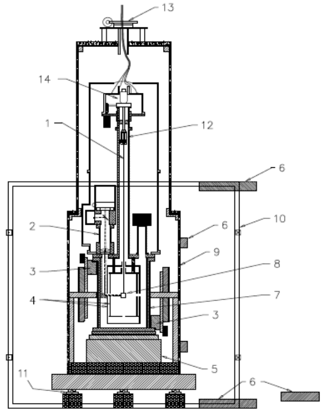
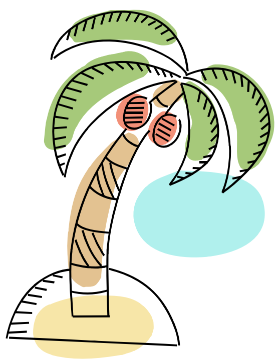
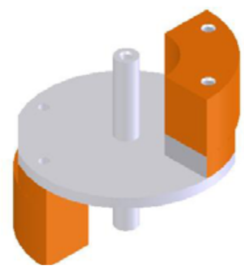


How I Spent my Summer Vacation





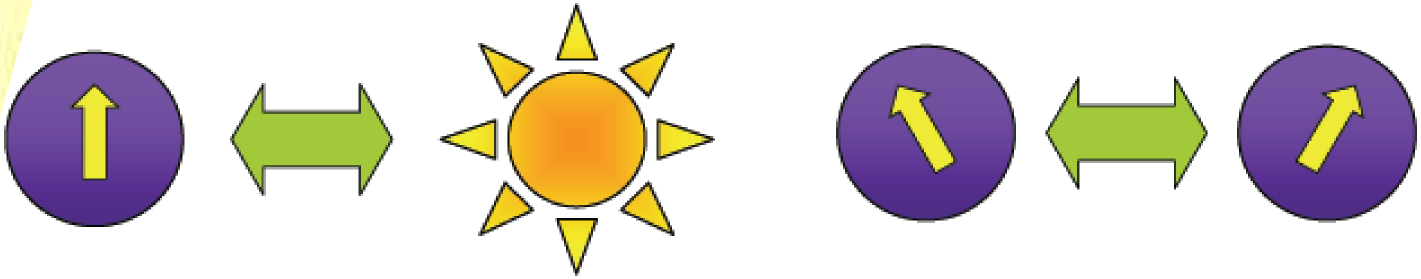
Searching for gravitational force violations and a theoretical 5th force.

Overview

- **Better Understanding of Forces**
  - Spin-Coupled Force
  - Inverse Square Law
  - Weak Equivalence Principle
- **Eöt-Wash Instrumentation**
- **Contributions and Improvements**
  - Magnetic Flux Detection
  - Pendulum for Sensitive Detection of Gravity Gradients

Spin-Coupled Force

- Theoretical 5th force coupling to fermion spin
- Force mediated by a new particle (axions?)



$V_{md} \propto \sigma_e \cdot r$ spin couples to point mass

$V_{dd} \propto \sigma_1 \cdot \sigma_2$ spins of two spin sources couple

Inverse Square Law Violation

$$F = \frac{Gm_1m_2}{r^2}$$

What if gravity is mediated by the exchange of a graviton AND another particle?

$$F = \frac{Gm_1m_2}{r^2}\left[\, 1 + \alpha\,(1 + r/\lambda)\, e^{-r/\lambda} \,\right]$$

2^{nd} term called Yukawa interaction

Consequence: $1/r^2$ is a large-scale limit on gravity

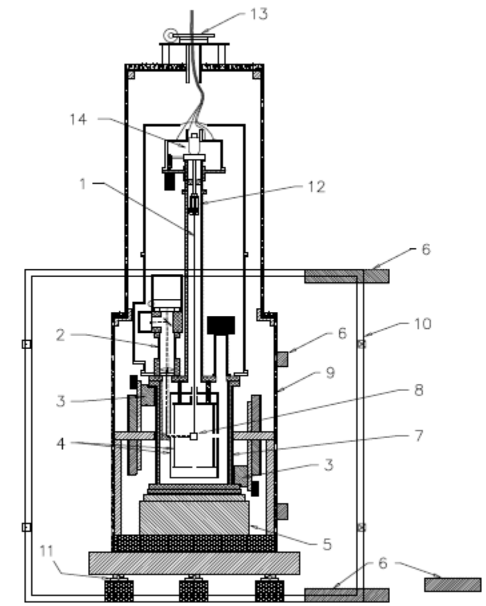
Weak Equivalence Principle Violation

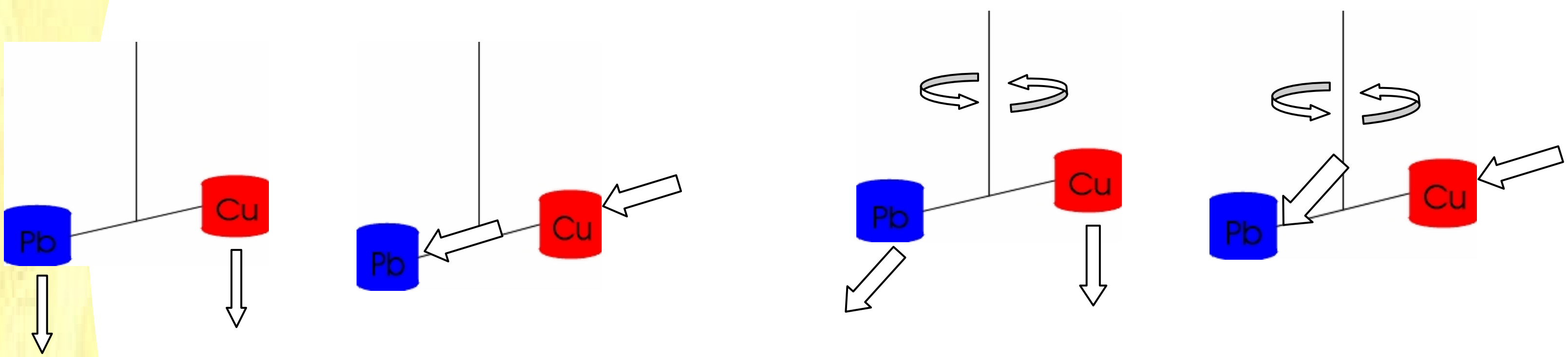
- WEP says inertial mass = gravitational mass

$$\left.\begin{array}{l} F = m_G g \\ F = m_I a \end{array}\right\} a = \frac{m_G}{m_I} g$$

- What if $\mathbf{F}_G \neq \mathbf{F}_I$?
- Two materials with same *weight* won't necessarily have the same $\boldsymbol{F}_I$

