Stanford Modular Gravitational Reference Sensor (MGRS) Technology Development

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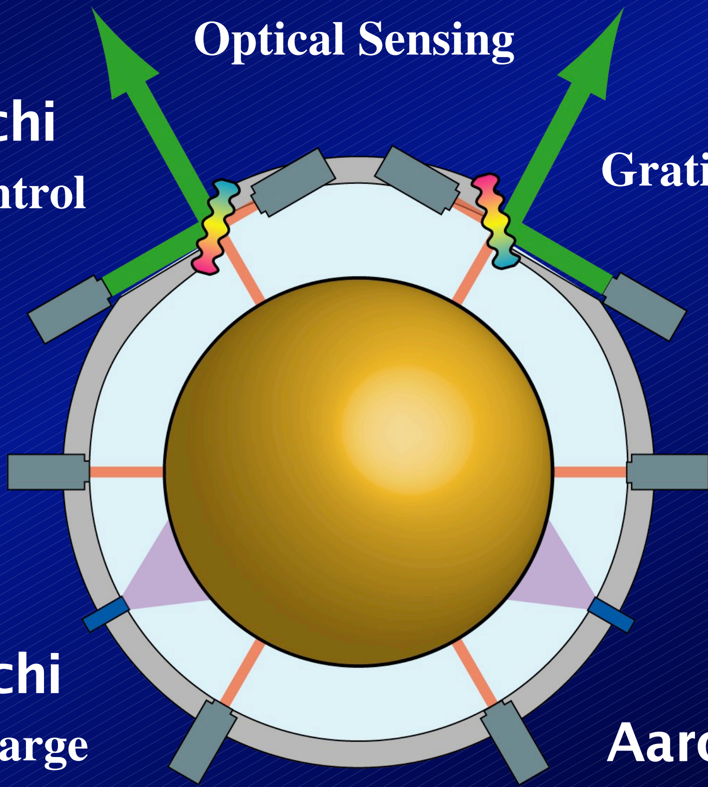
D. DeBra, D. Gill, A. Goh, S. Higuchi,
P. Lu, N. A. Robertson, K-X. Sun

Stanford University
Hansen Experimental Physics Laboratory

June 22, 2006

Stanford LISA Team



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Optical Sensing

Sei Higuchi
Thermal Control

Ke-Xun Sun
Grating Angular Sensing

Patrick Lu
Grating Fabrication

Allex Goh
ES Modeling
Surface Studies

John Conklin
Mass Center

Sei Higuchi
UV LED Charge
Management

Aaron Swank
Mass Attraction

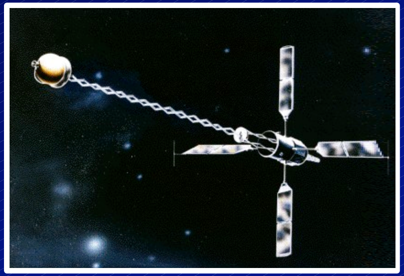
Robert L. Byer
Sasha Buchman
Dan DeBra
Norna A. Robertson
Ke-Xun Sun

Drag-Free Satellite History

1972
Triad/DISCOS

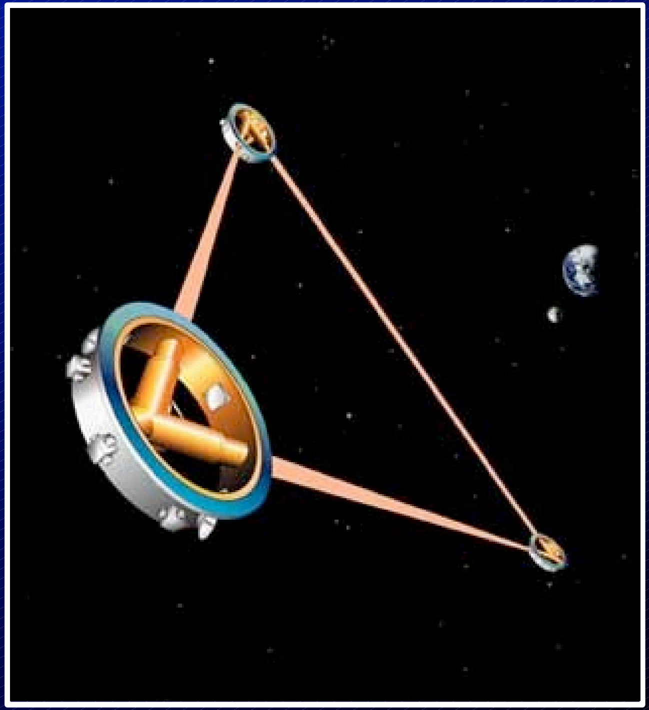
1975-1988

Triad 2 TIP 3
NOVA I-III

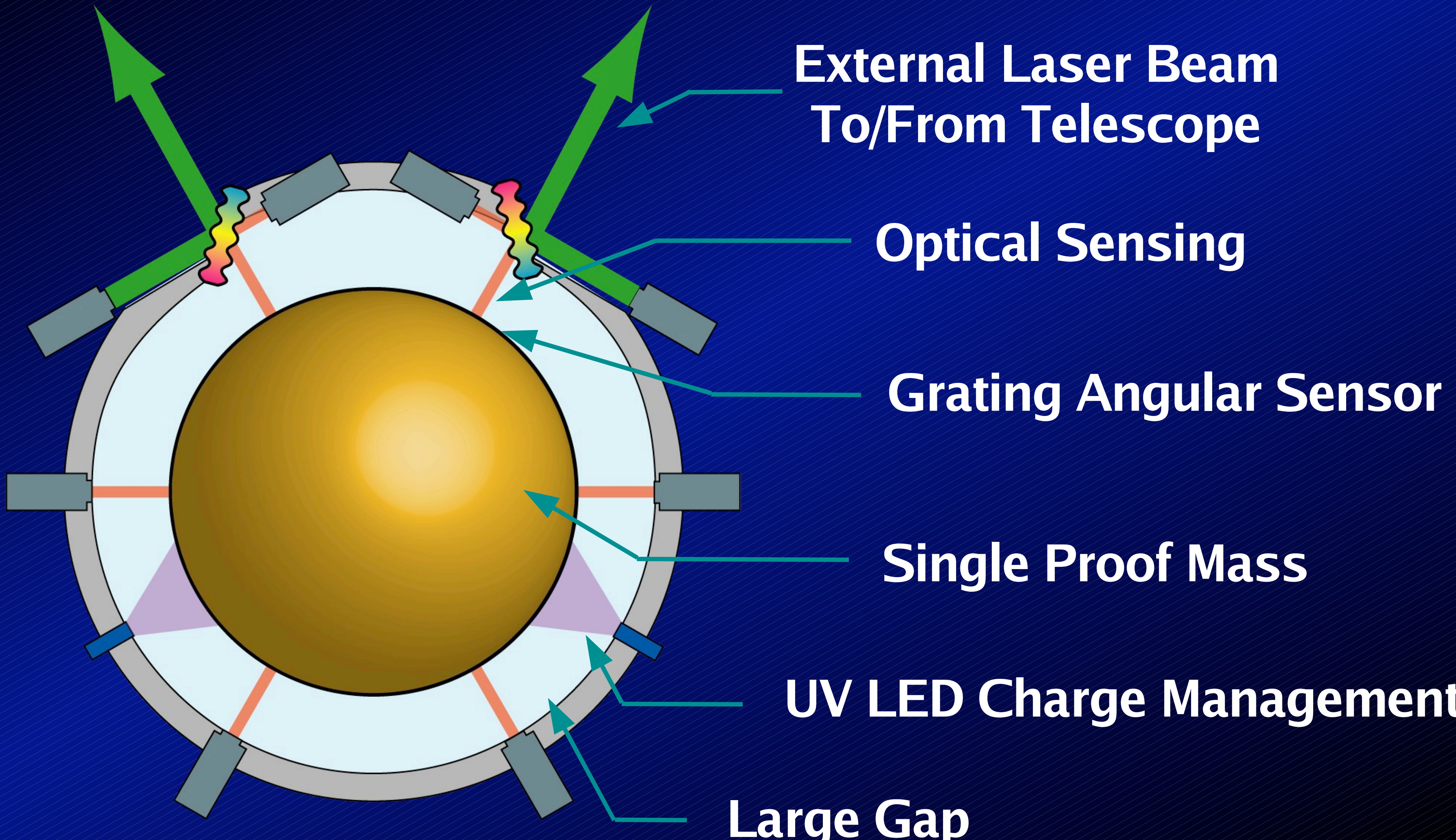


2004
Gravity Probe B

Future: STEP
LISA
BBO

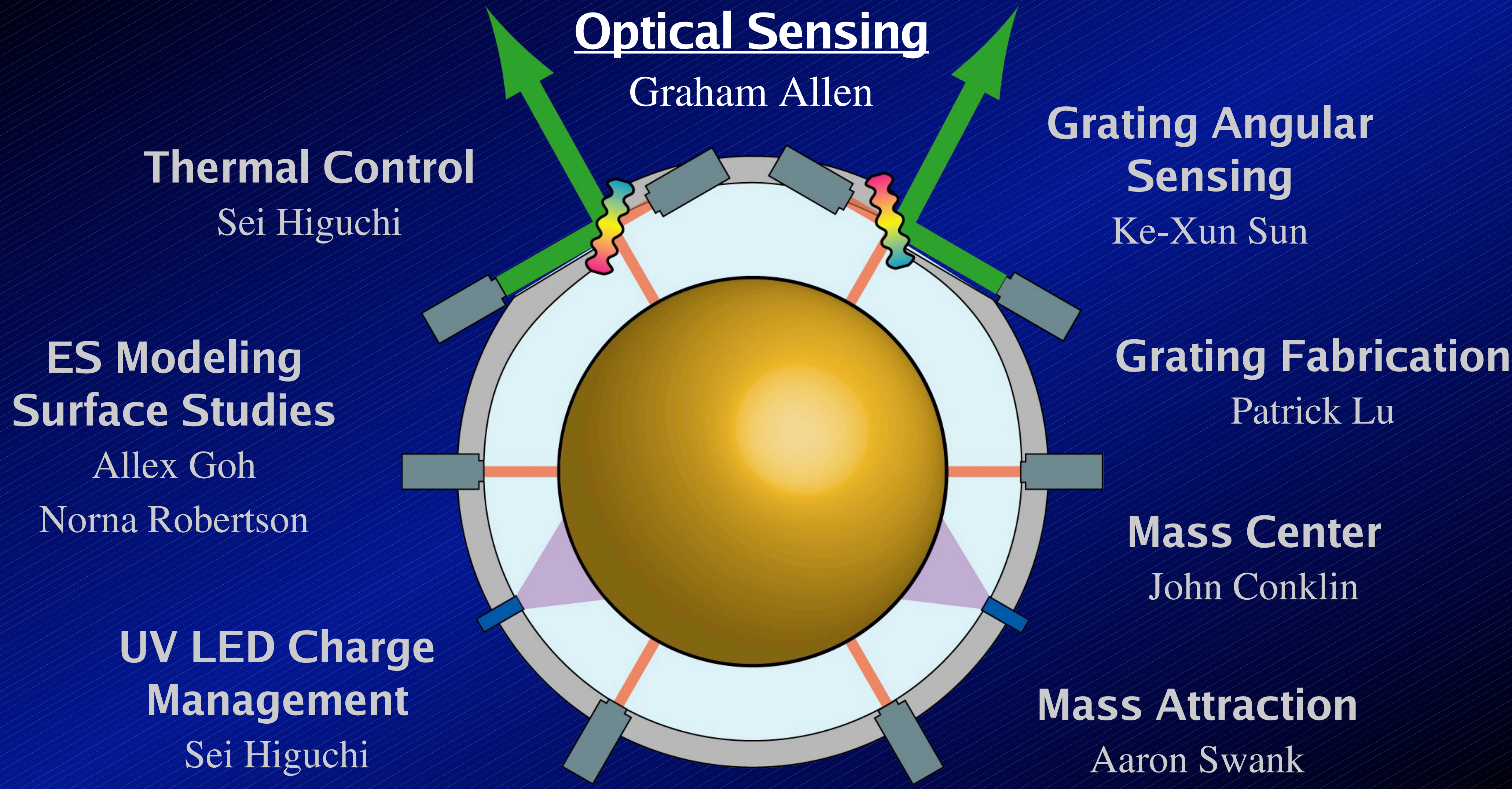


MGRS Design



*Sun et al. CQG (**22**) 2005 S287-S296, LISA 5.* *Sun et al. JPCS (**32**) 2006, 137-146*

