R and V_C and independent of Δd to $O(\Delta d)$

GP-B Gyro On-Orbit Initial Lift-off

First Indication of Gyroscope Charging

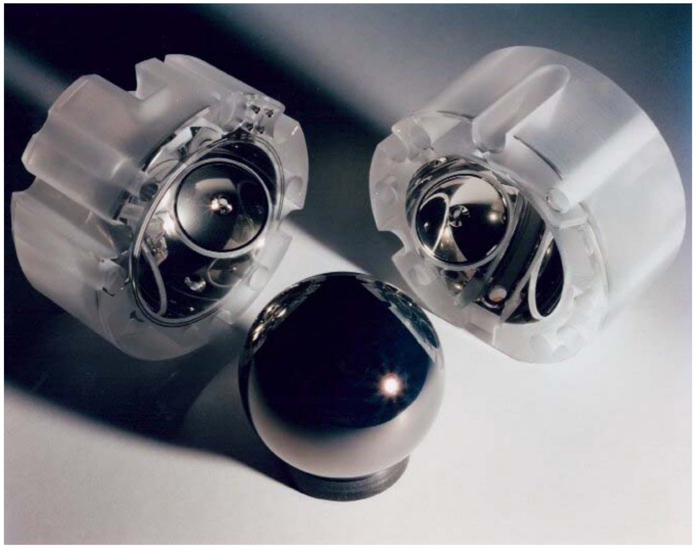
Initial gyro levitation and de-levitation using analog backup system



Initial suspension

Suspension release

Gyro "bouncing"



Gyro "falls" 30 μm in 2.7 sec:

Equivalent to

1) SC drag of ~10^{-5} m·s^{-2}

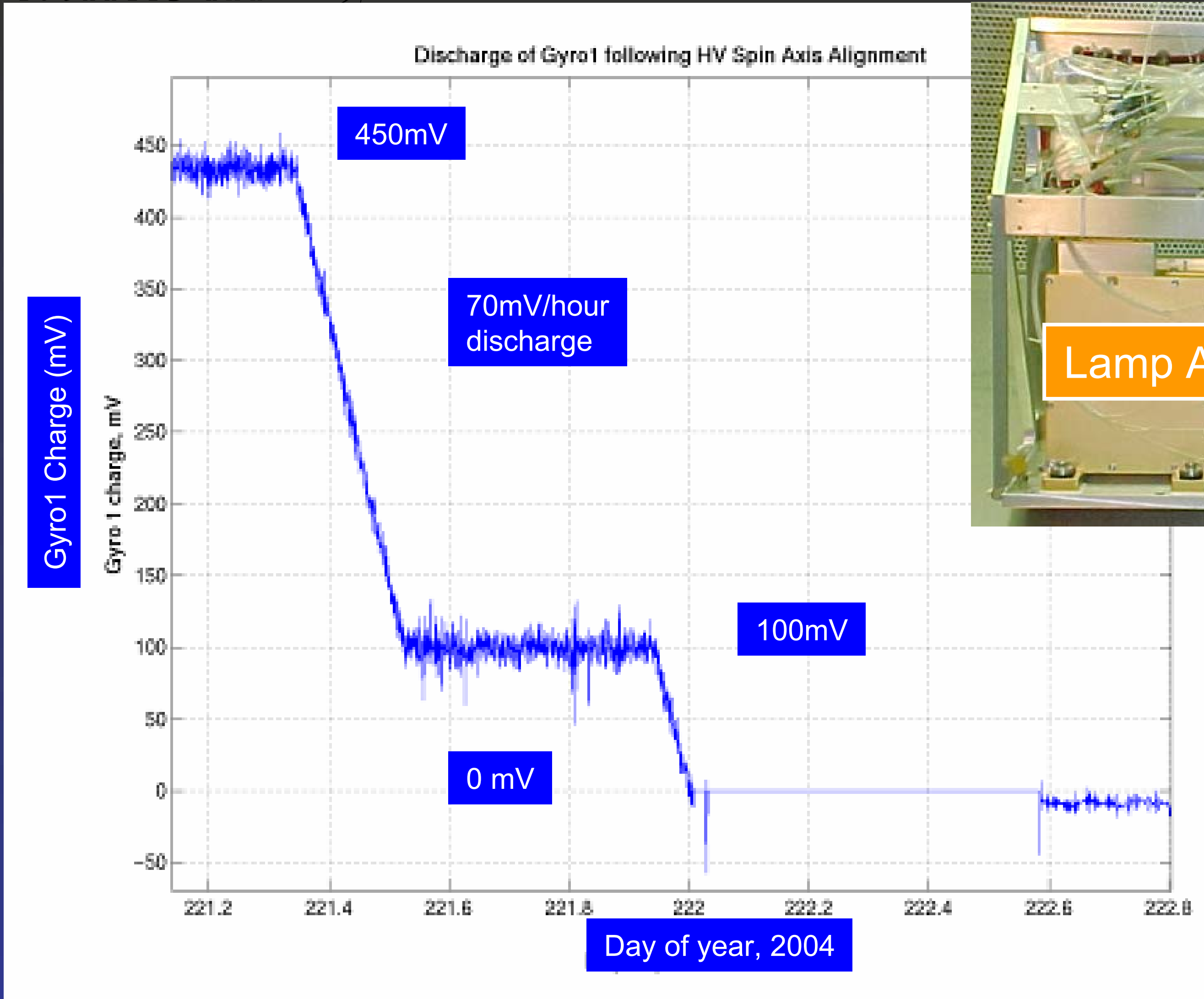
or

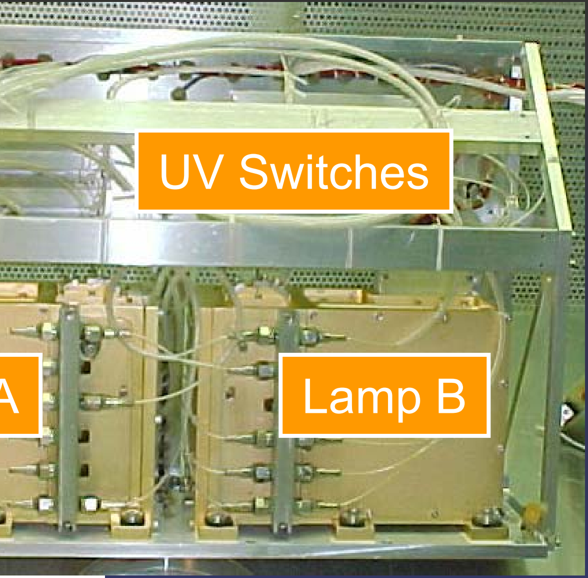
☞ **2) Rotor voltage of ~300 mV**

SC drag excluded:
$a_{DF} < 10^{-6}$ m·s^{-2}, Fall time >9 sec

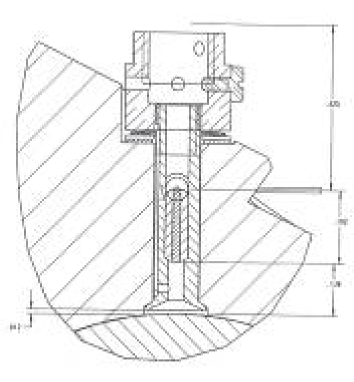
Gyroscope levitates with ~ 200 mV – 500 mV charge