Torsion Balance

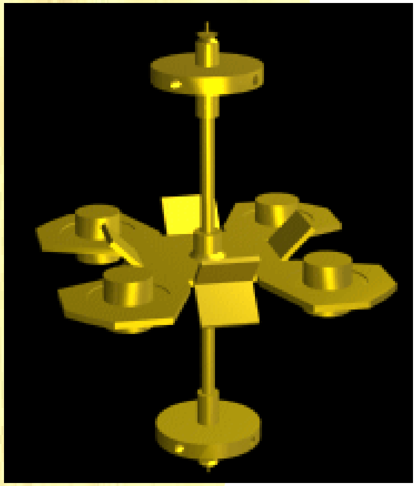


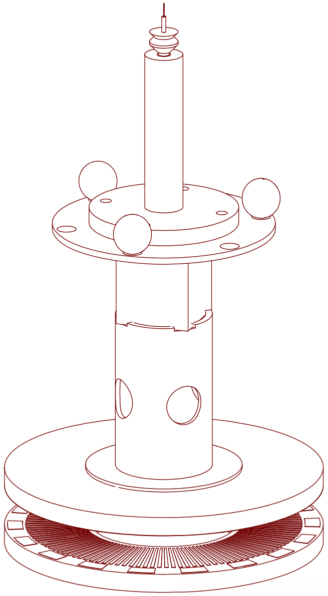


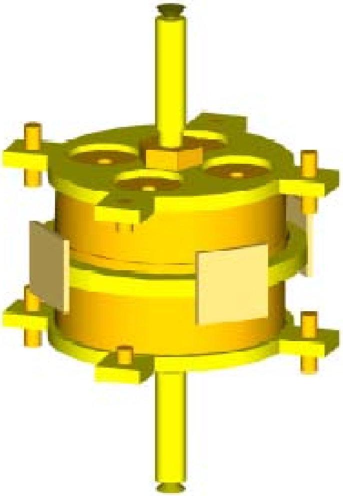
Uneven forces create torque on pendulum

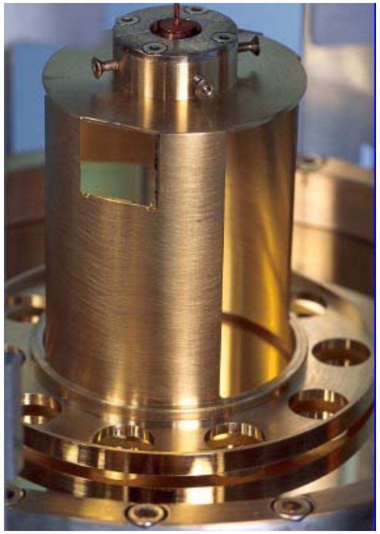
$$\Theta = T / \kappa$$

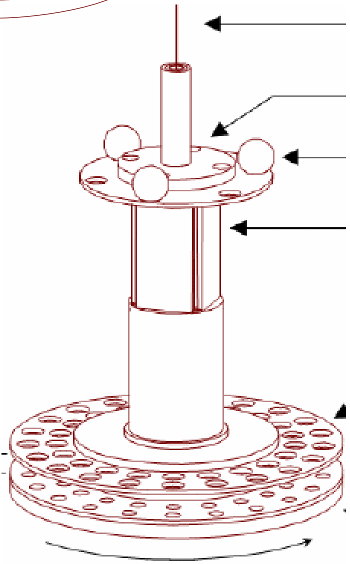
Eot-Wash Pendulums





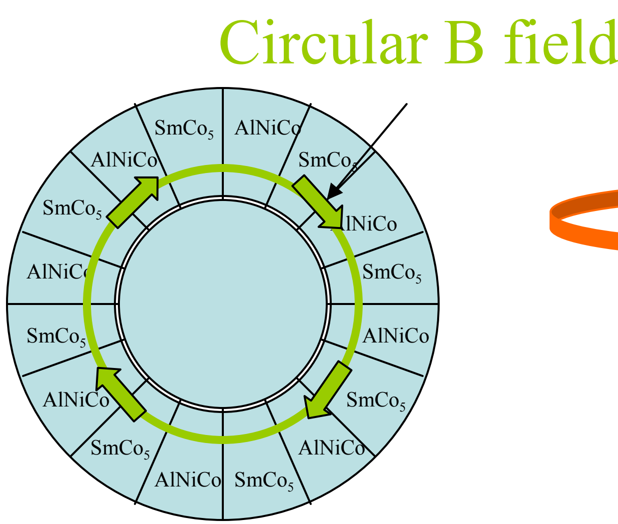


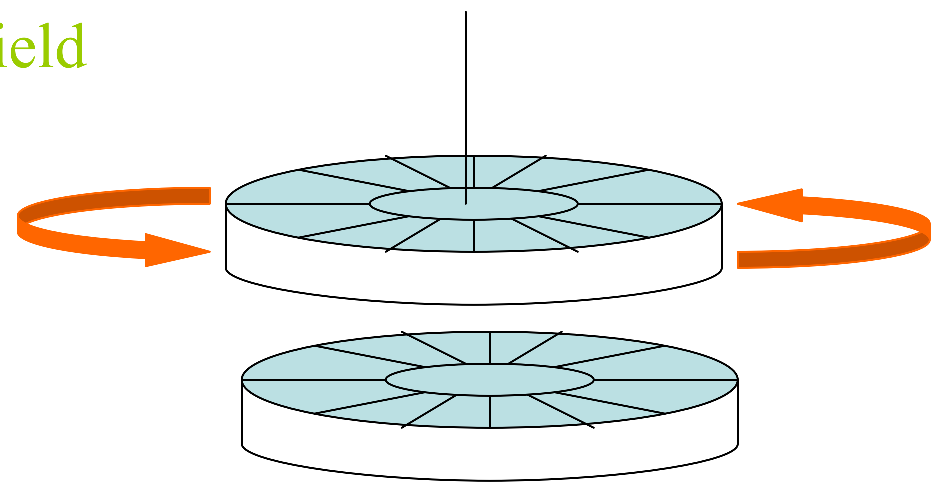




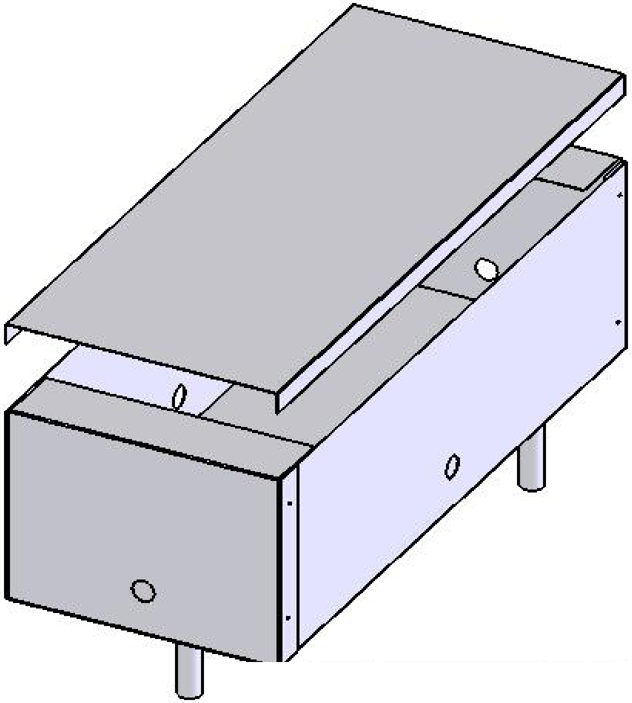
Spin Force: Experimental Setup

- Trapezoidal magnets form 10 spin dipoles
- Spin moments align to minimize V_{dd} → Torsion of pendulum
- Must evenly magnetize spin pendulum to minimize external flux





