Modular Gravitational Reference Sensor (MGRS)
A core fiduciary instrument for space Development Program at Stanford

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Stanford University

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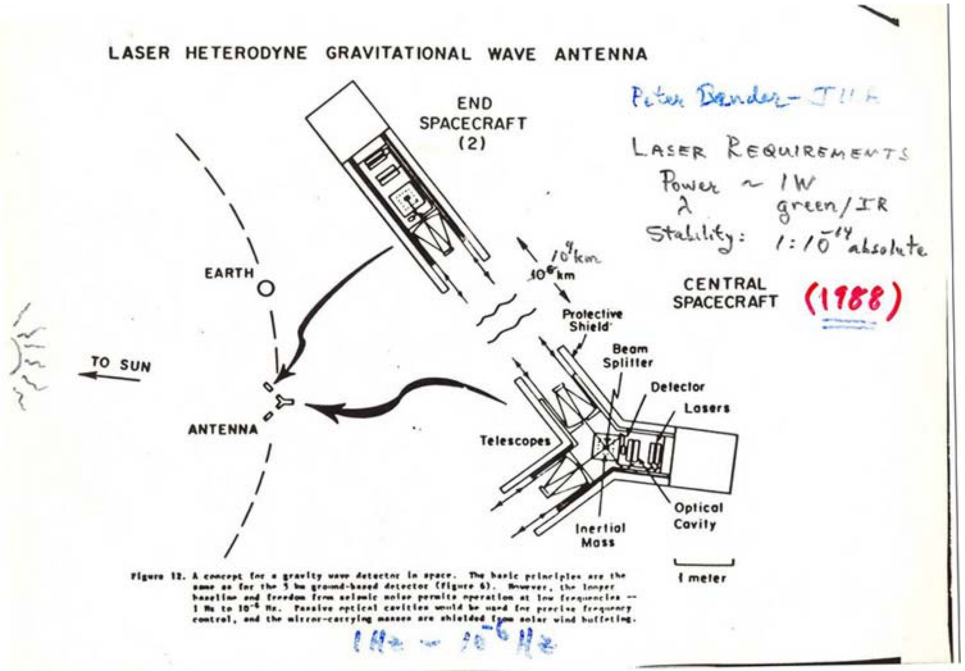
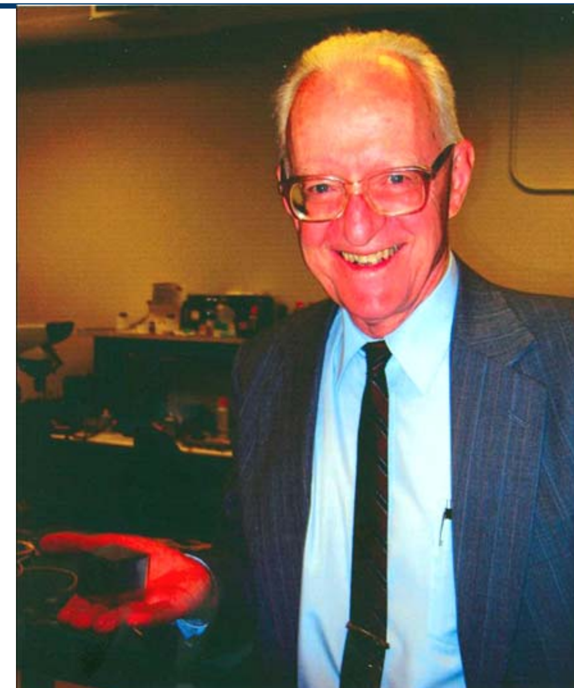
"Modular Gravitational Reference Sensor for Space Gravitational Wave Detection"

Quantum to Cosmos
Airlie Center
July 6-10, 2008

LISA Concept



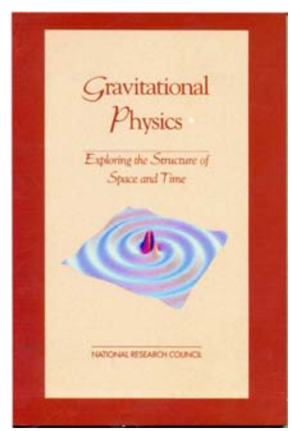
Schematic of LISA in 1988



Peter Bender holding 4x4cm Au/Pt cube

Expected Launch date of 1998 (now >2018)

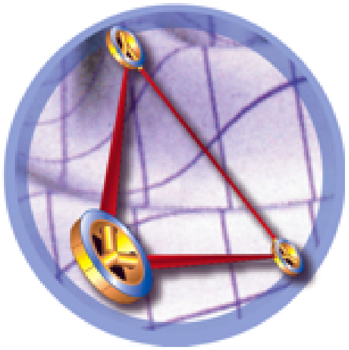
Laser power 1W
Laser stability extremely high
Laser reliability > 5 years

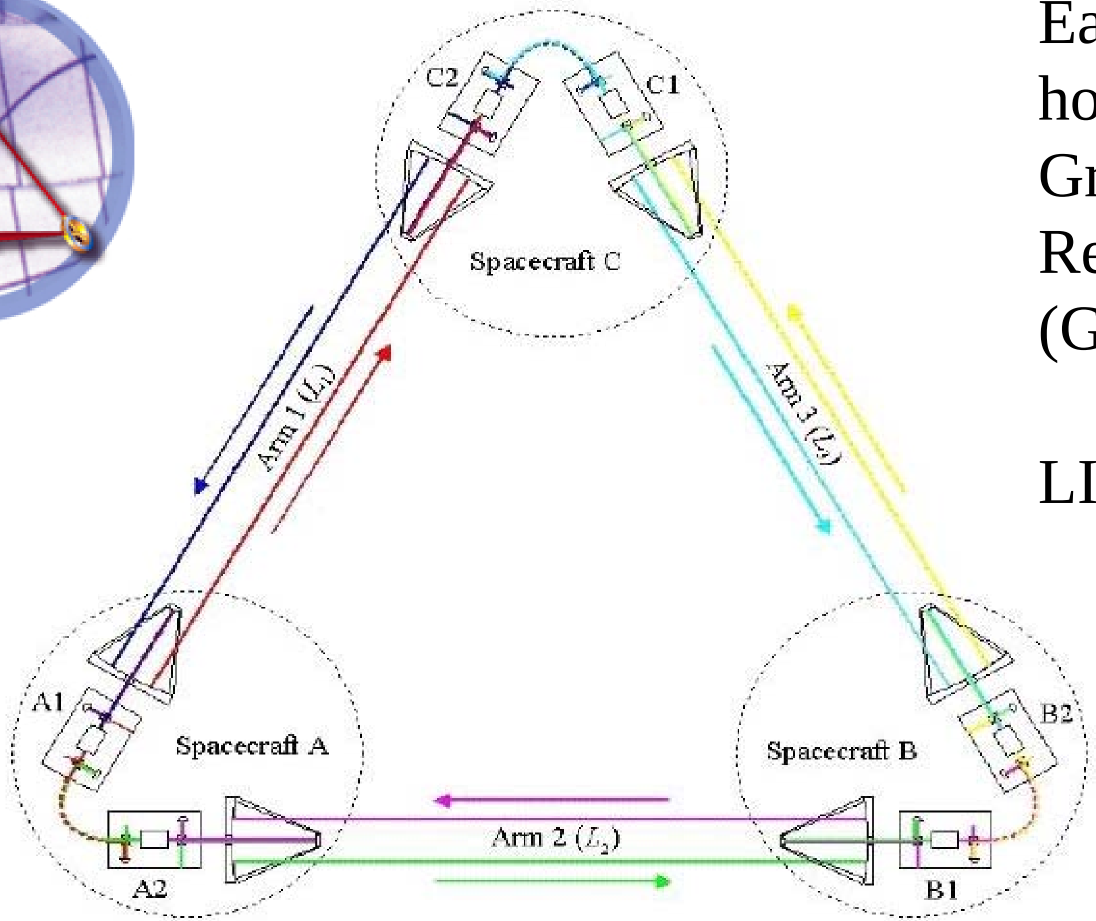


Gravitational waves open a new window on universe

Detect amplitude and phase of gravitational waves with sensitivity to detect back the era of galaxy formation.

LISA is a Spacecraft Constellation

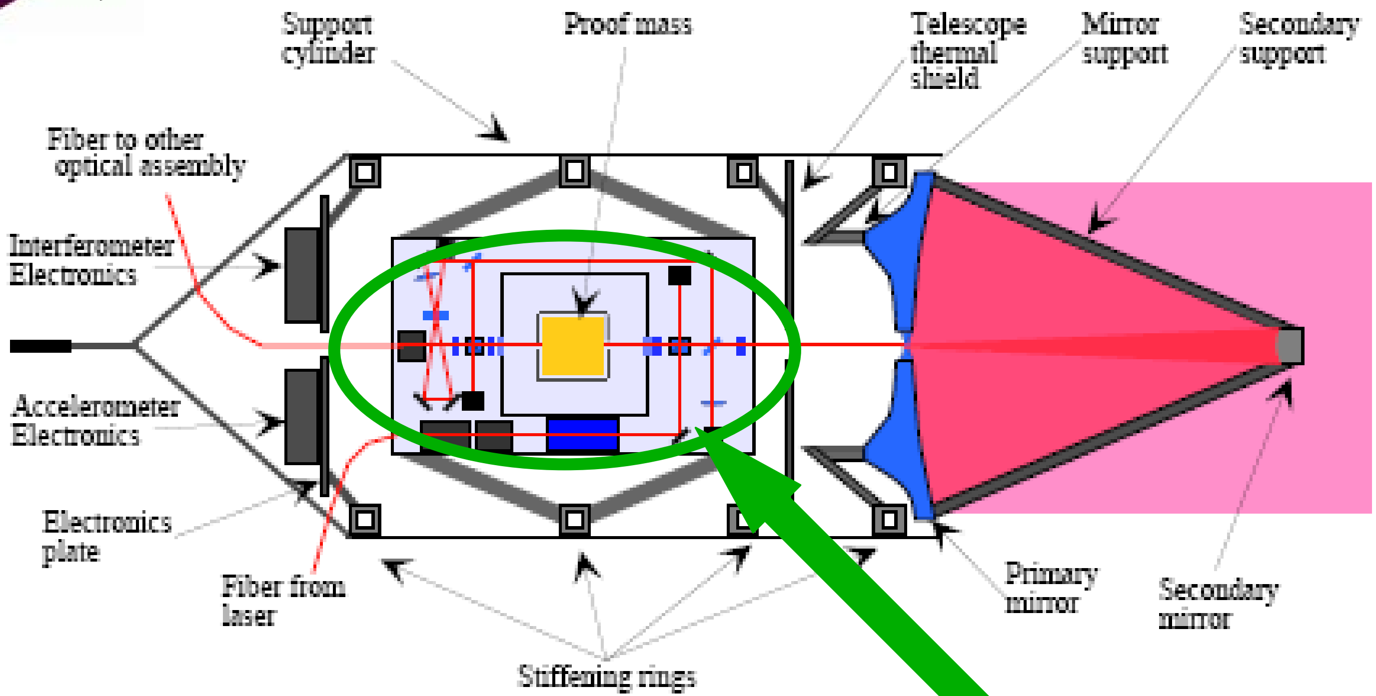




Each spacecraft houses two Gravitational Reference Sensors (GRS)

LISA has 6 GRS

LISA GRS Early Configuration



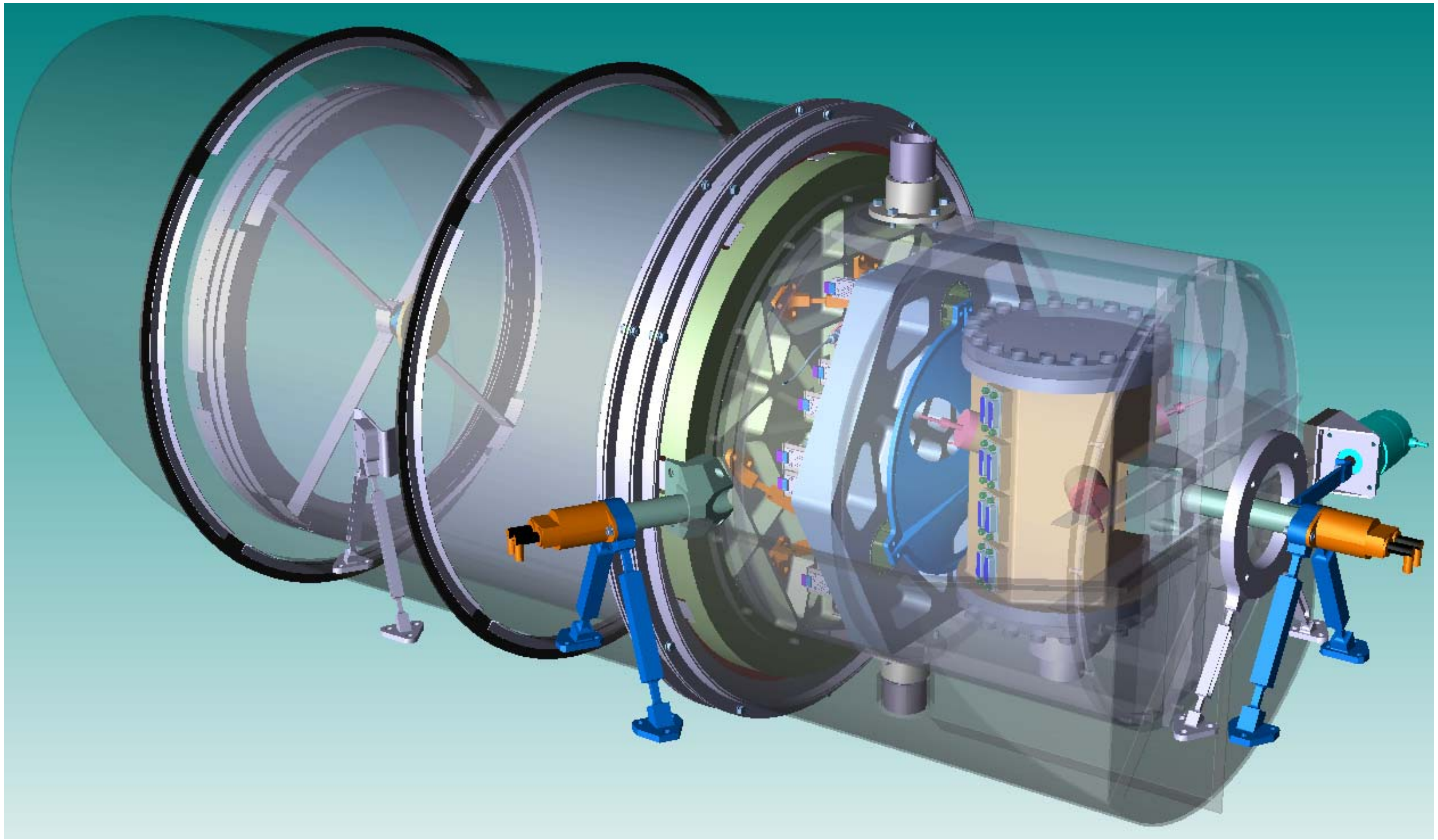
Flat Optical Bench

LISA Structure ("Strap Down") MGRS

Two step interferometry – inside MGRS and Satellite to Satellite

- **Front end optical sensing**
- **Vertical Bench**

- **Larger telescope**
- **More compact structure**

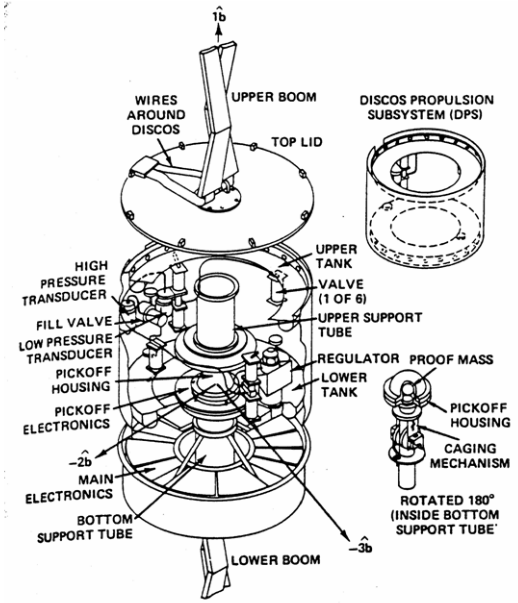


Graphics thanks to Ulrich Johann

GRS Heritage

- **Inertial Sensor based on Stanford experience with**
  - **TRIAD (Stanford/APL, 1972, < 5×10^{-11} m/s^2 RMS over 3 days)**
  - **GP-B (Stanford, launched 4/ 04, < 2×10^{-12} $m/s^2/\sqrt{Hz}$ at 5×10^{-3} Hz)**
- **Earlier sensors used spherical test masses**
  - **Fewer degrees of freedom to control**
  - **True drag free performance**
- **Proposed LISA sensor uses a faceted test mass**
  - **Control position of laser beam on test mass**
  - **Allows validation at picometer level**
    - **Test mass is 4-cm cube of Au/Pt alloy**
      - **Dense, to reduce motion in response to forces**
      - **Low magnetic susceptibility, used on TRIAD**
- **Charge Management**
  - **Charge Management design derived from GP-B**
  - **UV Source is GP-B flight spare.**