Charge Control: Discharge of Gyro #1





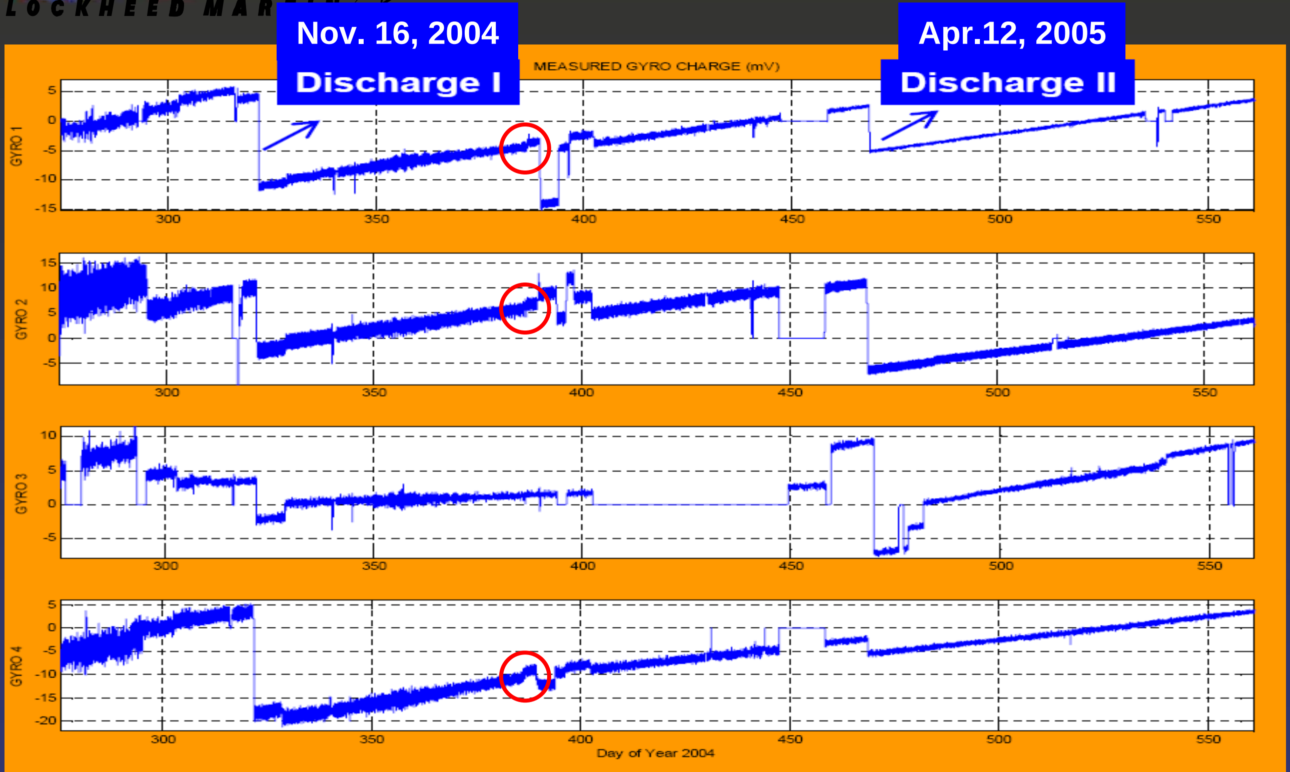
UV Lamp Assembly



UV Electrode

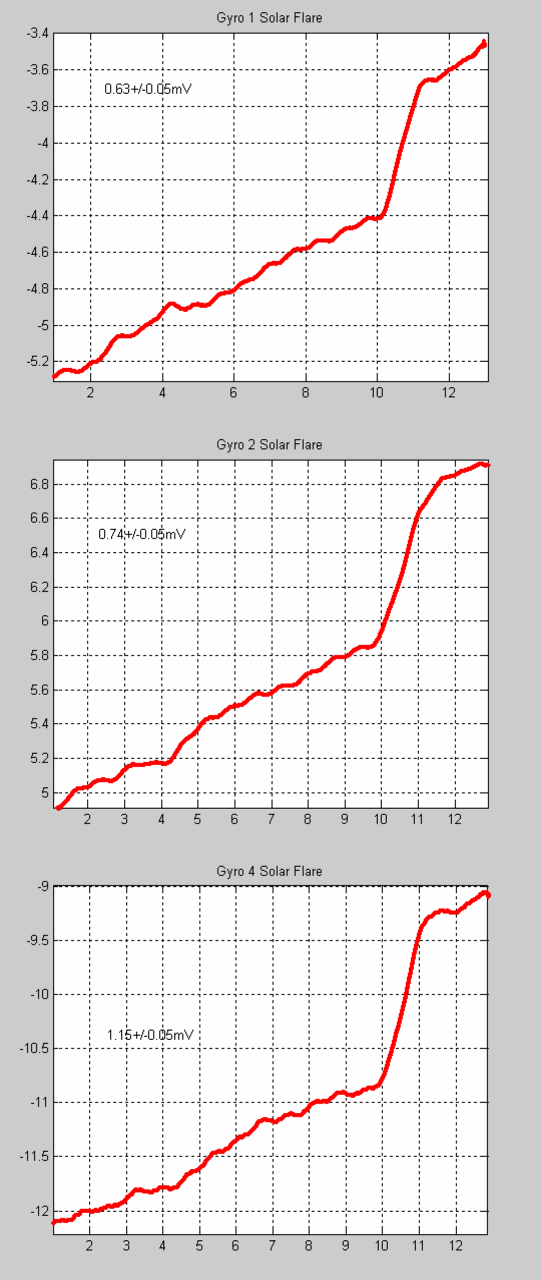
Charge controlled to < 5 mV

Charging History and Rates

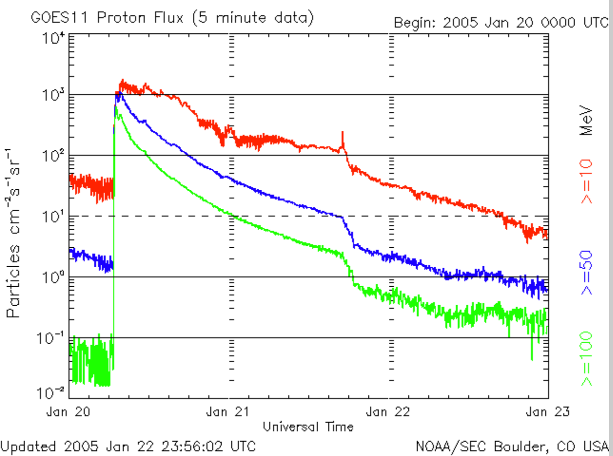

Nov. 16, 2004
Discharge I

Apr.12, 2005
Discharge II

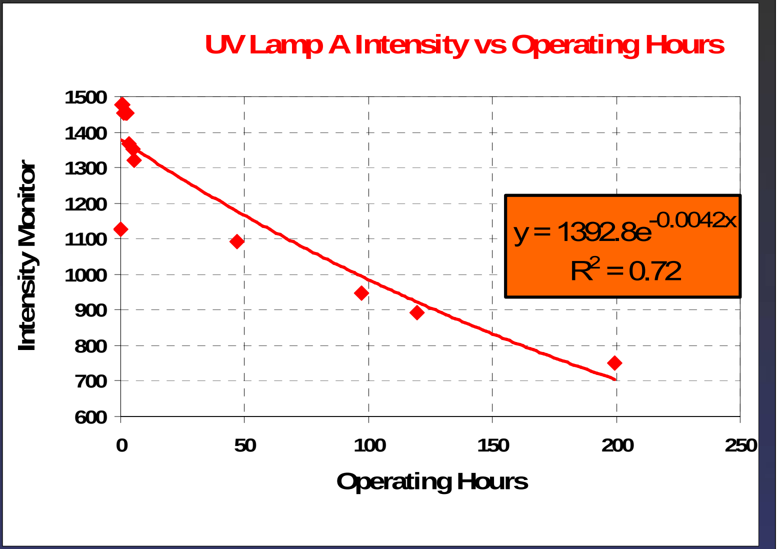
Measured Gyro Charge (mV) vs Day of Year 2004

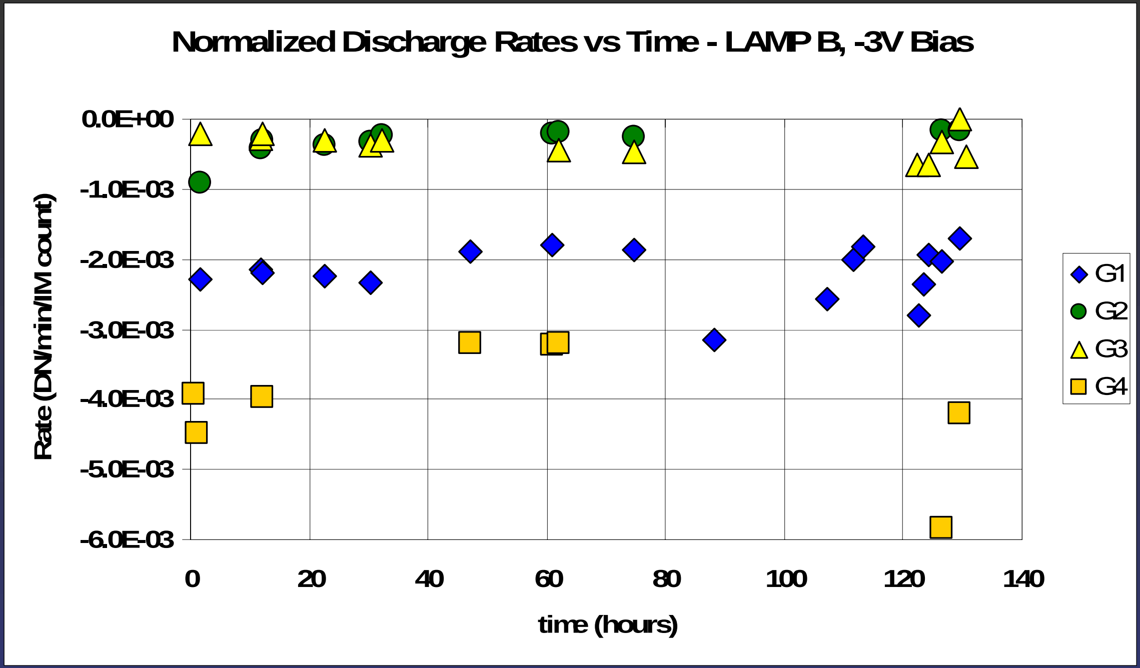


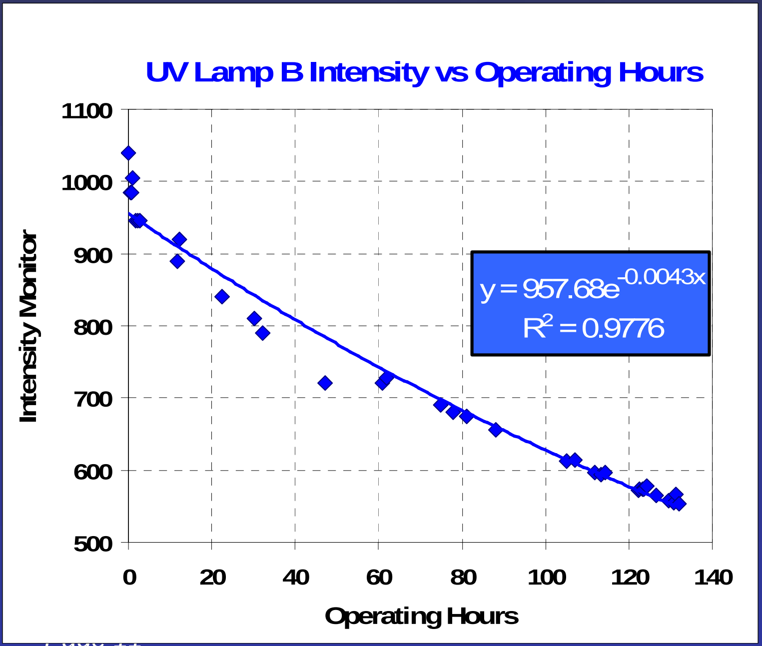
Charging rates to day 390		
	Average Charging Rate	Sun Spot 720
	mV/day	mV
Gyro 1	0.098+/-0.003	0.63+/-0.05
Gyro 2	0.114+/-0.003	0.74+/-0.05
Gyro 4	0.152+/-0.003	1.15+/-0.05



UV Lamps Lifetime


UV Lamp A Intensity vs Operating Hours


Normalized Discharge Rates vs Time - LAMP B, -3V Bias


UV Lamp B Intensity vs Operating Hours

- *UV lamp intensity decay time constant ~ 230 hours*
- **Large variability of discharge rates between gyroscopes**
- **The GP-B Hg UV lamps met all requirements**