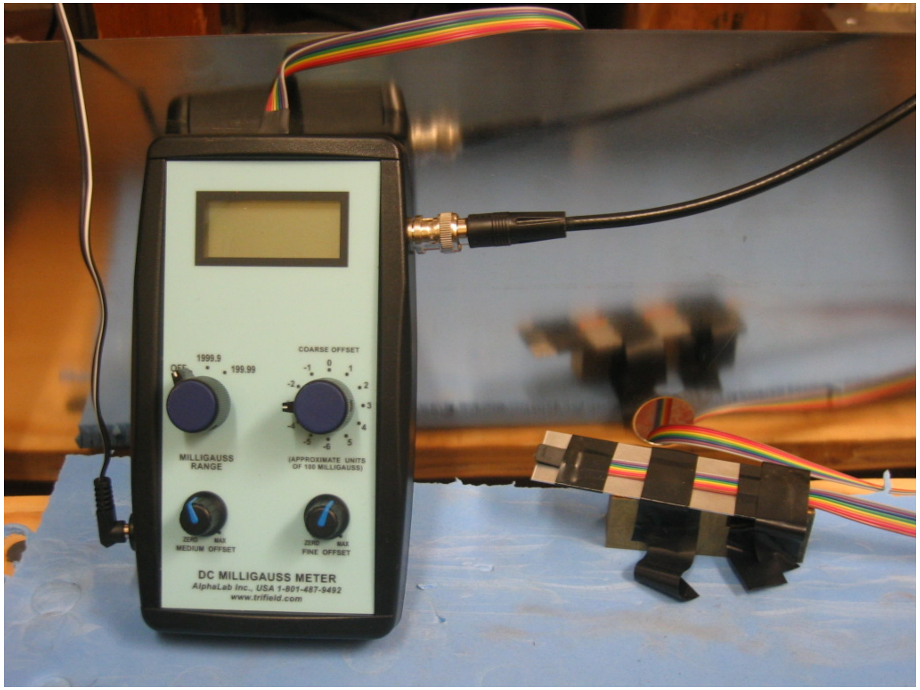
Magnetic Shield Box



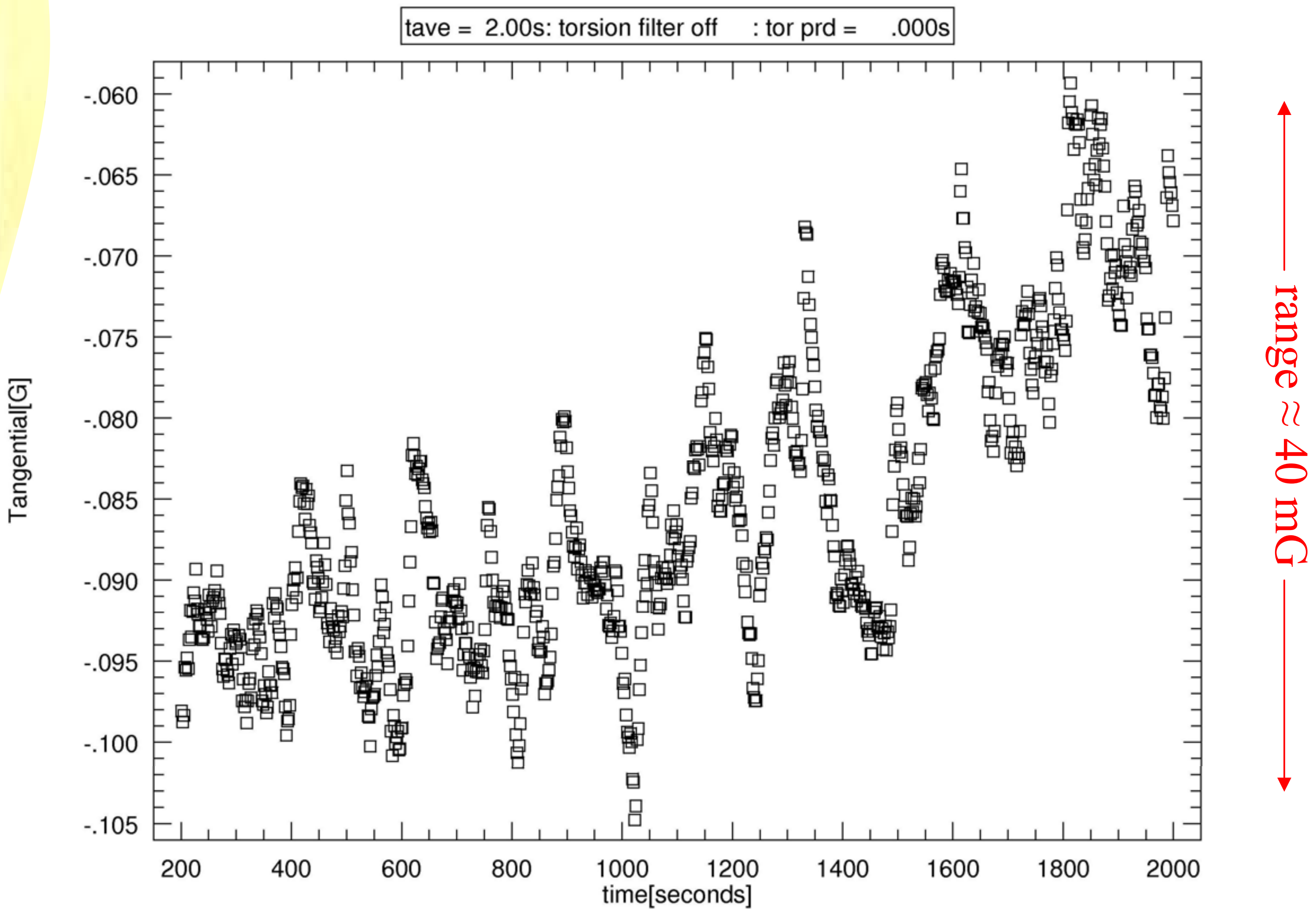
Permits us to determine external magnetic flux of the spin pendulum and make appropriate corrections.