Optical Sensing

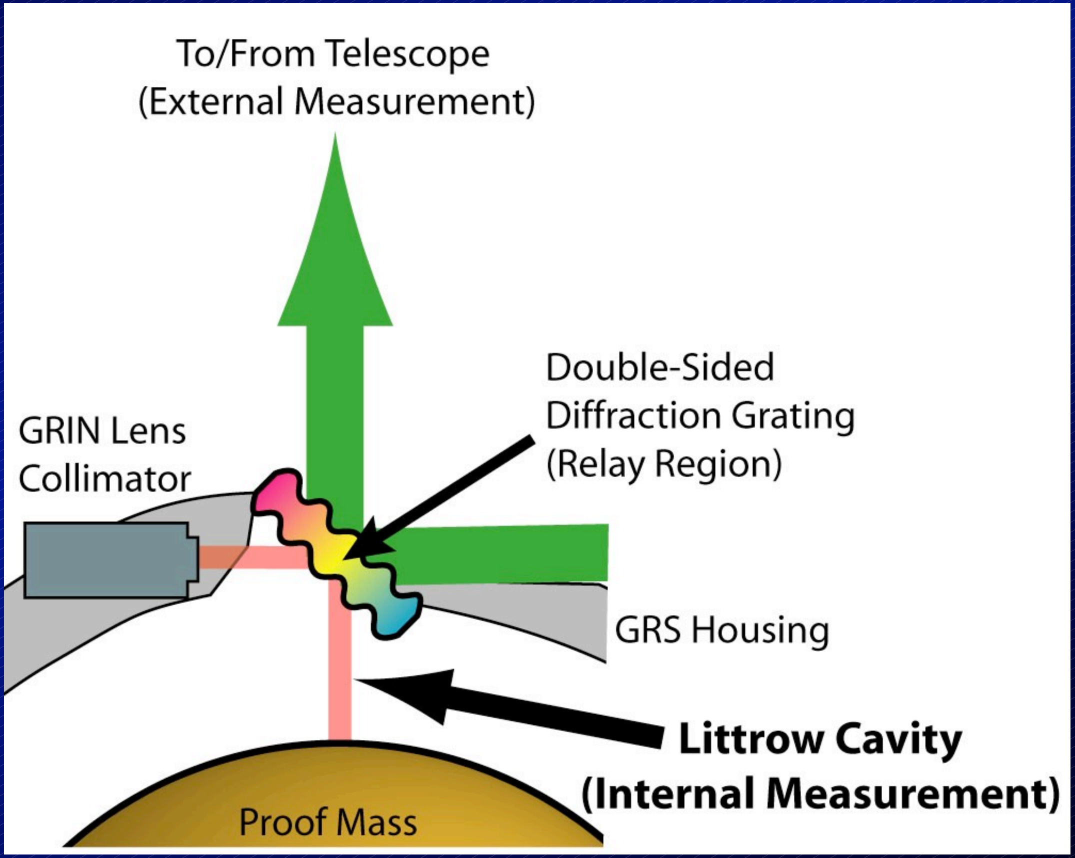


Graham Allen

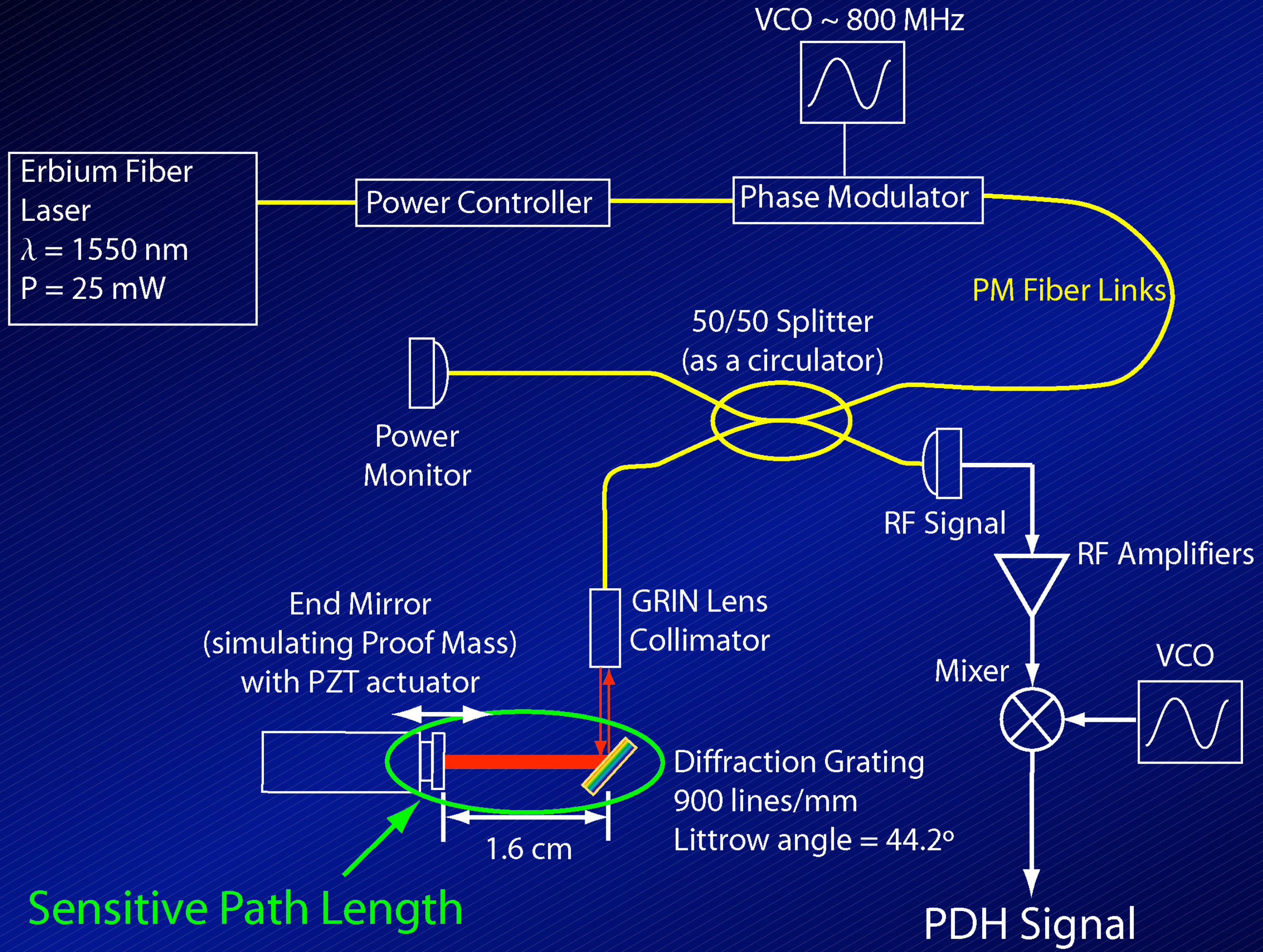
Internal Optical Sensing

Sensor Goals

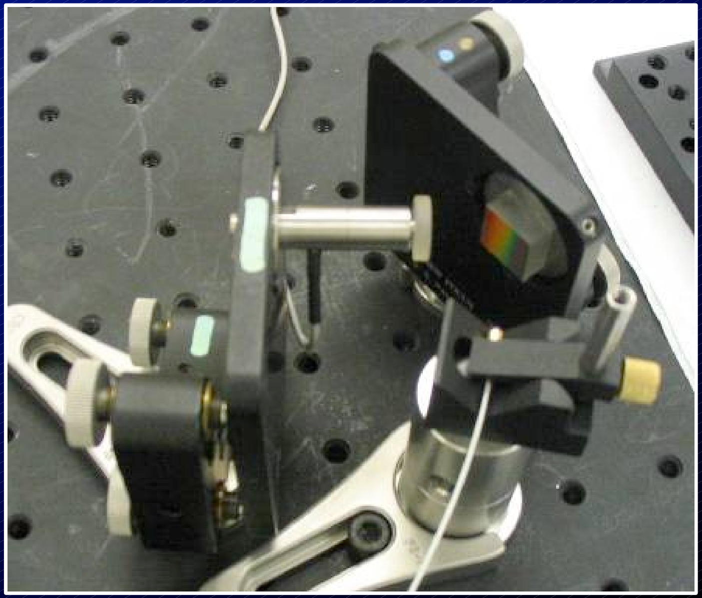
- High Precision
  - 1 pm/√Hz in LISA band
- Low Disturbance
  - < 10 μW optical power
- Compact
  - Fiber optics



Optical Sensor



- Fabry-Perot Cavity
  - Littrow mount
- Pound-Drever-Hall (PDH) RF Locking

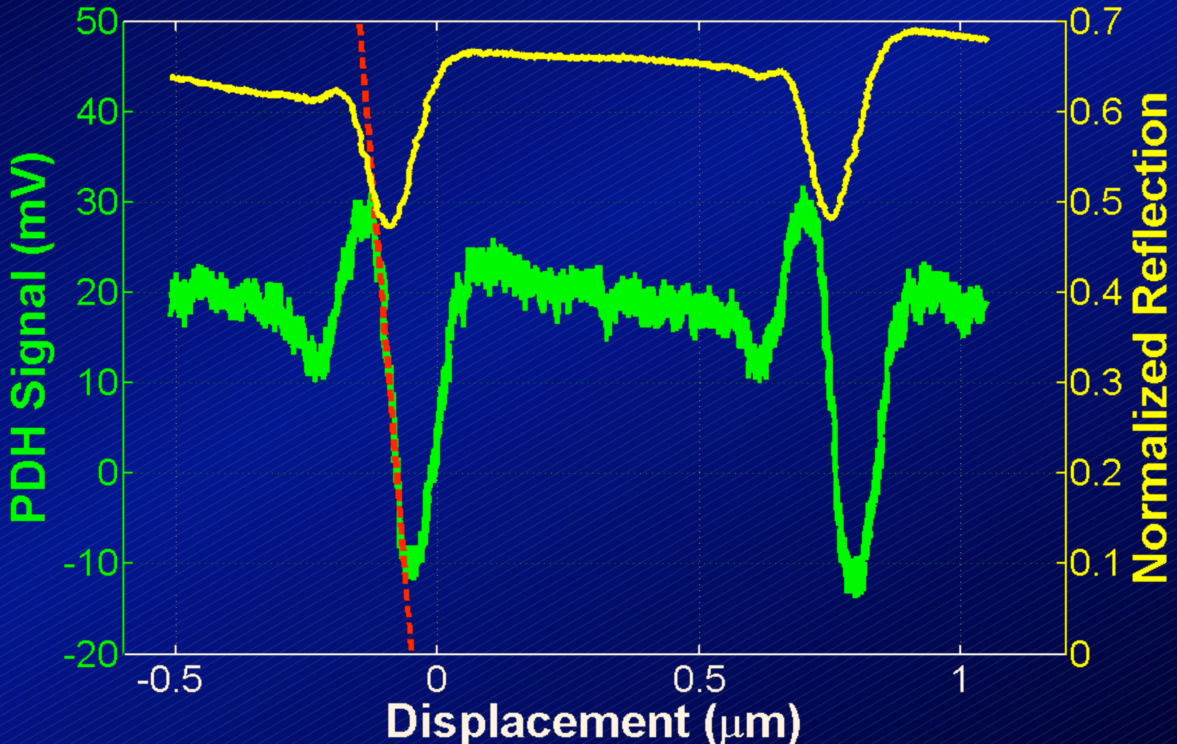


Optical Sensor

Sensitivity 10 pm/ √Hz

100 μW incident power

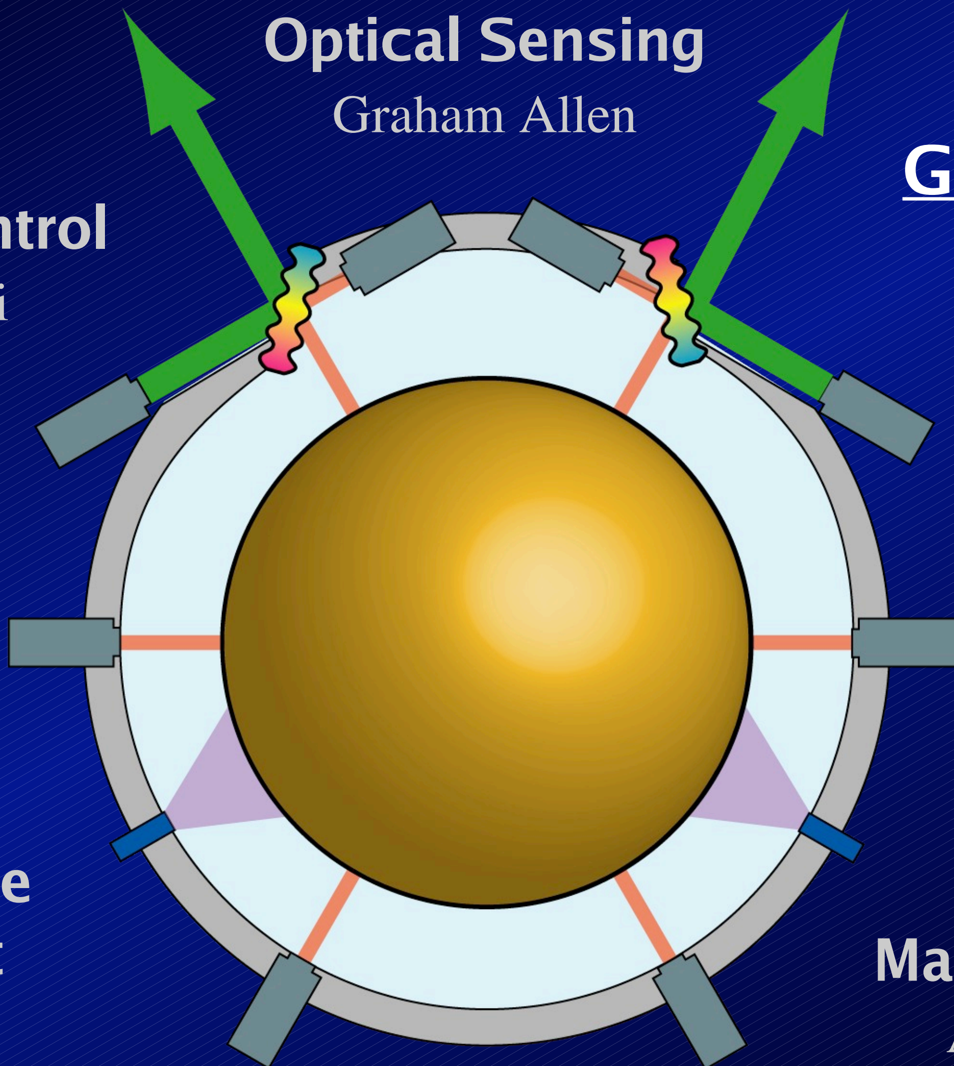
- New photodetector will improve performance



Finesse ~5, PDH linear range ~100 nm

Optical measurement at 3 kHz, Low frequency performance limited by environmental noise.

Grating Angular Sensor



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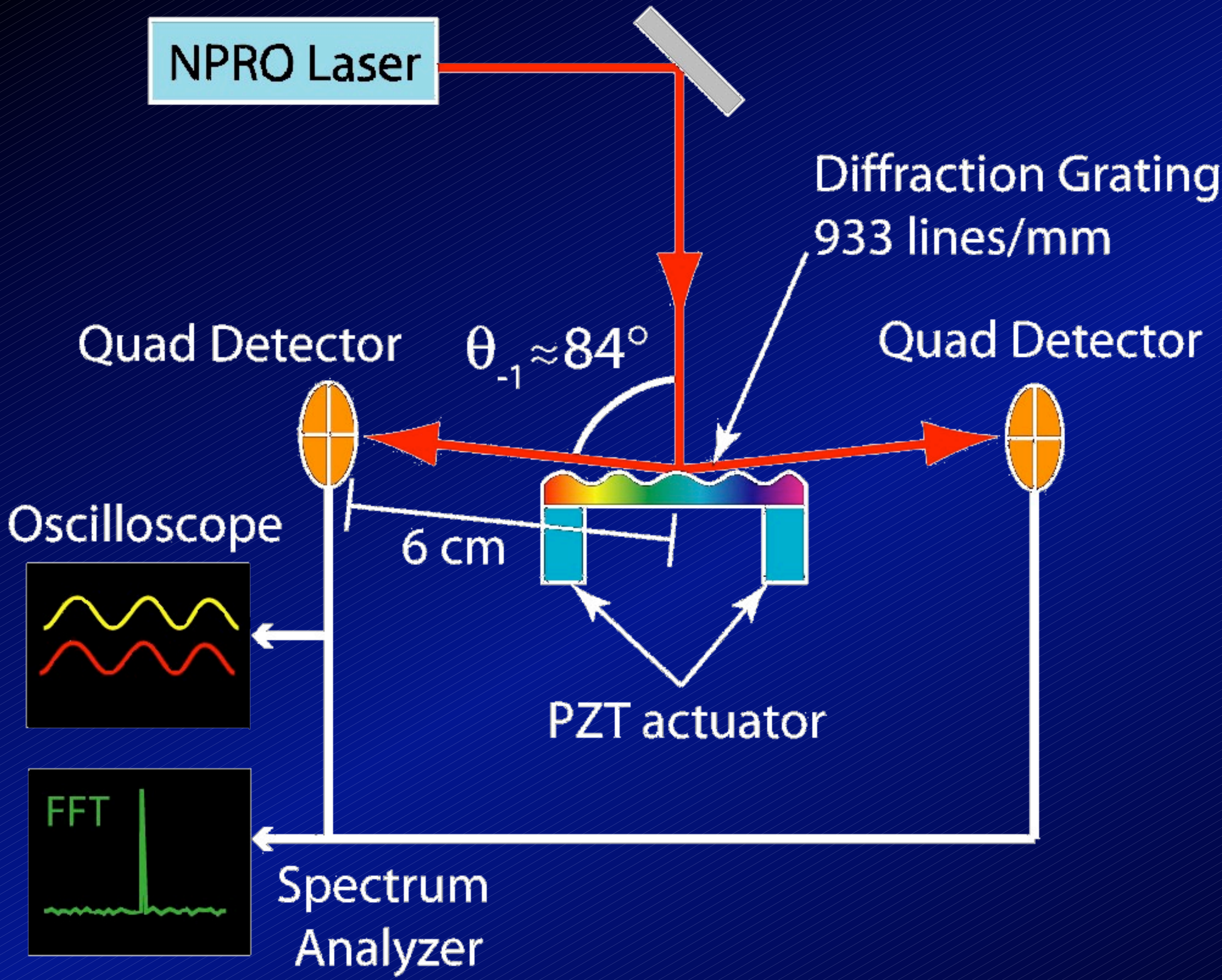
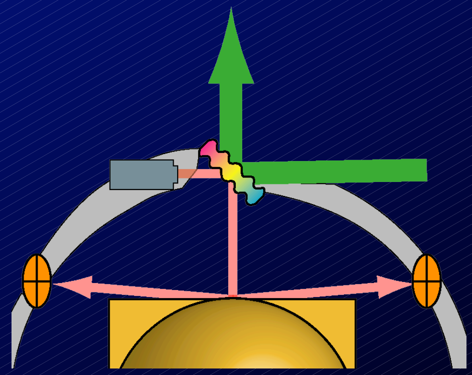
Grating Angular Sensor



