LISA: Drag-free Formation Flying at 5 million kilometers

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Abstract

The LISA mission requires drag free formation flying of three spacecraft in orbit around the sun with disturbances of less than a femto-g, and laser interferometer precision of 40 picometers.
This talk describes the progress toward realizing precision drag free flight of the LISA constellation.
The key is an optical sensed spherical proof mass spinning at 10 Hz as the true drag-free Gravitational Reference Sensor (GRS).

Stanford 2008 Position Navigation and Time Symposium
November 5 -6, 2008
Kavli Auditorium, SLAC

Outline

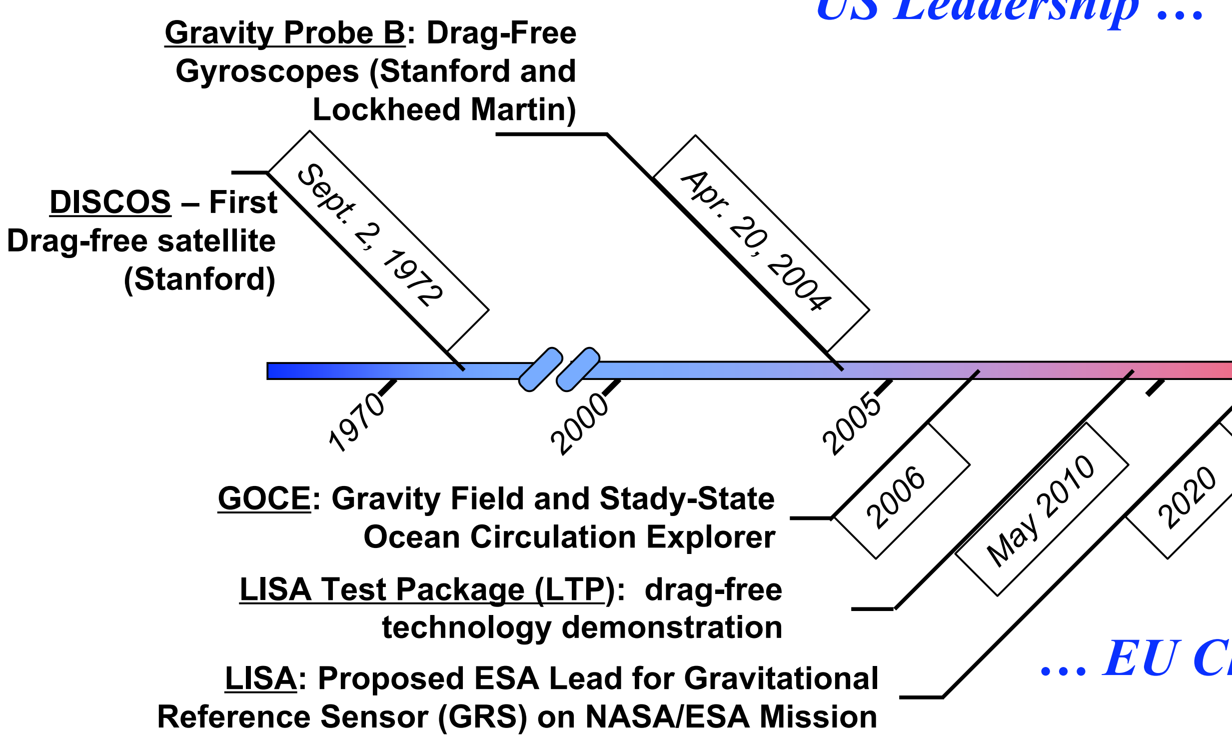
- Introduction
  - Drag Free Enabled Science Missions
    - LISA Mission
    - Gravitational Waves and sources
  - Drag Free Concept
    - History of Drag Free
    - Improvements Required for LISA
- The Modular Gravitational Reference Sensor
  - The MGRS Concept
  - Stanford Studies of the MGRS
  - Modular Gravitational Reference Sensor (MGRS)
- Future directions
  - Develop and Test LISA Technology
  - Small satellite missions for UV charge control/Gratings

Gravitational Reference Sensor Technology Addresses Future Vision of US Aerospace Commission

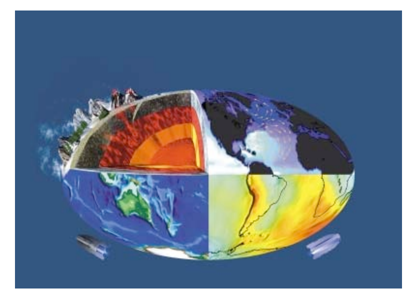
"Aerospace is a technology-driven industry. Long-term research and innovation are the fuel for technology. U.S. aerospace leadership is a direct result of preeminence in research and innovation."

Commission on the Future of the U.S. Aerospace Industry
Final Report, Nov 18, 2002

US Leadership …

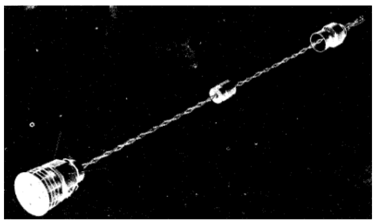


… EU Challenge



History of Drag-Free Missions

Triad
1972



Three-axis drag-free

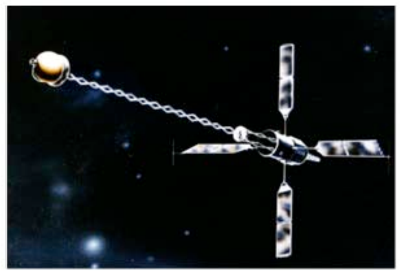
Spherical PM

Capacitive sensing

9 mm gap

5×10^{-11} m/s^2 rms

TIP 3 & NOVA
1975 - 1988



Single axis drag-free

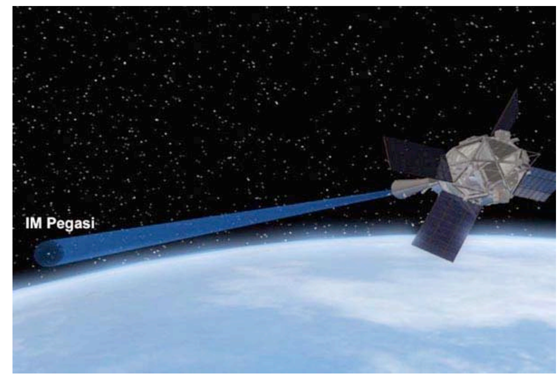
Cylindrical PM

Optical sensing

9 mm gap

5×10^{-11} m/s^2 rms

Gravity Probe B
2004



Three axis drag-free

Spherical PM

Capacitive sensing

25 μm gap

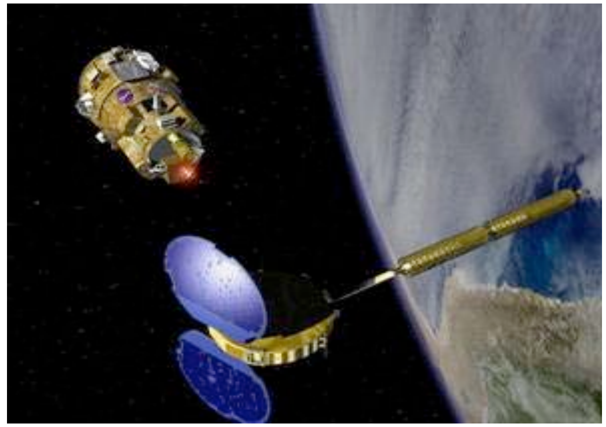
5×10^{-11} m/s$^2/\sqrt{\text{Hz}}$

Dan DeBra and Bob Byer

Dan DeBra and Bob Byer working toward True Drag Free LISA mission – June 2004

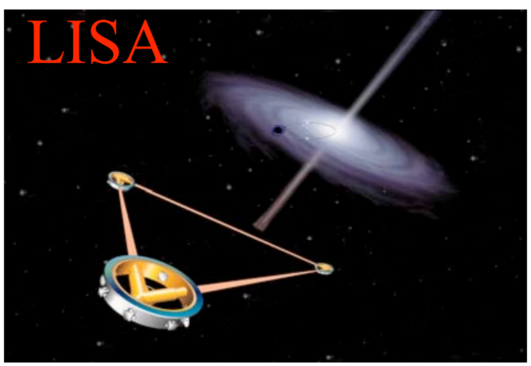
Drag-Free Enabled Science and Technology Projects