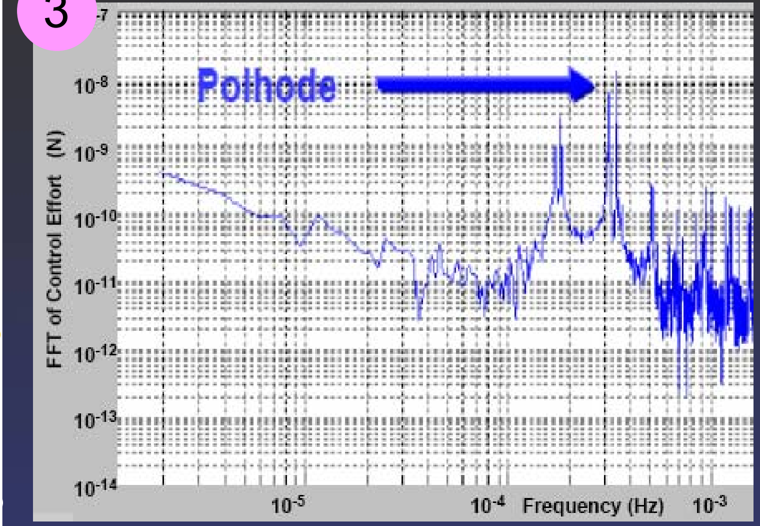
Experimental Observations

Coupling of rotor-fixed frame to the GSS

Modulation at polhode frequency

- 1 Z (telescope axis) bias: 2×10^{-8} N
- 2 Control effort at 1.3Hz spin: 30% of ~2×10^{-7} N
- Position & suspension voltage at 1.3Hz spin: 60nm_{pp}
- 3 Control effort at 80 Hz spin: 30% of ~10^{-8} N
- Orbit instability at polhode = orbit for drag free Gyro3

3



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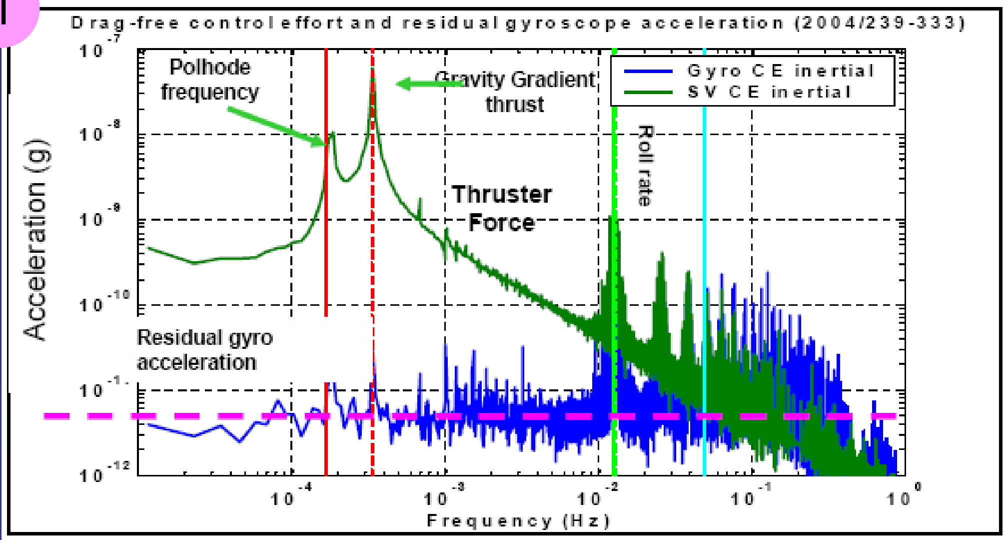

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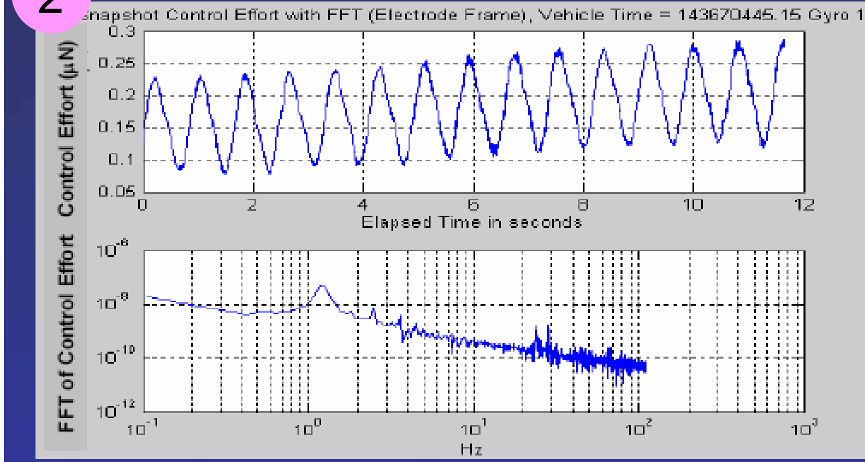


The Patch Effect

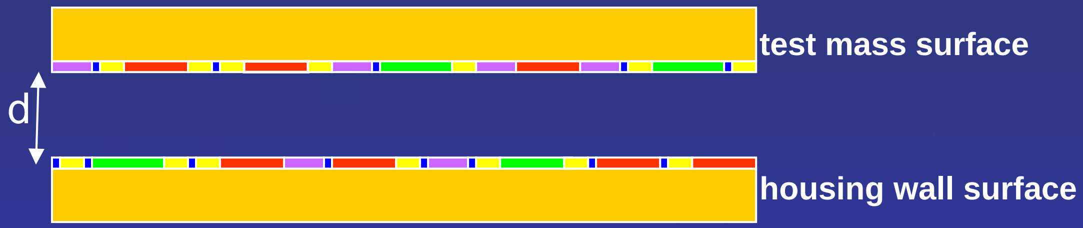
Possible Causes of Coupling

1. Rotor geometry
    a. Mass unbalance: ~10nm (3×10^{-3} of gap)
        ⇨ Small compared to > 10% effects
    b. Surface waviness: ~10nm (3×10^{-3} of gap)
        ⇨ Small compared to > 10% effects
2. Trapped flux interacting with housing
    Three independent calculations
        ⇨ Effect too small by orders of magnitude
3. Non uniform potential of rotor surface ☞
        ⇨ Patch effects consistent with data

Consequences

- ➢ Polhode damping
- ➢ Misalignment torque
- ➢ Spin-down torque
- ➢ Inconsistencies in the charge measurements

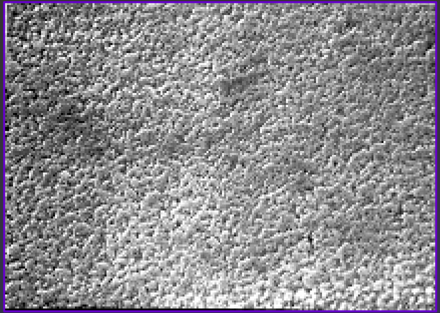
- ➢ Variation of electric potential over the surface
    - ♦ It can arise due to the polycrystalline structure
    - ♦ It can be affected by presence of contaminants
- ➢ Modeled as dipole layer
- ➢ Patch fields present on rotor and housing walls
- ➢ Cause forces and torques between surfaces