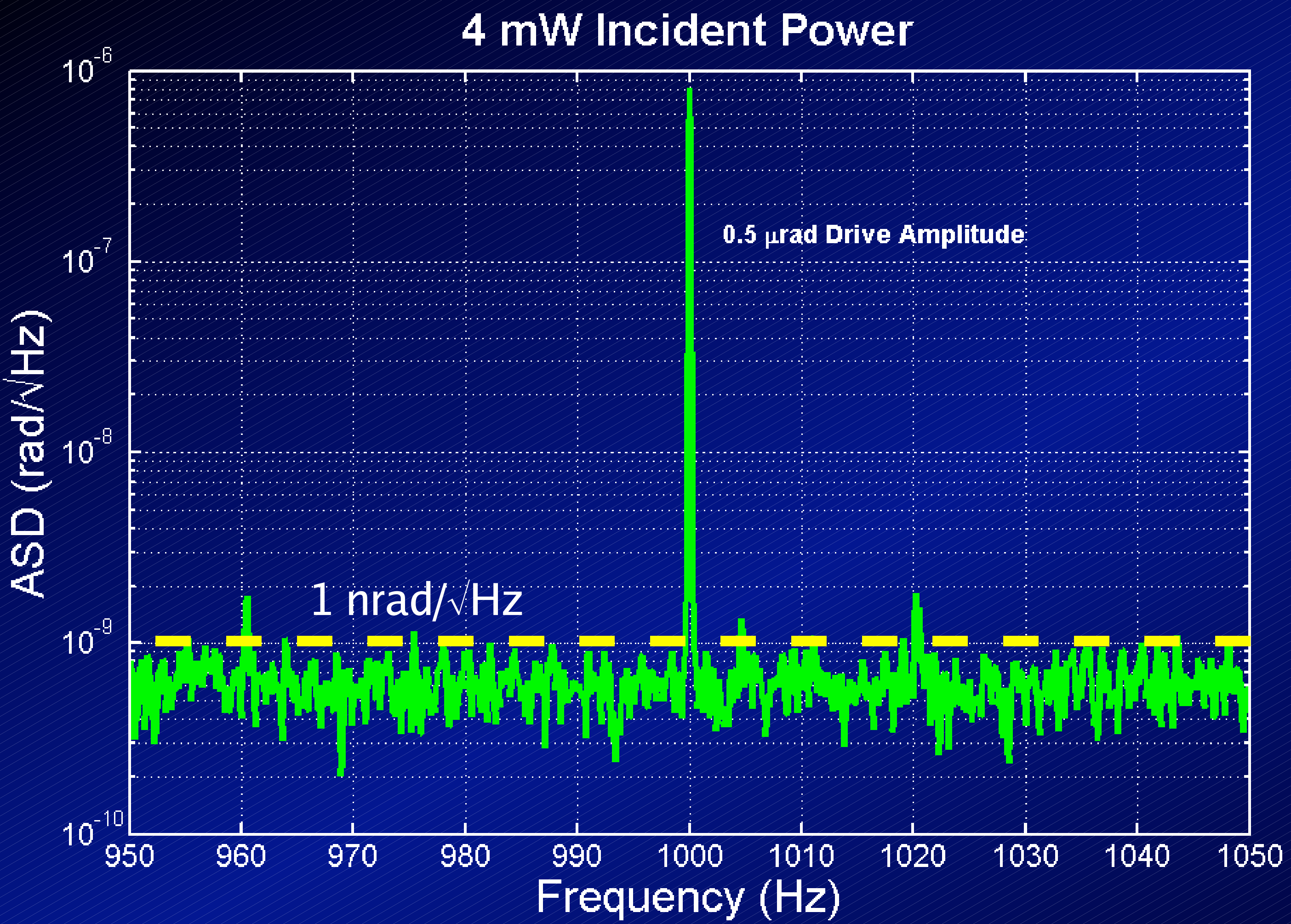
- Amplification
- Simple construction
- No extra optics
- No other uncertainty or noise



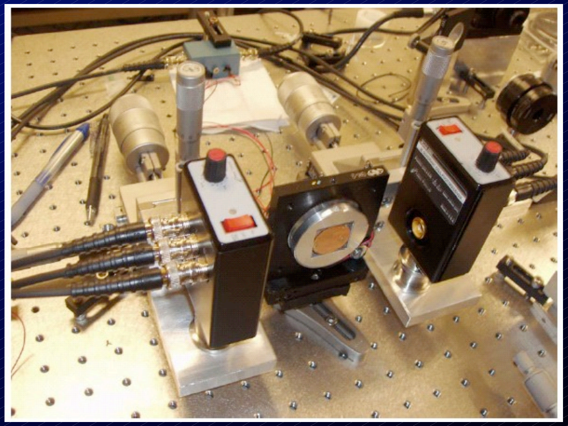
Special Thanks to Dr. Robert Spero at JPL [DRDF Program]

*Sun et al. JPCS (**32**) 2006 167-179, Amaldi 6*

Grating Angular Sensor



Angular Sensitivity 1 nrad/√Hz



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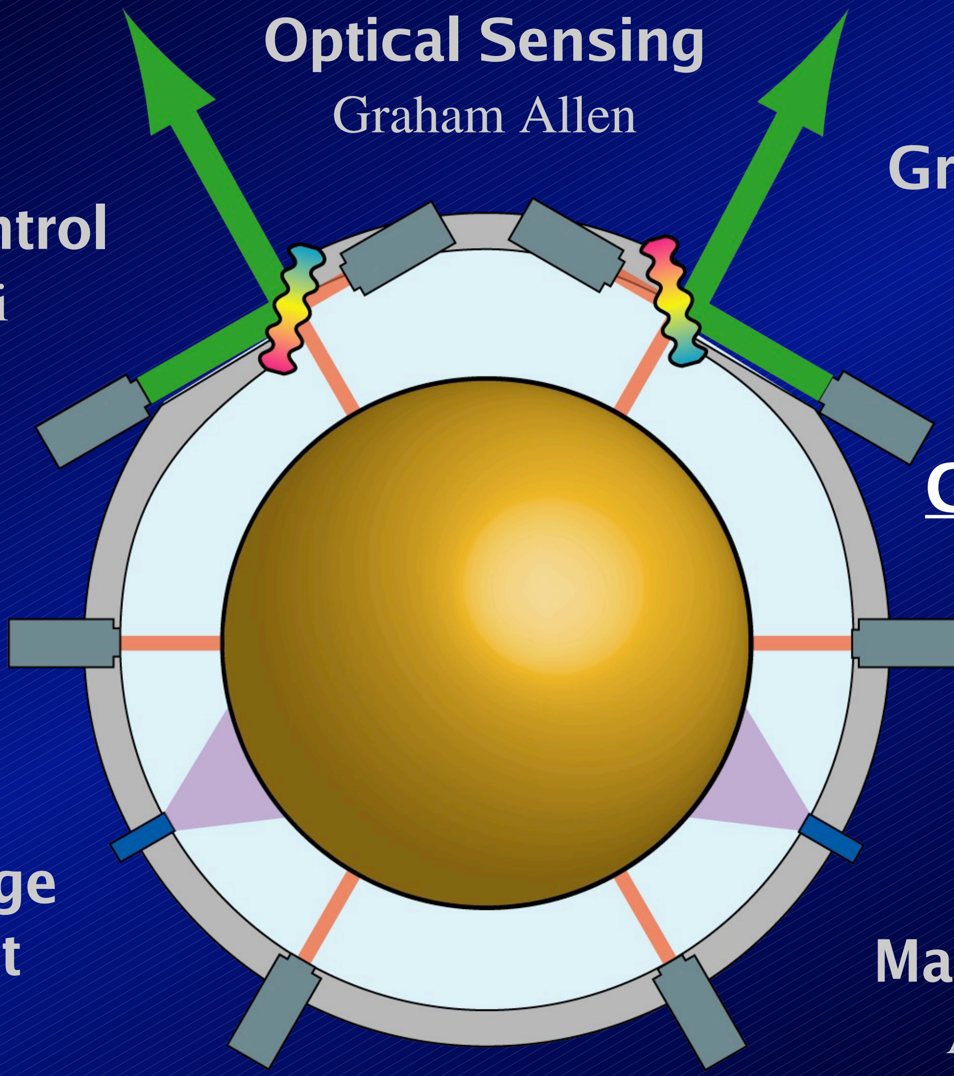
Grating Fabrication



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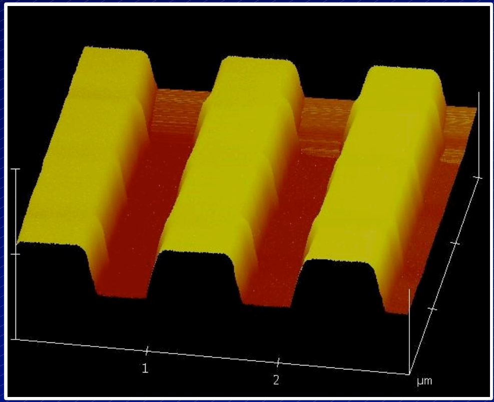
Grating Fabrication

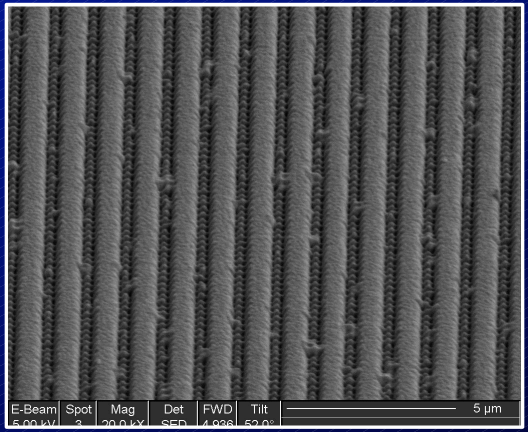
- Dielectric grating
  - e-beam lithography
- Gold grating
  - Transfer-imprinting of dielectric gratings
  - Focused ion beam milling
- Precise control over grating duty cycle



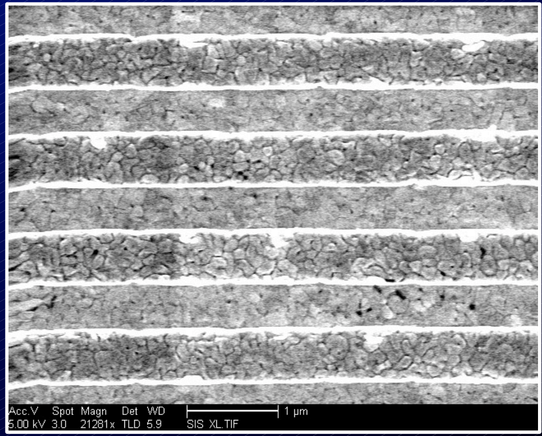
Dielectric grating

(AFM Image)

Gold Gratings, (SEM Images)