Imaging
National Security
Natural Resources
Geodesy

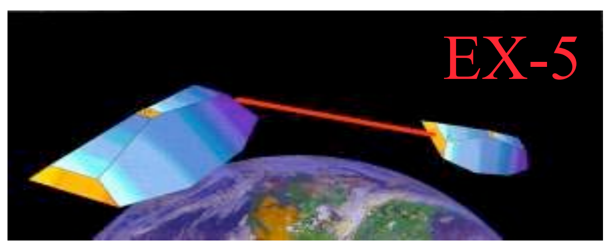


Integrated Precision Inertial Sensing of Translation and Rotation
Autonomous Spacecraft Rendezvous, Docking, Guidance, and Space-Based Target Tracking

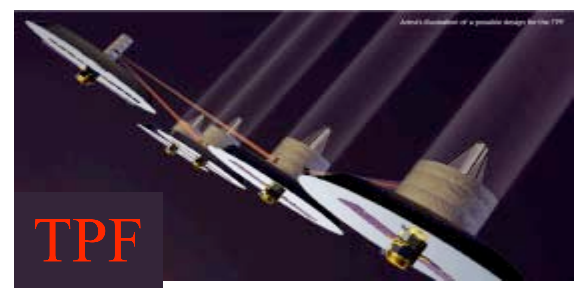
Inertial Formation Flying
Autonomous Constellation Management



Precision Inertial reference and drag-free control
Gravitational Wave Observatories



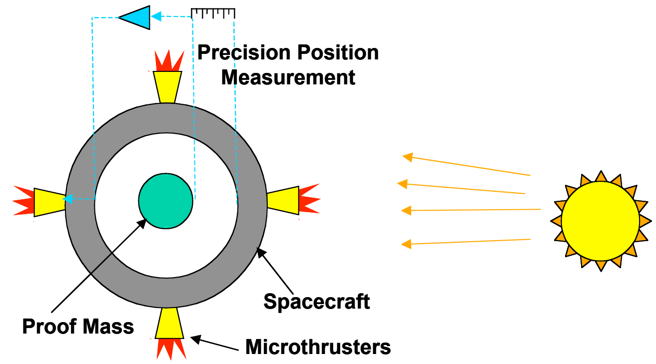
Integrated Precision Inertial Sensing and Formation Flying
Sensing and Characterization of Time-Varying Gravity

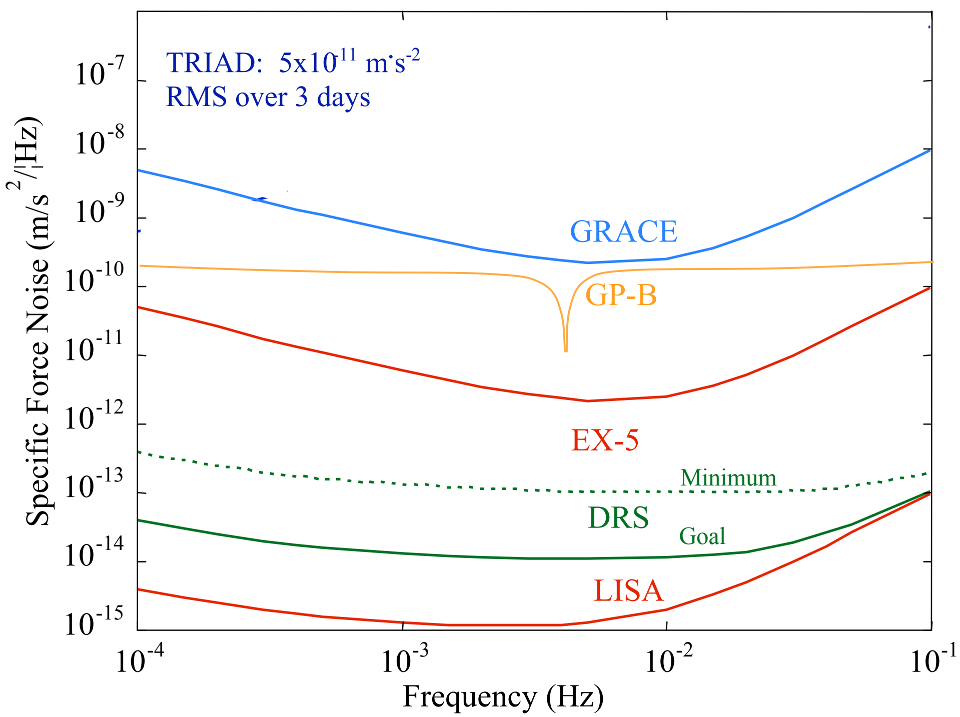


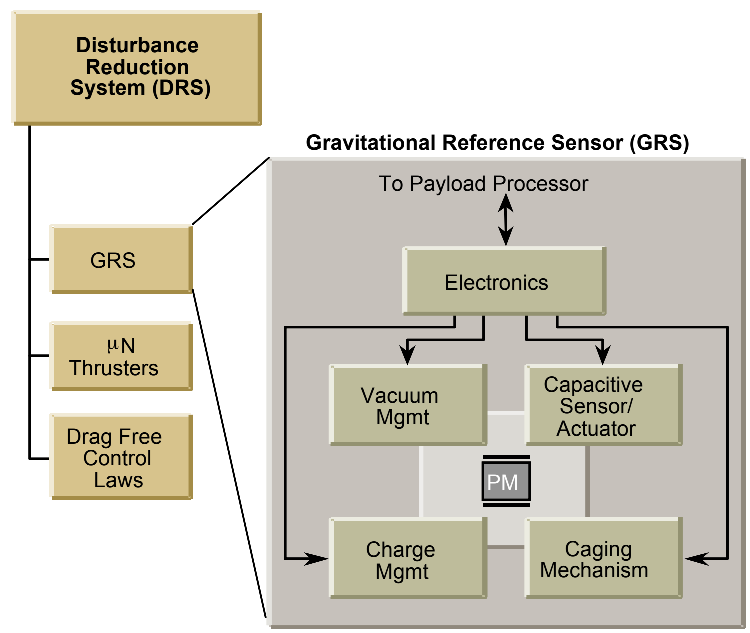
Precision Formation Flying
Imaging and Inteferometric Phased Array Optical Sensors

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

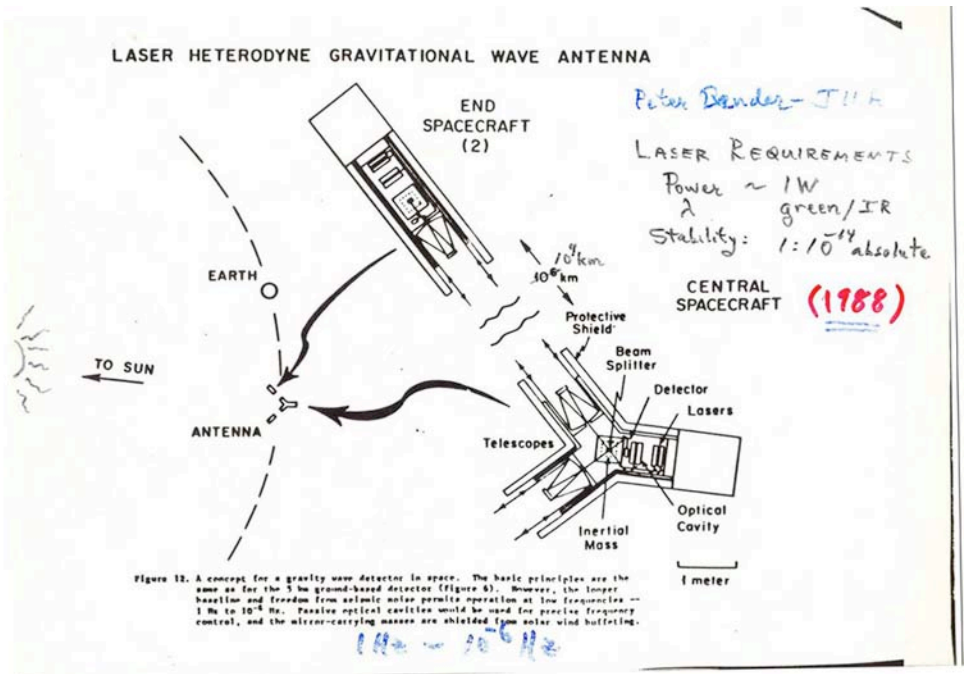
High Precision Reference
- **Inertial Anchor**
- **Accelerometer**
- **Gyroscope**