Magnetoresistance Magnetometer

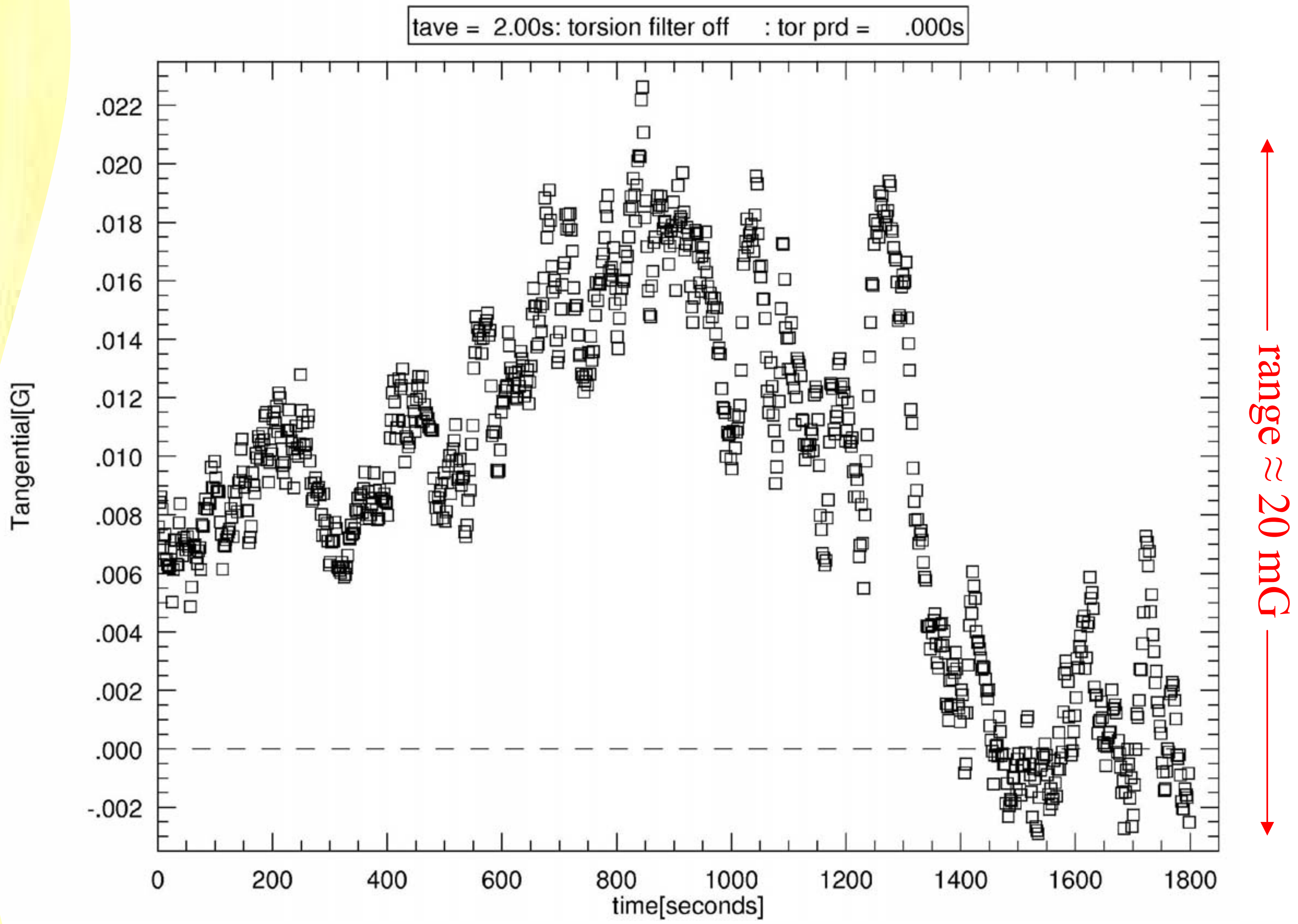
- Range of 2000 milligauss
- Resolution of 0.01 milligauss
- Ideal size



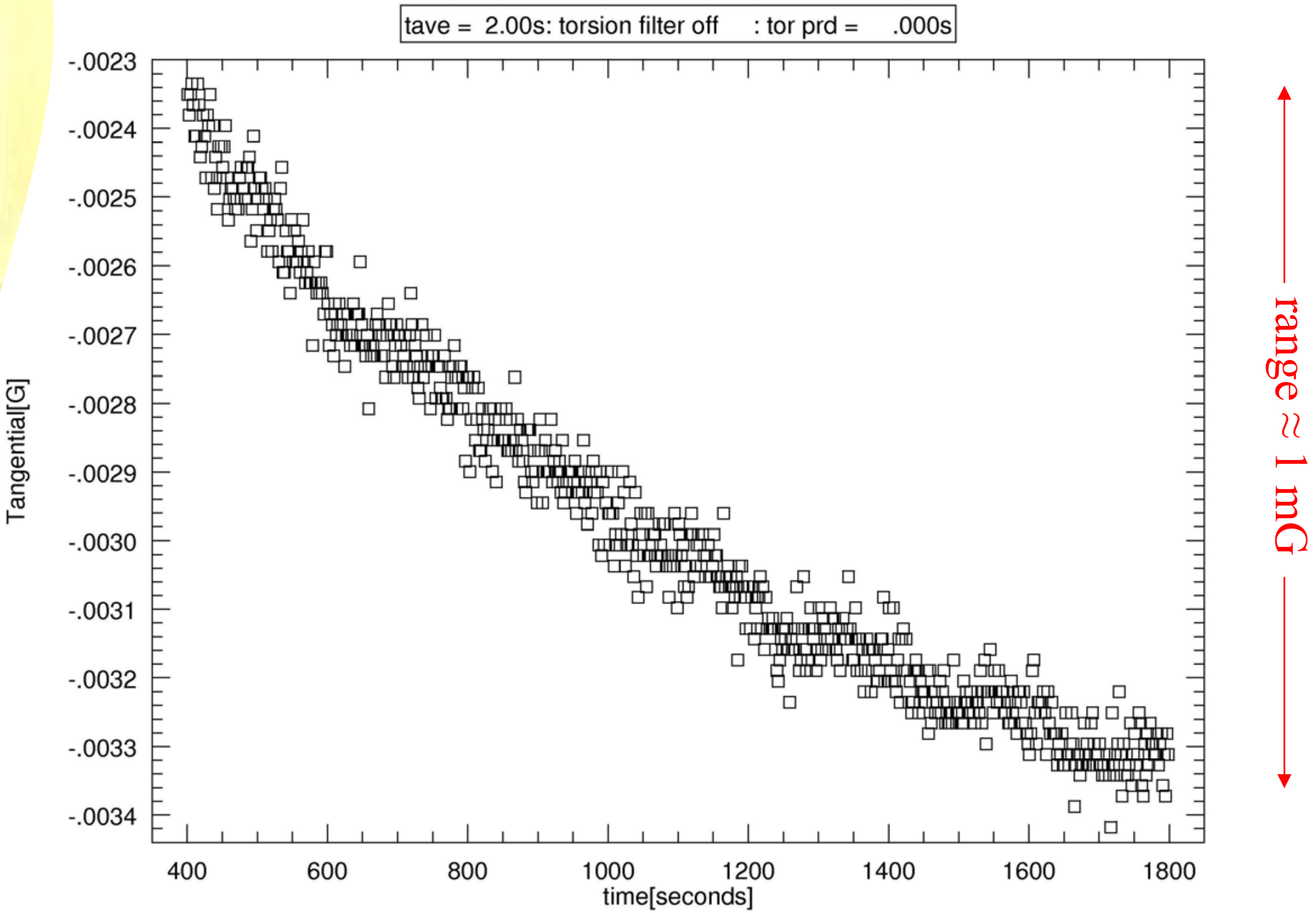
Noise Run:
Old Shield, Old Magnetometer



Noise Run:
New Shield, Old Magnetometer



Noise Run:
New Shield, New Magnetometer

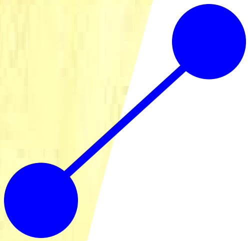


Gravity Gradient Pendulum: *Why do it?*

- Eot-Wash pendulums study fundamental forces
  - Spin-coupled force
  - Different law of gravity
- Pendulums highly sensitive to changing gravitational fields
- Measure effects of known gravitational forces and subtract from pendulum measurements

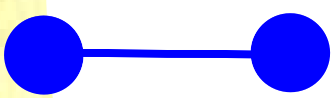
Pendulum Design:
The Gravitational Quadrupole Moment

$$q_{lm} = \int \rho_p(r)\, r^l\, Y^*_{lm}(r) d^3r$$



large q_{21}

$$q_{21} = \frac{-1}{2}\sqrt{\frac{15}{2\pi}} \int \rho_p(r)\, r^2 \sin\theta \cos\theta\, e^{-i\phi} d^3r$$