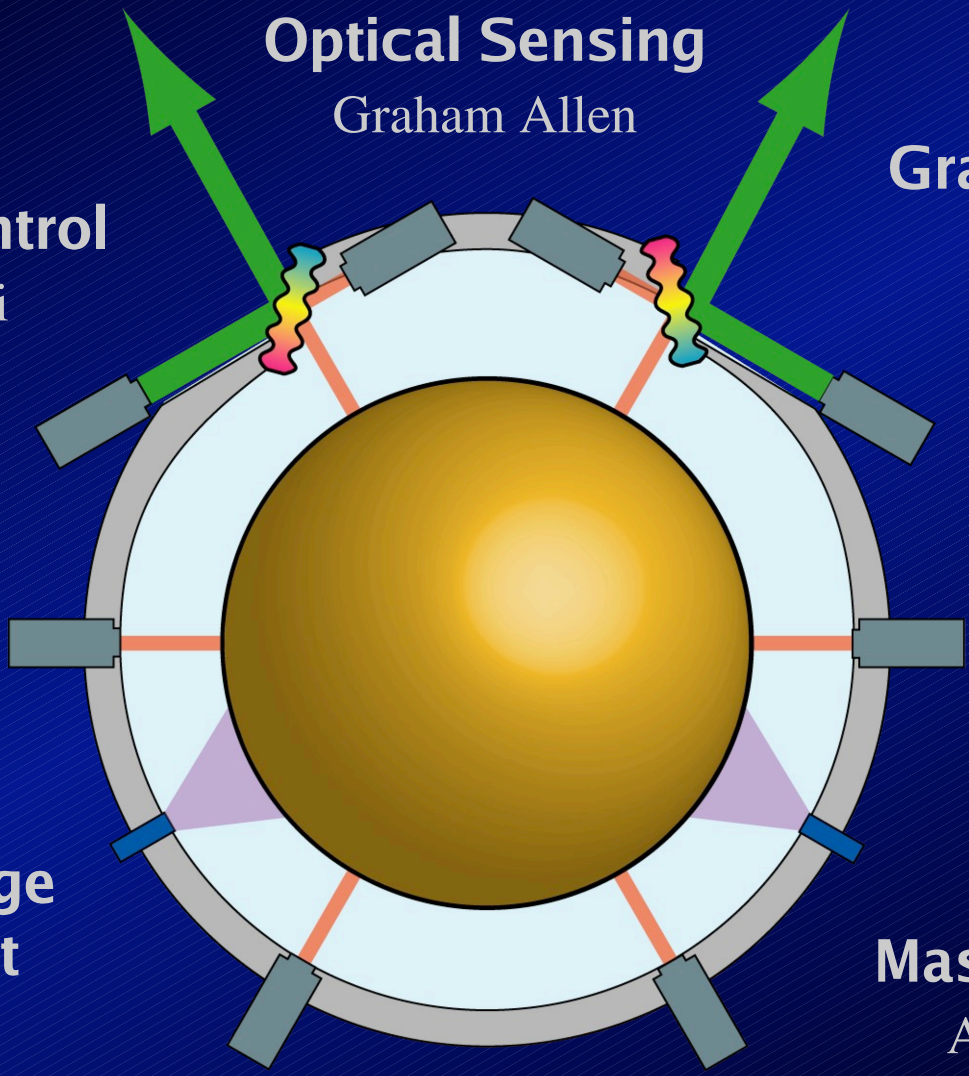


Focused ion beam milled



Imprinted

Mass Center Determination



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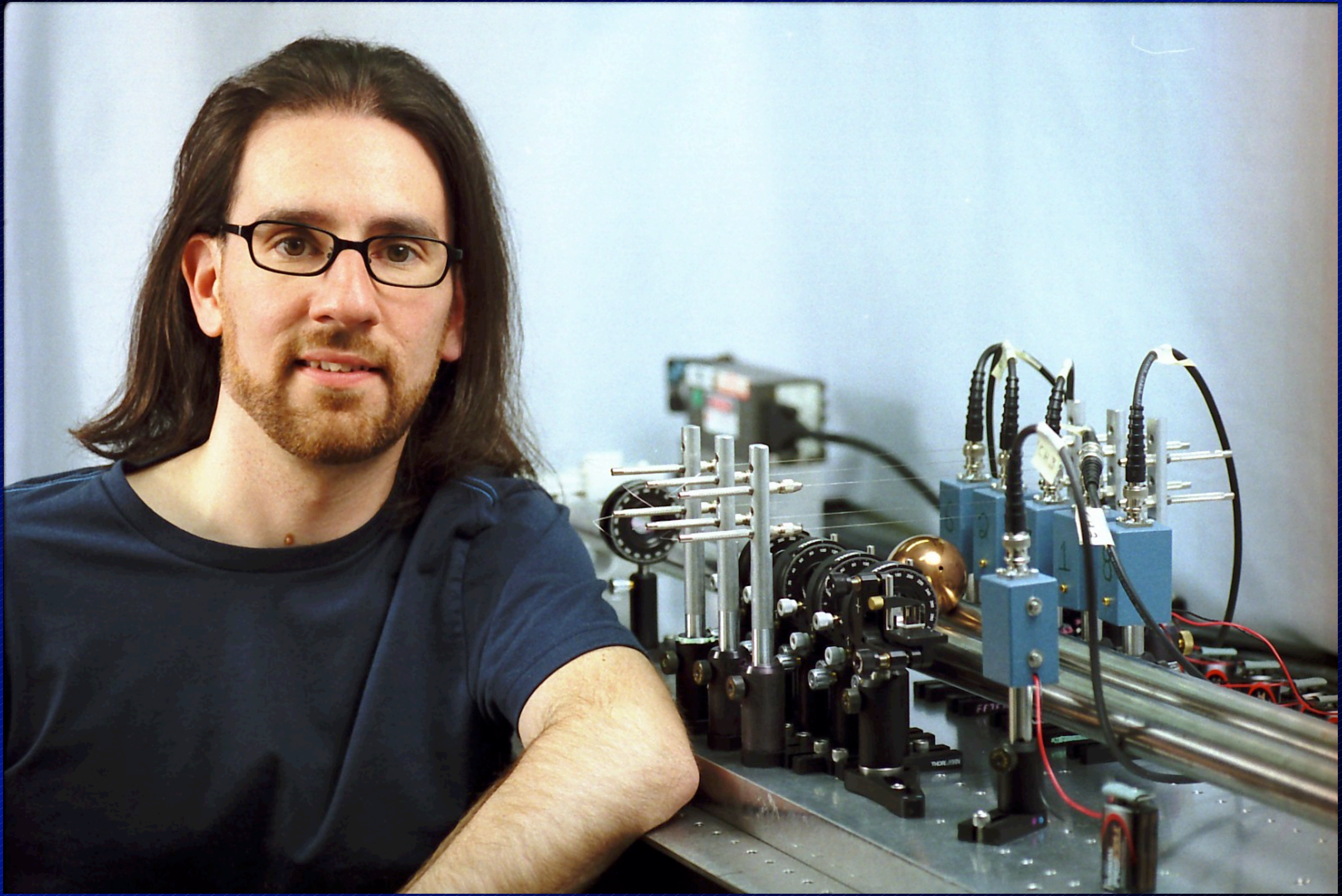
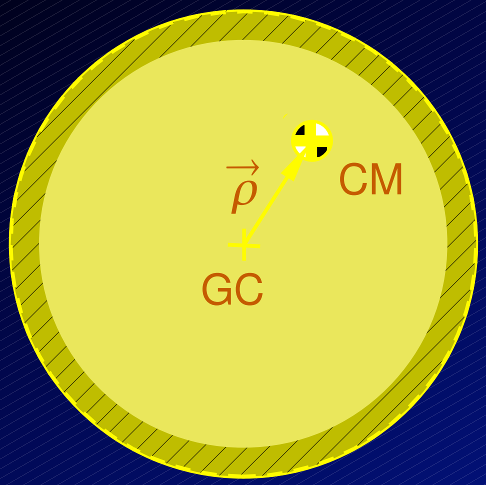


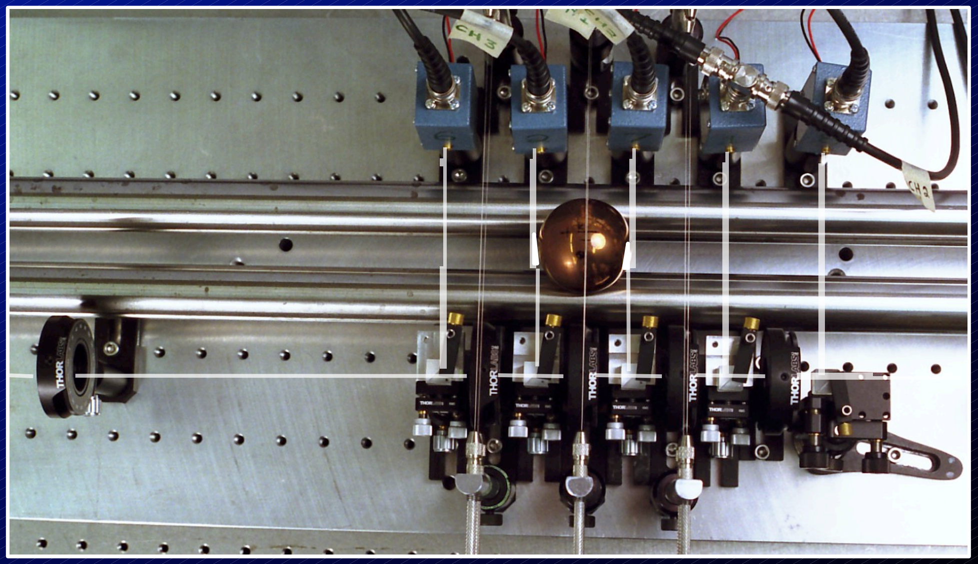
Mass Center Determination



Spherical Test Mass

- Optical sensing (100 ns accuracy)
- Different initial phases average out rail irregularities