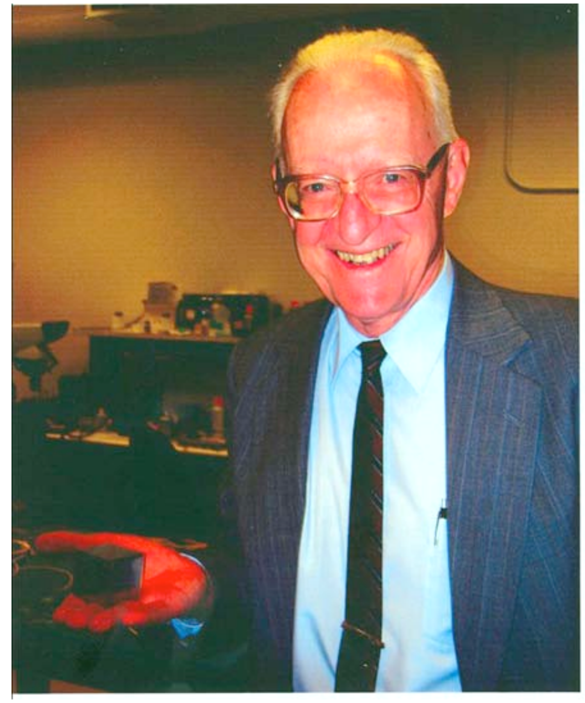




LISA Concept



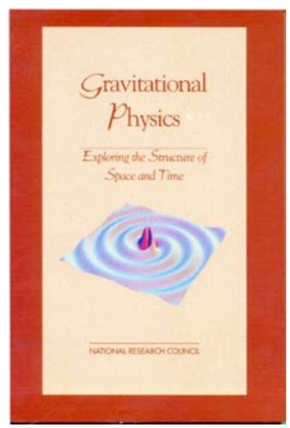
Schematic of LISA in 1988



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



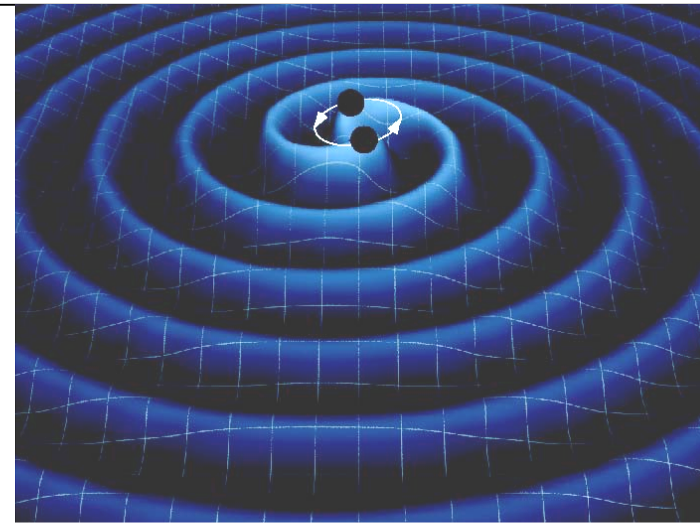
Gravitational waves open a new window on universe

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

What are gravitational waves?

- **Ripples in space-time**
  - **GW Strain**

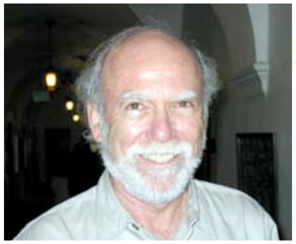
$$h = \frac{\delta L}{L} \approx 10^{-21}$$



- **Sources**
  - Time variation of the quadrupole moment
  - Large masses required → Astrophysical objects
  - Examples
    > **Binary systems, merging objects, pulars, supernovae**

The Amplitude of Gravitational wave strain is extremely small.
Equivalent to the diameter of an atom at a distance of the Sun!