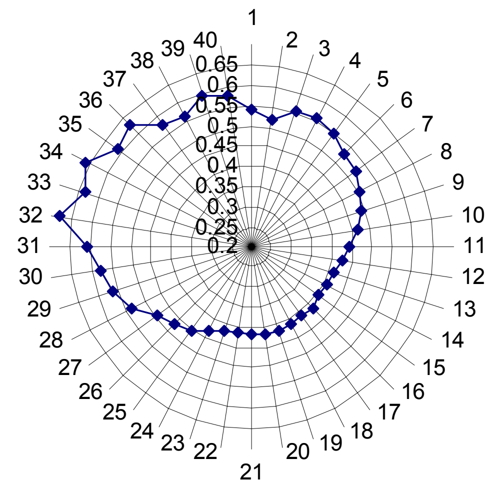
Observations explained by patch effect of ~50-100 mV on rotor and housing

Patch Effect Investigations

- Pre-launch investigation
  - Contact potential differences ~ 0.1V - 1V
  - Patches mitigated/eliminated by minute grain size, 0.1 μm << 30 μm rotor-electrode gap
  - Kelvin probe measurements on flat samples
- Additional ground-based investigations
  - Work function profile via UV photoemission
  - Detailed analytical modeling
  - Kelvin probe measurements

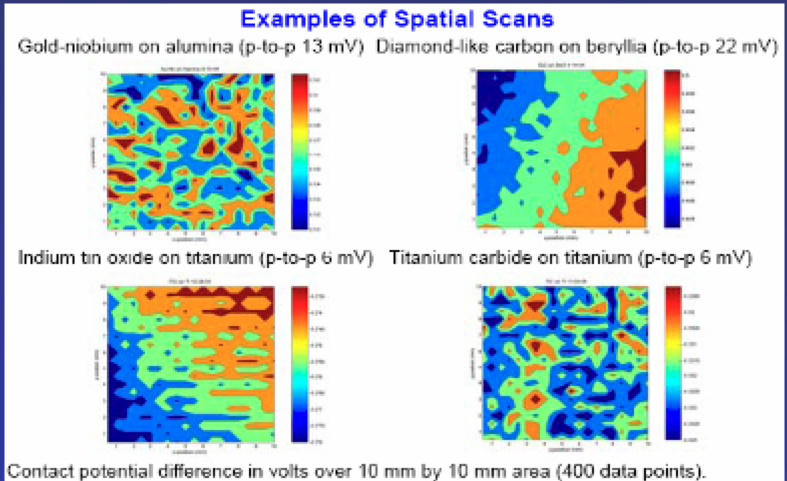


SEM image of rotor Nb film
average grain size 0.1 μm



Work function polar plot,
UV photoemission

Kelvin probe scans



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

Kelvin probe

Talks by Norna Robertson

and Jordan Camp

Charge Measurement by Force Modulation WITH PATCH EFFECT

$$V_{P\pm} = \langle V_{Pe\pm} \rangle - \langle V_{PR\pm} \rangle \qquad V_{Pg} = \langle V_{gH} \rangle - \langle V_{gR} \rangle$$

$$F \equiv F_+ - F_- = \frac{A_+ \varepsilon_0}{d_+^2} \left(V_{e+} + V_{Pe+} - V_R \right)^2 - \frac{A_- \varepsilon_0}{d_-^2} \left(V_{e-} + V_{Pe-} - V_R \right)^2$$

$$F(\omega_C) = \frac{2A\varepsilon_0}{d^2} \left[V_R - \frac{1}{2} \left(V_{P+} + V_{P-} \right) - \frac{\Delta d}{2d} \left(V_{P+} - V_{P-} \right) \right] V_C \cos(\omega_C t)$$

$P \Rightarrow$ patch potential average

$R\pm / H\pm \Rightarrow$ electrode pair rotor/housing side

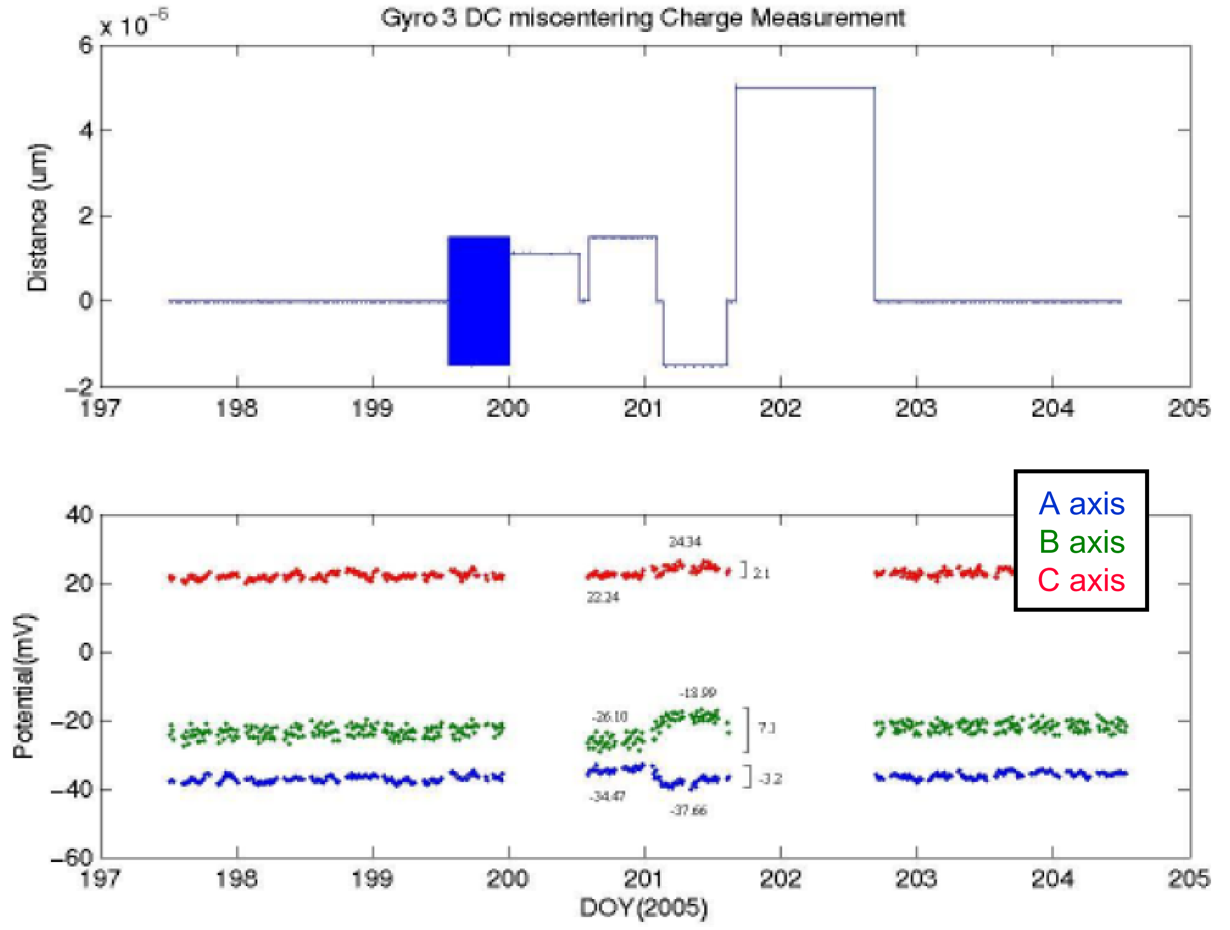
$gH / gR \Rightarrow$ ground plane rotor/housing side