Determine center of mass (CM) location to 100 nm

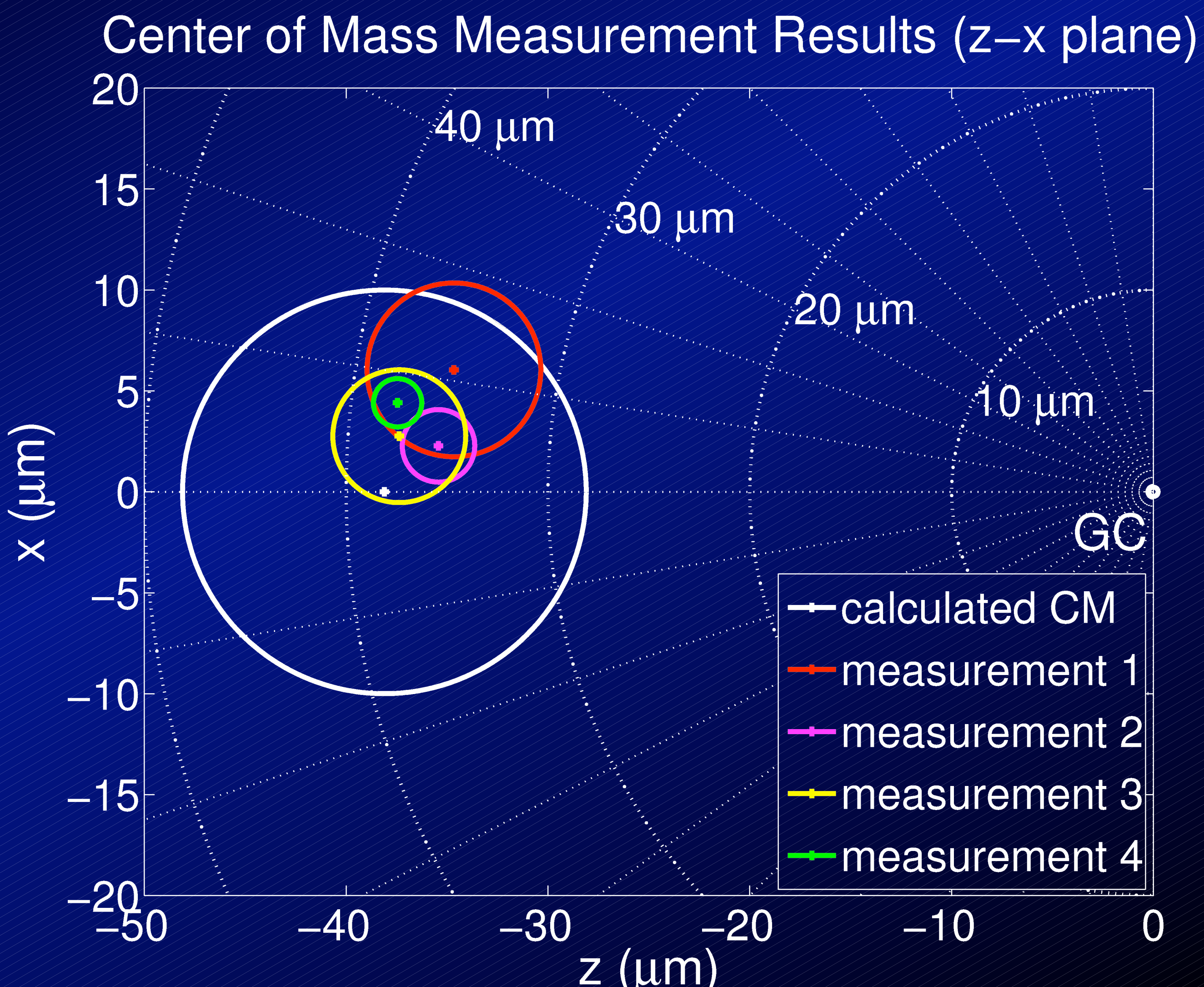


Mass Center Determination

Initial accuracy

2-3 μm

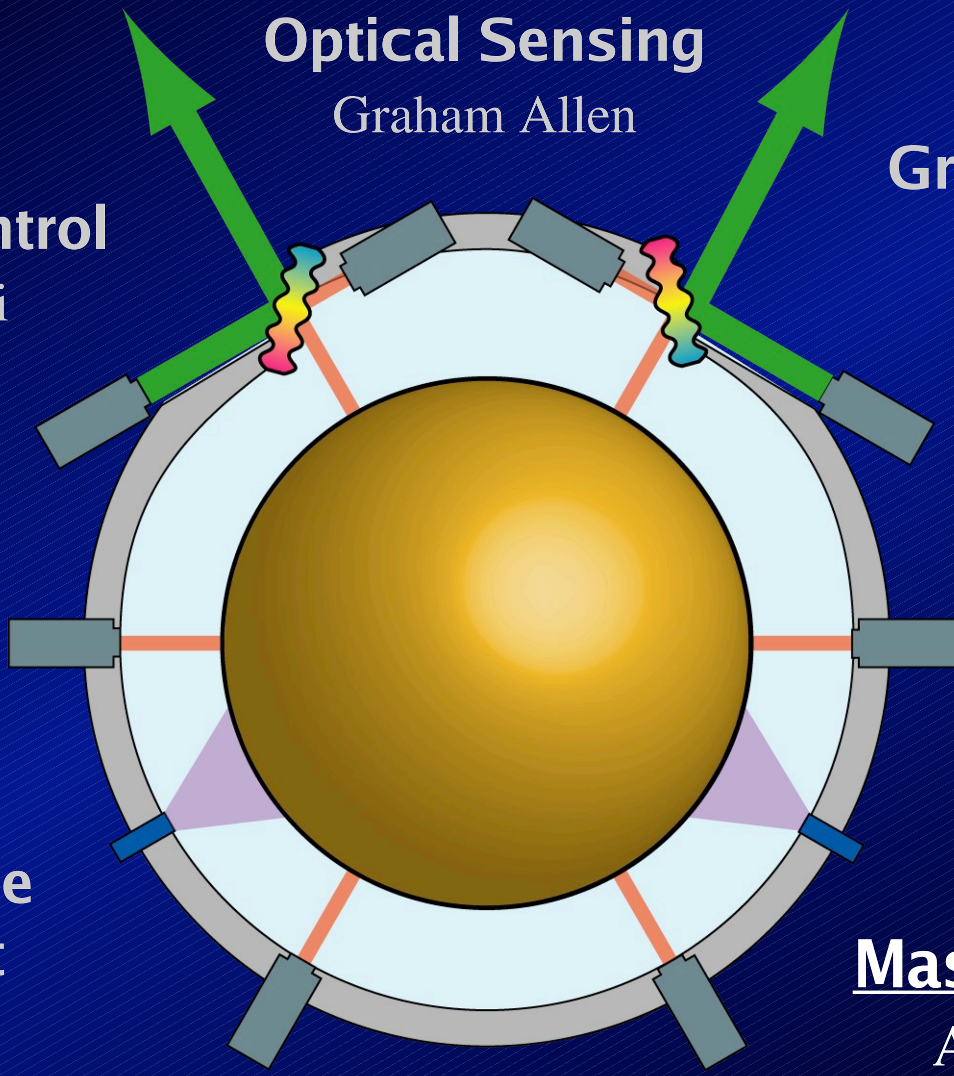
Future: < 1 μm



Tests with Calibration sphere

Conklin et al. Accepted for ASPE Monterey, 2006

Mass Attraction



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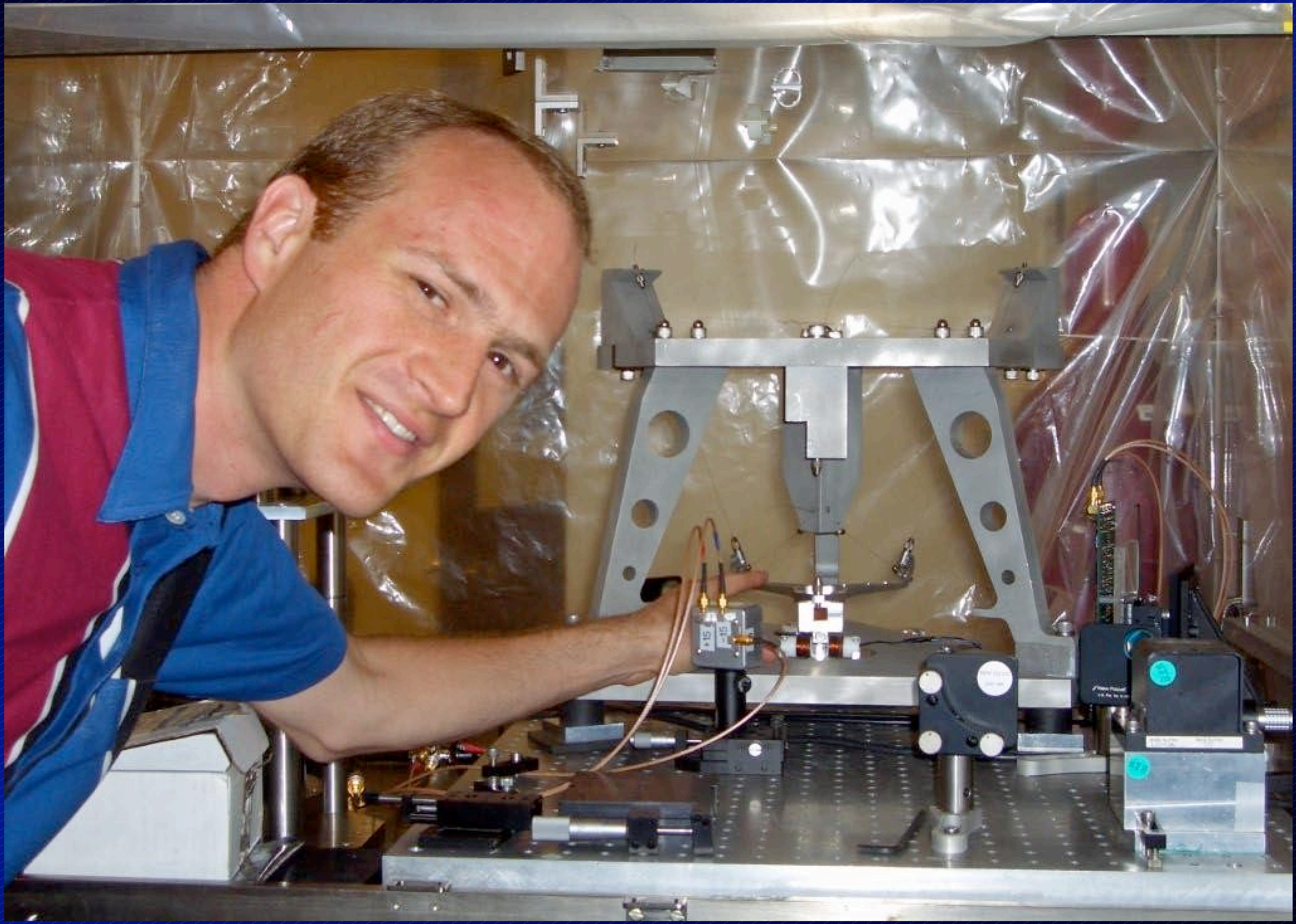
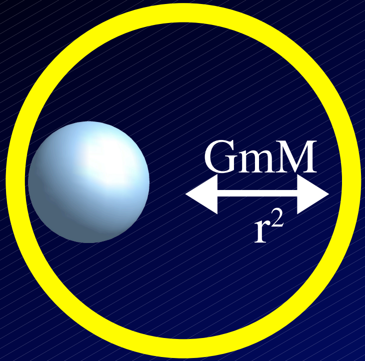


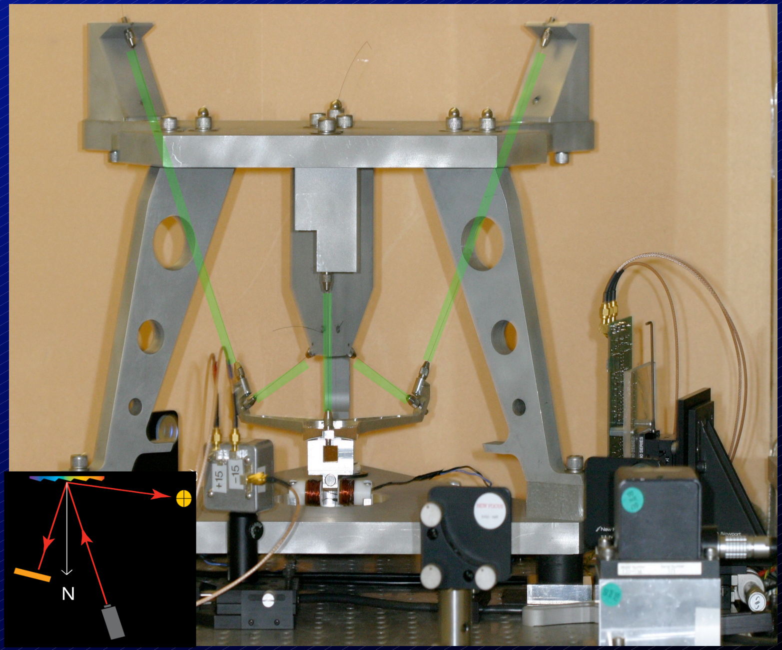
Gravitational Self-Attraction



- Density inhomogeneities and geometrical variations lead to uncertainty

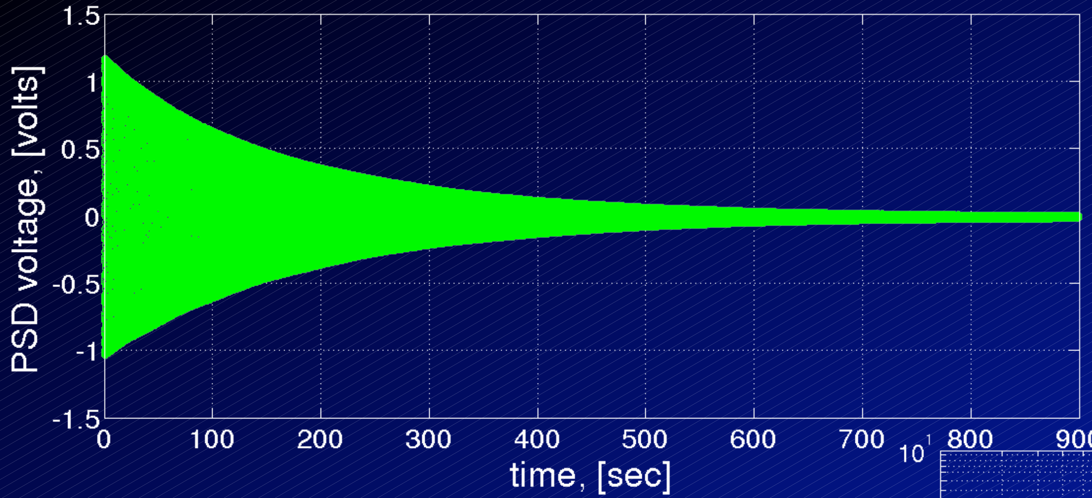
$$\nabla F_{Grav}, F_{Grav} = f(\text{ Mass, Mass Center, Inertia, ... })$$

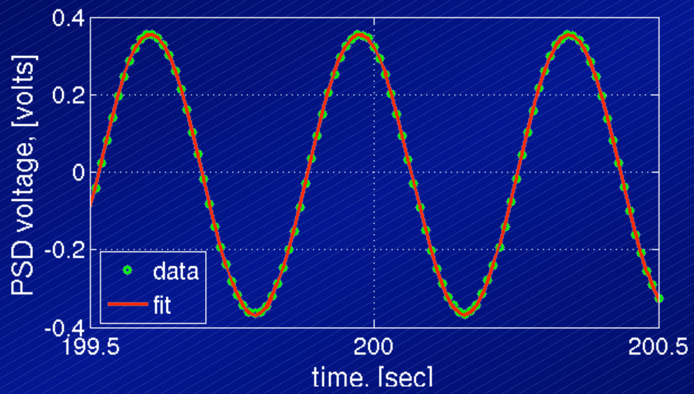
- Goal: Measure inertia to below 1 part in 10^4
  - Includes mass property uncertainties



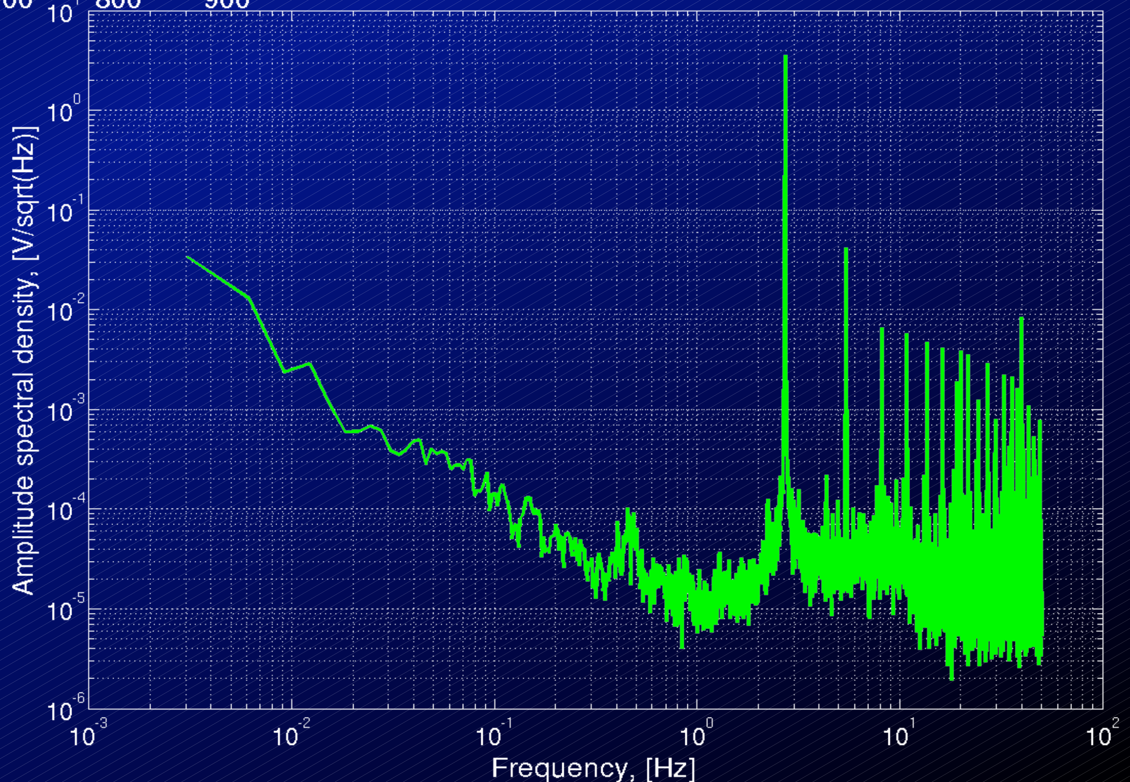
Swank et al. Accepted for ASPE Monterey, 2006