LIGO – two 4km ground based interferometers



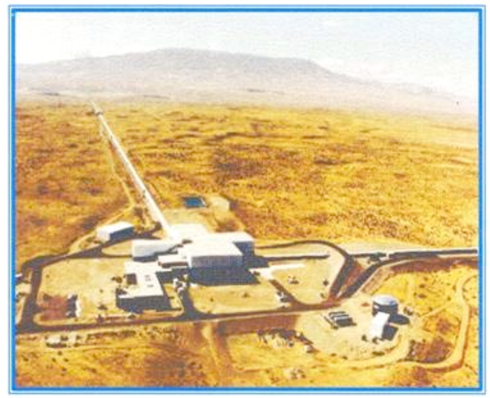
Barry Barish
CalTech

LIGO Sites

LIGO-G9900XX-00-M   NSF LIGO II Review   5

Rai Weiss
MIT

LIGO sites

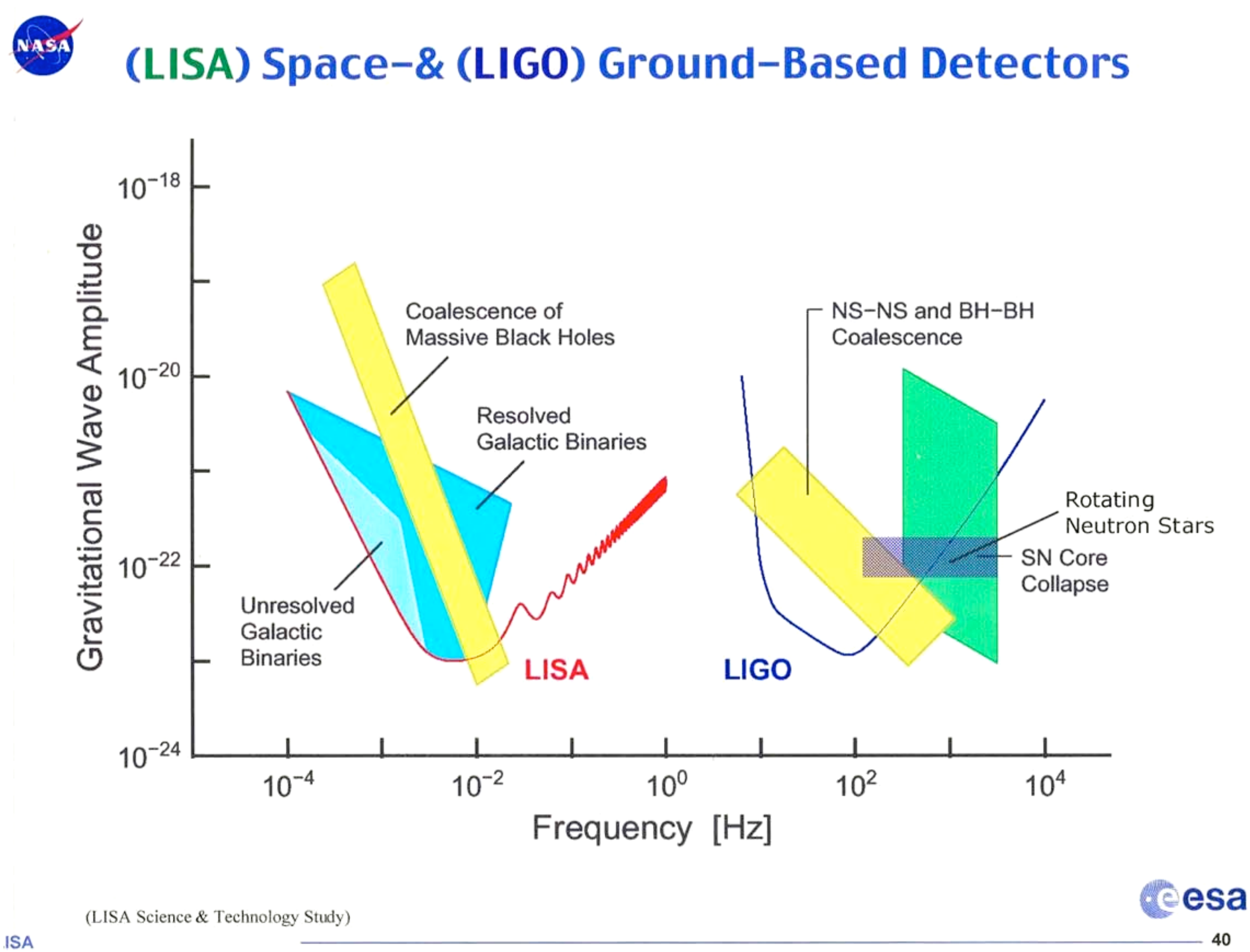


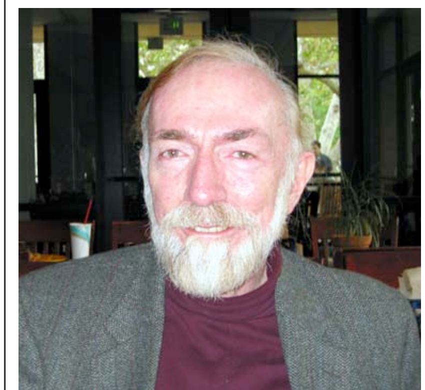
- Hanford Observatory

- Livingston Observatory

LIGO-G9900XX-00-M   NSF LIGO II Review   12

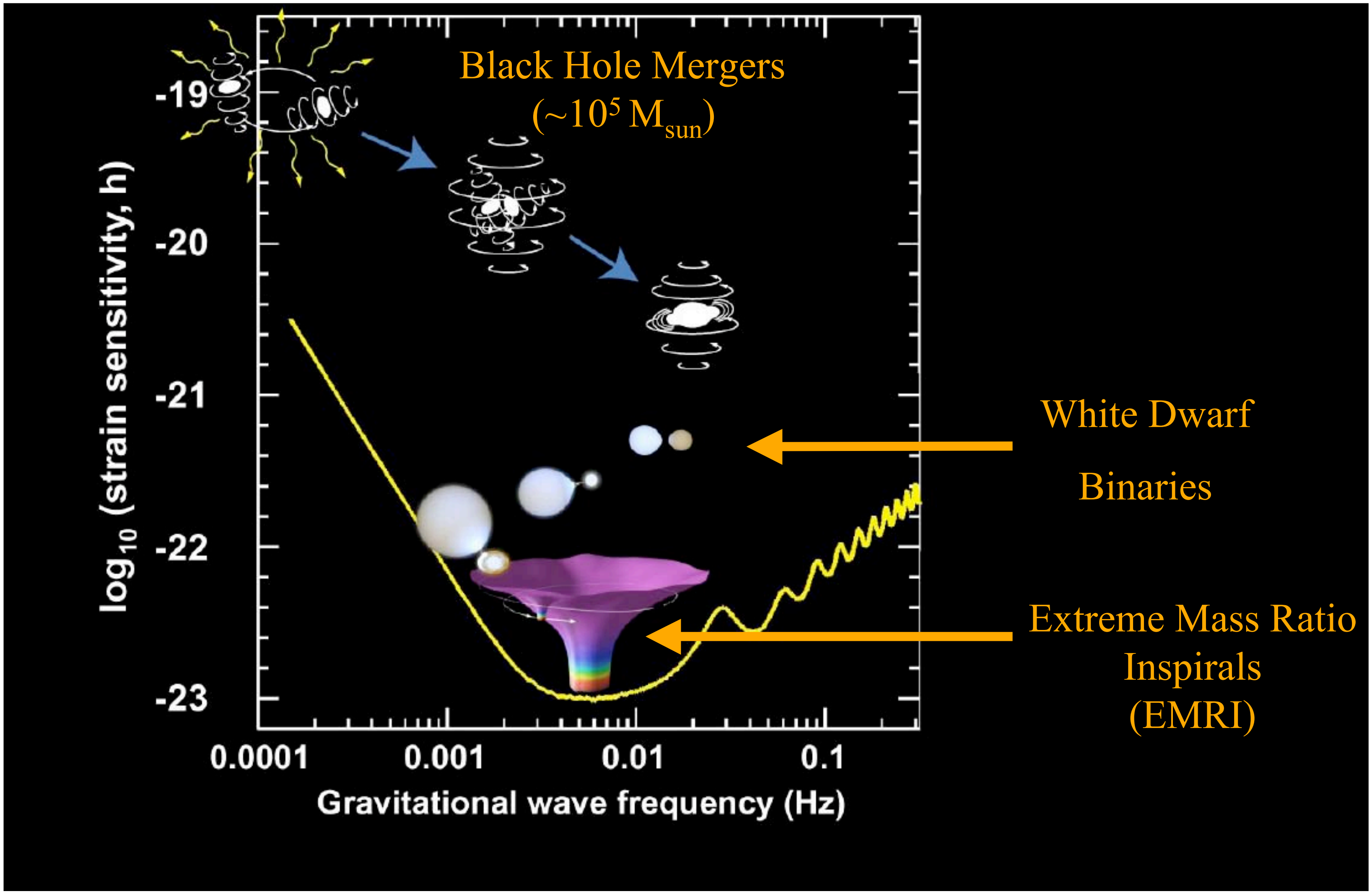
LISA and LIGO Detection Bands



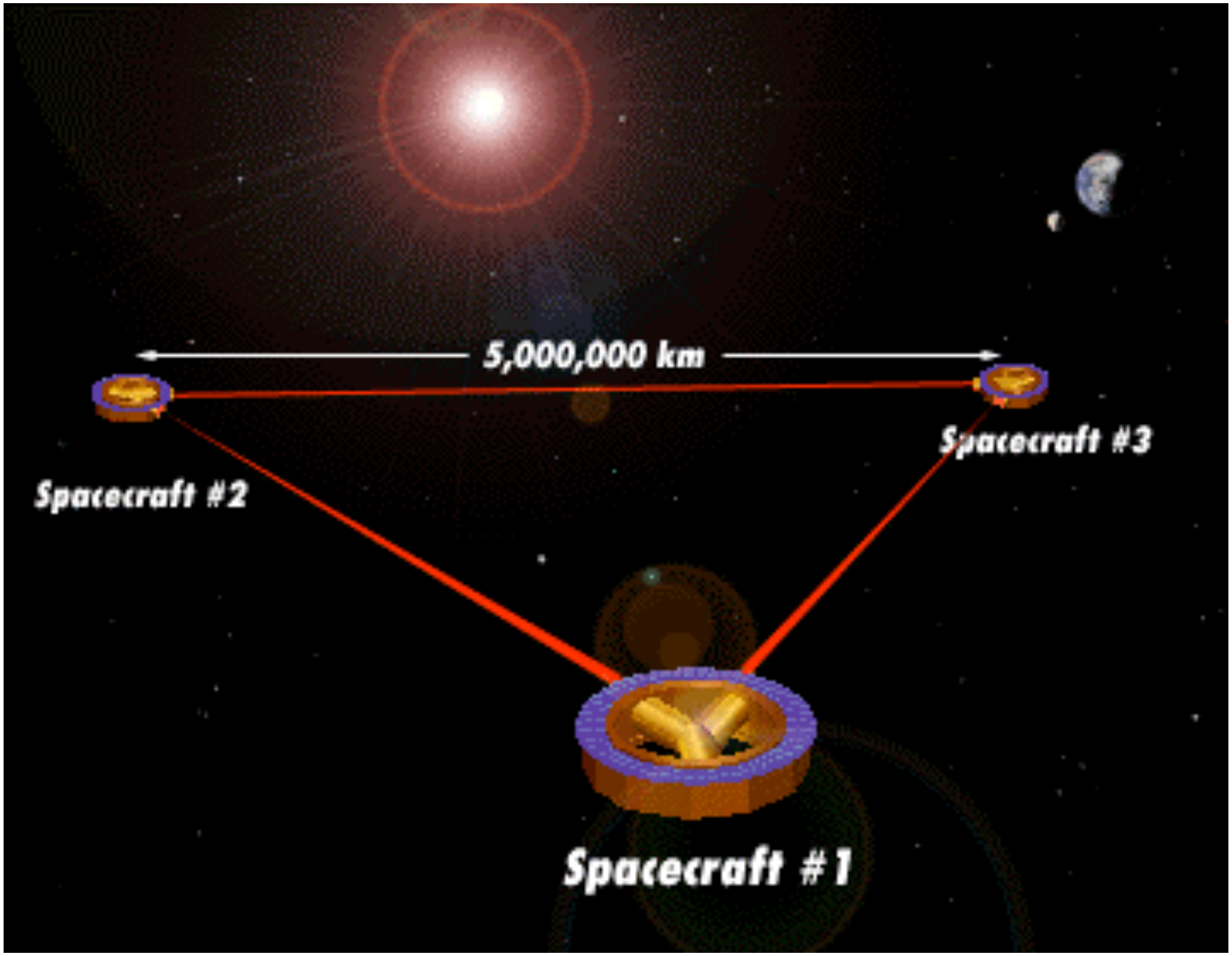


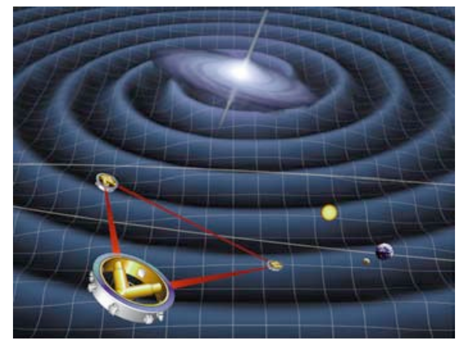
Kip Thorne,
CalTech

LISA Sensitivity and Sources

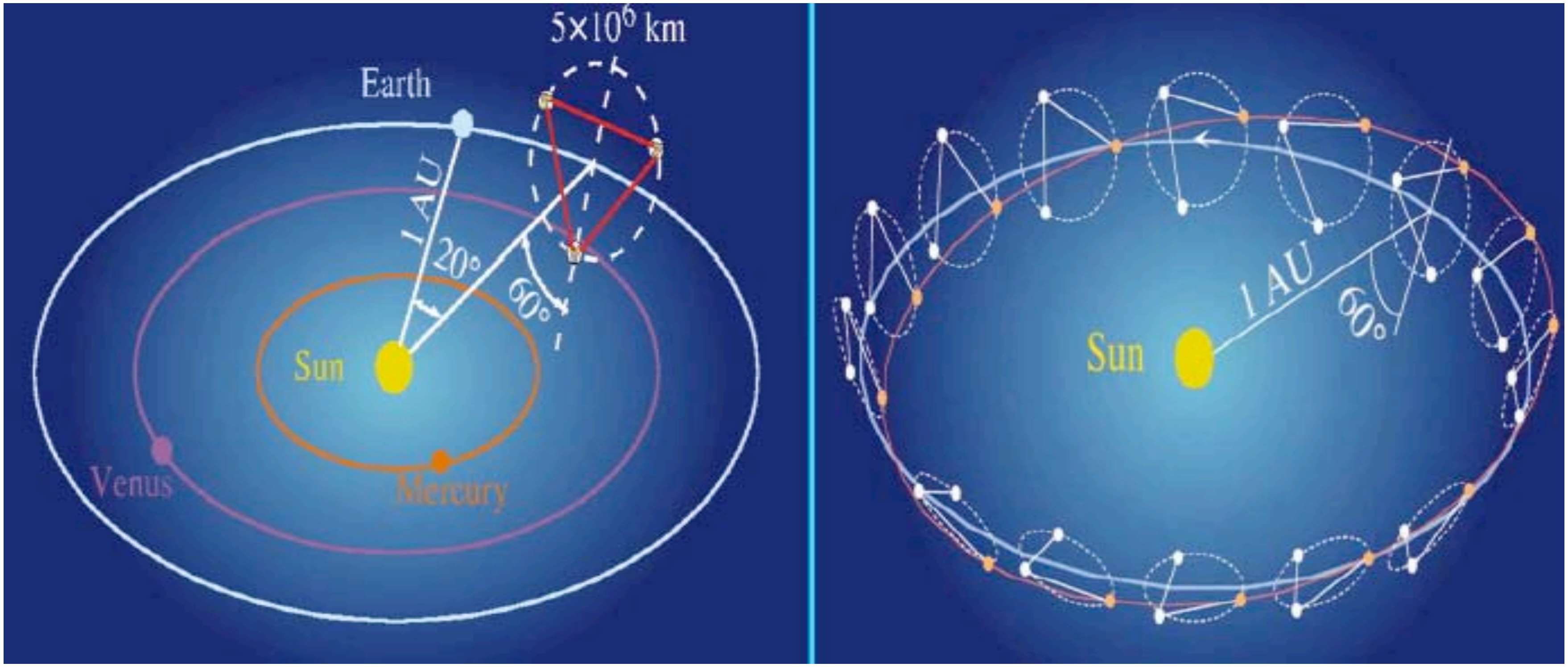


LISA Interferometer Space Antenna





LISA: mission and measurement concept

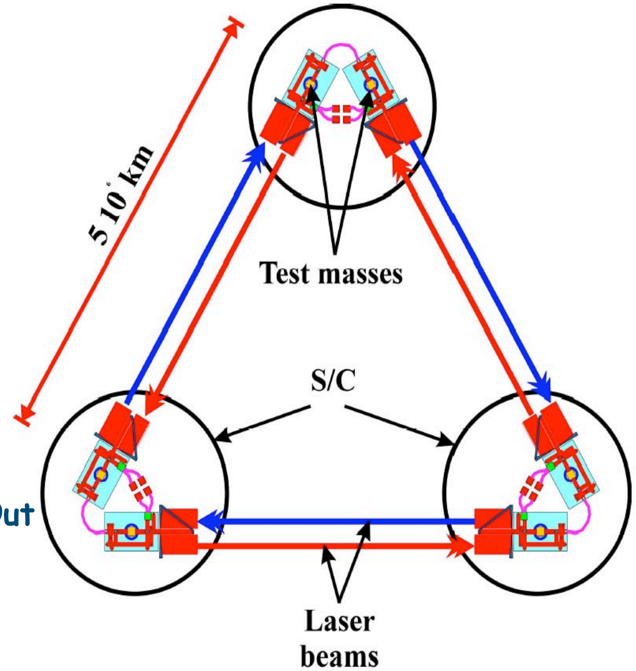