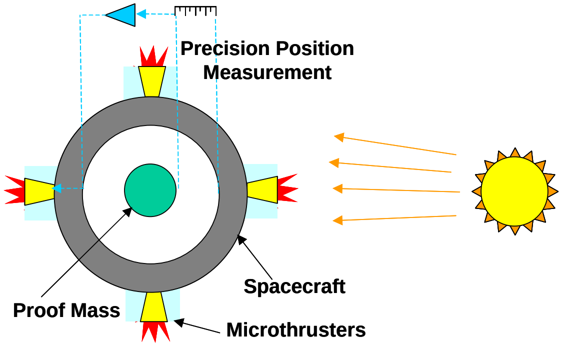
GP-B Flight Gyroscope

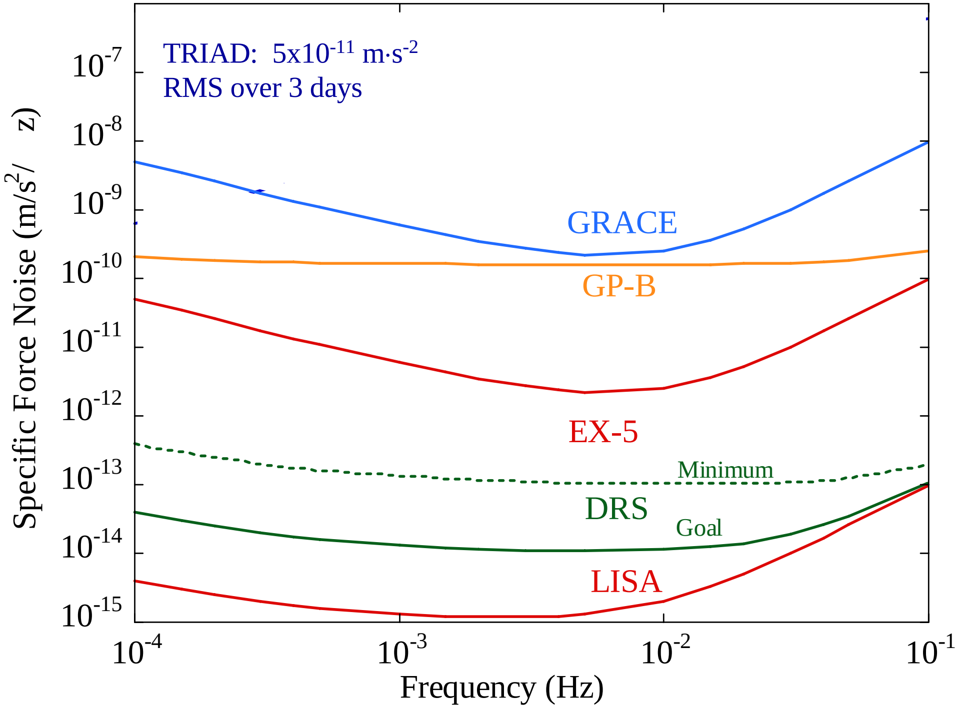


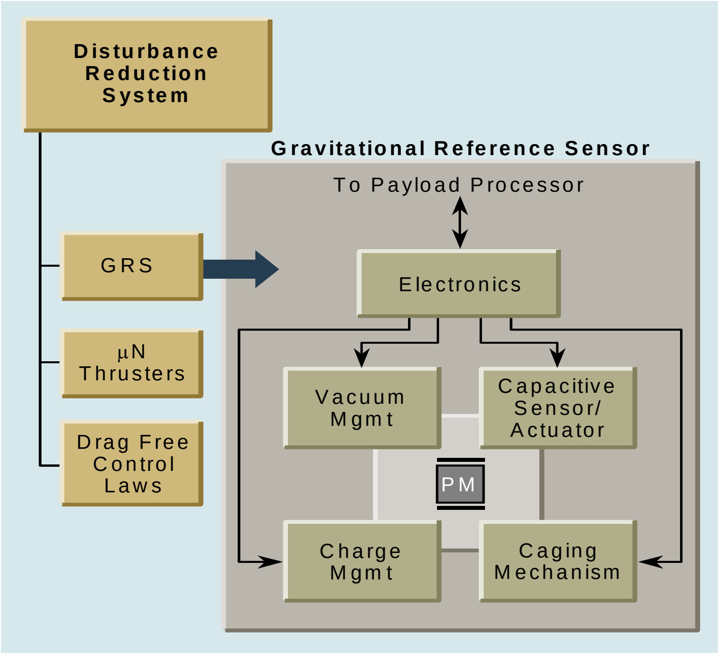
TRIAD sensor- 1972

The Drag Free Performance Challenge
Improve the State of the Art by 100,000

High Precision Reference
- **Inertial Anchor**
- **Accelerometer**
- **Gyroscope**







GP-B Lessons Learned

LISA Technology

- **Operations and simulation are necessary.**
  - -Significant data rates are to be expected for LISA
  - - High fidelity simulation tools are needed to support operations planning and anomaly resolution for LISA.

• Data Analysis
• Ground Simulations

- **Surface physics of coatings are important.**
  - - Probable patch effects observed on GP-B.
  - - Studies of spatial and temporal variations as well as impact of contamination are needed for LISA.

• Surface Coatings

- **Charge management is important.**
  - - Charge management was essential to establish GR-B operation. GP-B demonstrated concept and successful operations.
  - - A larger dynamic range is needed for LISA.

• Charge management

- **Simplify design and reduce coupled degrees of freedom.**
  - -Interacting multiple degrees of freedom and cross-coupling complicates operation concepts and instrument mode definitions.
  - -LISA system must be designed for realistic operations.

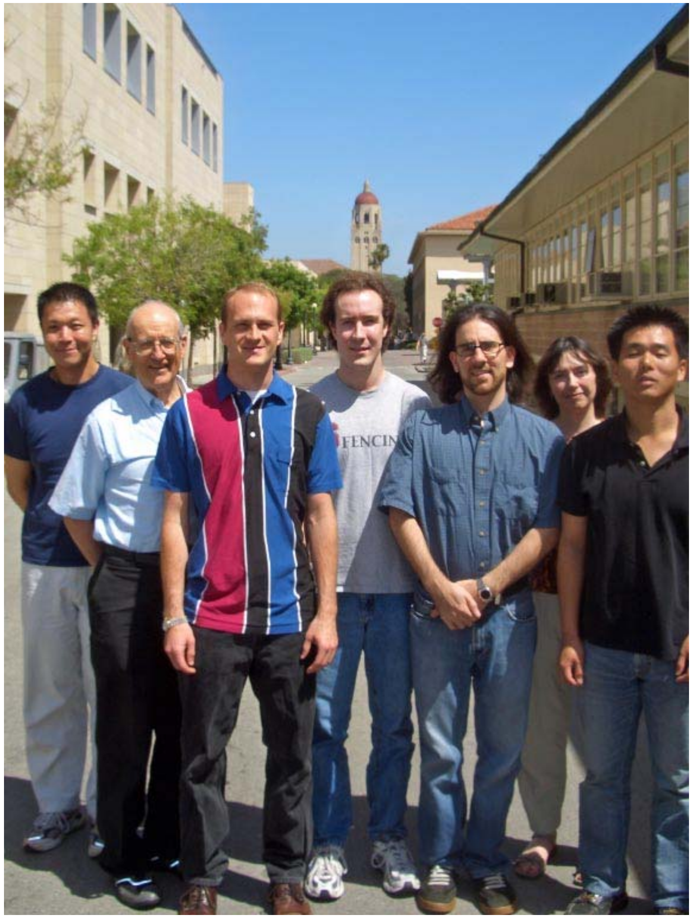
• Mod GRS – reduce X-talk & coupled DOF

- **The noise tree is critical**
  - - Maintenance and test validation of noise budget parameters was critical to enable engineering decisions for GP-B.
  - - Cross-coupling must be carefully modeled for LISA.

Stanford ST-7/GRS Team - April 2005

Descoped – May 2005

The Stanford LISA team - 2006



The Stanford LISA Team - 2006

*Alex Goh
Dan DeBra
*Aaron Swank
*Graham Allen
*John Conklin
Norna Robertson
*Sei Higuchi

Not shown
Ke-Xun Sun
Sasha Buchman
Mac Keiser
Bob Byer

*graduate students

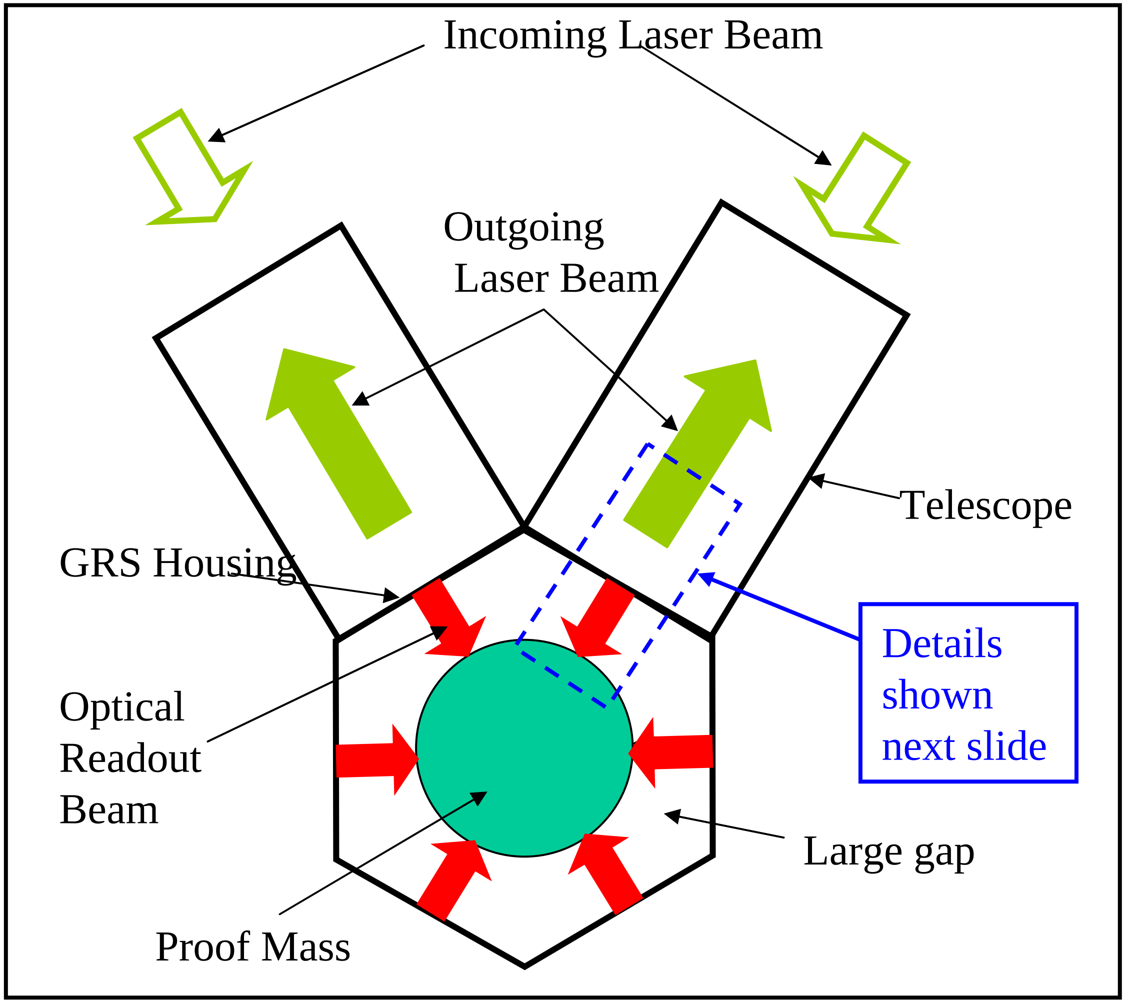
Fairbank's Principle – Disaster compels Creative Thought.

Modular GRS Architecture

Presented at LISA 5th Symposium July 2004

Modular GRS Concept

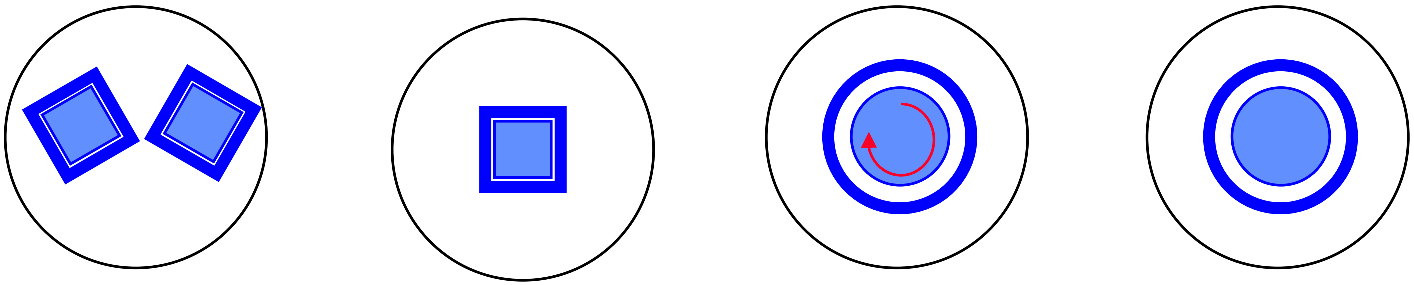
- Single proof mass
- Modularized, stand-alone GRS
- GW detection optics external to GRS
- External laser beam not directly shining on test mass
- Internal optical sensing for higher precision
- Large gap for better disturbance reduction
- **True 3-dim drag-free architecture**
- Determine the geometric center and **center of mass**



Sun, Allen, Buchman, DeBra, Byer, CQG ***(22)*** *2005* ***S287-S296***

Gravitational Reference Sensor (GRS) Configuration Trade-Off

- **GRS configurations under review**
  - **Collaborative work between Stanford and EADS Astrium**
  - **Overview of technology candidates**
  - **Targeting future Advanced LISA, DECIGO, or BBO class missions**
  - **Four configurations under the trade studies**



Pro #1	**Baseline, most tested**	**Simplified**	**Control simplicity**	**Control simplicity**
Pro #2	**Redundancy**	**Backup possible**	**Lower stiffness**	**Lower stiffness**
Pro #3	**LPF flight test**	**Cube convenience**	**Lowest noises**	**Non spin simplicity**

**** Spin at 10 Hz rate, use sphere with 10% moment of inertia ratio. Polhode frequency At 1Hz above the LISA band. Spinning sphere shifts noise out of the LISA band.**

GRS Configuration Trade Studies on Noises and Stiffness Limited Performance (EADS Astrium Collaboration)

- **GRS configuration trade off studies**
  - **Investigate performance in the presence of disturbance and stiffness related noises**
  - **Spinning spherical proof mass shows lowest noises due to:**
    - > **Reduced stiffness**
    - > **Intrinsic signal averaging process**

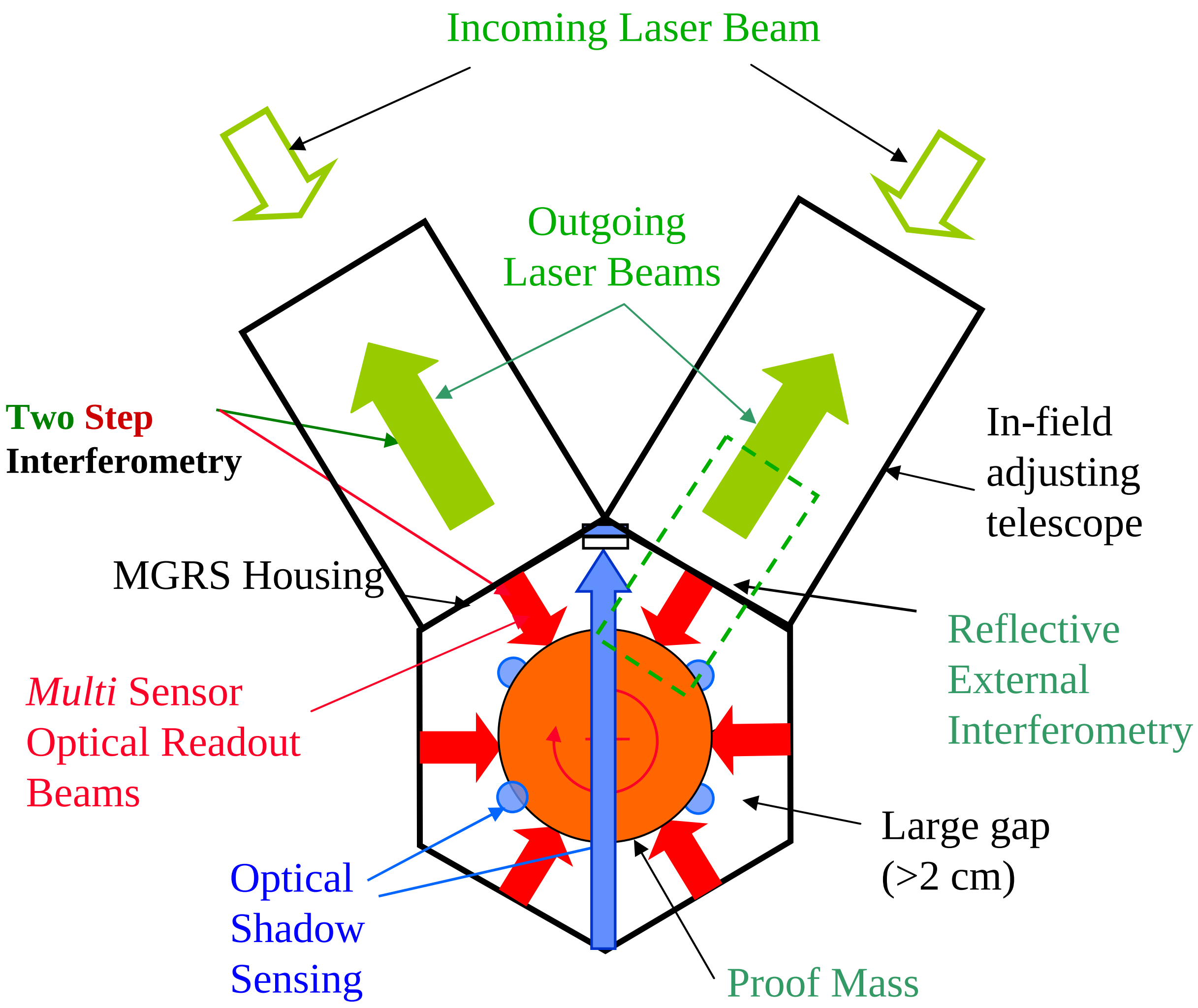
Draft2.1: Acceleration noise from stiffness