- ***F(ω_C) dependent on $V_{P\pm}$ and Δd***

Charge Measurement with Patch Effects

Ed Fei senior thesis

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



Gyroscope #3 potentials and their shifts due to miscentering

$$V_{RA} \neq V_{RB} \neq V_{RC}$$

$$V_{R(A,B,C)} = f\left(\Delta d_{(A,B,C)}\right)$$

Patches on test mass and housing require additional measurements and modeling

The Spin Averaging GP-B Gyroscopes

Ed Fei senior thesis

Rotor Patches Δd=0

$$V_{RA} = V_R + \frac{V_1 + V_2}{2}$$

$$V_{RB} = V_R + \frac{V_1 + V_2}{2}$$

$$V_{RC} = V_R + V_3$$

$$V_{RA} = V_{RB} \neq V_{RC}$$

$$V_{R(A,B,C)} \neq f\left(\Delta d_{(A,B,C)}\right)$$

Rotor Patches Δd≠0

$$V_{RA} = V_R + \frac{V_1 + V_2}{2} + \Delta d_A \left(V_1 - V_2\right)$$

$$V_{RB} = V_R + \frac{V_1 + V_2}{2} - \Delta d_B \left(V_1 - V_2\right)$$

$$V_{RC} = V_R + V_3$$

$$V_{RA} \neq V_{RB} \neq V_{RC}$$

$$V_{R(A,B)} = f\left(\Delta d_{(A,B)}\right)$$

$$V_{RC} \neq f\left(\Delta d_C\right)$$

Rotor + Electrode Patches Δd≠0

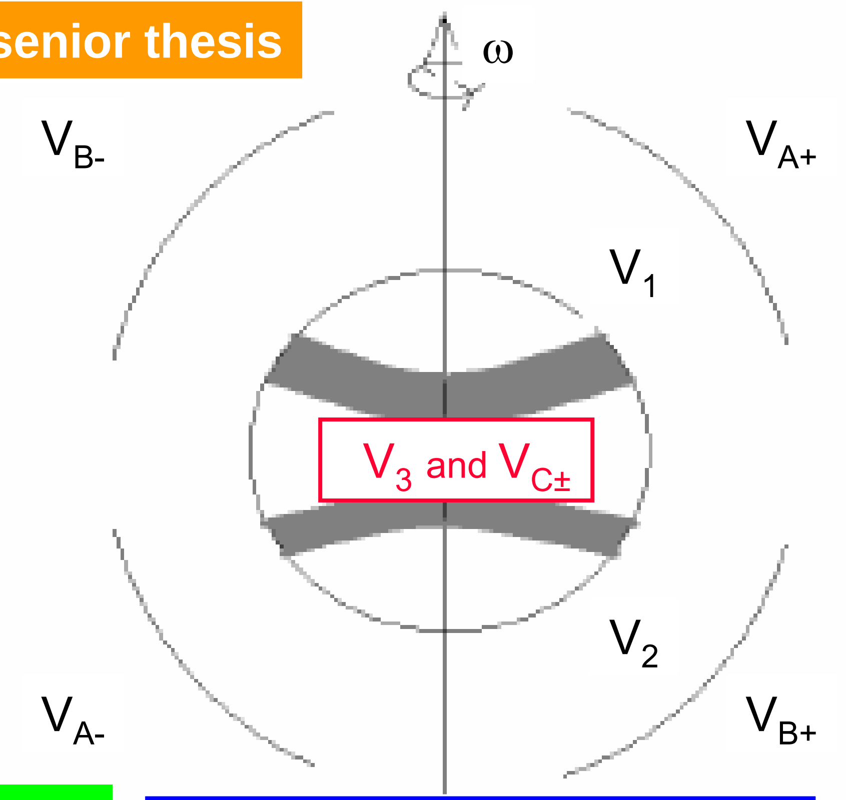
$$V_{RA} \neq V_{RB} \neq V_{RC}$$

$$V_{R(A,B,C)} = f\left(\Delta d_{(A,B,C)}\right)$$

$$V_{RA} = V_R + \frac{\left(V_1 - V_{A+}\right) + \left(V_2 - V_{A-}\right)}{2} + \Delta d_A \left[\left(V_1 - V_{A+}\right) - \left(V_2 - V_{A-}\right)\right]$$

$$V_{RB} = V_R + \frac{\left(V_1 - V_{B+}\right) + \left(V_2 - V_{B-}\right)}{2} - \Delta d_B \left[\left(V_1 - V_{B+}\right) - \left(V_2 - V_{B-}\right)\right]$$

$$V_{RC} = V_R + V_3 - \frac{V_{C+} + V_{C-}}{2} - \Delta d_C \left(V_{C+} - V_{C-}\right)$$



- **Patches on test mass and electrodes required for data modeling**
- **With patches on test mass and electrodes the GP-B data is insufficient for unique solution**

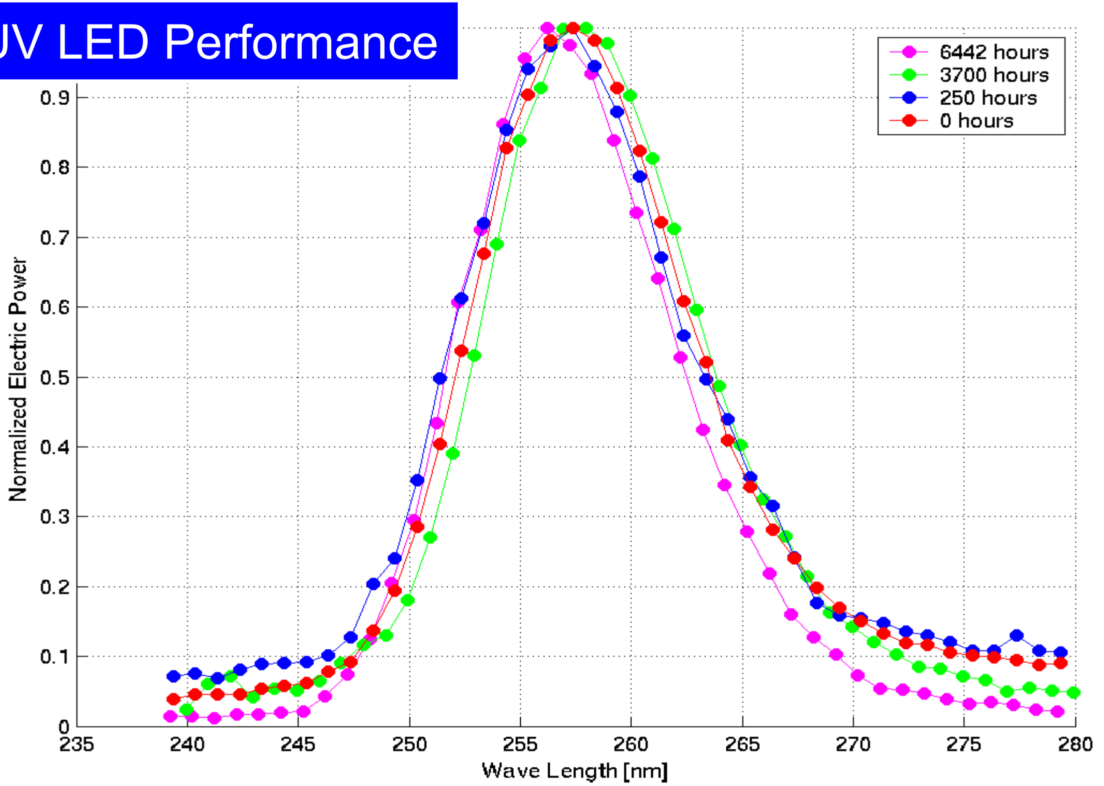
The Path to Future Experiments I
UV Sources