Gravitational Self-Attraction





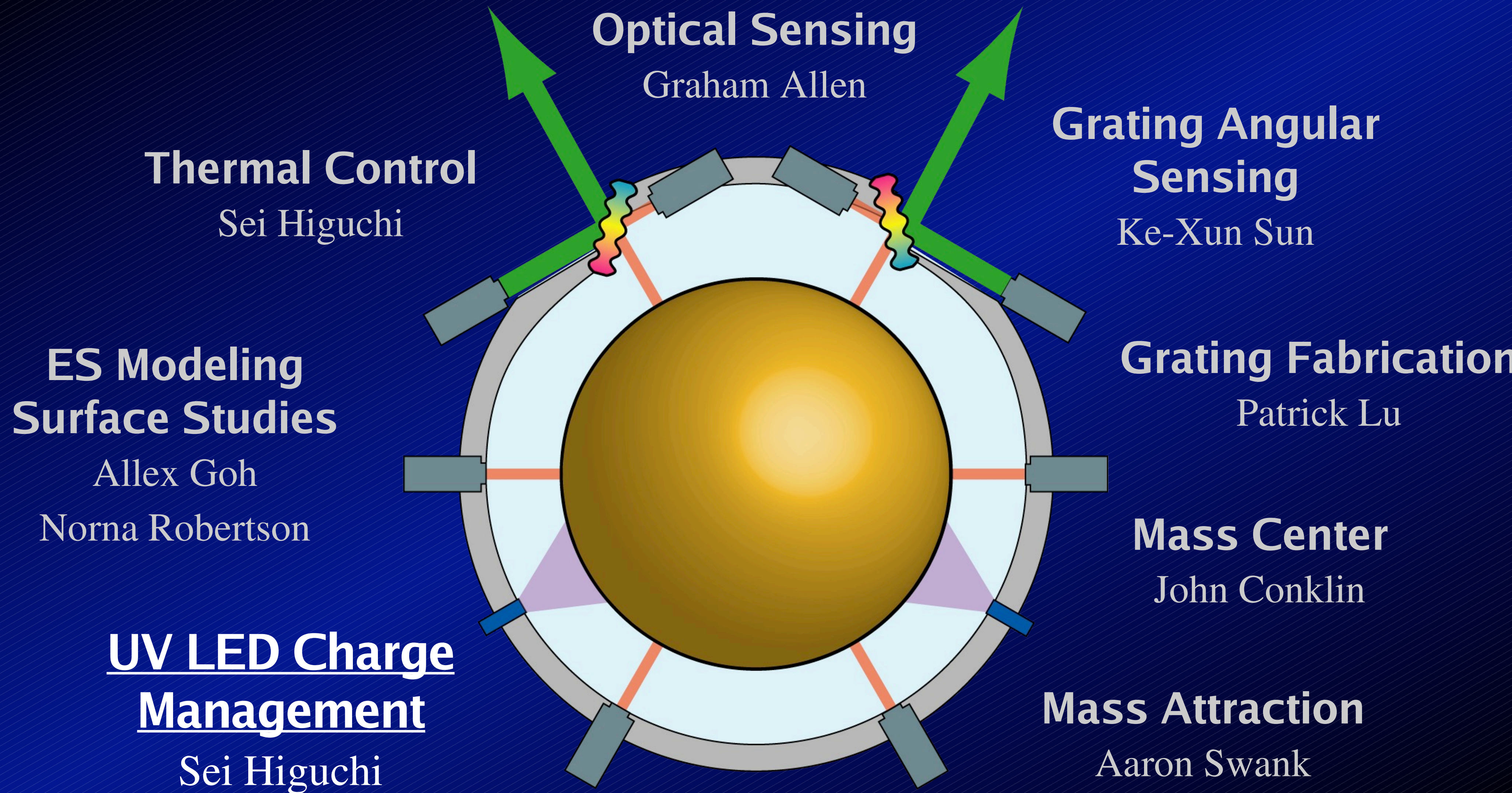
Spectral resolution < 1 mHz



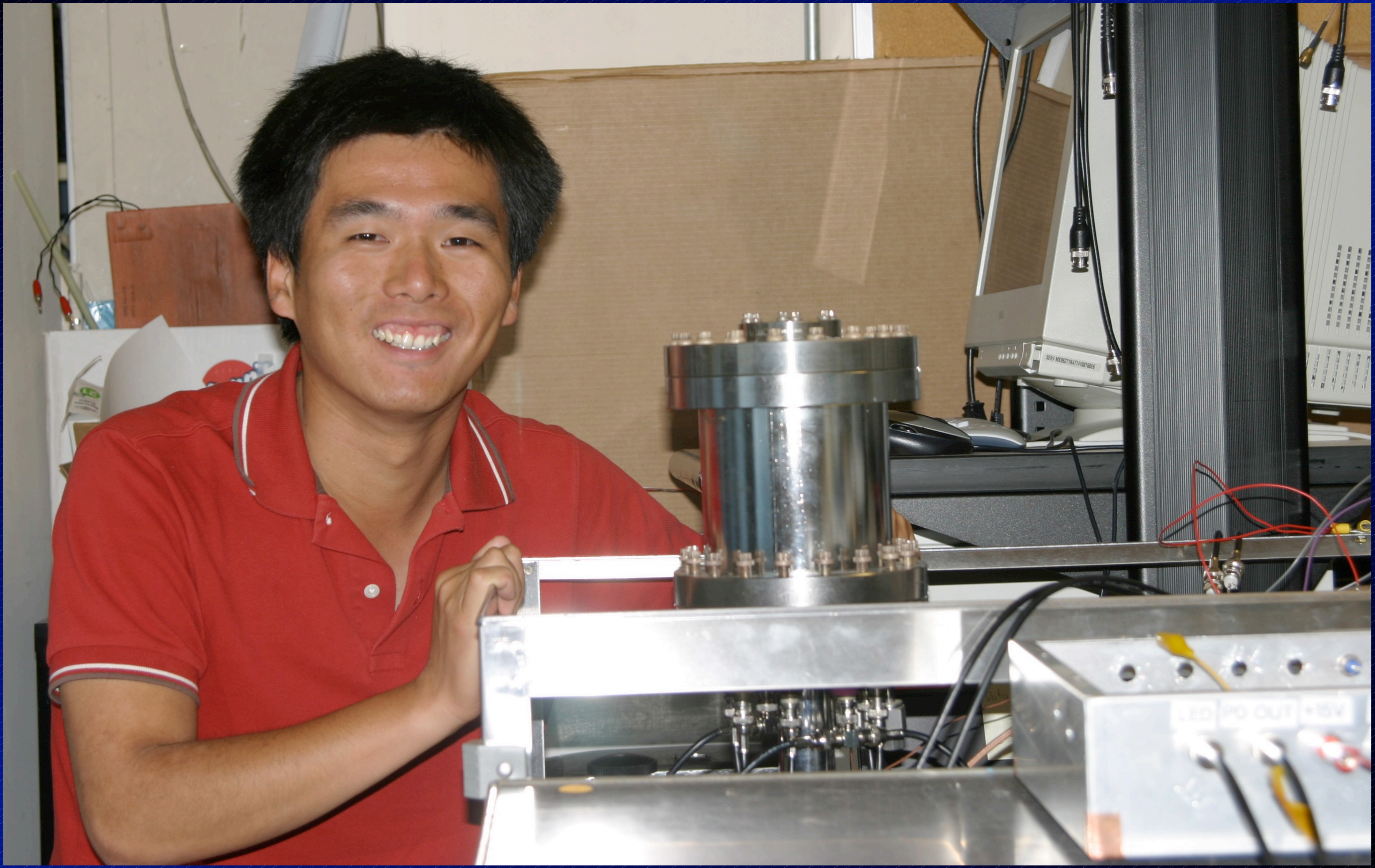
$Q = 1500$

$f = 2.715$ Hz

LED UV Charge Management

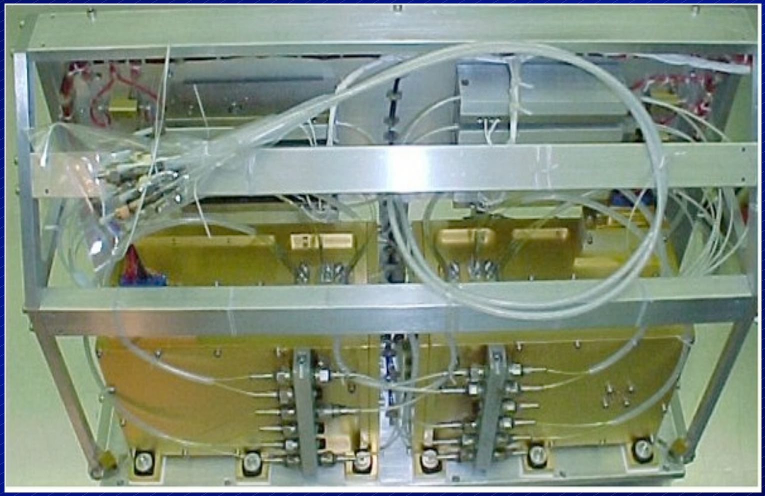


Sei Higuchi

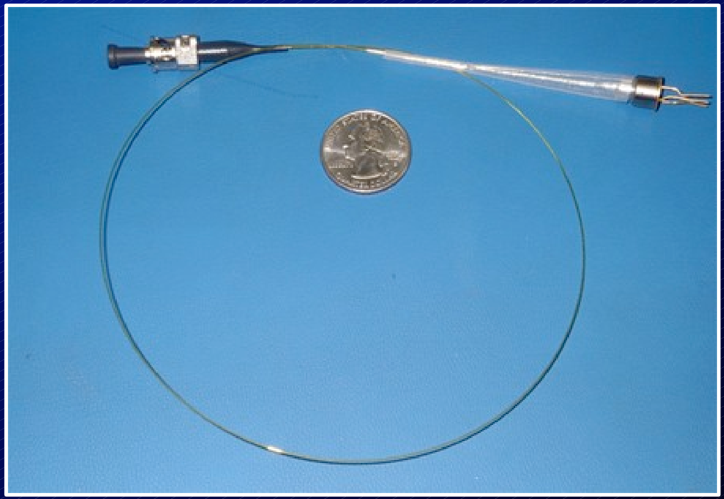


UV LED Charge Management

- Charge management essential for drag-free satellites
- UV LEDs are compact, efficient devices
  - Fast modulation → AC charge management
- Deep UV LEDs are new technology



GP-B Mercury Lamp

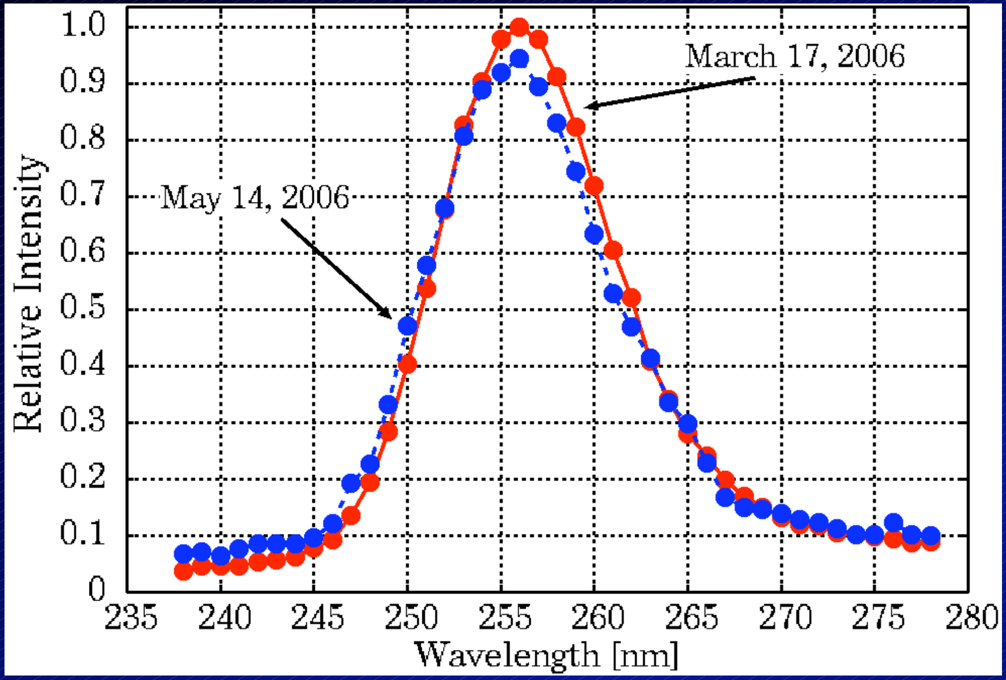


UV LED

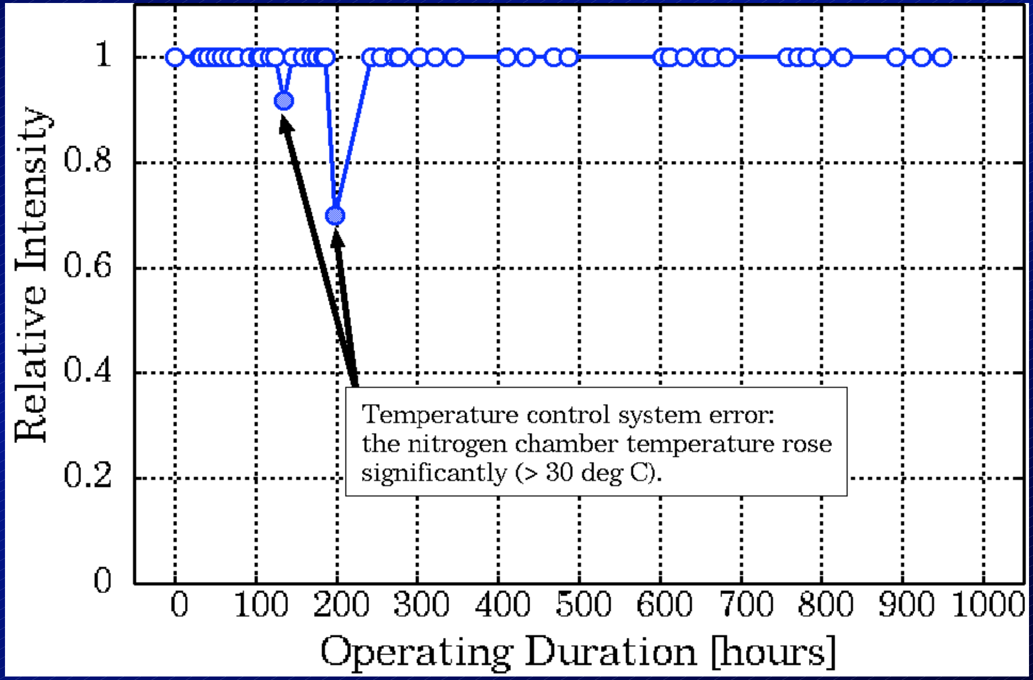
*Sun et al. CQG **(23)** 2006 S141-S150, Amaldi 6*

UV LED Lifetime Tests

Spectral Intensity Measurement



Power Stability Measurement



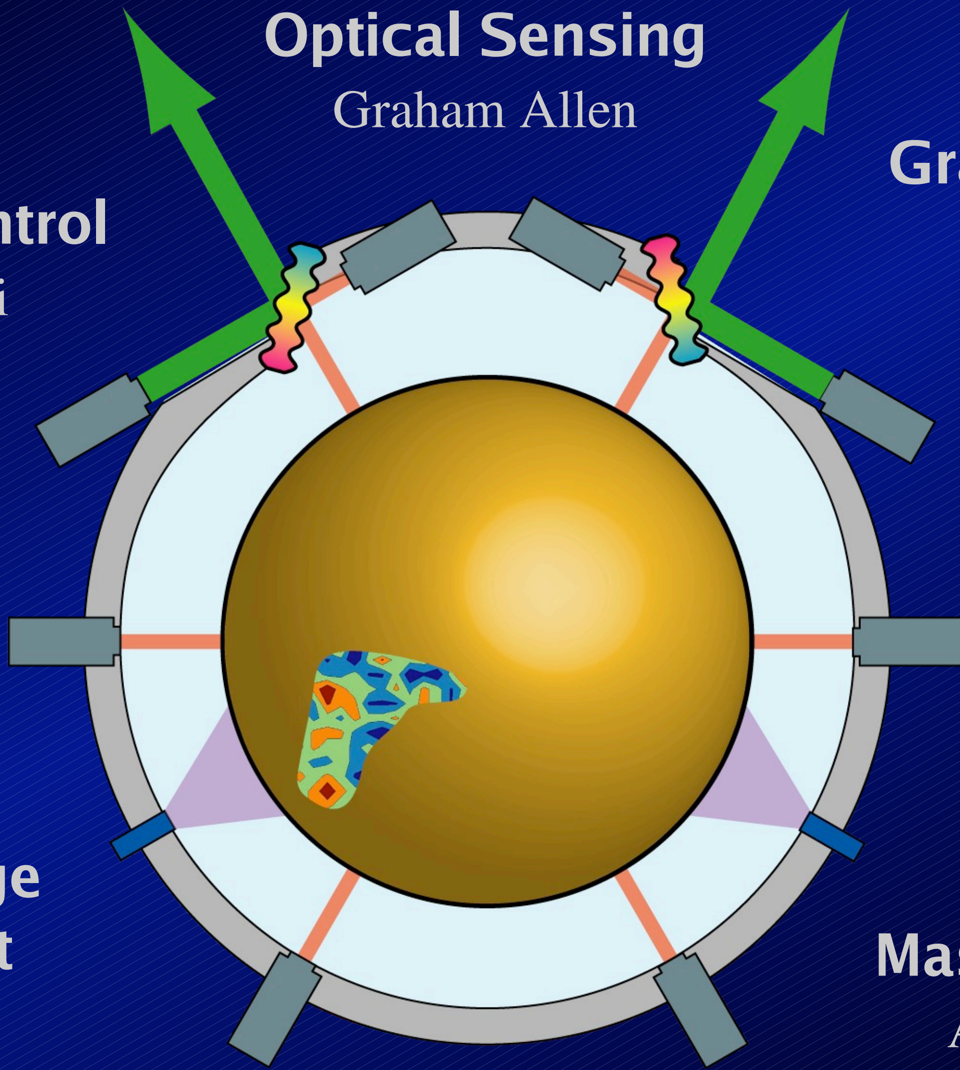
More than 1000 hours of operation demonstrated

Surface Studies

Optical Sensing
Graham Allen

Thermal Control
Sei Higuchi

Grating Angular Sensing
Ke-Xun Sun



<u>ES Modeling Surface Studies</u>
Allex Goh
Norna Robertson

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UV LED Charge Management
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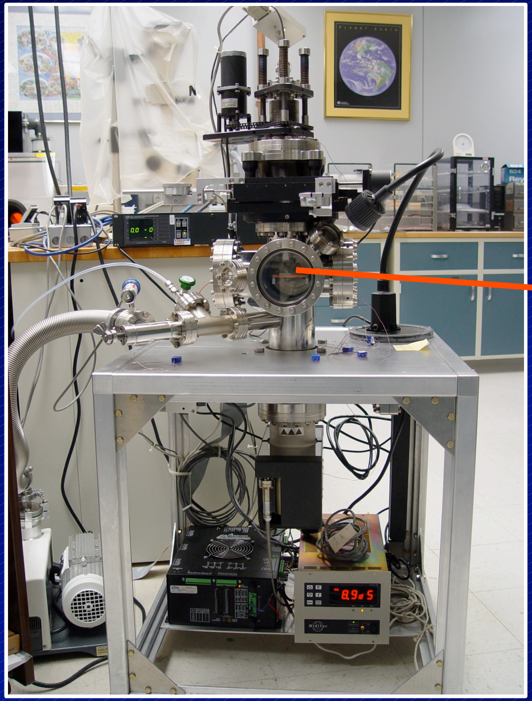
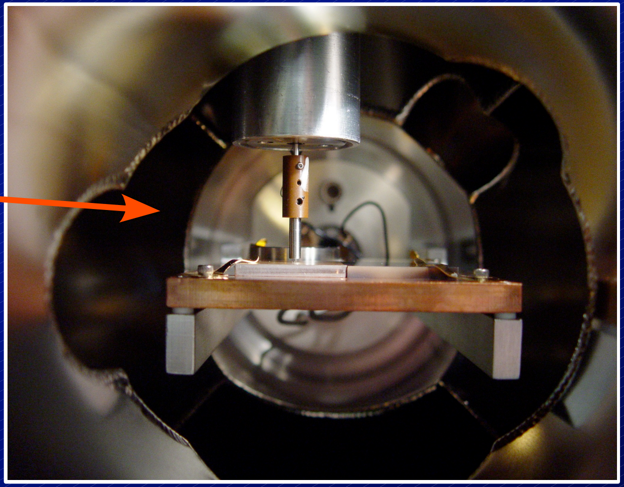
Mass Attraction
Aaron Swank