Stiffness-related acceleration (δa_{stiff})	2 cubes: $[10^{-16}\,\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$, 1 mHz	1 cube: $[10^{-16}\,\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$, 1 mHz	1 sphere (spinning): $[10^{-16}\,\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$, 1 mHz	1 sphere (no spin): $[10^{-16}\,\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$, 1 mHz
Total stiffness in LoS (*) : magnetic stiffness (DC magnetic field gradient) self-gravity stiffness (DC self-gravity gradient) electric stiffness image charges DC voltages patch fields	$k^m + k^{sg} + k^e \sim 4\cdot10^{-7}s^{-2}$ [13] k^m, [13] table 4, footnote a $k^{sg} \sim \frac{2GM_{dis}}{r^3}$ $k^e = k^{ic} + k^v + k^{pf}$ [13] $k^{ic} \sim \frac{q^2}{da_p}$ ([13], model) $k^v \sim \frac{qV_{og}}{d^2}$ ([13], model) $k^{pf} \sim \frac{a_p V_{pe}^2}{d^3}$ ([13], model)	$k^m + k^{sg} + k^e \sim 4\cdot10^{-7}s^{-2}$ [13] k^m, [13] table 4, footnote a $k^{sg} \sim \frac{2GM_{dis}}{r^3}$ $k^e = k^{ic} + k^v + k^{pf}$ [13] $k^{ic} \sim \frac{q^2}{da_p}$ ([13], model) $k^v \sim \frac{qV_{og}}{d^2}$ ([13], model) $k^{pf} \sim \frac{a_p V_{pe}^2}{d^3}$ ([13], model)	$k^m + k^{sg} + k^e \sim 5\cdot10^{-8}s^{-2}$ (**) k^m, [13], table 4, footnote a $k^{sg} \sim \frac{2GM_{dis}}{r^3}$ $k^e = k^{ic} + k^v + k^{pf}$ [13] $k^{ic} \sim \frac{q^2}{da_p}$ ([13], model) $k^v \sim \frac{qV_{og}}{d^2}$ ([13], model) $k^{pf} \sim \frac{a_p V_{pe}^2}{d^3}$ ([13], model)	$k^m + k^{sg} + k^e \sim 5\cdot10^{-8}s^{-2}$ (**) k^m, [13], table 4, footnote a $k^{sg} \sim \frac{2GM_{dis}}{r^3}$ $k^e = k^{ic} + k^v + k^{pf}$ [13] $k^{ic} \sim \frac{q^2}{da_p}$ ([13], model) $k^v \sim \frac{qV_{og}}{d^2}$ ([13], model) $k^{pf} \sim \frac{a_p V_{pe}^2}{d^3}$ ([13], model)
Relative PM-to-S/C jitter (in LoS)	$\delta x \approx 1.44\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 1 mHz (electrostatic readout) $\delta x \approx 0.32\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 1 mHz (optical readout) [47]	$\delta l = \sqrt{\left(\delta x\cos(\frac{\alpha}{2})\right)^2 + \left(\delta y\sin(\frac{\alpha}{2})\right)^2} \approx$ $\approx 0.29\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 1 mHz (optical readout) [46]	$\delta l = \sqrt{\left(\delta x\cos(\frac{\alpha}{2})\right)^2 + \left(\delta y\sin(\frac{\alpha}{2})\right)^2} \approx$ $\approx 0.3\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 1 mHz design and closed-loop simulation from [23]	$\delta l = \sqrt{\left(\delta x\cos(\frac{\alpha}{2})\right)^2 + \left(\delta y\sin(\frac{\alpha}{2})\right)^2} \approx$ $\approx 12\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at 1 mHz (***) design and closed-loop simulation from [23]
Total acceleration from stiffness	5.75 (electrostatic readout) 1.26 (optical readout)	1.17	0.15	6 (***)

Domenico Gerardi ***et al*** **study: “Advanced concepts for future space-based interferometers: design and performance considerations”**

MGRS Architecture

Presented at LISA 5th Symposium July 2004

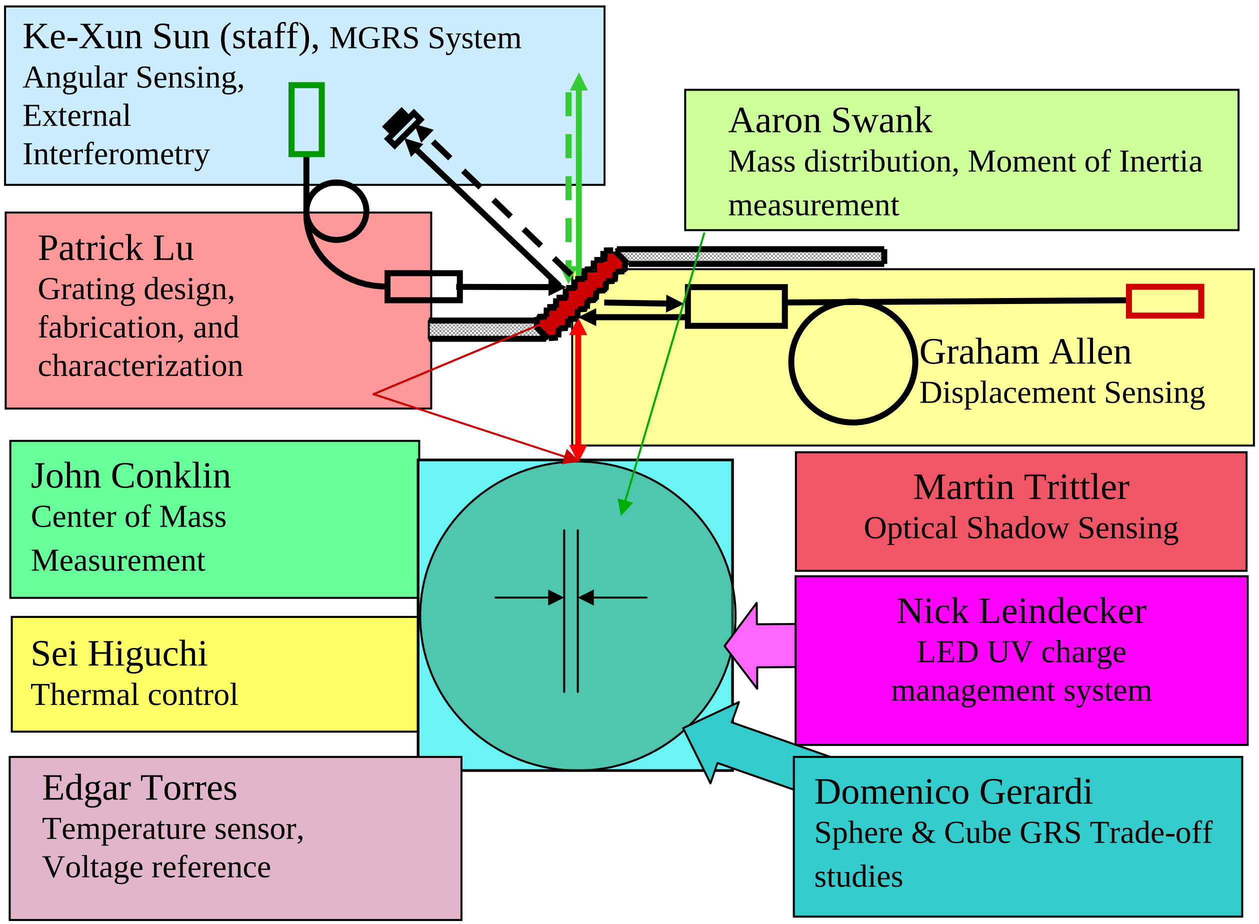


Sun, Allen, Buchman, DeBra, Byer, CQG ***(22)*** *2005 S287-S296*

MGRS in the Lab – investigate key elements of the system

Technologies equally applicable to LISA configuration

Ph. D Graduate Students involved in LISA work



Modular Gravitational Reference Sensor (MGRS)

- **MGRS Program in FY07/08 Made Significant Progresses in All Planned Areas**
  - Higher performances in all experiments than what reported in LISA 6th symposium
  - Opened new R&D areas in system technologies and key components

- **Areas of R&D**

1. **System technologies**
   - System perspective
   - GRS Trade off studies
   - Two-layer sensing & control
   - Multi-sensor algorithm

2. **Optics**
   - Grating cavity displacement sensing
   - Grating angular sensing
   - Diffractive optics
   - Differential optical shadow sensing
   - Laser frequency stabilization

3. **Proof mass**
   - Mass center offset measurement
   - Moment of inertia measurement
   - Spherical proof mass fabrication

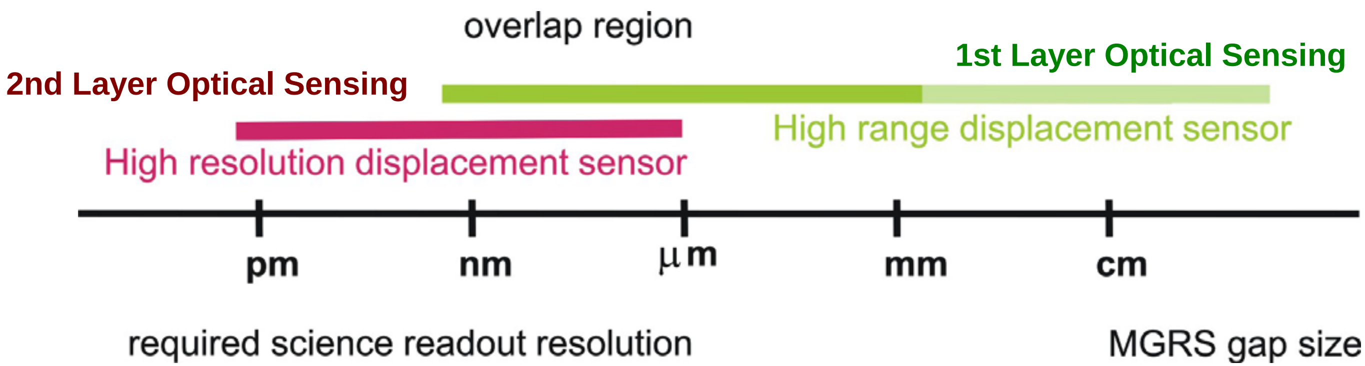
4. **UV LED charge management**
   - UV LED AC charge management
   - UV LED lifetime test
   - UV LED space qualification
   - Alternative charge management

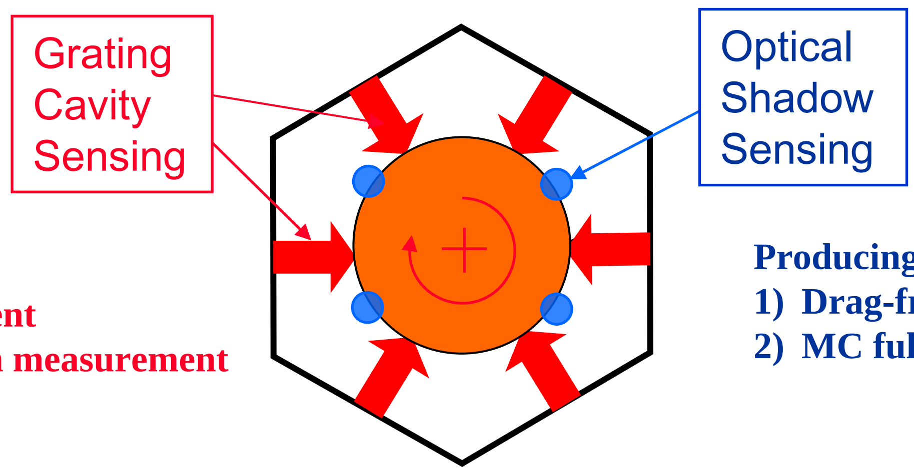
5. **Thermal control**
   - Passive thermal control
   - Active thermal control
   - Temperature sensor
   - Thermal test facility

6. **Small satellites**
   - Space qualification of MGRS
   - Further Technology development

Two-Layer Optical Sensing for Proof Mass

- **First layer:**
  - **1 nm precision drag free sensing using differential optical shadow sensing (DOSS)**
- **Second layer:**
  - **1 pm precision science measurement using grating cavity interferometry**

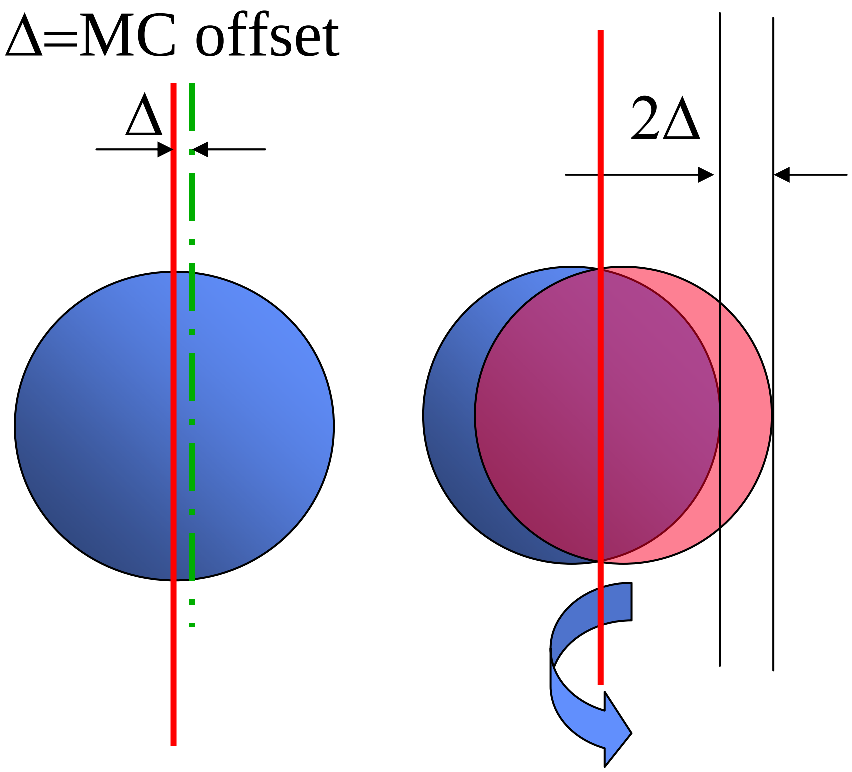


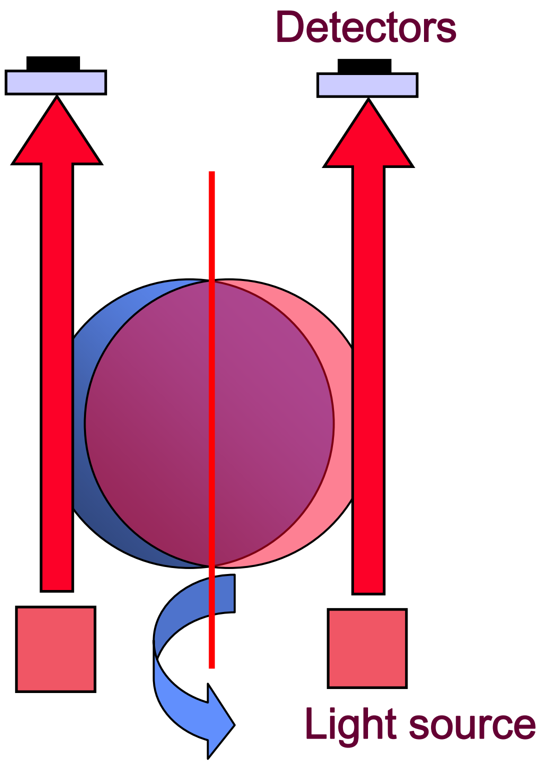


Producing signals for
1) **Science measurement**
2) **MC high resolution measurement**

Producing signals for
1) **Drag-free control**
2) **MC full range measurement**

Spinning Sphere Movement and Optical Sensing





Center of Mass Offset Δ ~ 10~ 300 nm

Spinning sphere: 2Δ variation

Other variations

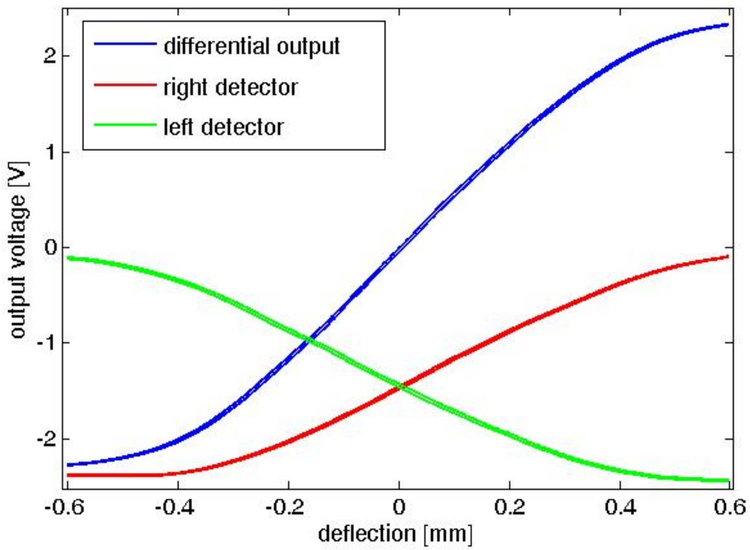
- **Surface modulation**
- **Displacement**

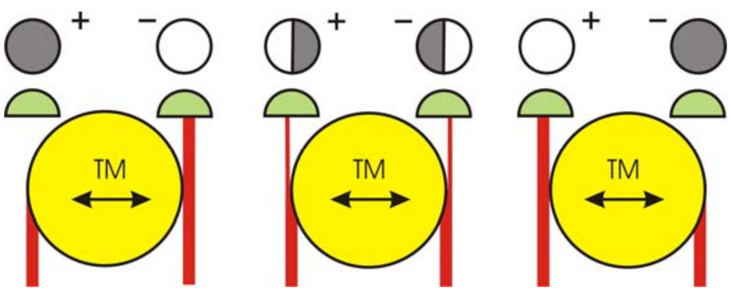
Optical shadow sensing is appropriate

- **Moderate sensitivity**
- **(0.1 ~ 10 nm/Hz$^{1/2}$)**
- **Large dynamic range (~ mm)**
- **May use incoherent light sources**