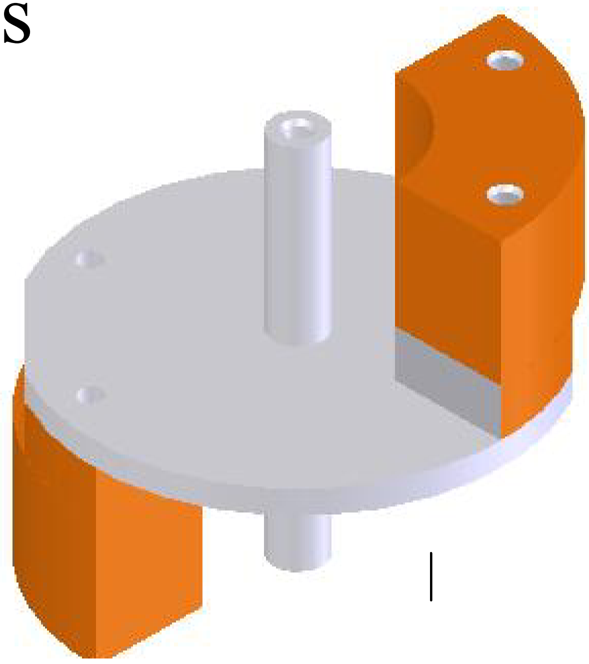


large q_{22}

$$q_{22} = \frac{1}{4}\sqrt{\frac{15}{2\pi}} \int \rho_p(r)\, r^2 \sin^2\theta\, e^{-2i\phi} d^3r$$

q2 Pendulum

- q_{21} = -110.02 gcm^2 (10000x greater than normal)
- q_{22} = 62.79 gcm^2
- Mass and dimensions similar to other pendulums



Effect of Gravity Gradients on Pendulum

Pendulum angle of deflection:

$$\Theta_g = T_g / \kappa = -4\pi i G/\kappa \sum \frac{1}{2l + 1} \sum \bar{m} q_{lm} Q_{lm} \text{ x } e^{-imwt}$$

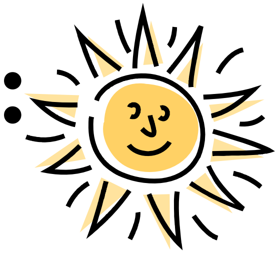
Gravitational Multipole Field caused by Environmental Factors:

$$Q_{lm} = \int \rho_s(r')r'^{-(l + 1)} Y_{lm}(r')d^3r$$

Torsion balance is capable of detecting $\Theta_g \geq 5$ nrads/day

→ $Q_{2m} \geq 2 \text{ x } 10^{-5}$ g/cm^3

Possible Q_{2m} Contributors: Sun and Moon



Time of Day	Θ sun	Q_{21} (x 10^{-7})	Q_{22} (x 10^{-7})	Θ moon	Q_{21} (x 10^{-7})	Q_{22} (x 10^{-7})
6:00 AM	90	0	2.2	150	4	1.16
8:00 AM	66	-1.64	1.84	129	4.52	2.79
10:00 AM	41	-2.18	0.947	105	2.31	4.31
12:00 PM	20	-1.41	0.257	83	-1.12	4.55
2:00 PM	-25	1.68	0.393	63	-3.74	3.67
4:00 PM	-48	2.19	1.22	50	-4.55	2.71
6:00 PM	-73	1.23	2.01	141	4.52	1.83
8:00 PM	-96	-0.458	2.18	156	3.43	0.764
Closest approach r (sun) = 1.497E13 cm r (moon) = 35639888500 m	90	0	2.29	90	0	6.27

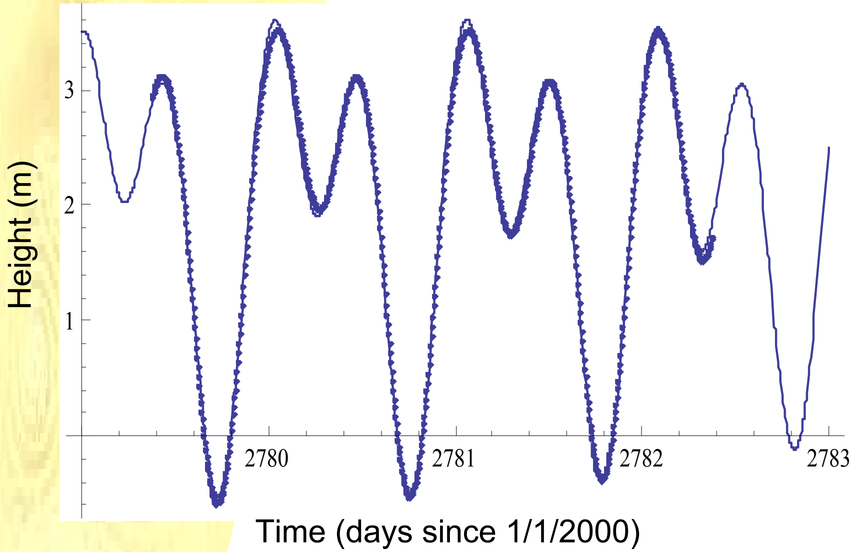
Possible Q_{2m} Contributors: Daily Traffic

Location	Mass (g)	Distance (cm)	Θ (degrees)	Q_{21}	Q_{22}
Alex 1m away	54431.08	100	90	0	2.10×10^{-2}
Alex 2m away	54431.08	200	90	0	2.63×10^{-3}
Nikolai's office	74842.74	320.79	18.16	-5.19×10^{-4}	8.51×10^{-5}
Office next to Nikolai's	217724.34	476.11	50.19	-7.67×10^{-4}	4.60×10^{-4}
Parking Lot - Cars	7801788	3000	7	-2.70×10^{-5}	1.66×10^{-6}
Parking Lot - UPS Delivery Truck	4082331	2700	2	-5.59×10^{-6}	9.76×10^{-8}
Parking Lot - GMC Delivery Truck	4082331	2000	3	-2.06×10^{-5}	5.40×10^{-7}

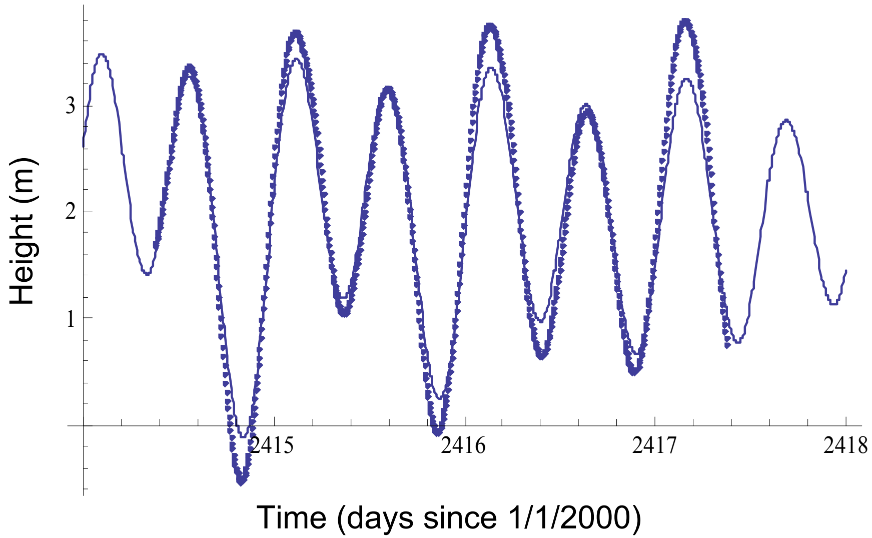
Possible Q_{2m} Contributors:
Puget Sound Tides