Patch Effects

- Surface potential variations produce acceleration noise
- Forces due to patch effects observed by Gravity Probe B
- Strong function of gap size: bigger gap ⇒ smaller force





Kelvin probe at GSFC

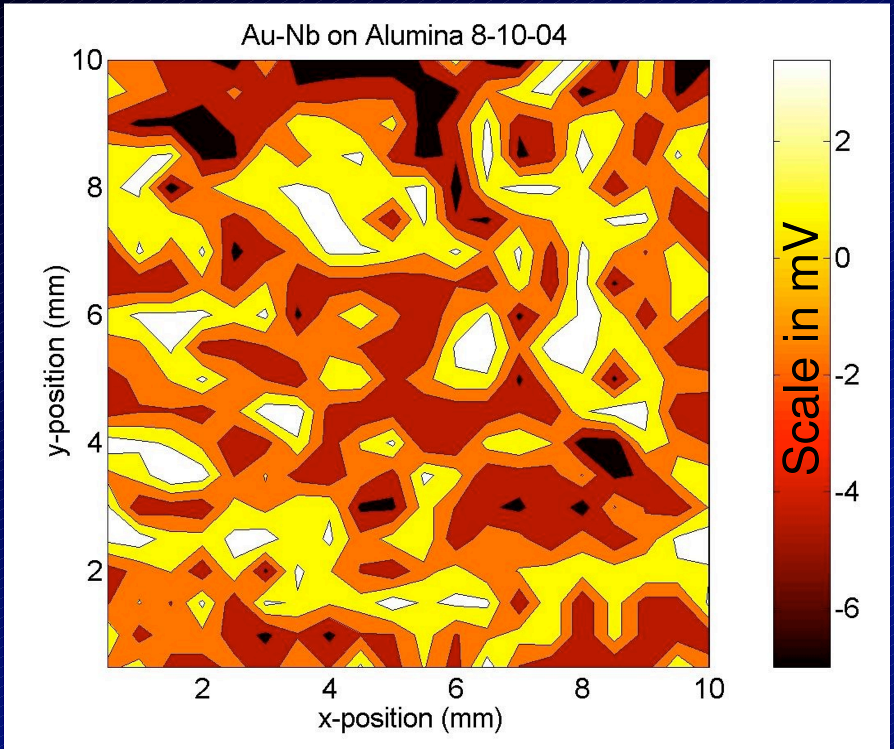
- Patch effects have been studied with a Kelvin probe at GSFC
- Many samples precision coated in-house at Stanford

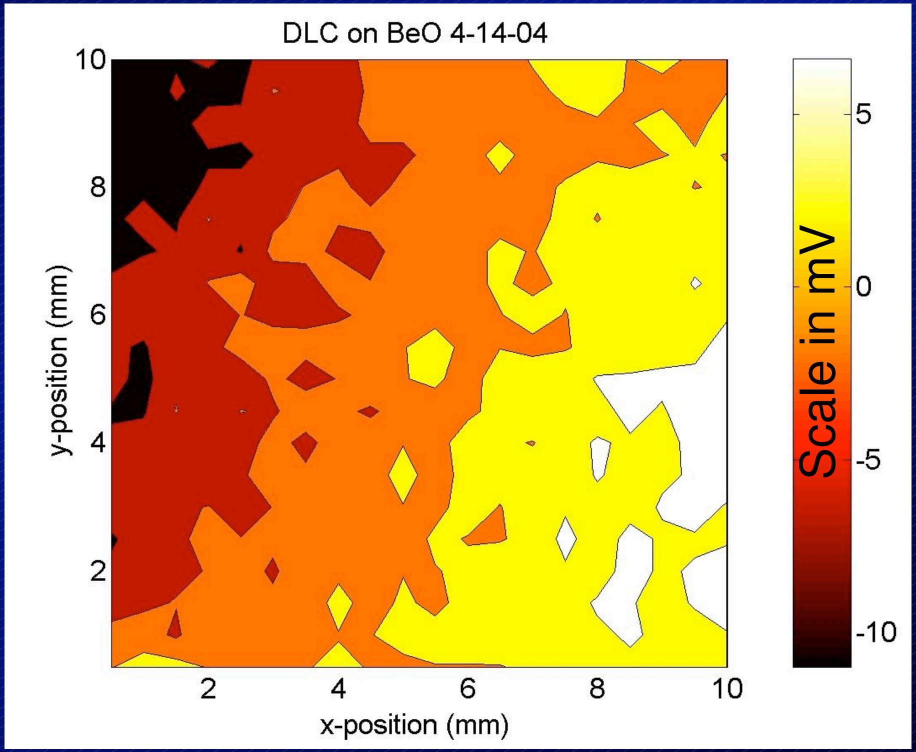
Special Thanks to Dr. Jordan Camp at GSFC

*Robertson et al. CQG (**23**) 2006 p2665*

Surface Potential Distribution

Spatial variations over 1 cm square



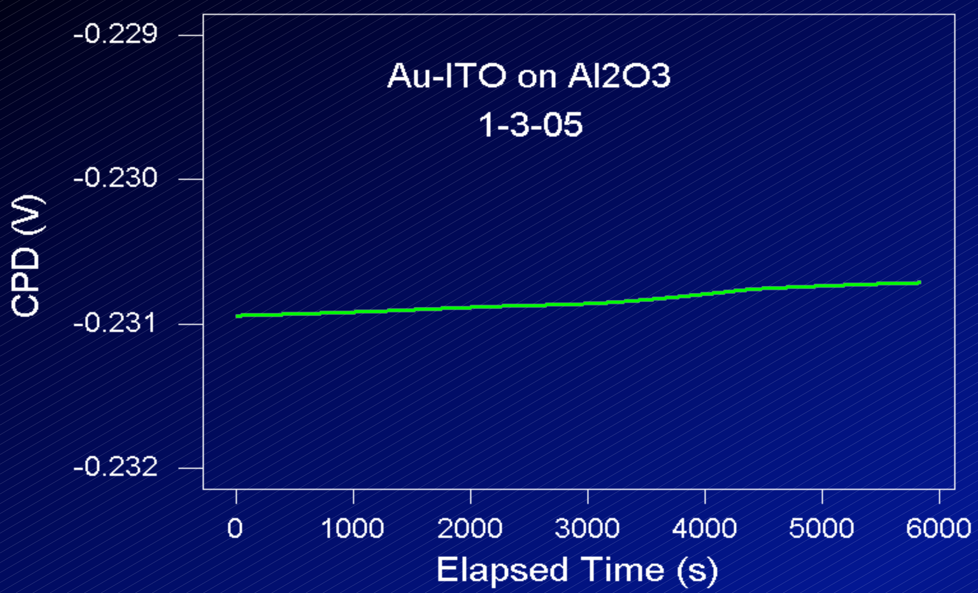


- Typical standard deviations 1-10 mV with 3 mm probe
- Random and non-random structure seen: evidence for contamination

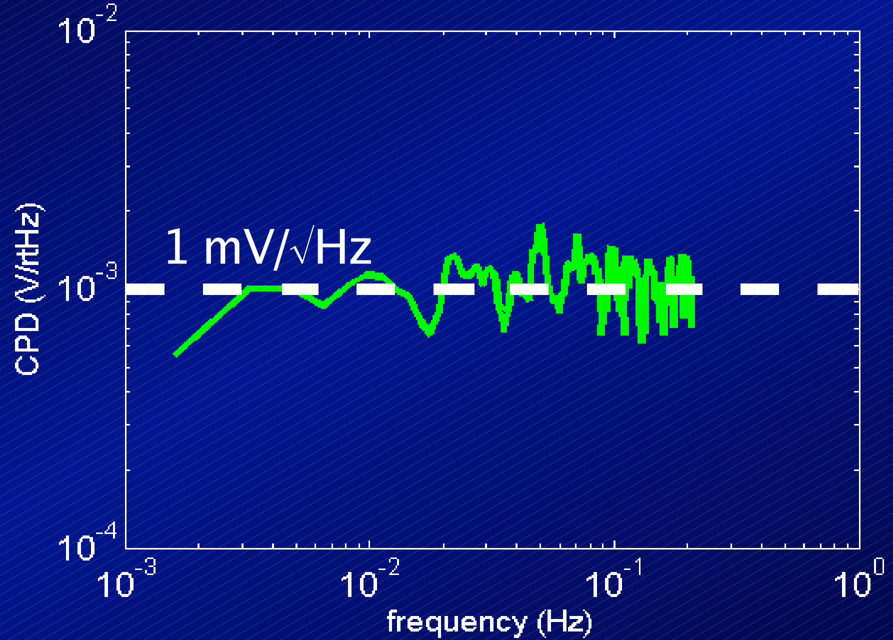
Special Thanks to Dr. Jordan Camp at GSFC

*Robertson et al. CQG (**23**) 2006 p2665*

Surface Potential



Variation of surface potential with time



Amplitude spectral density of variations

Larger gap size mitigates patch effects

- Further investigations required
  - UV scanning system

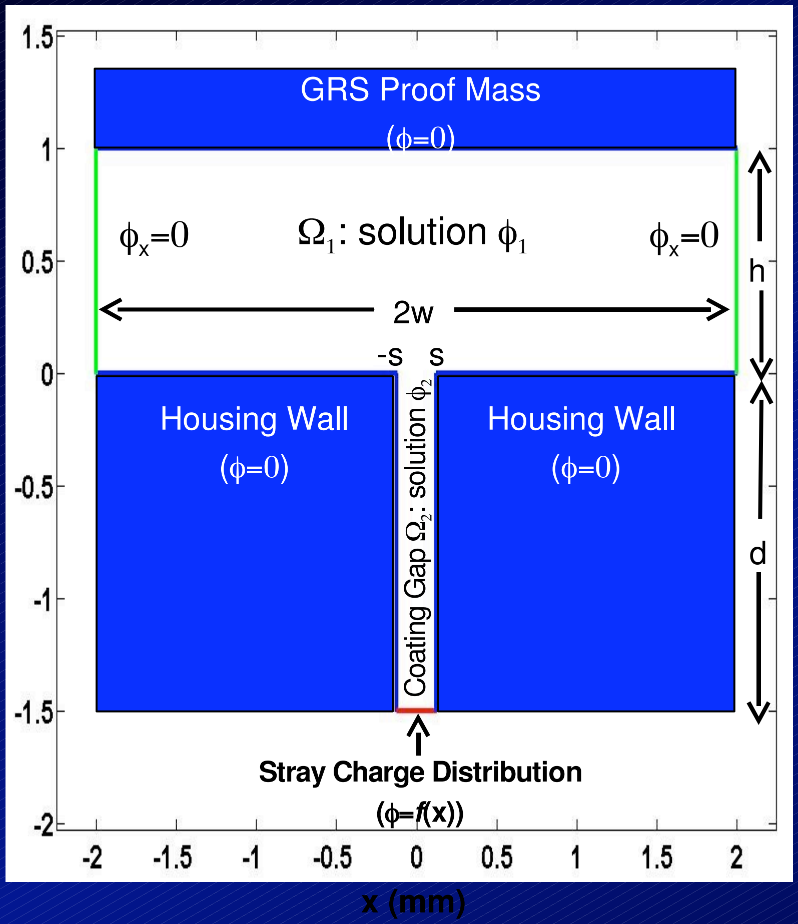
Special Thanks to Dr. Jordan Camp at GSFC