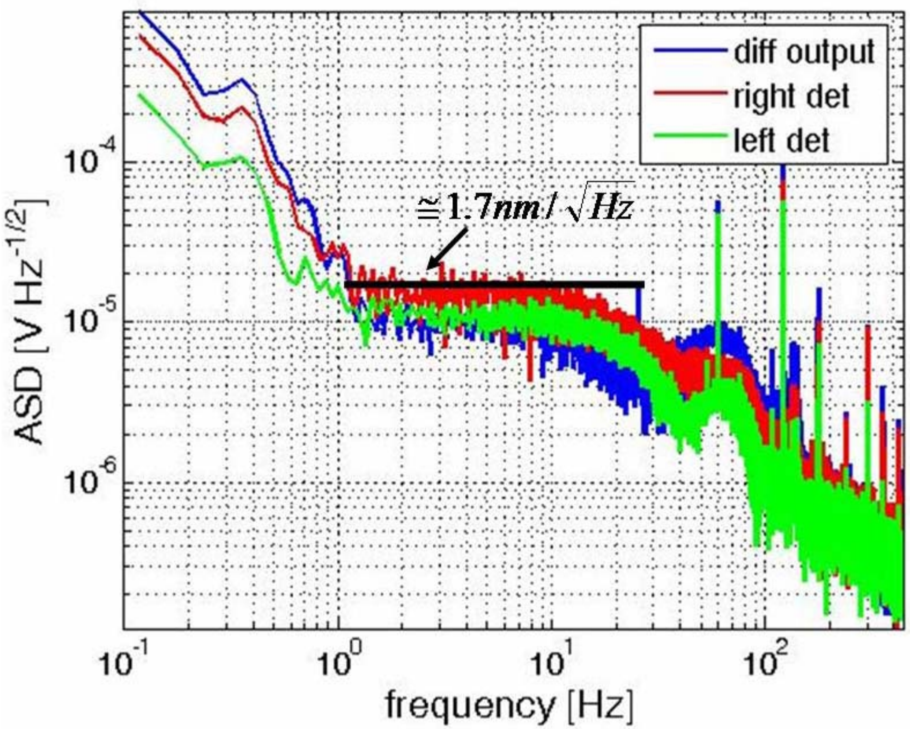
Differential Optical Shadow Sensing (DOSS)

Showing Addequate Sensivity (1.7 nm/Hz$^{1/2}$)





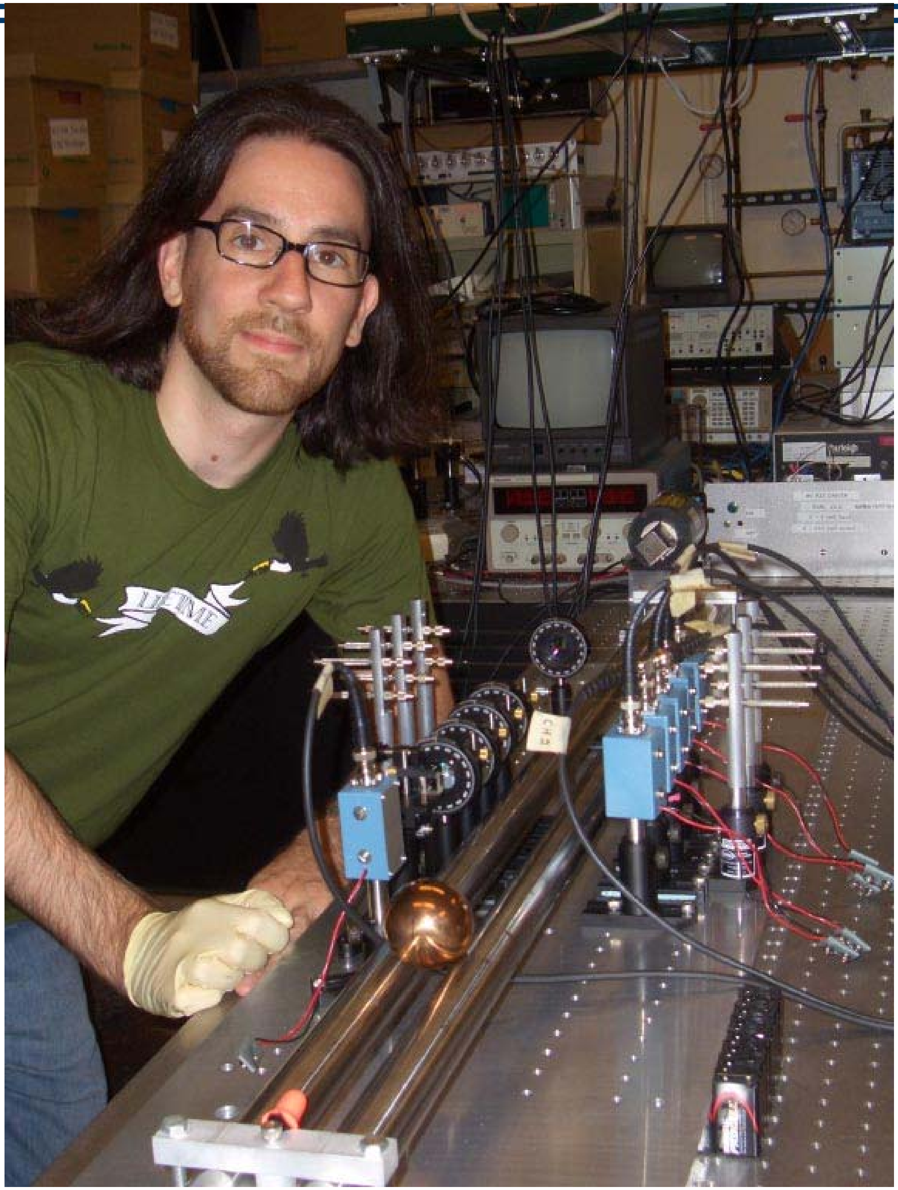
PSD of sensor noise for 10s of data



Sun, Trittler, Conklin, Byer, "Differential optical shadow sensing (DOSS) for LISA and MGRS applications", Poster on Wednesday

John Conklin

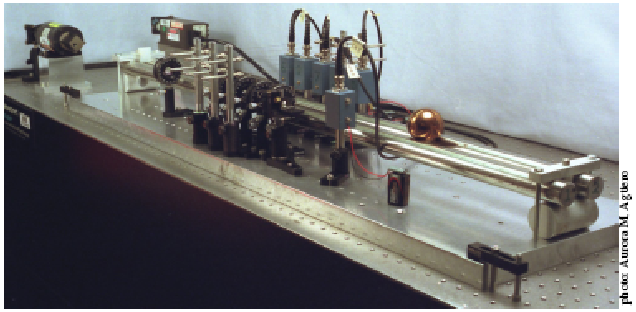
Graduate student Aero-Astro GP-B/LISA



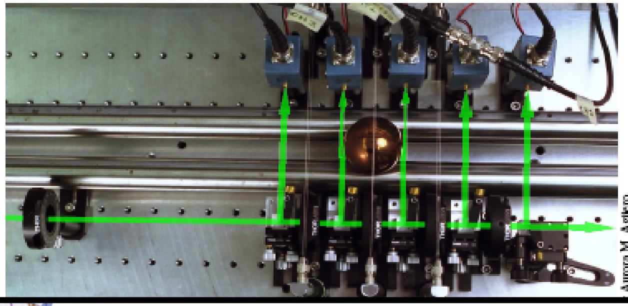
DOSS Measurement of Velocity Modulation
Determine Sphere Mass Center Offset to ~150 nm

Measuring Velocity Modulation

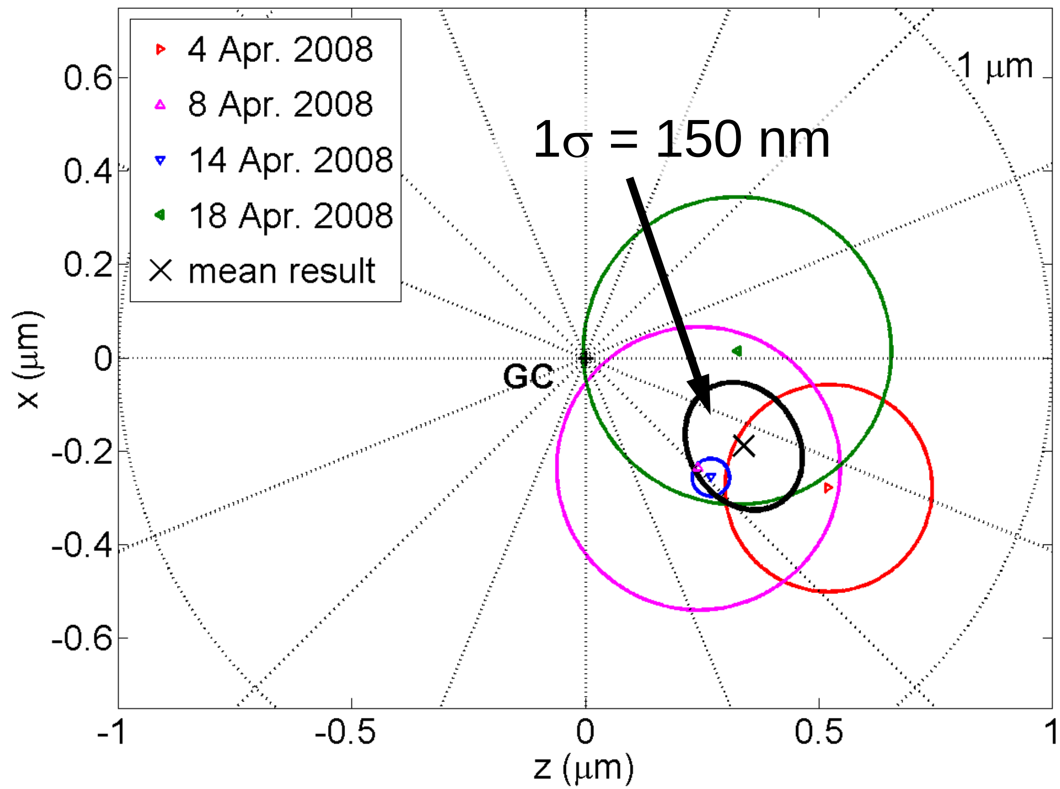
- Roll sphere down rails to spectrally shift CM information, avoid 1/*f* noise boundary
- Sense sphere trajectory optically (100 ns timing accuracy)



- Optical subtraction to eliminate laser intensity noise: ~1 kV/m sensitivity
- Compare measured times with model
- Recover CM location with Monte Carlo parameter search



Experimental Results



Present measurement accuracy: 150 nm

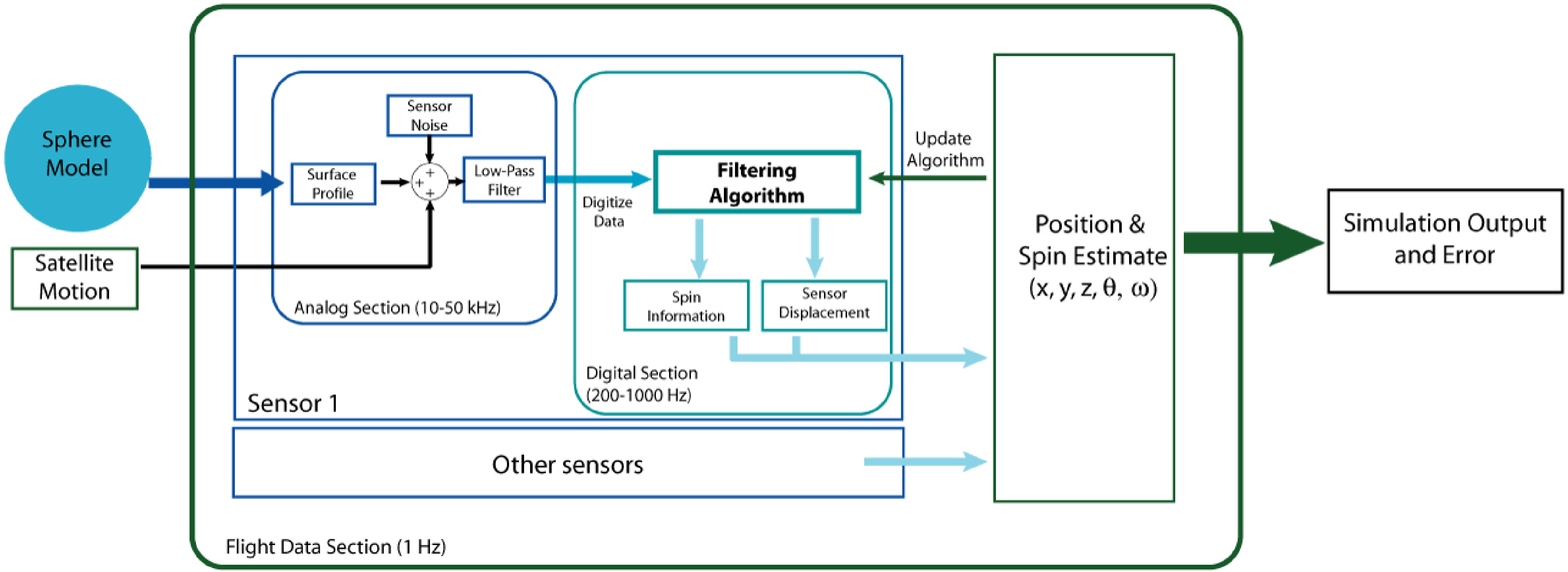
Conklin, Sun, Swank, DeBra: "Mass Center Measurement for Drag-free Test Masses",

Simulation of Precision Test Mass Measurement

Graham Allen, John Conklin

- **GOAL: Model the mass center location of a spinning spherical mass**
  - **better than <10 pm/rt(Hz)**
- **Assumptions:**
  - **MC offset as large as 100 nm**
  - **Surface variations of 30 nm**
  - **Satellite motion of 30 nm**
- Outcome**: Identified and tested algorithms that can successfully determine the mass center location**
  - **Determine sensor requirements: sampling rates, non-linearity, etc**
  - **System is robust – will operate with five sensors**
  - **System allow recapture of test mass – restart time less than 30sec**

Simulation Block Diagram



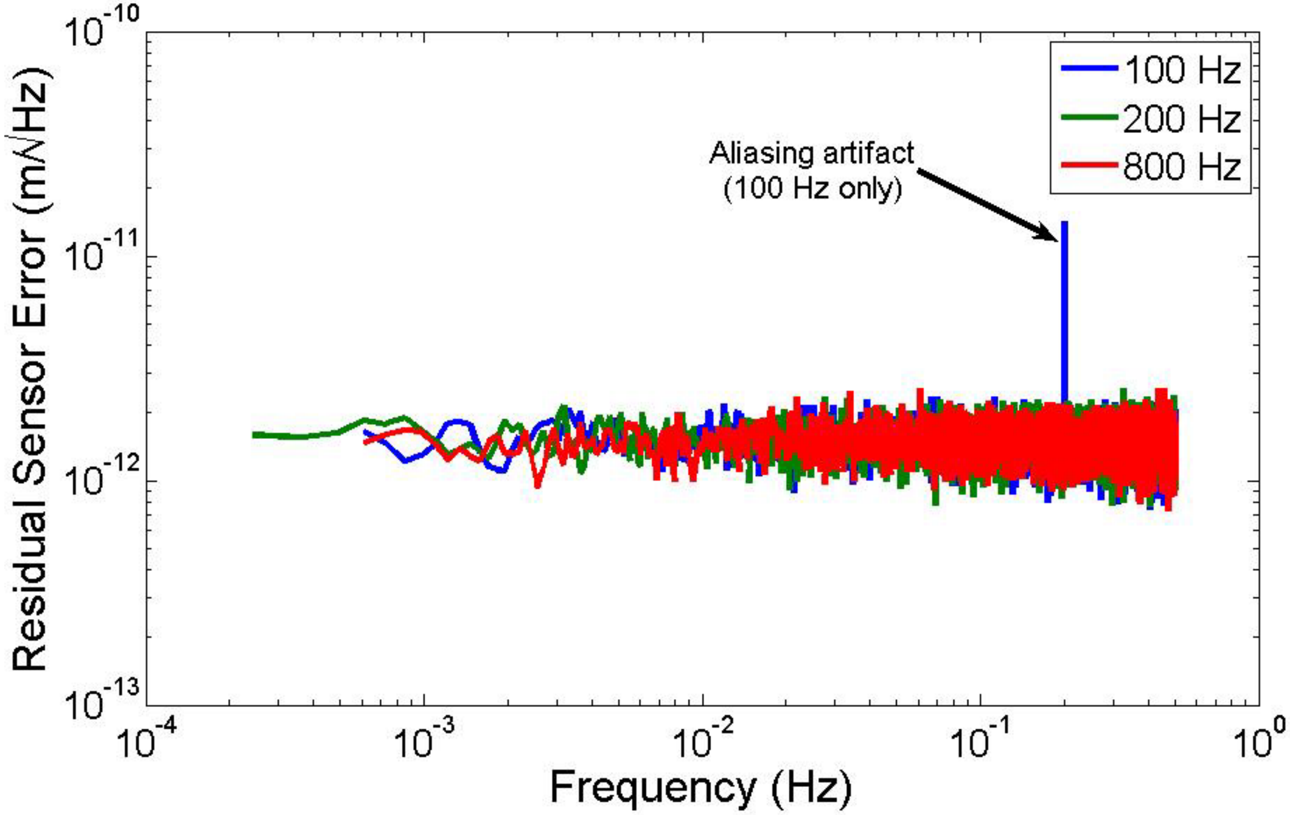
- **Model the analog and digital systems of the satellite**
- **Most simulation parameters are adjustable**
  - **Spin frequency, sample rates, non-linearity, noise levels**

Tested Three Algorithms

	Complexity (12 sensors) (1000s of μops)	Accuracy (pm)	Spin Rate Knowledge
Digital Filter	624	0.5	0.1
Mapping	≈ 200	0.5	10^{-5}
Sine Fit (Preferred)	537	0.01	10^{-3} (req) 10^{-6} (best)