Location	Mass–HT (g)	Mass-LT (g)	Distance (cm)	Q_{22} - HT	Q_{22} - LT	ΔQ_{22}
All mass centered in middle of Elliot Bay	9.31×10^{14}	8.80×10^{14}	7.83×10^{5}	7.49×10^{-4}	7.08×10^{-4}	4.10×10^{-5}
All mass centered farthest from UW	9.31×10^{14}	8.80×10^{14}	1.00×10^{6}	3.60×10^{-4}	3.40×10^{-4}	2.00×10^{-5}

Mapping the Tides



Curve fit to 2007/2008 data

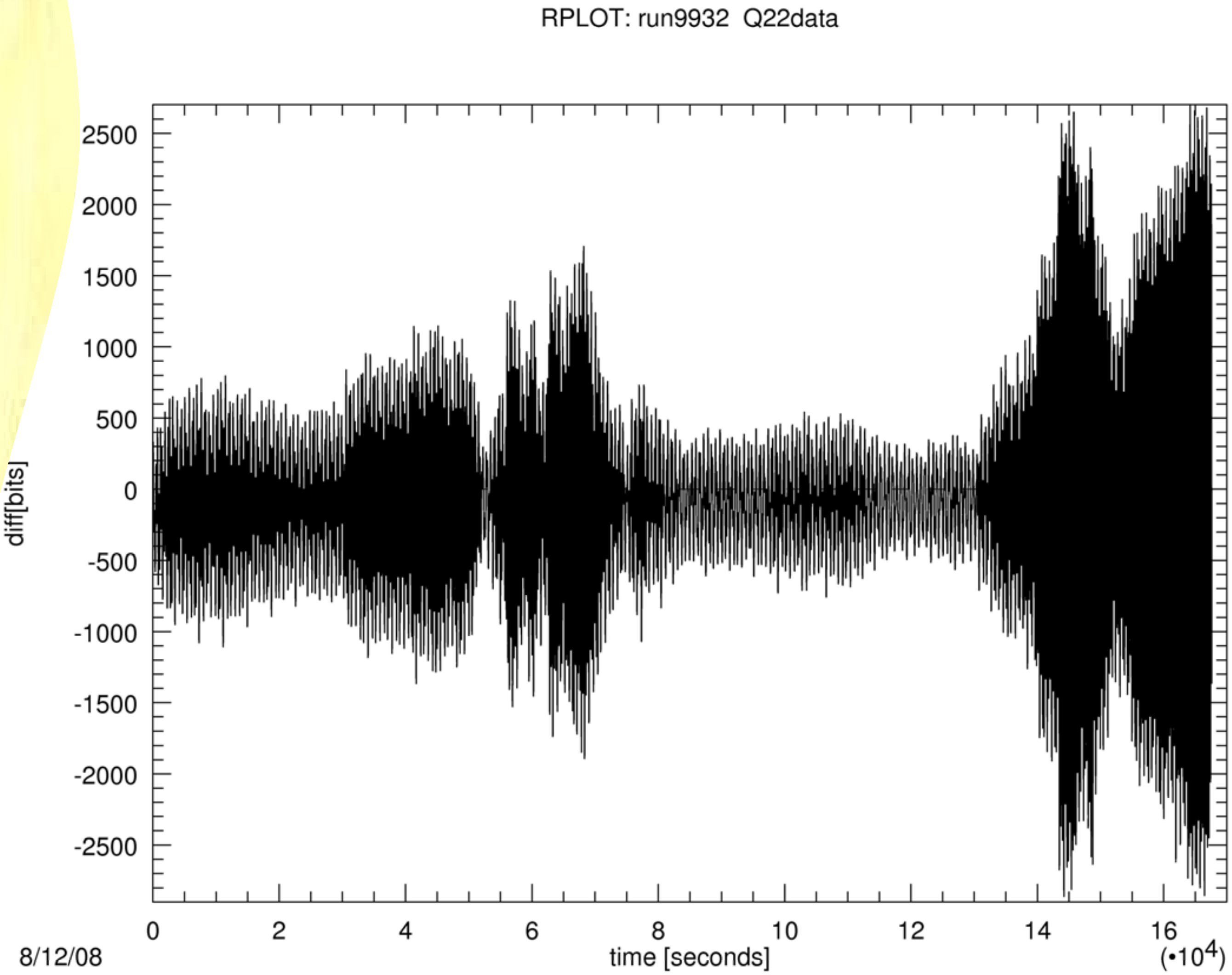


Compared with 2006 data

Puget Sound Tides Function

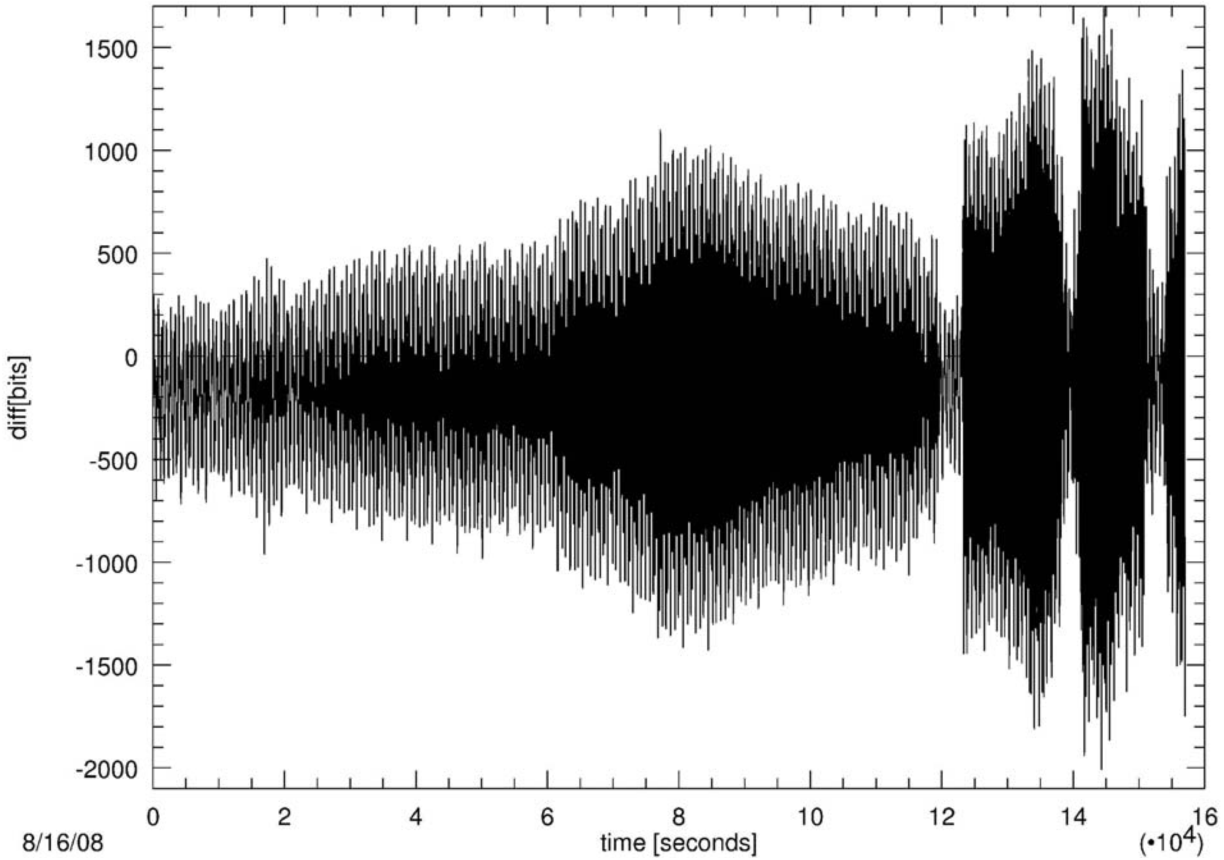
$$h(t) = 1.405 \, Sin\,[(2\pi\,(1.00274)\,x + 2.98127] + 0.548\,Sin[(2\pi\,(0.92954)\,x + 5.60001]$$
$$+ -0.978\,Sin\,[(2\pi\,(1.93227)\,x + 0.61891] + 0.282\,Sin[(2\pi\,(2)\,x + 0.875285]$$
$$+ 0.138\,Sin\,[(2\pi\,(1.89598)\,x + 1.90958] + 0.709\,Sin[(2\pi\,(0.99726)\,x + 1.52675]$$
$$+ 0.022\,Sin[(2\pi\,(3.86455)\,x + 2.41113] + 1.96$$