*Robertson et al. CQG (**23**) 2006 S2665*

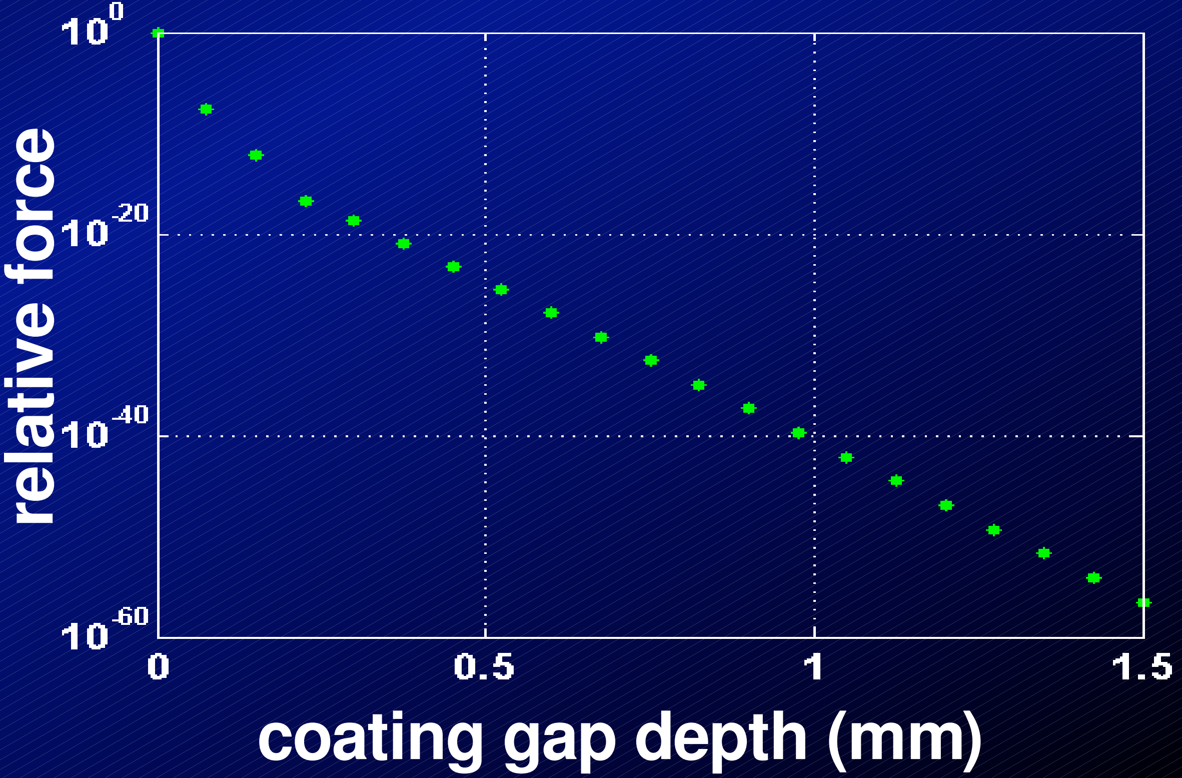
Allex Goh

Electrostatic Modeling

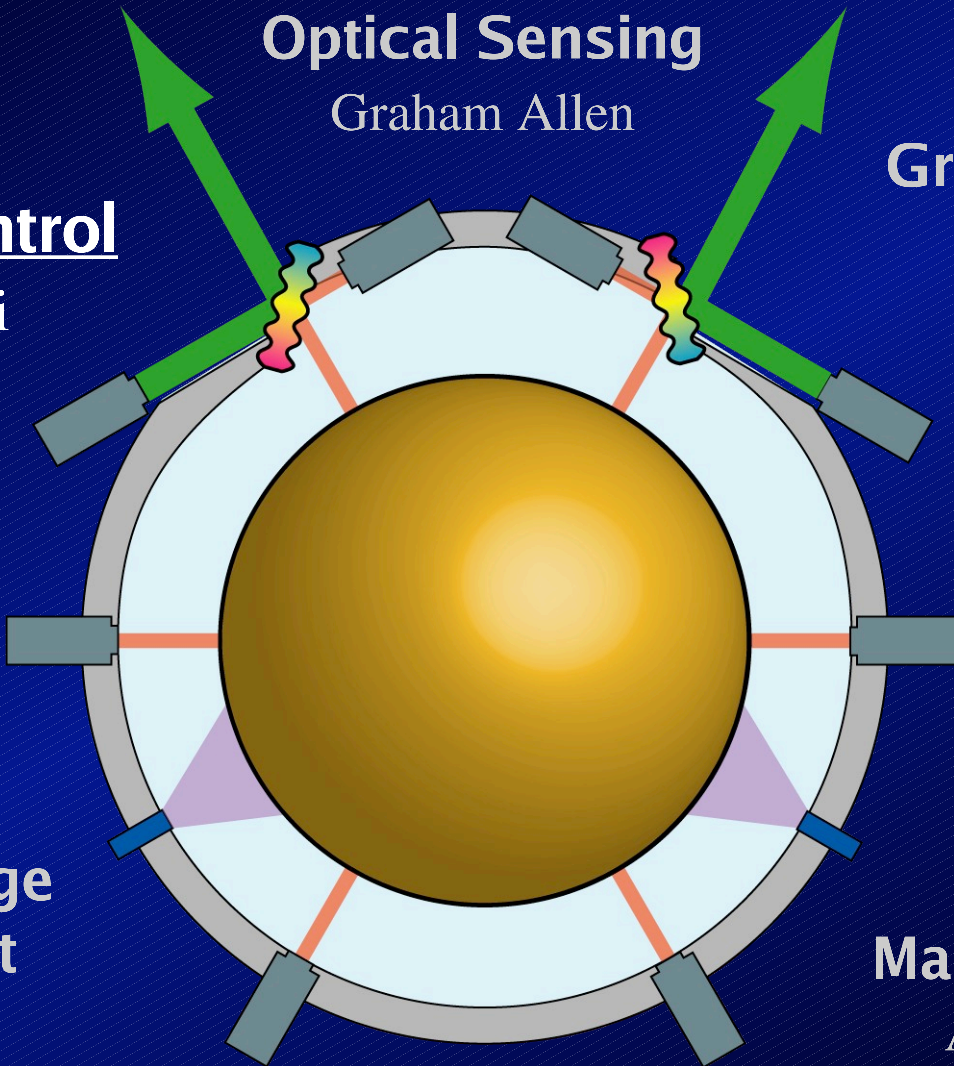
Numerical techniques inaccurate for extreme aspect ratio cases



Analytical solution exists!



Thermal Control



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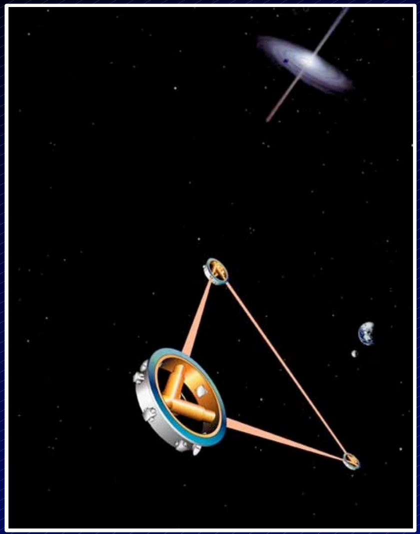
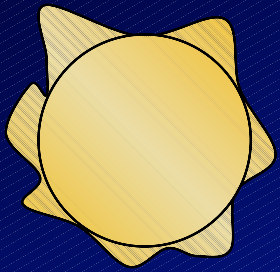
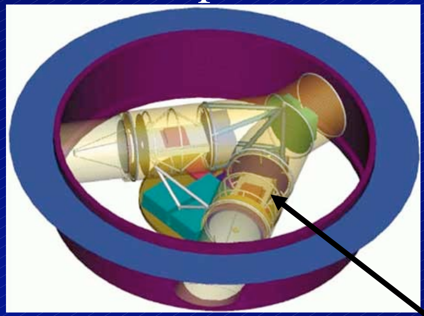




Solar Radiation

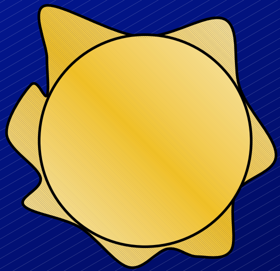
LISA Spacecraft



GRS

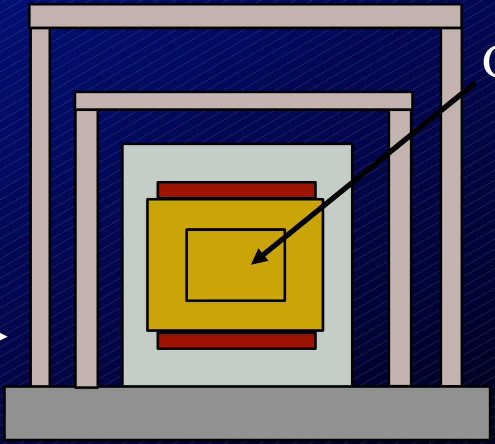
LISA Thermal Stability: 3x10^{-5} K/√Hz for f > 0.01 mHz

- Low frequency disturbance input
- Time-delays



Daily Ambient Temperature Variation

GRS

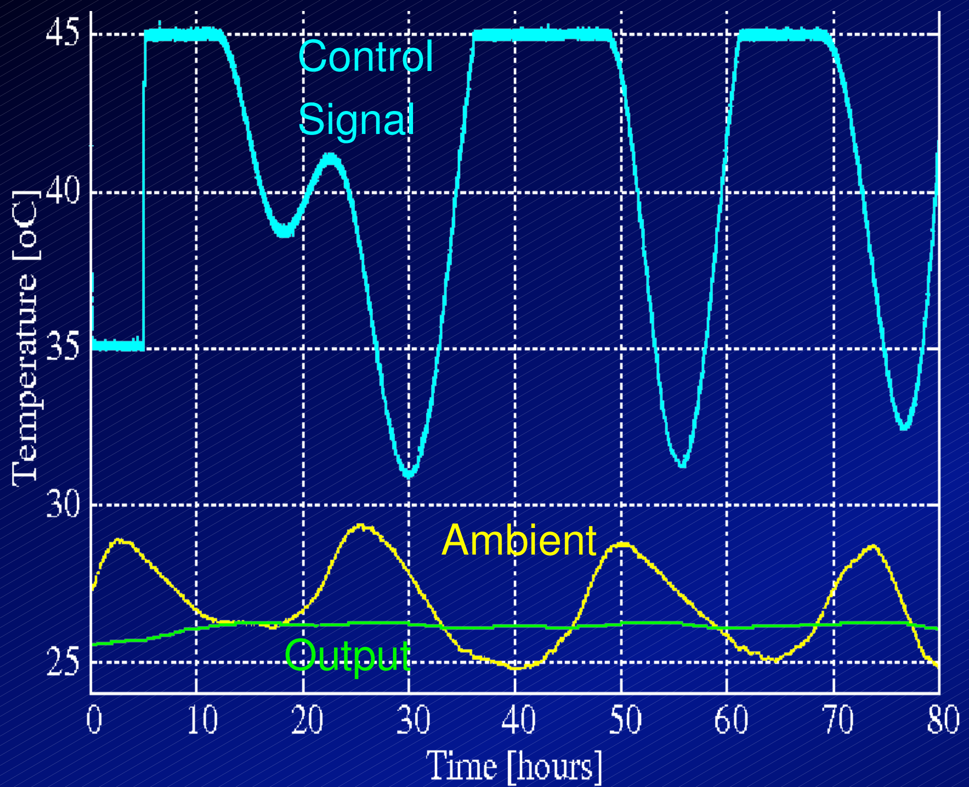


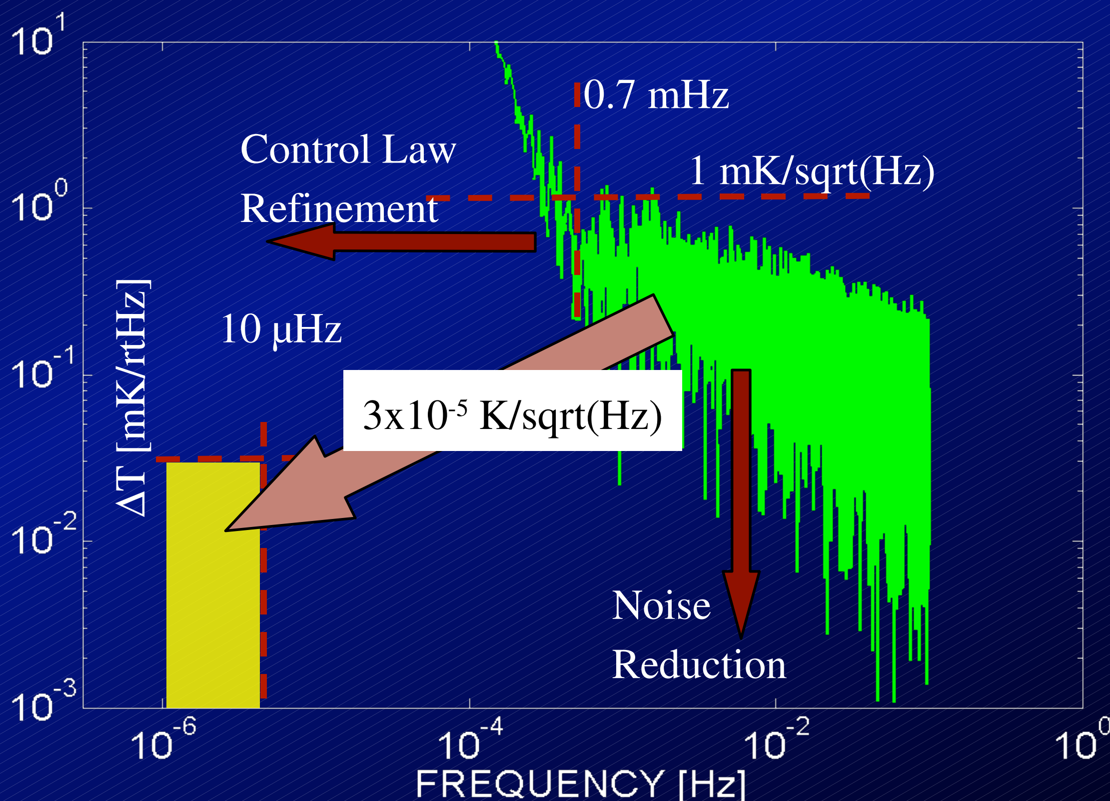
Ground Verification System

Higuchi et al. J. Physics ***(32)*** *2006 S125-S131, Amaldi 6*

Thermal Control

Experimental Results



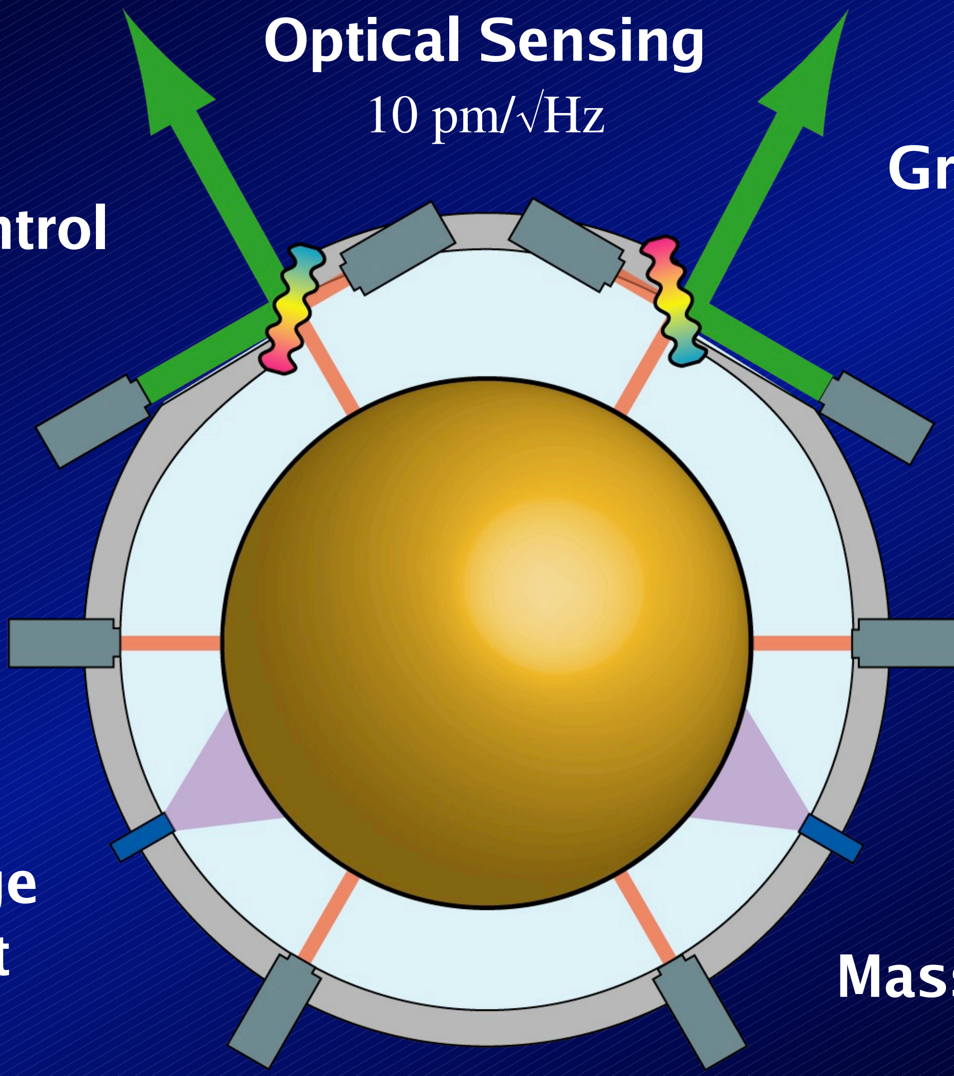


Smith Regulator Control

Stability = 1 mK/√Hz
for f > 0.7 mHz

Higuchi et al. Accepted for ASPE Monterey, 2006

Summary



Optical Sensing
10 pm/√Hz

Thermal Control
1 mK/√Hz

Grating Angular Sensing
1 nrad/√Hz

ES Modeling Surface Studies
1 mV/√Hz
Analytic Solution

Grating Fabrication
Gold & Dielectric Surfaces

Mass Center
$< 3\ \mu m$

UV LED Charge Management
> 1000 hrs

Mass Attraction
$\Delta I < 10^{-3}$

Graduate Students Supported by Stanford Deans Office of Research