Each S/C in a 1-year solar orbit, nearly equilateral triangle at 60° to the ecliptic, rotates in its plane once/yr, the constellation plane precesses around the ecliptic pole once/yr

The LISA Constellation is 20° behind the Earth, slightly changing arm-lengths, nominally 1/30 AU (5 million km).

LISA Interferometer Basics

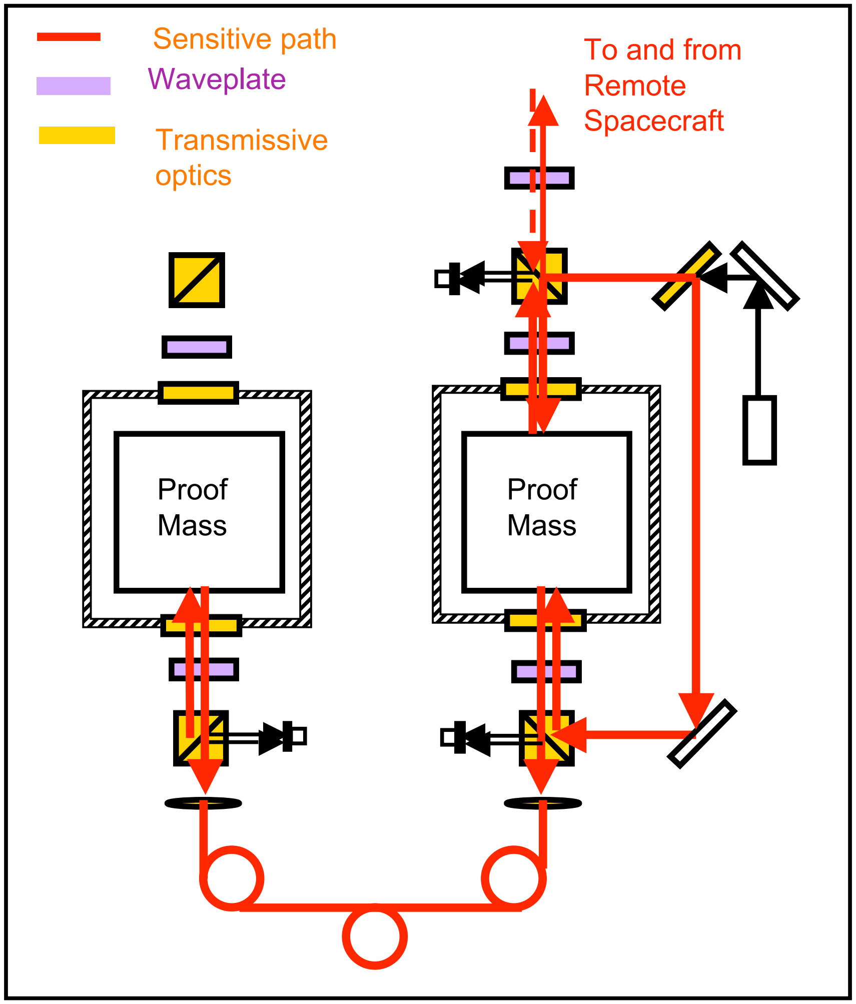
- Transponder technique
  - Incoming beam locked to local laser
  - Overcomes low power from far spacecraft
- Gravitational signal
  - Phase difference of arms measures
  -
- Correction of common phase shifts due to optics fixed to S/C
  - Reflected signals from back of test masses
- Time Delayed Interferometry (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

Measure the Center of Mass separation to picometers at a 5 gigameter separation using a 1 micrometer light beam!