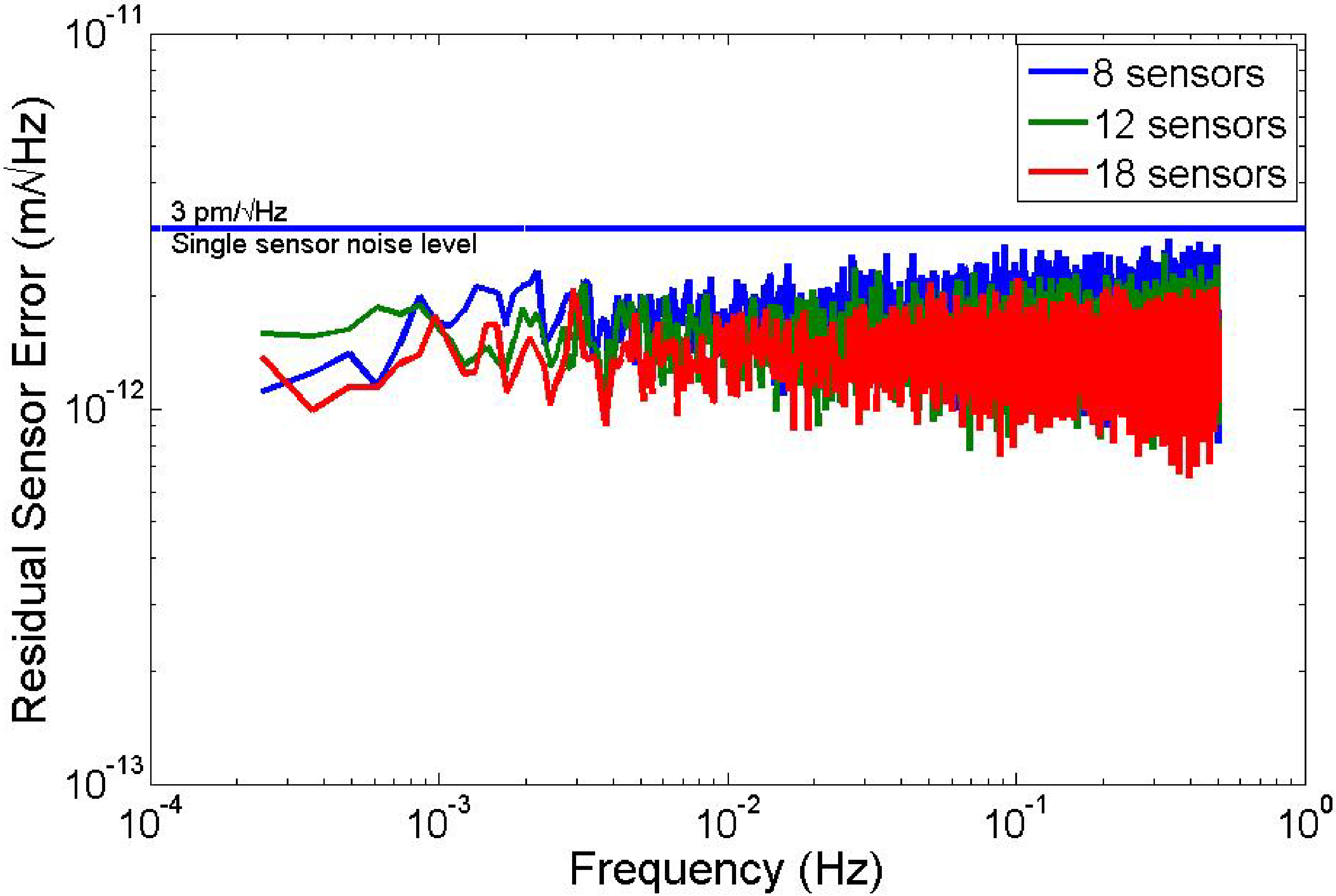
- **1 MHz CPU is sufficient for all algorithms**
  - **1 Hz Science Data Rate, 400 Hz sample rate**
- **Sine Fitting is preferred**
  - **Highest resolution**
  - **Polynomial fit → Easy interpolation for science data**
  - **Provides sphere phase automatically**

Tested Sampling Rates



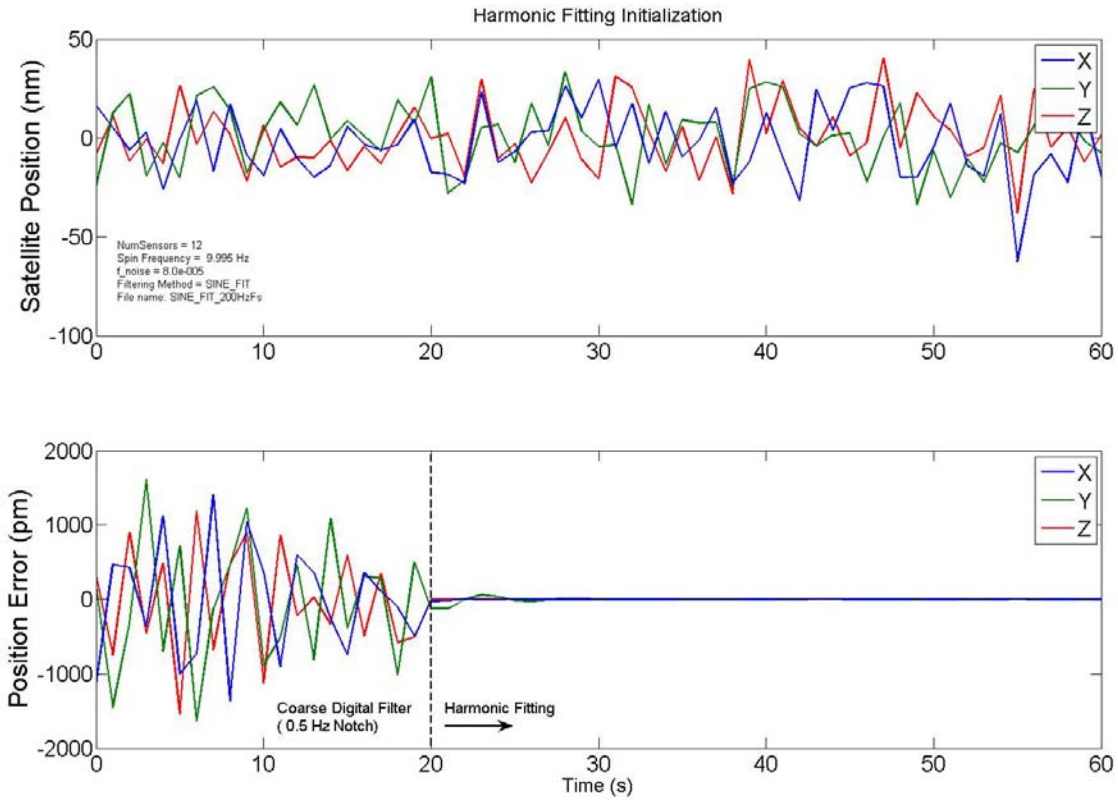
- **12-bit sampling at 200 Hz is sufficient**
  - **16 bit at 400 Hz is ideal**
  - **Mass center offset provides a reliable dither**

Tested Robustness to loss of Sensors



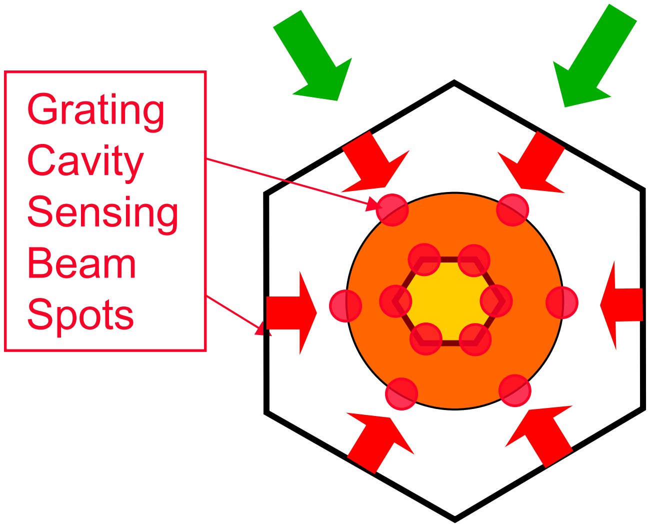
- **Works well with 5+ sensors**
  → Highly redundant with 8 sensors

Confirmed Initialization

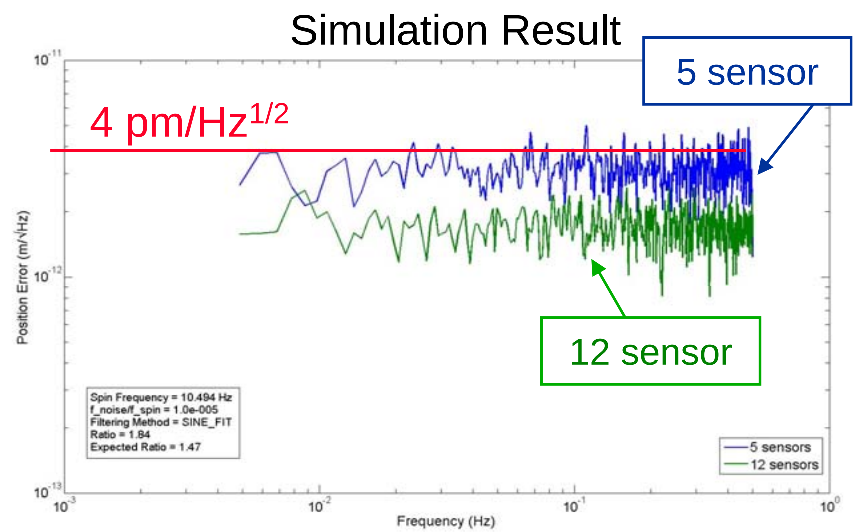


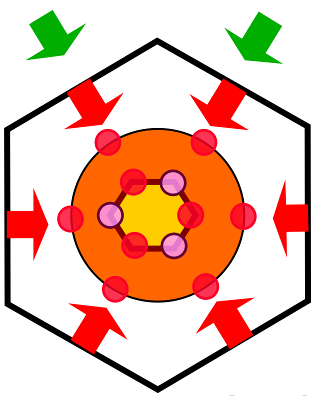
- **Coarse digital filter is used to provide initial drag-free position**
- **When system stabilized, harmonic fitting algorithms activated**
- **Picometer precision in less than 30 seconds**

Robustness of Redundant Multi-Sensor Configuration Shown via Computer Simulation

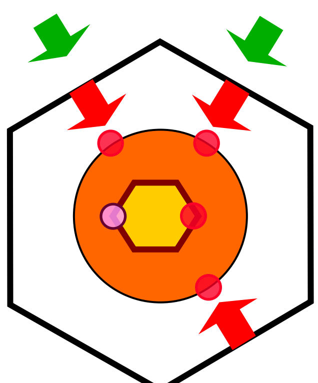


18 sensor, full 3d
6-6-6 Pattern





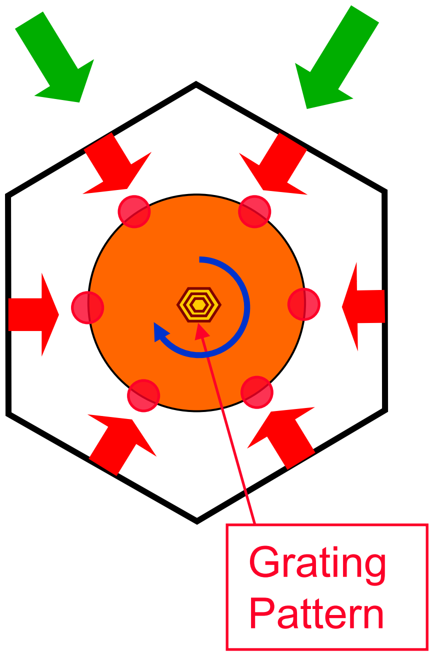
12 sensor, 1d+2d
6+3+3 Pattern



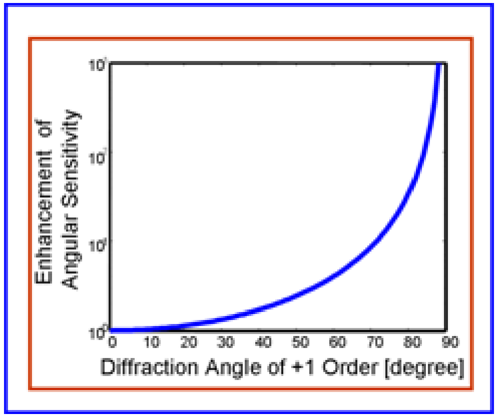
5 sensor, 1d+1d
3+1+1 Pattern

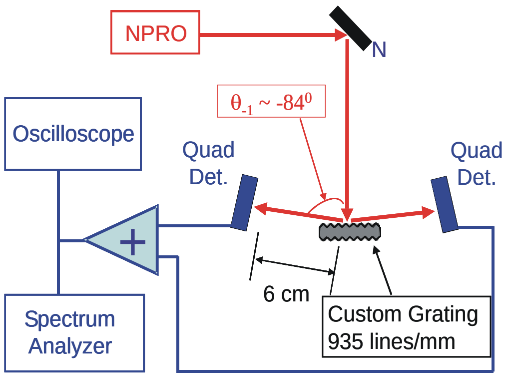
- **Multi-sensor algorithm for MGRS with a spinning sphere**
  - **Picometer precision measurement possible using multiple sensors for realistic sphere characteristics (GP-B sphere data used)**
  - **Redundancy demonstrated: Simulation done for 18, 12, and 5 sensors**
  - **Reliability confirmed by modeling**

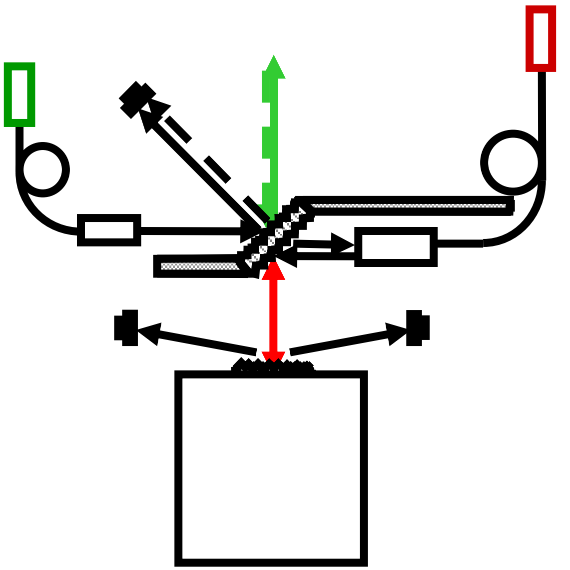
Grating Angular Sensor in LISA and MGRS



Grating Angular Sensor





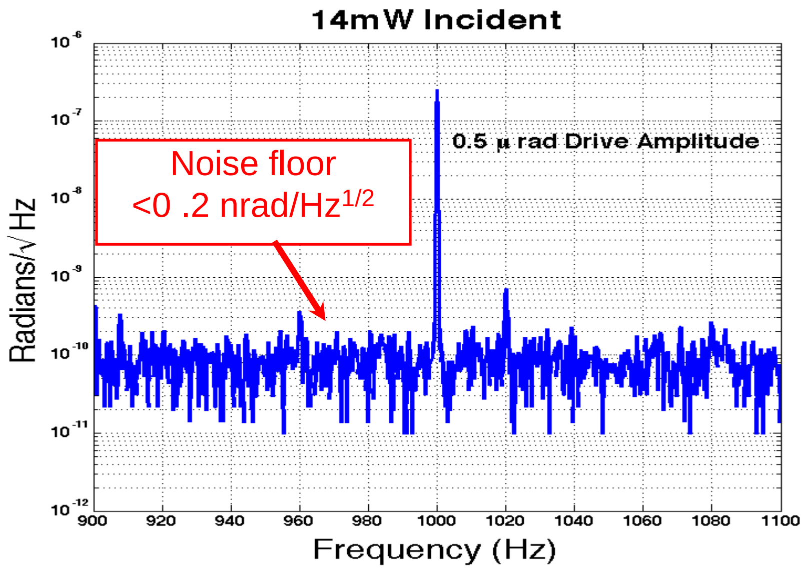


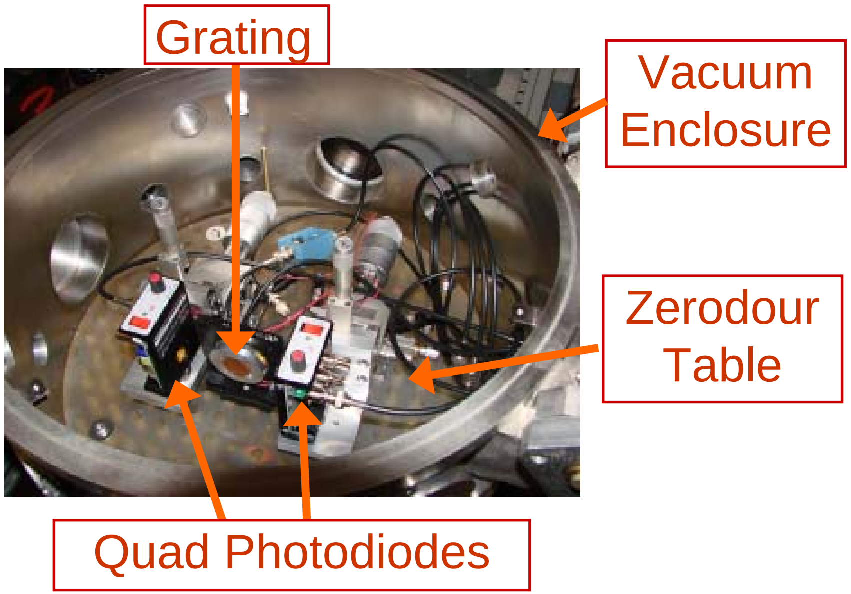
Grating pattern on a sphere:
1) **Sphere orientation determination**
2) **Spin rage determination**
3) **Facilitate sphere mapping**