➢ 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

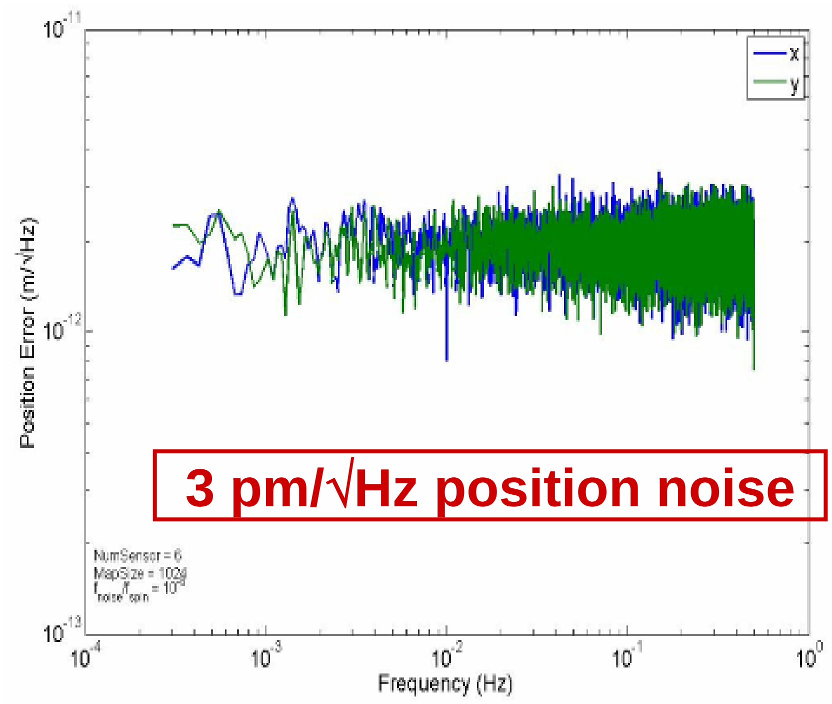
- Materials development
- Ground testing

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

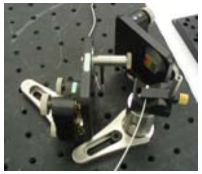
A. Charge measurement
- **Not required**
- Frequency of measurement below SM band
- Continuous measurement

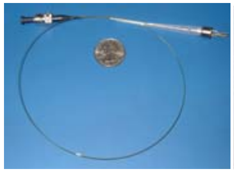
B. Charge generation (use UV LED)
- **Continuous**
- Frequency of discharging below SM band

C. Charge control loop
- **Not required**
- Frequency of discharging below SM band
- Continuous control

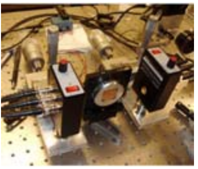
NASA- Stanford Gravity Reference NanoSatellites

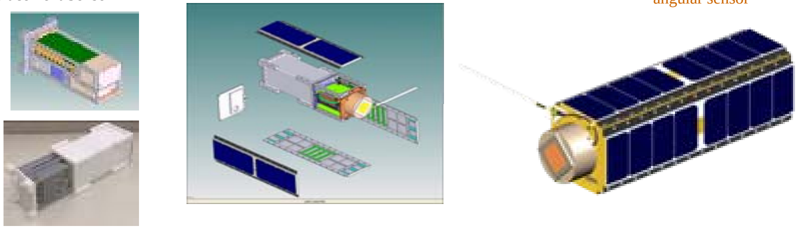
Towards ultra high precision gravitation reference sensors and multi vehicle space interferometry


1 pm/Hz$^{1/2}$ Grating Cavity Displacement Sensor


256 nm Deep UV LED


Roundest sphere and drag free sensor


1 nrad/Hz$^{1/2}$ grating angular sensor

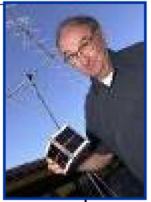


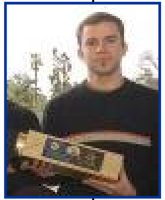
The Program

- Frequent launches on ride-along platforms
- Standard low cost bus configurations
- 12 - 24 month project duration

The Benefits

- New science: Physical, Life, Engineering
- Critical technology demonstrations
- Fast advance of NASA mission objectives
- Train engineers and scientists for the future


Stanford NANOSAT


AMES GENESAT

•NASA-Ames has a spaceflight proven nanosatellite Platform which can accommodate and demonstrate technologies critical for implementing a low-cost, fast response Space Gravity Reference program

• Stanford has the gravity reference technologies and proven expertise and track record

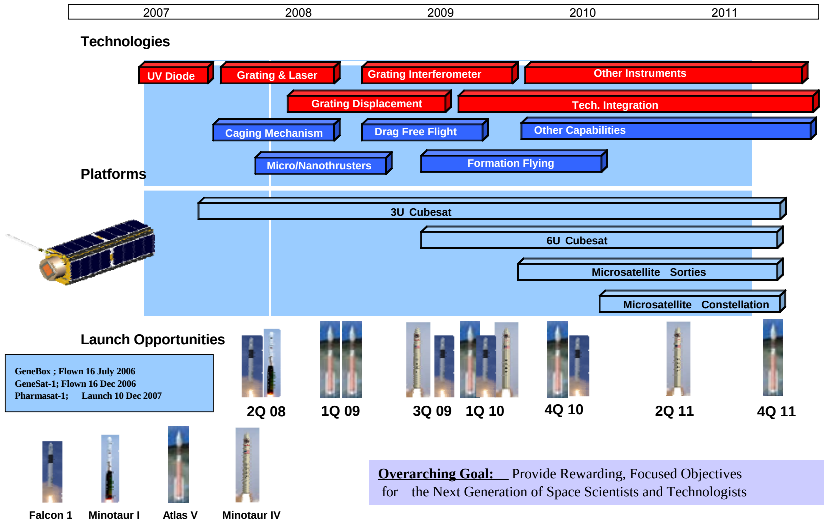
• Under this collaborative effort,NASA will provide the spacecraft, payload integration, and mission ops support