Each Spacecraft has Two Cubic Proof Masses



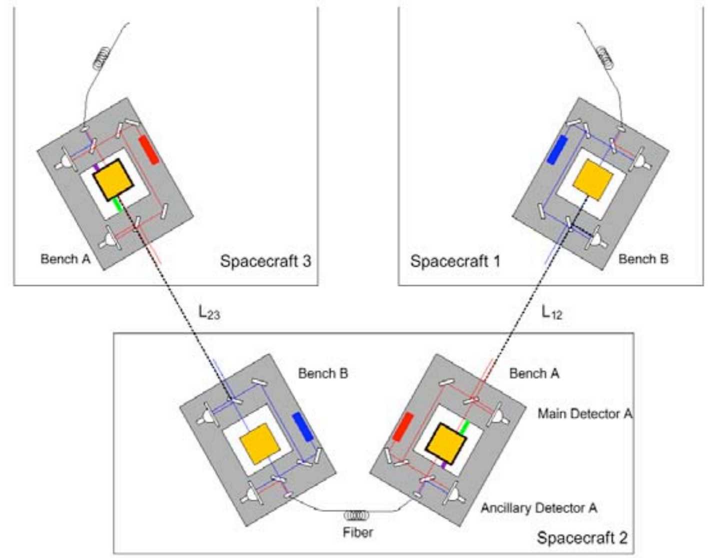


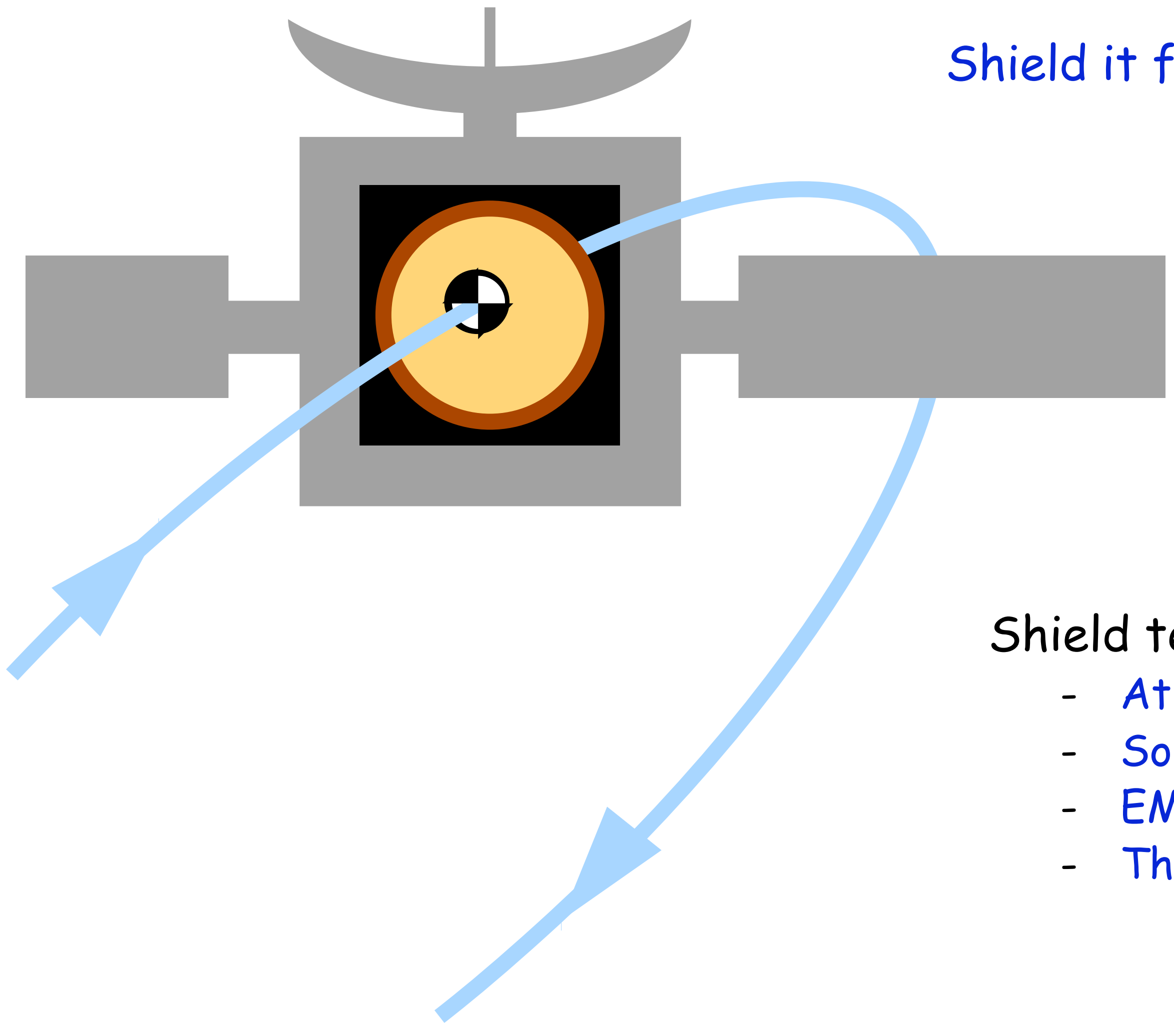
Figure A.4 *LISA measurement setup*

Great elaborated structure, but …

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

Cross Talk and Forcing of Cubic Test Mass is leading noise source

What is True Drag-Free?



Drag-free spacecraft follows test mass
to
Shield it from disturbances

Shield test mass from
- Atmospheric drag
- Solar radiation pressure
- EM fields/gradients
- Thermal variations

Outline

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    - LISA Mission
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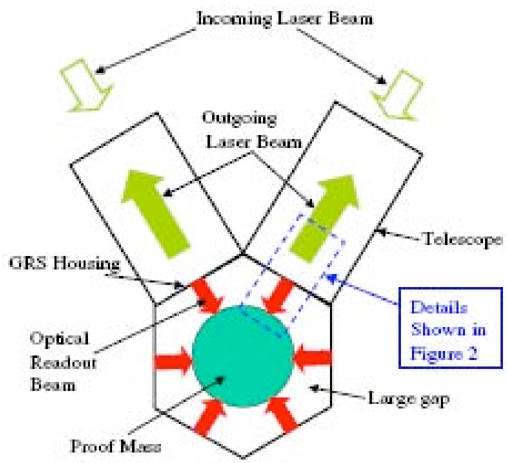
  - Drag Free Concept
    - History of Drag Free
    - Improvements Required for LISA
- The Modular Gravitational Reference Sensor
  - The MGRS Concept
  - Stanford Studies of the MGRS
  - Modular Gravitational Reference Sensor (MGRS)
- Future directions
  - Develop and Test LISA Technology
  - Small satellite missions for UV charge control/Gratings

Modular GRS has Only One Proof Mass (spherical)

Reduced Cross Talk & True Drag Free

Modular GRS: The New LISA Baseline Architecture



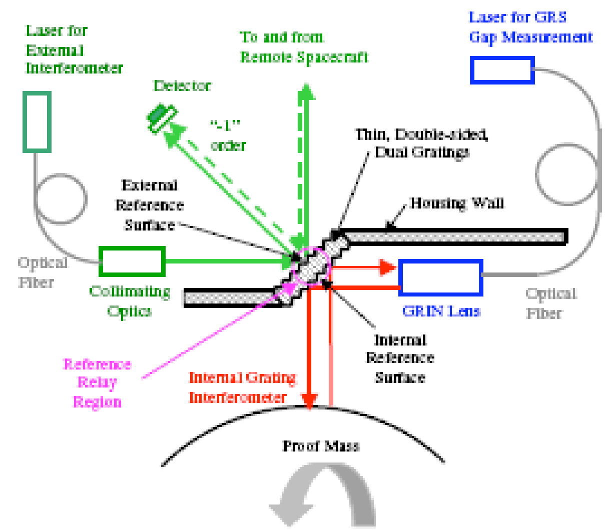
LISA 5 (2004)

INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. 22 (2005) S287–S296 doi:10.1088/0264-9381/22/10/021

Advanced gravitational reference sensor for high precision space interferometers

Ke-Xun Sun, Graham Allen, Sasha Buchman, Dan DeBra and Robert Byer



Amaldi 6 (2005)

Institute of Physics Publishing Journal of Physics: Conference Series 32 (2006) 137–146

doi:10.1088/1742-6596/32/1/022 Sixth Edoardo Amaldi Conference on Gravitational Waves

Modular Gravitational Reference Sensor: Simplified Architecture to future LISA and BBO

Ke-Xun Sun*, Graham Allen, Scott Williams, Saps Buchman, Dan DeBra, and Robert Byer

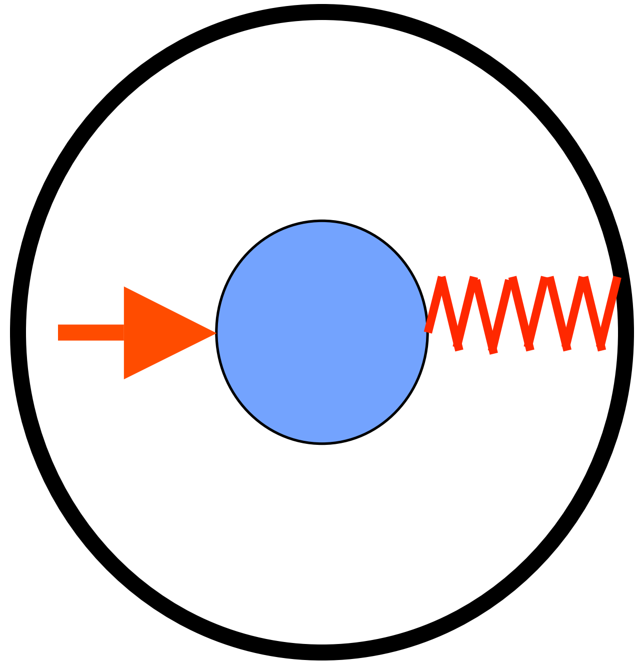
Hansen Experimental Physics Laboratory, Stanford University, CA 94305-4085, USA

*kxsun@stanford.edu, tel: 650-736-1056

Limits to Drag-free

- **Direct Forces (0.1 mHz – 1 Hz)**
  - **Radiation Pressure**
  - **Electrostatics**
  - **Residual gas**
  - **Req. $3 \cdot 10^{-15}$ m/s^2/√Hz**

- **Stiffness (0.1 mHz – 1 Hz)**
  - **$F = k_{stiff} \cdot x_{drag\text{-}free}$**
  - **Electrostatics**
  - **Magnetics**
  - **Gravitation gradient**
  - **~ 10^{-7} 1/s^2**



- **DC Bias (< 0.1 mHz)**
  - Causes satellite to deviate from geodesic
  - Electrostatics
  - Self-Gravity

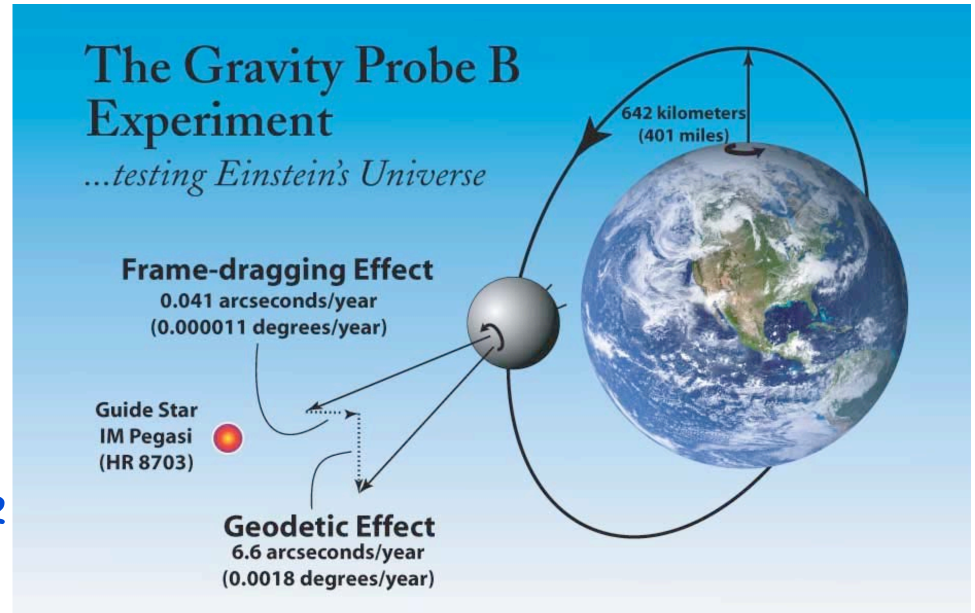
Stanford Gravity Probe-B and Lessons Learned

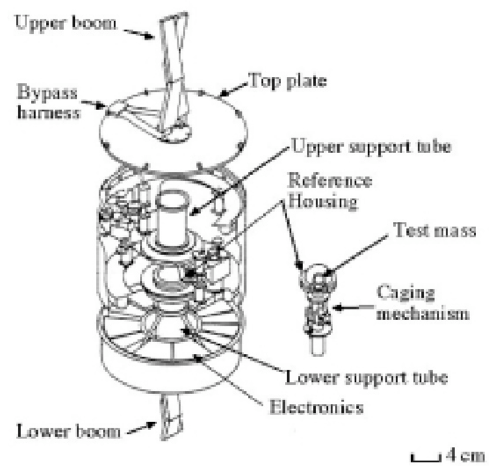
- **GP-B was launched April 2004 and initiated science measurement in August**
- **GP-B has experimentally measured frame-dragging effects**

- GP-B experiences are an important asset to LISA R&D

- **GRS based on Stanford experience with**
  TRIAD (Stanford/APL, 1972, < 5x10-11 m/s2 RMS over 3 days)
  GP-B (Stanford, launch 2002, < 2x10-12 m.s-2/√ Hz at 5x10-3 Hz)

- **Position sensing, charge control from GP-B**
- **GP-B: 17 DOF**
- **GP-B is a critical development for high precision space flight, including LISA**
  - Drag-free technology*
  - Cryogenics
  - Precision fabrication*
  - Caging*
  - Charge management*
  - Patch effect forces*





GP-B - Lessons Learned

- **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.

- **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.

- **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.

- **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.

  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.

• Data Analysis
• Ground Simulations

• Surface Coatings

• Charge management

• Mod GRS – reduce X-talk & coupled DOF

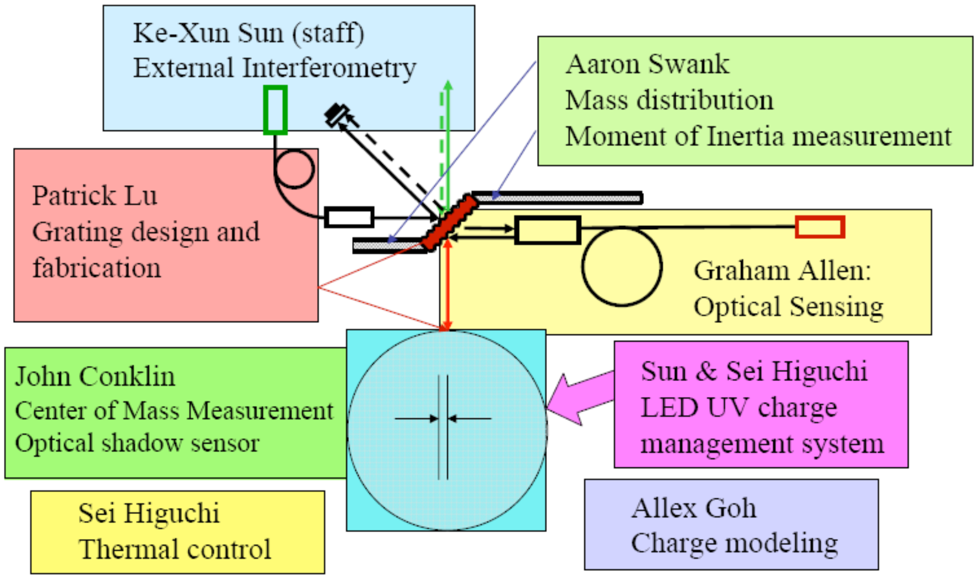
Acceleration Noise Study

	LISA Baseline (10^{-16} m/s^2√ Hz)		**MGRS** (10^{-16} m/s^2√ Hz)	
	10^{-3} Hz	10^{-4} Hz	10^{-3} Hz	10^{-4} Hz
Environmental	10.7	10.7	8.5	8.5
Stiffness	5.8	5.8	0.2	0.2
Forcing	10.8	8.2	0.0	0.0
Sensor back-action	3.88	23.0	0.0	0.0
Total (rss)	**16.7**	**27.3**	**8.5**	**8.5**