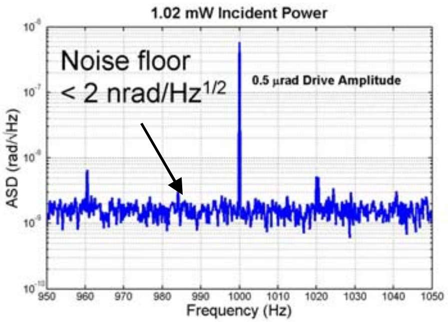
Grating pattern on a cube
1) **Cube orientation determination**
2) **Decouple cube orientation from displacement data**

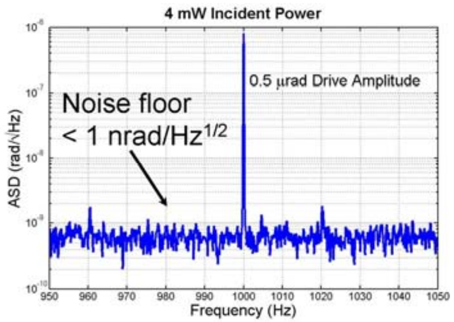
Grating Angular Sensor Experiment

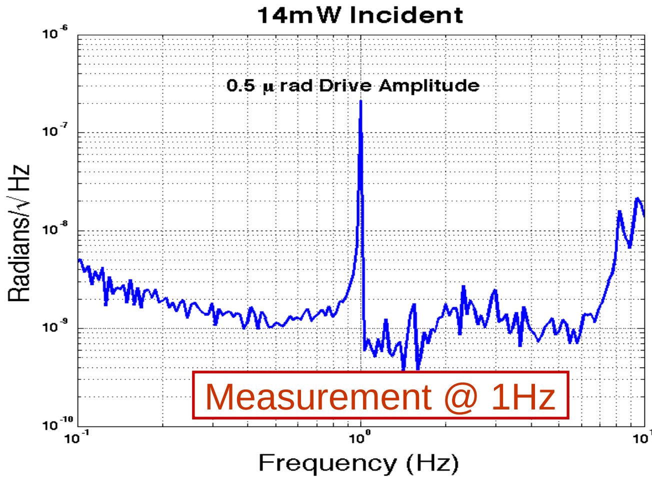
Sensitivity Improved to 0.2 nrad/Hz$^{1/2}$





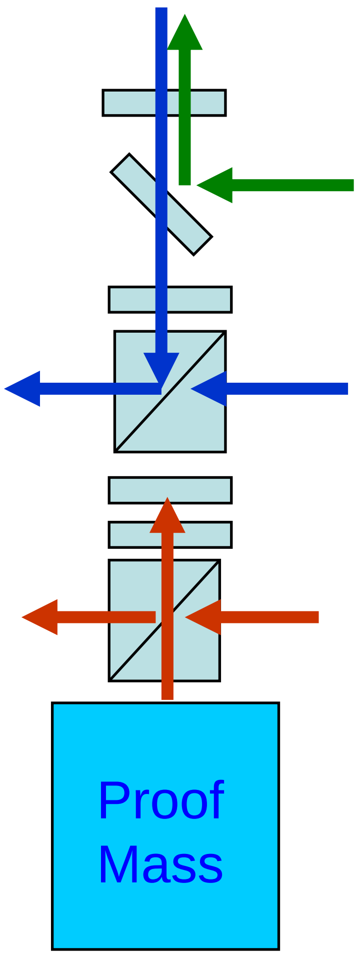




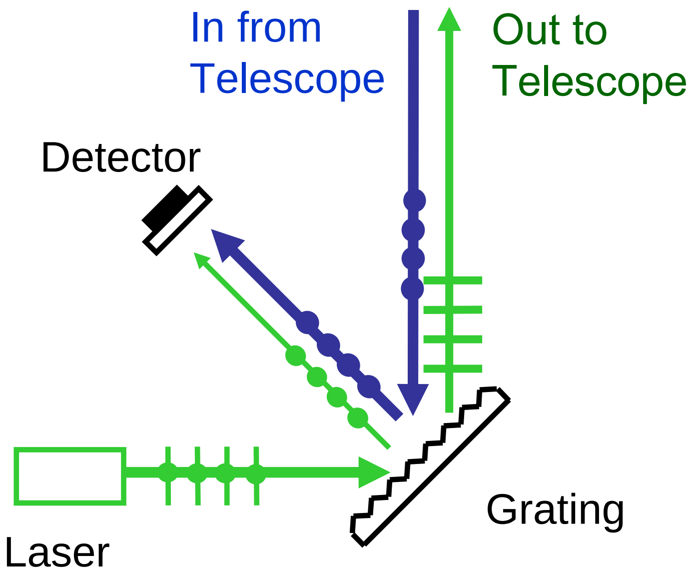


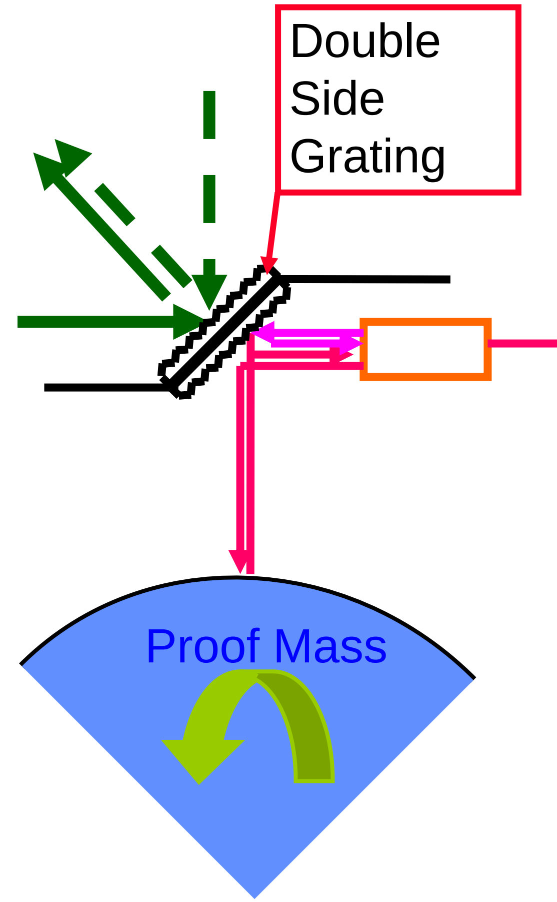
Sun, Lu, Byer, "Gating angular sensor for LISA and MGRS applications". (Poster Wednesday)

Diffractive Optics for External Interferometry



Transmissive
Optics





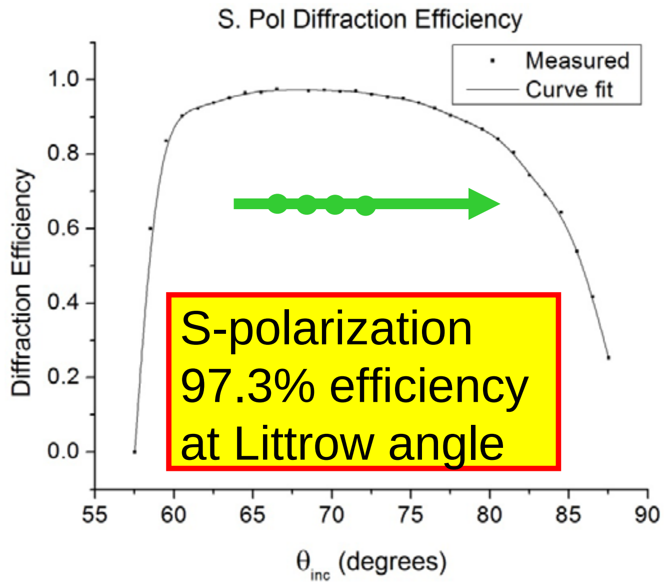
Reflection
Diffractive
Optics

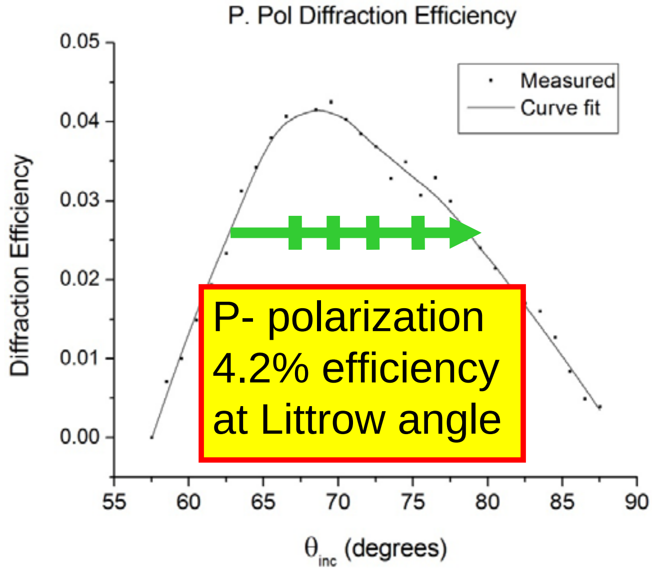
Desired polarization sensitivity
~ 1-2 % in S-polarization
~ 96-100% in P-polarization

Reflective grating interferometry

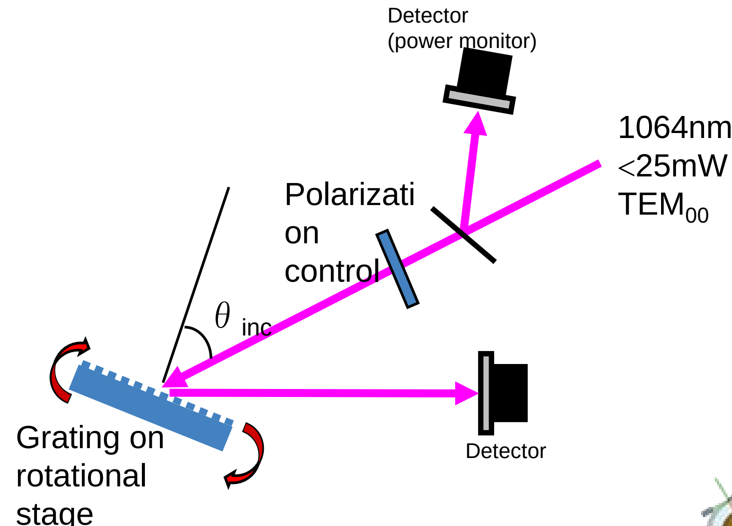
1) **Simplify the interferometer**
2) **Reduce *dn/dT* effects**

Diffractive Optics for External Interferometry





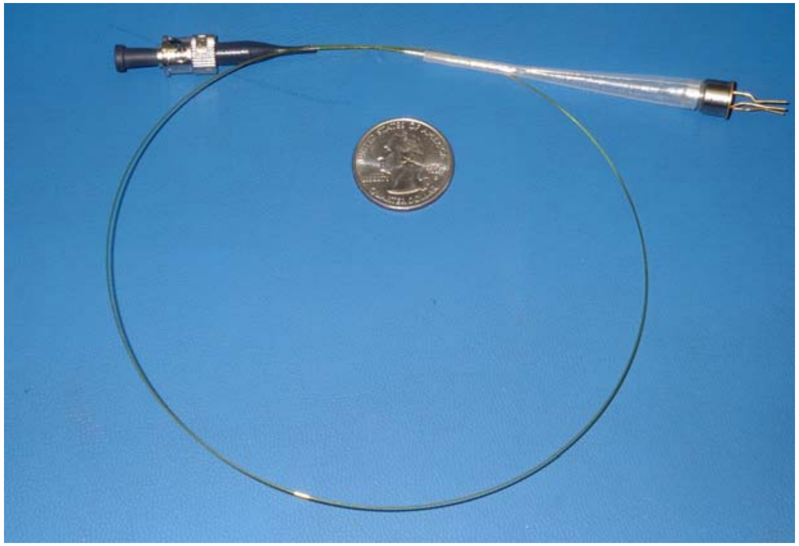
Polarization	S	P	Extinction Ratio
s	0.955	1.67E-04	5729
p	1.78E-04	0.038	213

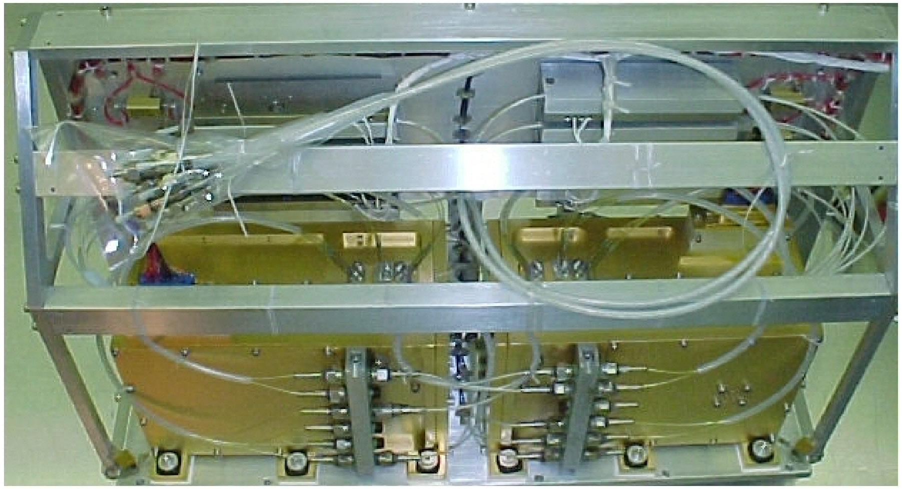


Sun, Britten *et al* "Gating angular sensor for LISA and MGRS applications". (Poster Wednesday)

Charge Control: UV LED vs. Mercury Lamp

Ke-Xun Sun and Sasha Buchman





UV LED

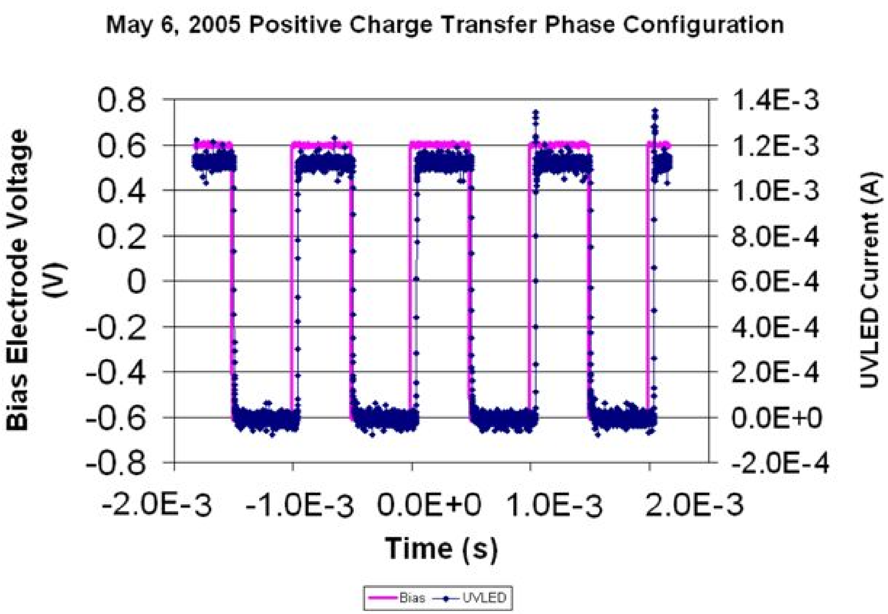
- *TO-39 can packaging*
- *Fiber output with ST connector*
- *Reduced weight*
- *Power saving*
- *Reduced heat generation, easy thermal management near GRS*

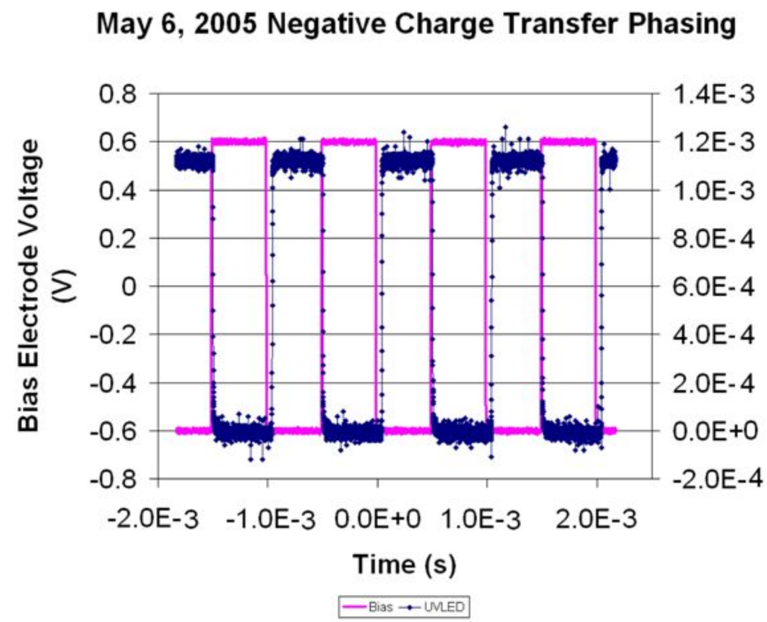
GP-B CMS in Flight

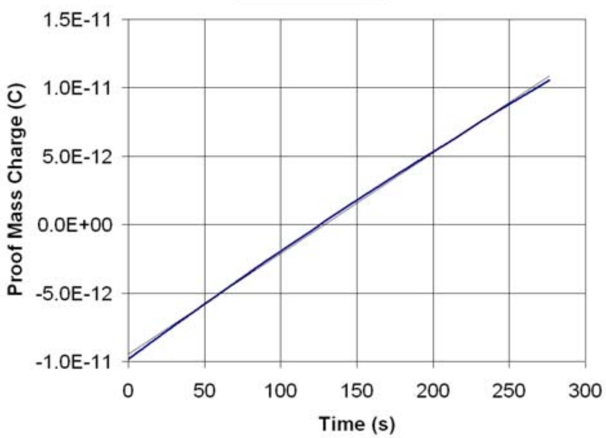
- 2 Hg Lamps
- Weight: 3.5 kg
- Electrical Power 7~12 W (1 lamp on, 5 W for lamp, 5 W TEC cooler)