Sample Pendulum Run



Over the course of 2 days: 8/12/08 – 8/14/08

Daily Fluctuations



Data taken from Saturday, 8/16 through Monday, 8/18

Program detects daily modulation in theta:

Direction 1: -91.32 ± 15.92 nrad

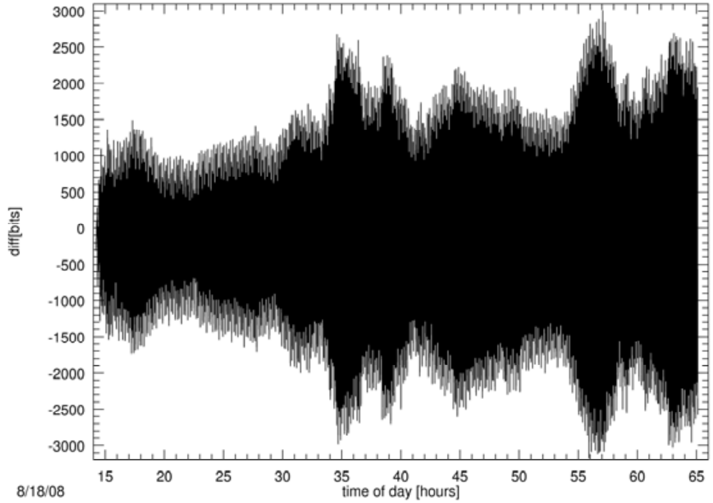
Direction 2: 84.48 ± 15.92 nrad

Daily Fluctuations

Weekday Amplitude:

Direction 1 = 146 +/- 44 nrad

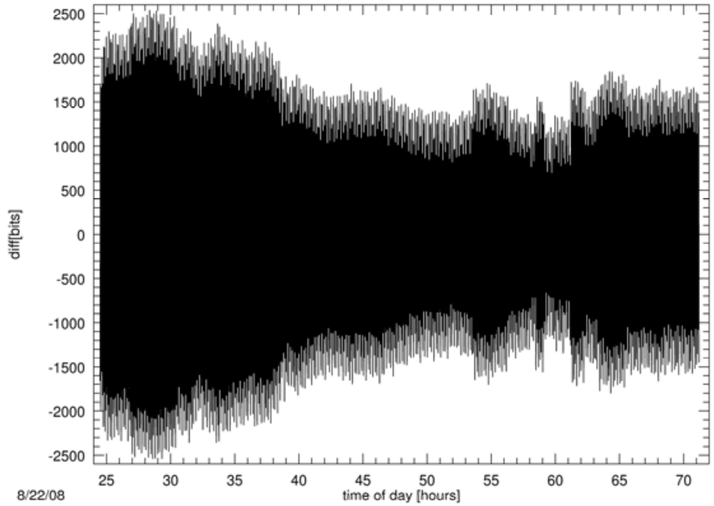
Direction 2 = 125 +/- 44 nrad



Weekend Amplitude:

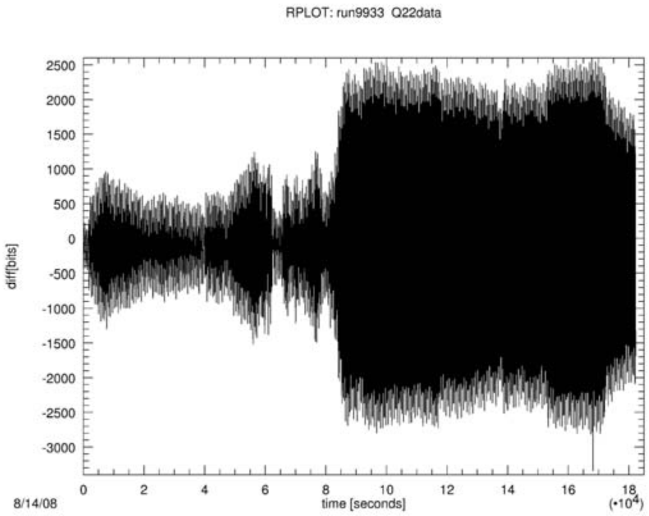
Direction 1 = 6.3 +/- 3.2 nrad

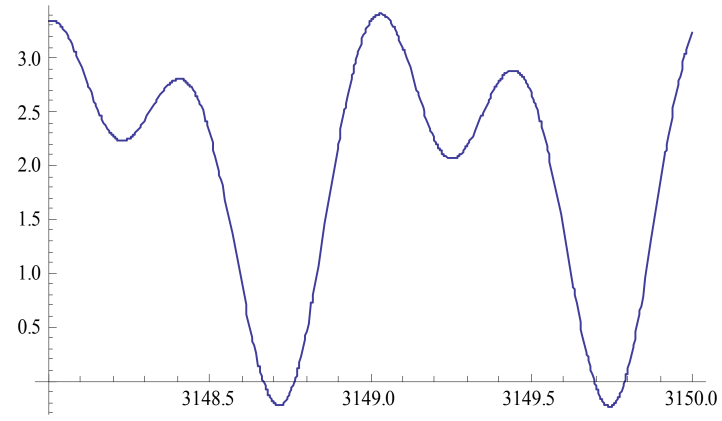
Direction 2 = 41 +/- 3.2 nrad



Tidal Fluctuations

- Pendulum movement tracked for 10 days
- Program used to compare Pendulum Run data to Puget Sound Tidal Function