• Stanford will provide the GRS Payloads and instruments

•Approximately one mission per year is planned, in a phased, iterative development approach, beginning in 2008

• Estimated total cost per mission is $3-5M, depending on mission and technological complexity

Roadmap

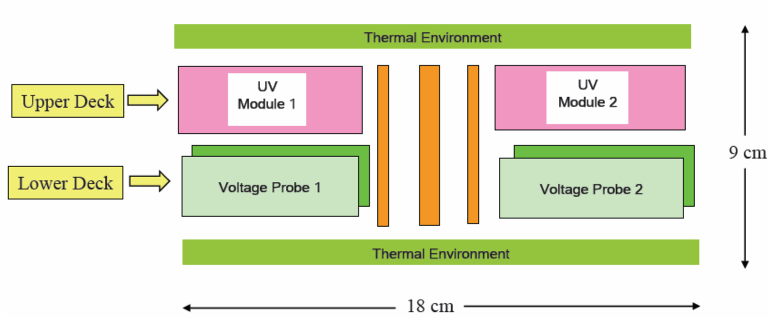


Overarching Goal: Provide Rewarding, Focused Objectives for the Next Generation of Space Scientists and Technologists

Patent pending

The First Planned Project: UV LED Space Demonstration 2008-2009

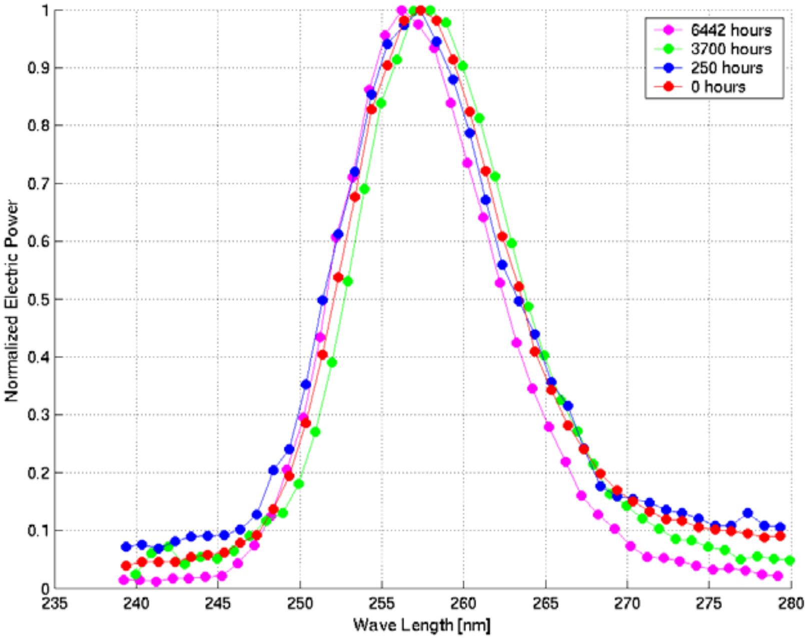
- Charge management for high precision GRS
- Calibration source for UV and X-ray telescope
- Telescope surface and window de-charging
- Life maintaining system for manned space flight



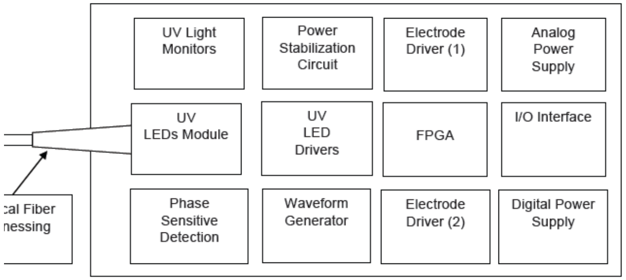
Payload Configuration: Side View

Nick Leindecker

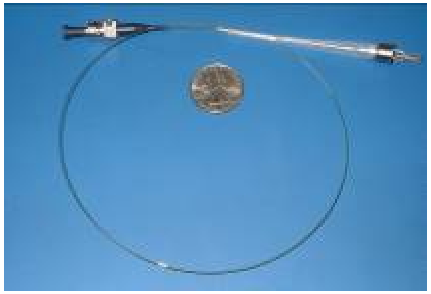
GENESAT



UV LED Performance



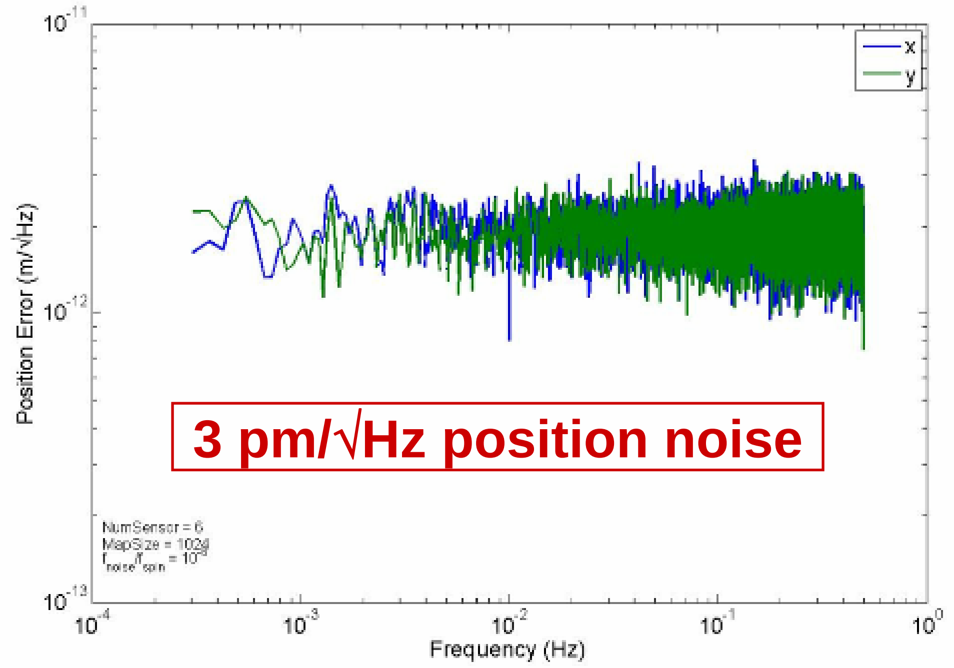
Payload Functional Components



UV LED

Optical Position Determination: Simulation

- ➢ Spinning sphere, 10 Hz
- ➢ 2 Dimensional
- ➢ 6 Optical sensors
- ➢ Experimental laser noise
- ➢ 50 nm position noise
- ➢ 50 nm surface roughness
- ➢ 1024 map size
- ➢ $f_{noise}/f_{spin} = 10^{-6}$



3 pm/√Hz position noise