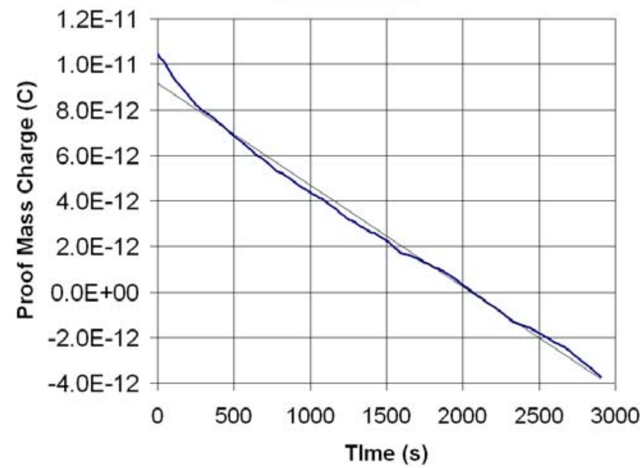
Positive and Negative AC Charge Transfer

UV LED and bias voltage modulated at 1 kHz – Out of GW Signal Band





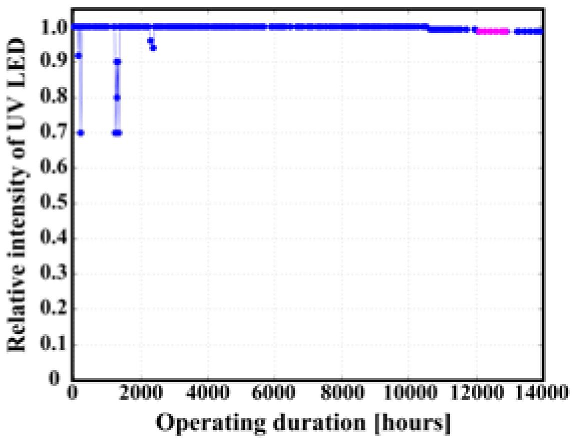


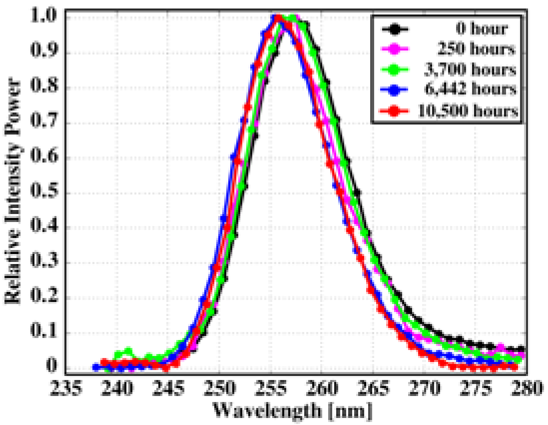


UV LED Power and Spectral Stability

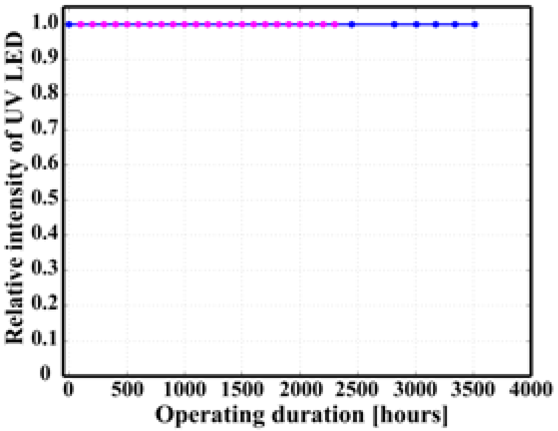
The LED Reported at LISA 6th Symposium Still Running, and Running!

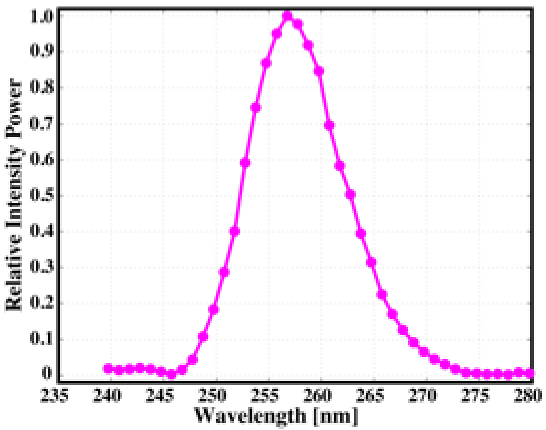
Operation Lifetime in Nitrogen > 14,000 hours



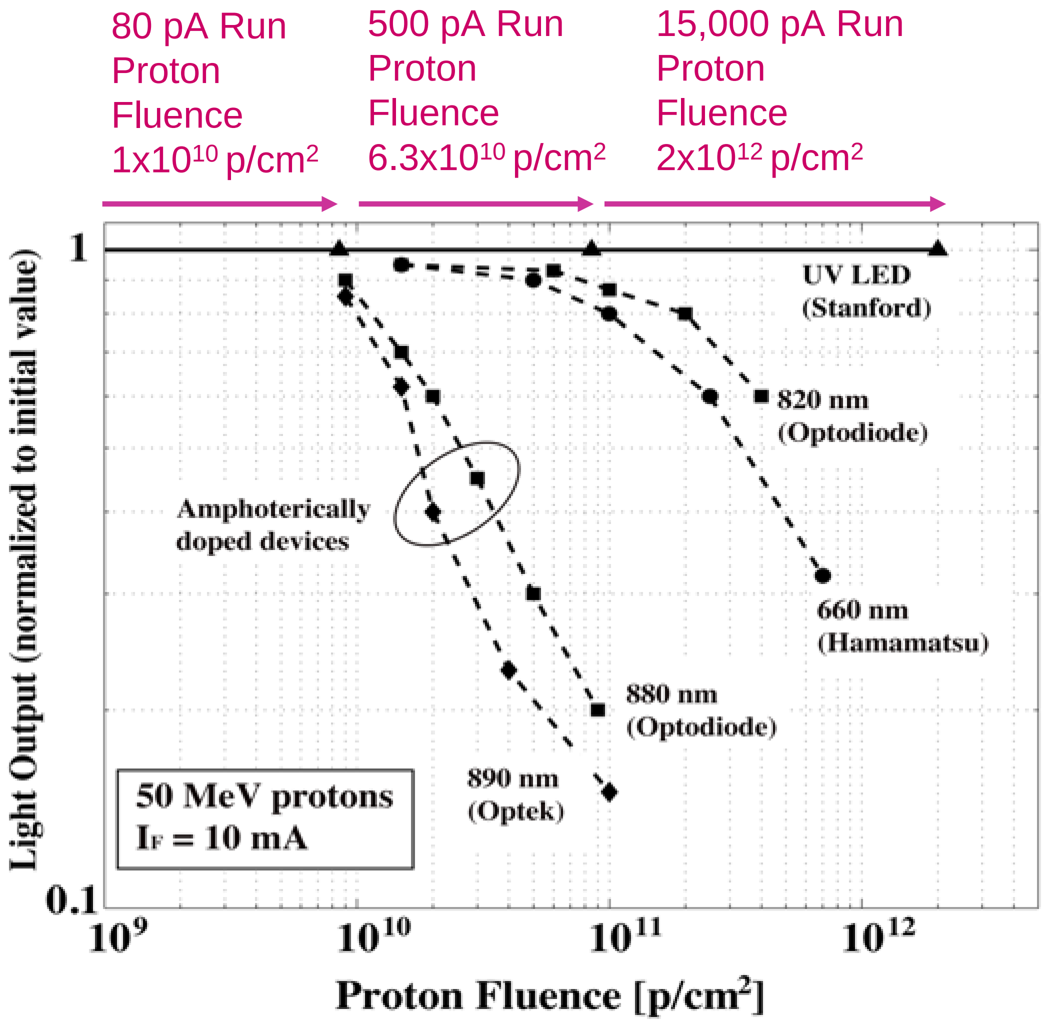


Operation Lifetime in Vacuum > 3,500 hours





UV LED Space Qualification Using Proton Irradiation



UC Davis proton energy:
59 MeV for 80pA & 500 pA
63.8 MeV for 15,000 pA

Space proton energy:
2~5 MeV

Total fluence: > 100 year proton fluence in LISA orbit

Reference for proton test of other LED and laser diodes:
A. H. Johnston and T. F. Miyahira, "Characterization of Proton Damage in Light-Emitting Diodes", IEEE Trans. Nuclear Science, **47** (6), 1999

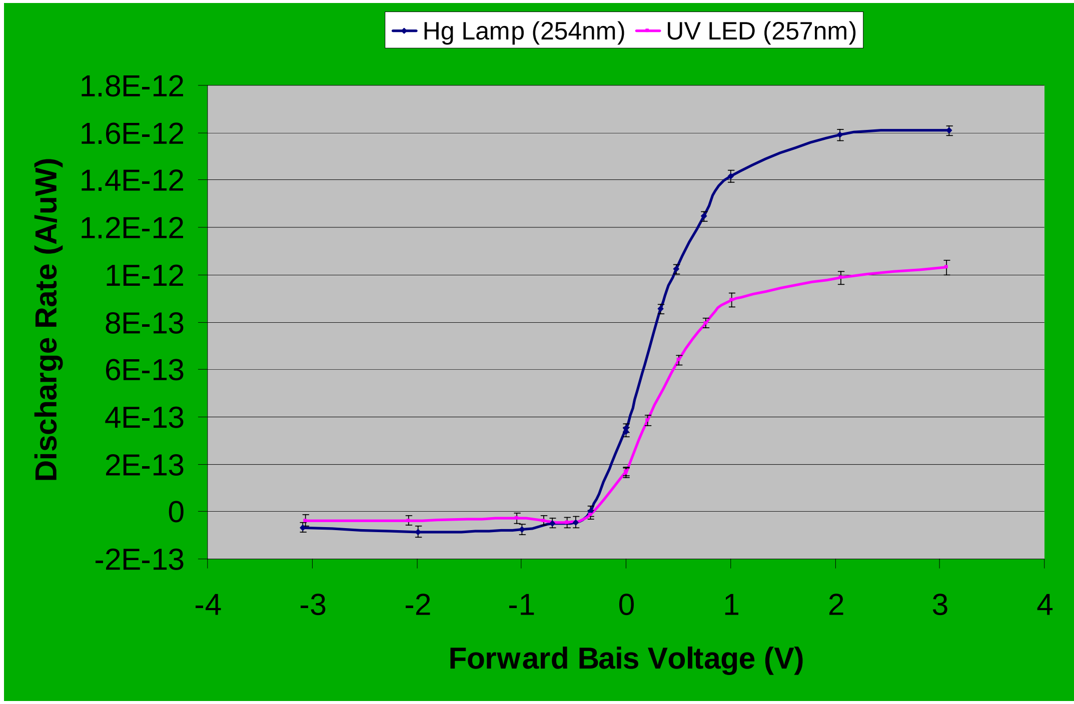
Sun, Leindecker, Higuchi, Buchman, Byer, "UV LED Qualification for Space Flight", Poster Wednesday.

UV LED Charge Management System has the Potential Significant Scientific Pay Off

Direct Replacement of Mercury Lamp with UV LED ---

Save electrical power ~15 W per spacecraft

- The power can be used to increase laser power by 2x--
  - Enhance sensitivity by 41%,
  - Increase event rate and detection volume by a factor of 282%.
  - Significant astrophysical observational pay off



Comparable Discharge Rates For First UV LED Experiment

Summary

- **Modular Gravitational Reference Sensor (MGRS) is a true drag free approach to picometer precision formation flying**

- **MGRS is a promising core fiduciary instrument for future space gravitational science**

- **Stanford MGRS Program in FY07/08 Made Significant Progresses in All Planned Areas**
  - Higher performances in all experiments
  - New R&D areas in system technologies and key components
  - UV LED space qualification
  - GRS trade studies
  - Differential optical sensing
  - Grating angular sensor
  - Gratings for external interferometry
  - Thermal test facility

Acknowledgement :Work Supported by NASA NNX07AK65G
"Modular Gravitational Reference Sensor for Space Gravitational Wave Detection"

Recommendations regarding LISA

Back to LISA:

NASA Beyond Einstein Program Review

November 2006 – September 2007

National Research Council
The National Academies, Washington, DC

…NASA should invest additional Beyond Einstein funds in LISA Technology

•

BEPAC Recommendations for LISA:

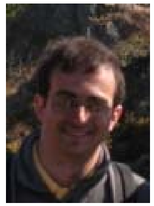
- "On purely scientific grounds LISA is the mission that is most promising and least scientifically risky. Even with pessimistic assumptions about event rates, it should provide unambiguous and clean tests of the theory of general relativity in the strong field dynamical regime and be able to make detailed maps of space time near black holes. **Thus, the committee gave LISA its highest scientific ranking."**
- " LISA is an extraordinarily original and technically bold mission concept. LISA will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of physics and astronomy in unforeseen ways. **LISA, in the committee's view, should be the flagship mission** of a long-term program addressing Beyond Einstein goals."
- **"NASA should invest additional Beyond Einstein funds in LISA technology** development and risk reduction, to help ensure that the Agency is in a position to proceed in partnership with ESA to a new start after the LISA Pathfinder results are understood."
- "LISA was recommended second in implementation because of money and programmatics. But even assuming an unnecessarily pessimistic financial contribution from ESA, and being second in Beyond Einstein, the assumed **launch date of LISA as ESA Cosmic Vision Mission L1 in 2018 is still feasible and the committee strongly recommends that."**

Stanford LISA MGRS Team

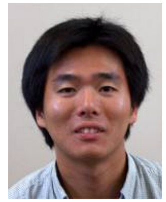
Graduate Students

Graham Allen

John Conklin



Domenico Geradi



Sei Higuchi

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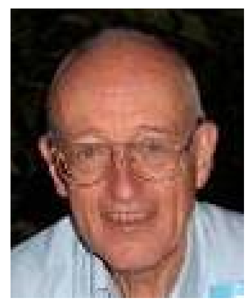
Martin Trittler