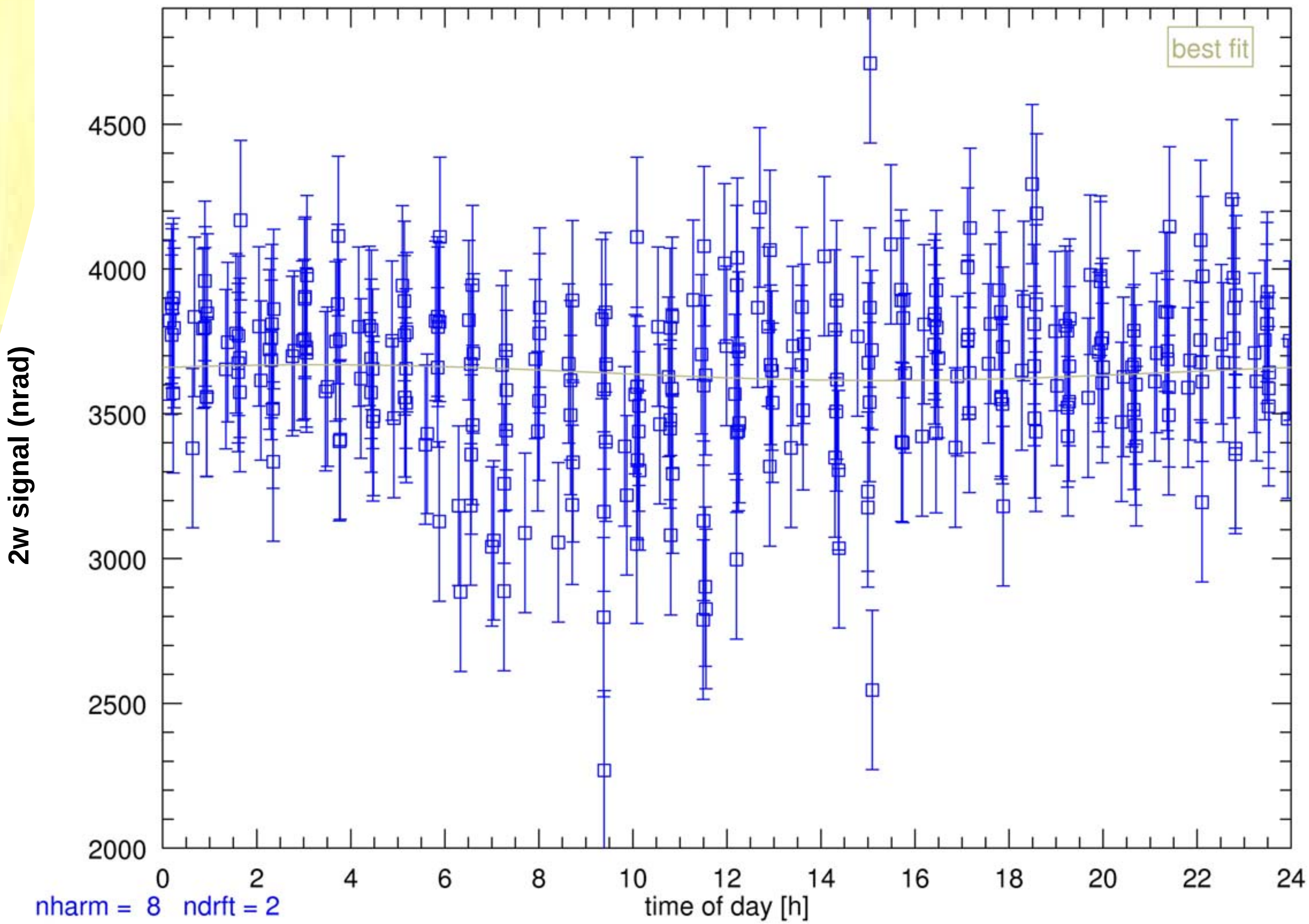




Modulation in theta due to tidal forces:

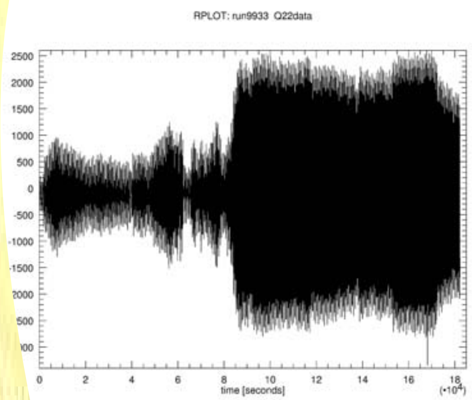
34 $\pm$ 14 nrad

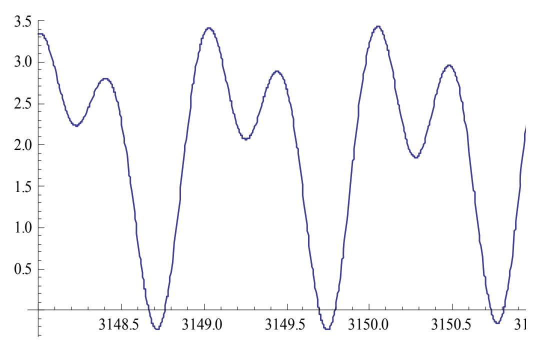
Solar Fluctuations

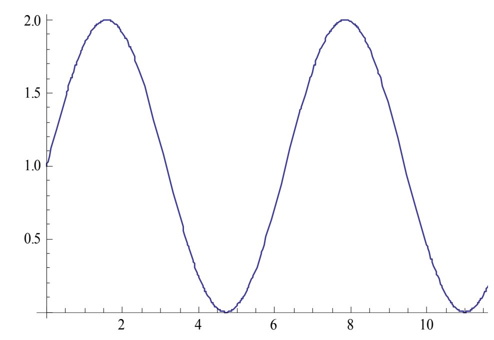


Conclusions

- Strong correlation between signal and lab traffic
- Evidence of tidal influence
- No noticeable solar interference

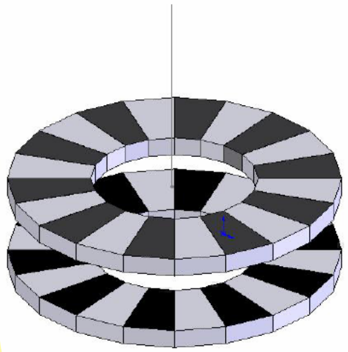


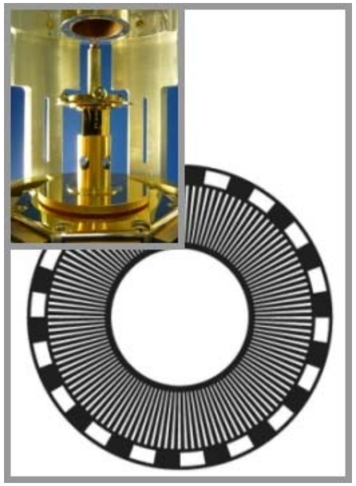




What's Left?

- Magnetize and test Spin Pendulum
- Lunar interference for q2 Pendulum
- More conclusive tidal evidence
- Apply q2 Pendulum results to other Eöt-Wash pendulums





Thanks

Special thanks to past and present members of the CENPA Gravity Group, especially

Blayne Heckel

Eric Adelberger

William Terrano

Todd Wagner

Ted Cook

Frank Fleischer

Claire Cramer

Yue Su

Thanks also to Warren Buck, Wick Haxton, and the NSF for a wonderful summer!

Appendix

Spin-Coupled Potentials

$$V_{md}(r) = \frac{g_p^e g_s^N}{\hbar c} \frac{\hbar^2}{8\pi m_e} \frac{(\sigma_e \cdot \hat{r})}{m_e} \left(\frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-r/\lambda}$$

$$V_{dd}(r) = \frac{g_p^e g_p^e}{4\pi \hbar c} \frac{\hbar^3}{4m_e^2 c} \left[(\sigma_1 \cdot \sigma_2) \left(\frac{1}{\lambda r^2} + \frac{1}{r^3} \right) - (\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) \left(\frac{1}{\lambda^2 r} + \frac{3}{\lambda r^2} + \frac{3}{r^3} \right) \right] e^{-r/\lambda}$$

Spherical Harmonics

$$Y_2^1(\theta, \varphi) = \frac{-1}{2} \sqrt{\frac{15}{2\pi}} \sin\theta \, \cos\theta \, e^{i\varphi}$$

$$Y_2^2(\theta, \varphi) = \frac{1}{4} \sqrt{\frac{15}{2\pi}} \sin^2\theta \, e^{2i\varphi}$$