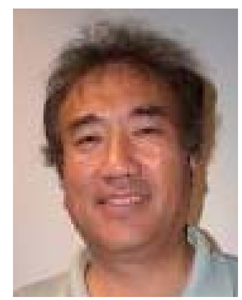
Staff

Sasha Buchman

Robert Byer

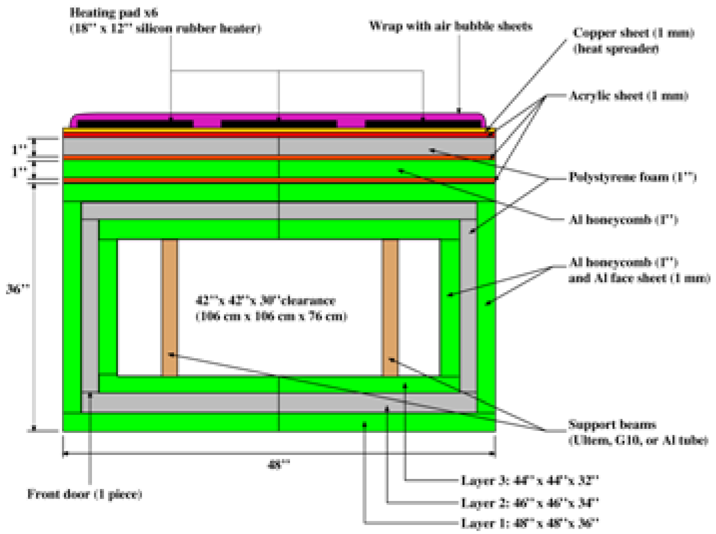


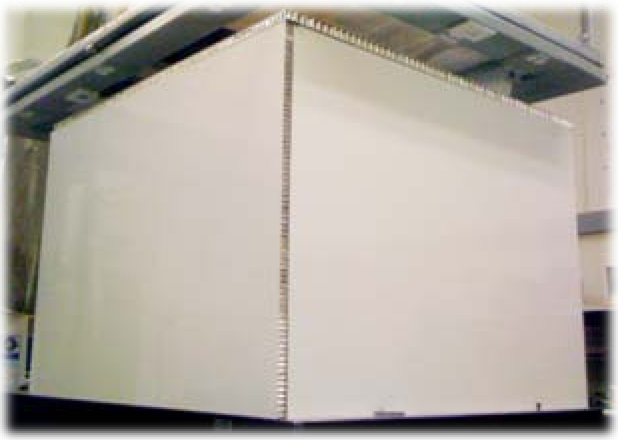
Dan DeBra

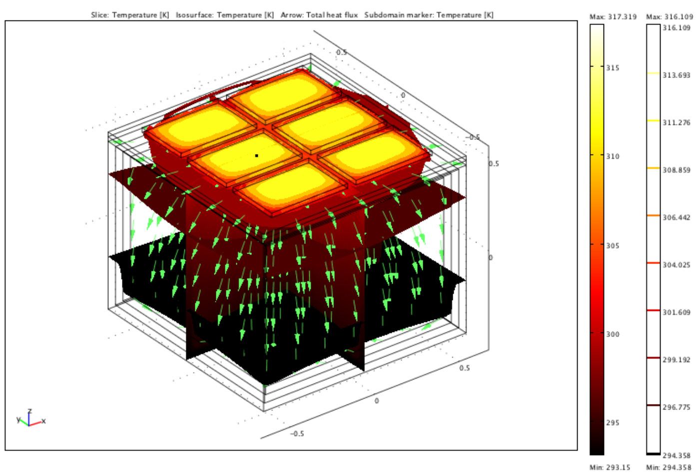


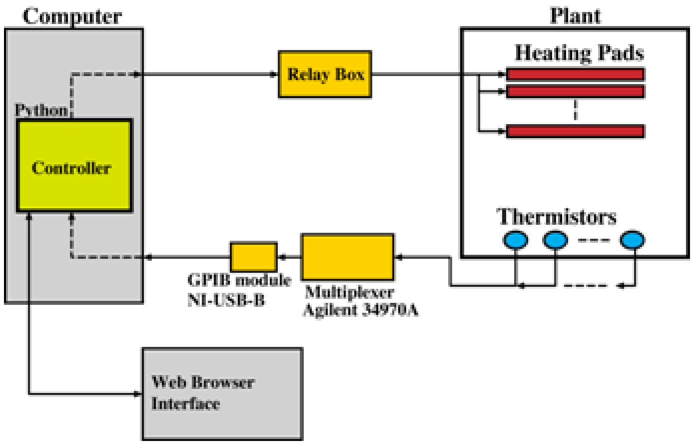
Ke-Xun Sun

Thermal Test Facility



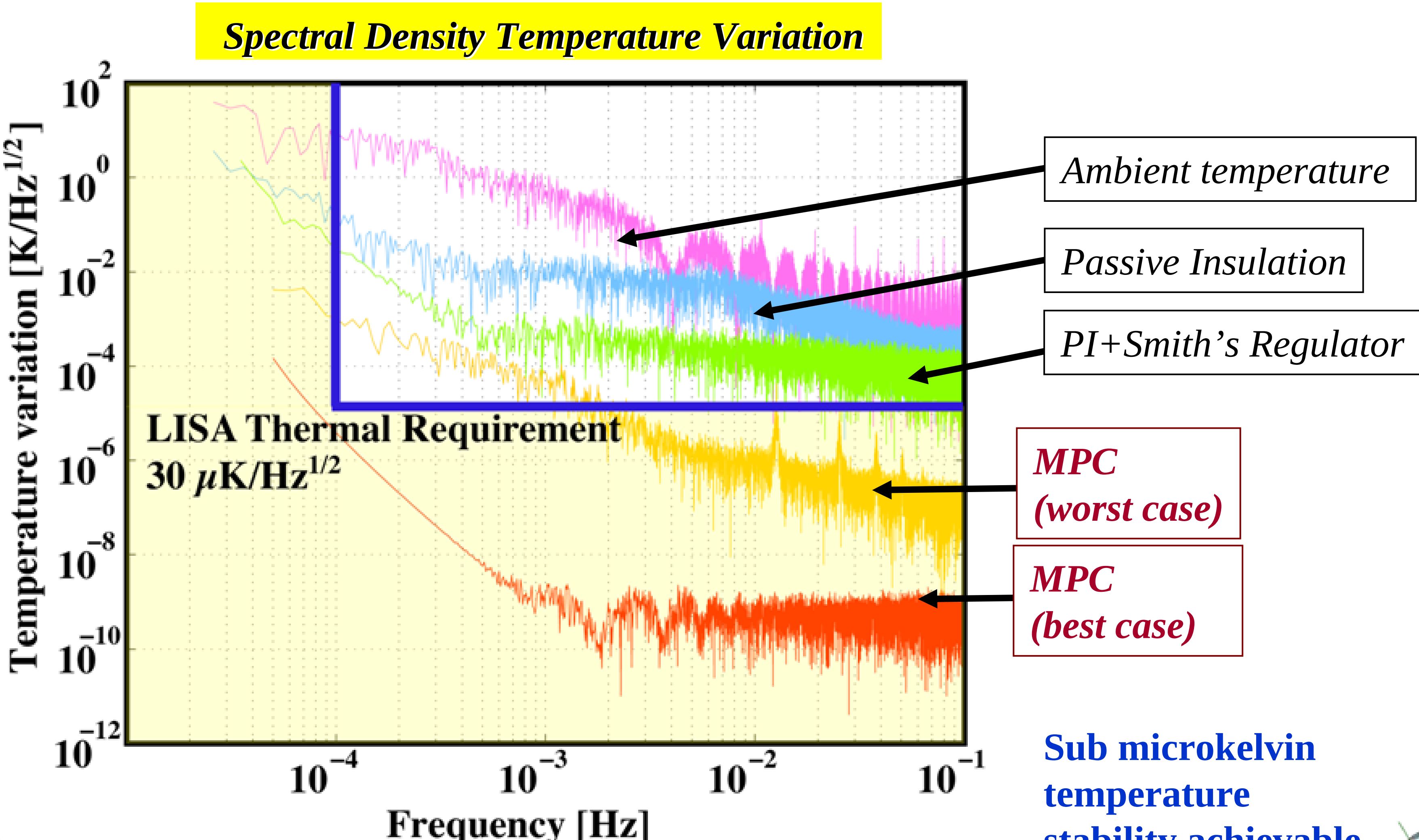






Higuchi, Sun, DeBra, Buchman, Byer, "Design of a Highly Stable and Uniform Thermal Test Facility for MGRS Development" . (Poster Wednesday)

Model Predictive Control



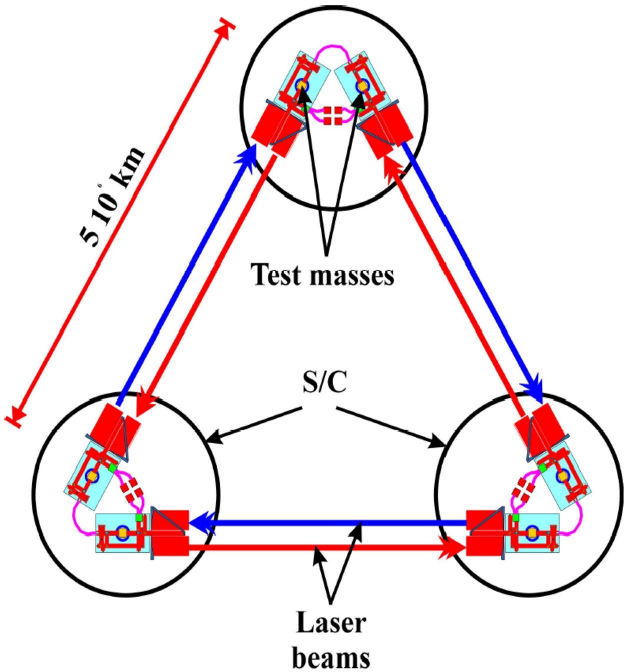
Sub microkelvin temperature stability achievable

LISA Interferometer Basics

- Transponder technique
  - Incoming beam locked to local laser
  - Overcomes low power from far spacecraft

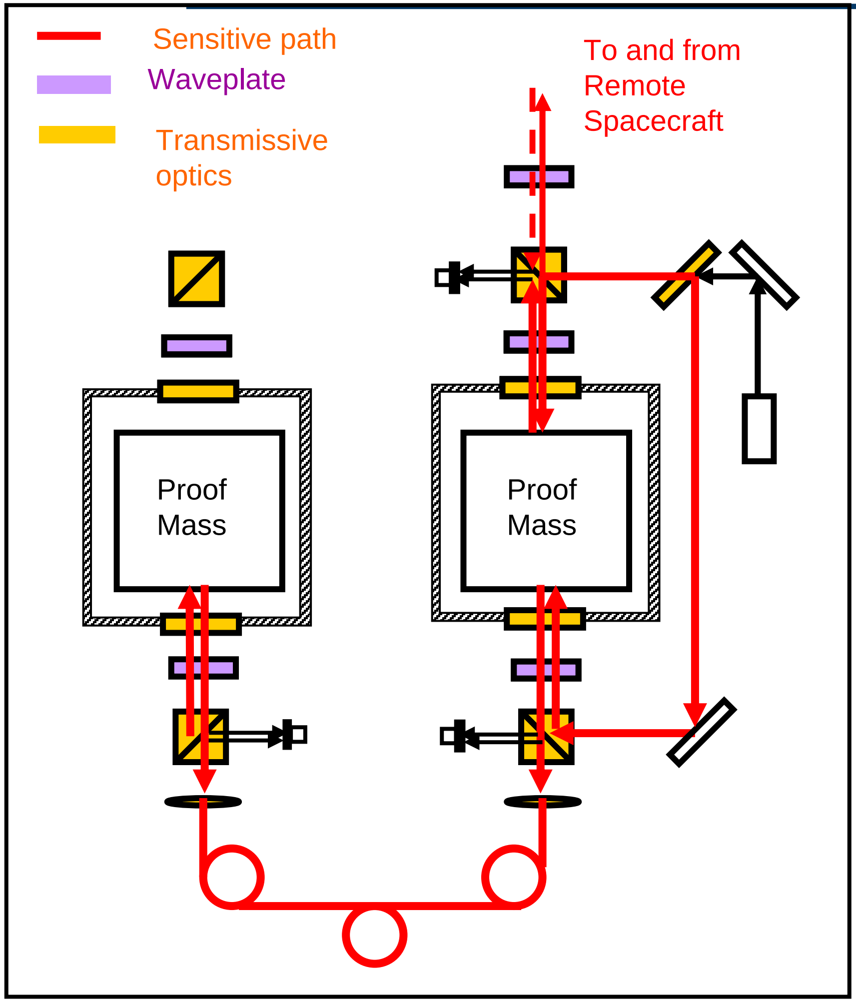
- Gravitational signal
  - Phase difference of arms measures
  -
- Correction of common phase shifts due to optics fixed to S/C
  - Reflected signals from back of test masses

- Time Delayed Interferometry (TDI)
  - Frequency noise correction by signal average of arms
  - 12 interference beat signals measure as function of time
    - In/Out beams at each optical system (6) @ Out/adjacent Out (6)
  - Combinations of TDI
    - Gravitational signal without laser frequency noise
    - Instrument noise without gravitational signal



40 pm $Hz^{-1/2}$ from 10^{-4} Hz to 10^{-1} Hz

LISA Two-Mass Configuration



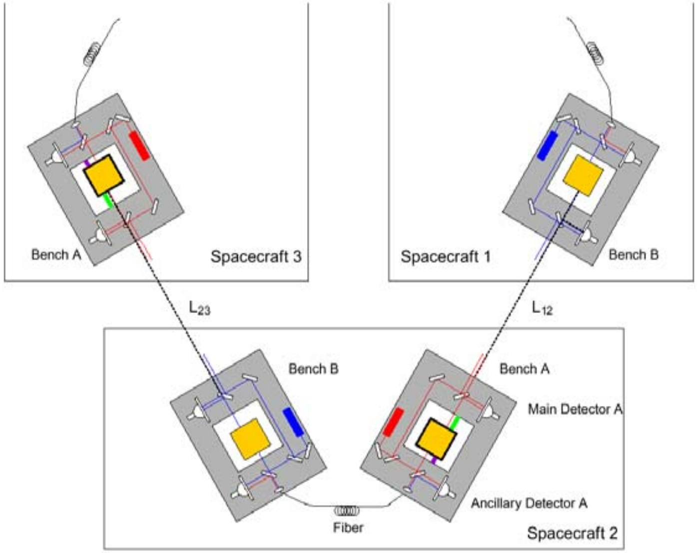


Figure A.4 *LISA measurement setup*

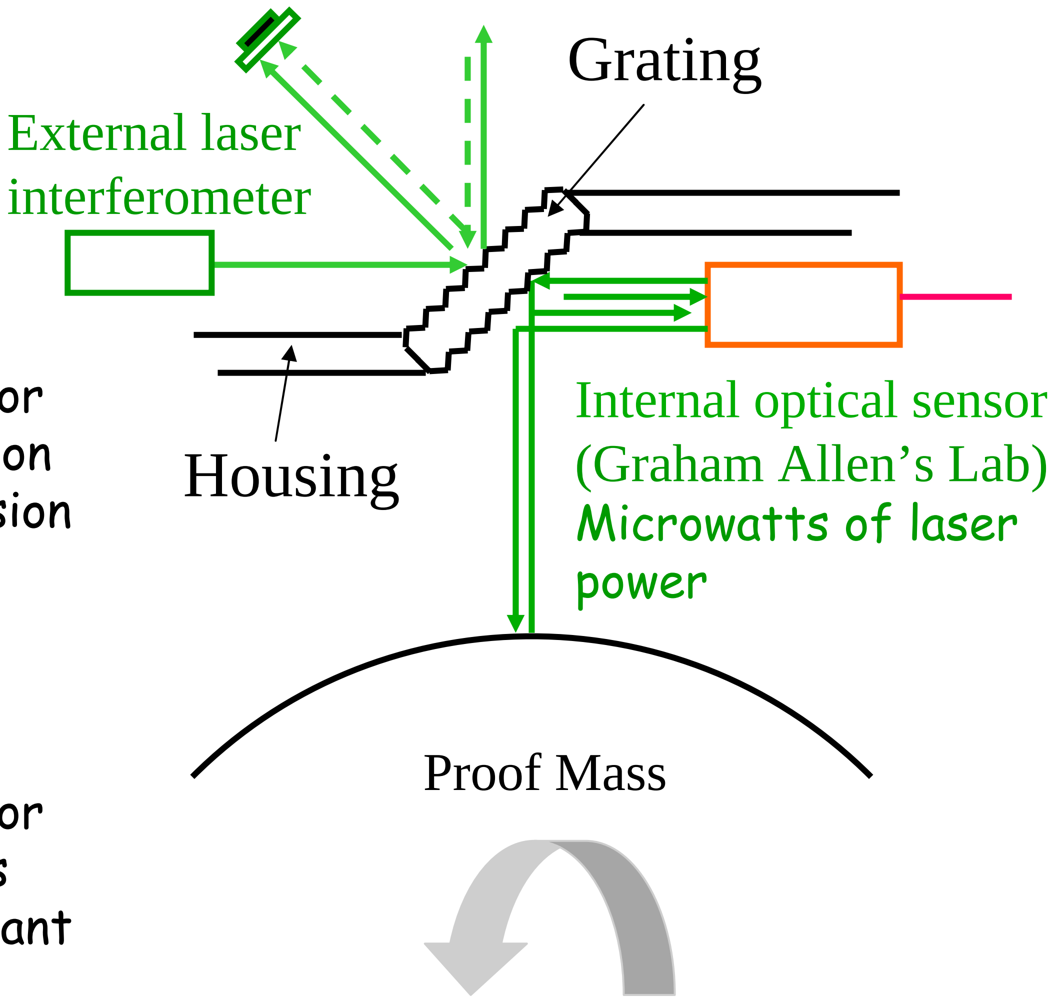
- Elaborated interferometer structure
- Interlinked scheme for re-correlation
- Long sensitive path
- Coupling throughout the system
- dn/dT problem in transmissive optics
- Alignment coupling

Modular GRS
Compact, Reflective Optical Sensing Configuration

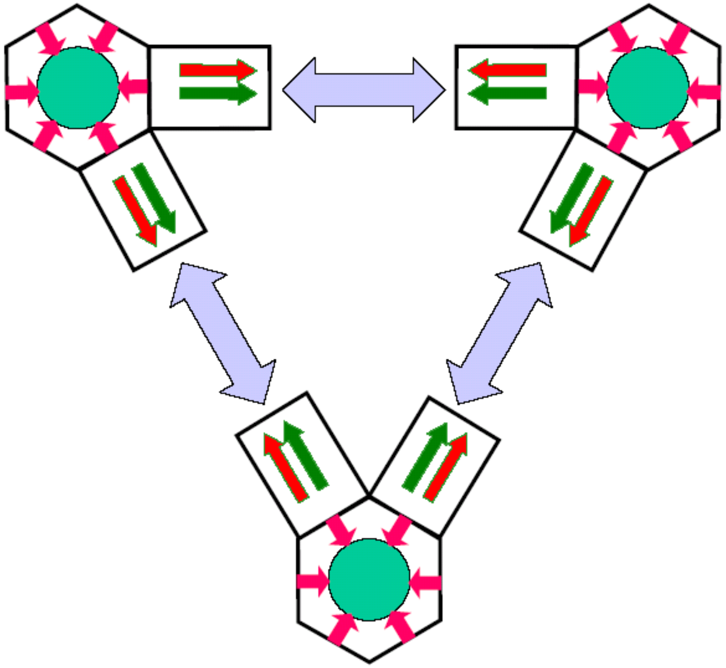
Double Sided Grating
- not transparent
- low known expansion
- interferometer mirror

Outside GRS Housing
Grating at 1064 nm or 532nmfor polarization separated transmission and heterodyne detection

Inside GRS Housing:
Grating at 1534 nm or shorter wavelengths for reflective resonant optical readout



Modular GRS Simplifies Control



- Transfer matrix contains diagonal blocks thanks to non-direct illumination
- Self calibration mechanism reduces command flow

DOFs Comparison Table

Mission & DOF Counts		GP-B	LISA	MGRS
One SC	Displacement	6	9	3+3
	Angular	3	9	3
	Telescope		1	1
	Total DOF		19	3+7
Total Fleet DOF		9	57	(3+7)x3
Control Matrix Dimension		9x9	57x57	30x30
Time to setup experiment		~ 4 mo.	> 4 mo	

Stanford Presentations at 7th LISA Symposium

1. **Stanford Modular Gravitational Reference Sensor Program (MGRS)**
   Technology Overview (This talk)
2. **Advanced concepts for future space gravitational wave detectors**
   GRS trade-Off studies. (Presentation Tuesday afternoon)
3. **Reflective gratings for inter spacecraft interferometry**
   Highly polarization sensitive gratings (Poster Wednesday)
4. **0.2 nrad/Hz$^{1/2}$ grating angular sensor for LISA and MGRS**
   Improved sensitivity and frequency range. (Poster Wednesday)
5. **Differential optical shadow sensing (DOSS)**
   1.7 nm/Hz$^{1/2}$ displacement sensitivity. (Poster Wednesday)
6. **150 nm precision measurement of mass center offset**
   Improved from 1000 nm when LISA 6. (Presentation Monday afternoon)
7. **UV LED qualification for space flight**
   2x10^{12} protons/cm2 radiation hardness. 14000 hours of operation.
   (Poster Wednesday, WG2/3 Presentation Monday)
8. **Design of a Highly Stable and Uniform Thermal Test Facility for MGRS Development**
   Sub microkelvin plant design and control law. (Poster Wednesday)