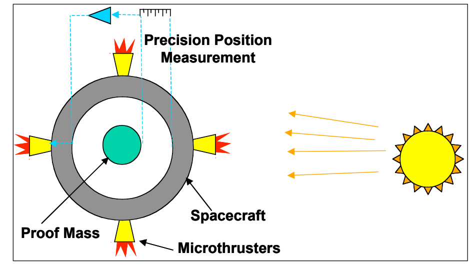
LISA Requirement: 30 × 10^{-16} m/s^2√ Hz @ 10^{-3} Hz

Present Work - Gravitational Reference Sensor

Improve the state of the art by 10^5 to 10^6 for LISA

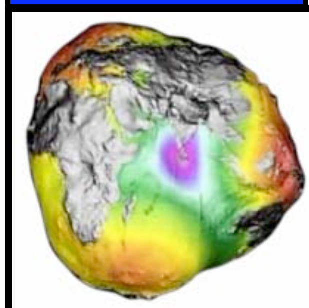


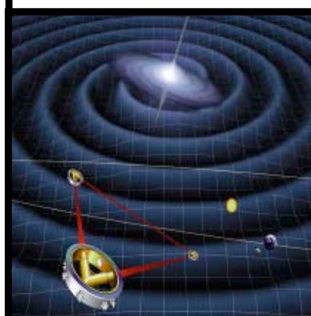
Graham Allen | John Conklin | Allex Goh | Sei Higuchi | Patrick Lu | Aaron Swank



Natural Resources Exploration

Earth and Space Imaging





- **Formation Flying**
- **Gravitational Wave Detection**

Satellite Orbit Management

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**

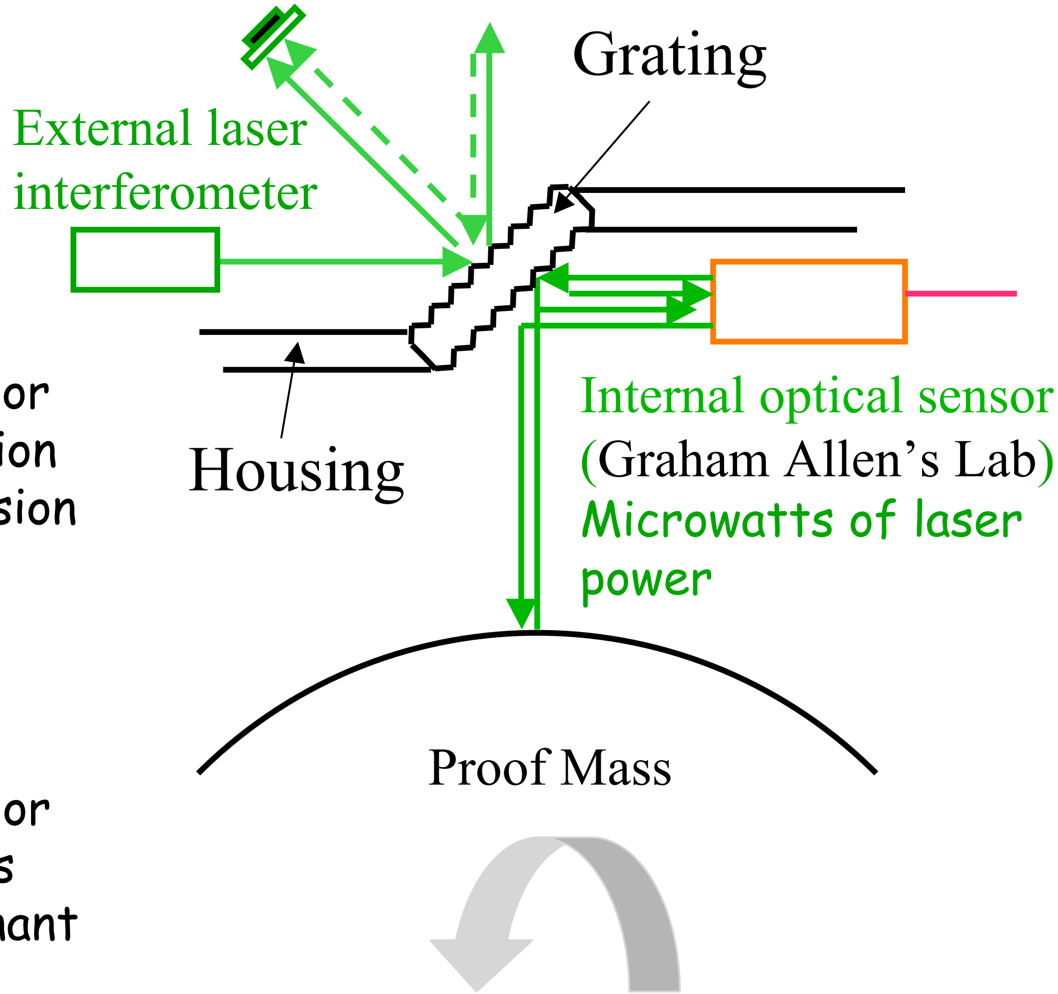
1. **System technologies**
   - System perspective
   - GRS Trade off studies
   - Two-layer sensing & control
   - Multi-sensor algorithm
2. **Optics**
   - Grating cavity displacement sensing
   - Grating angular sensing
   - Diffractive optics
   - Differential optical shadow sensing
   - Laser frequency 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

Modular GRS
Compact, Reflective Optical Sensing Configuration

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

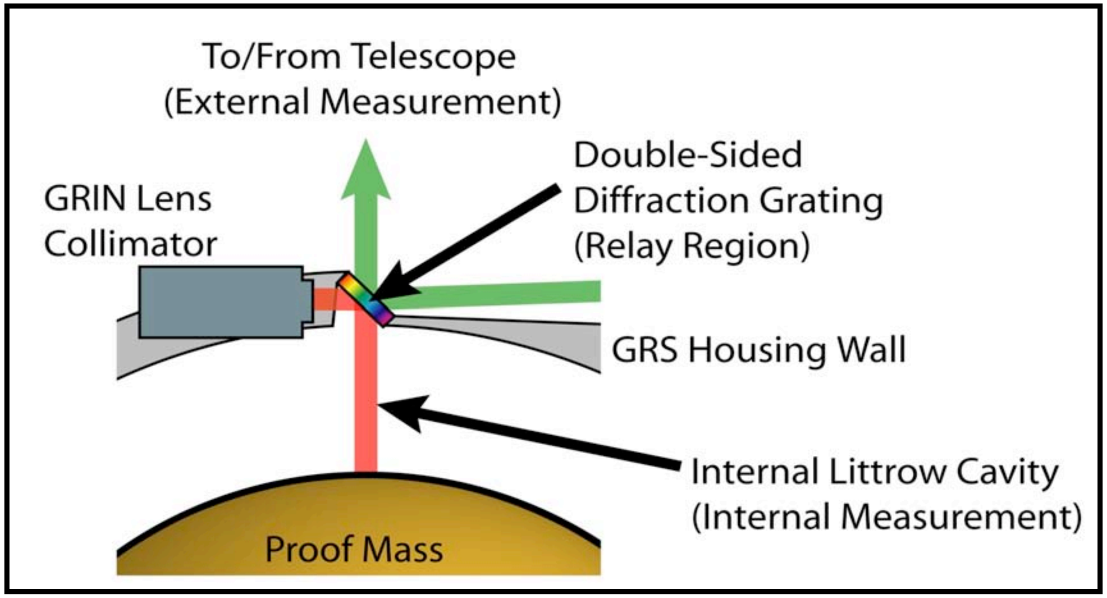
Outside GRS Housing
Grating at 1064 nm or 532nmfor polarization separated transmission and heterodyne detection

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



Internal Optical Interferometer Sensing
(Graham Allen)

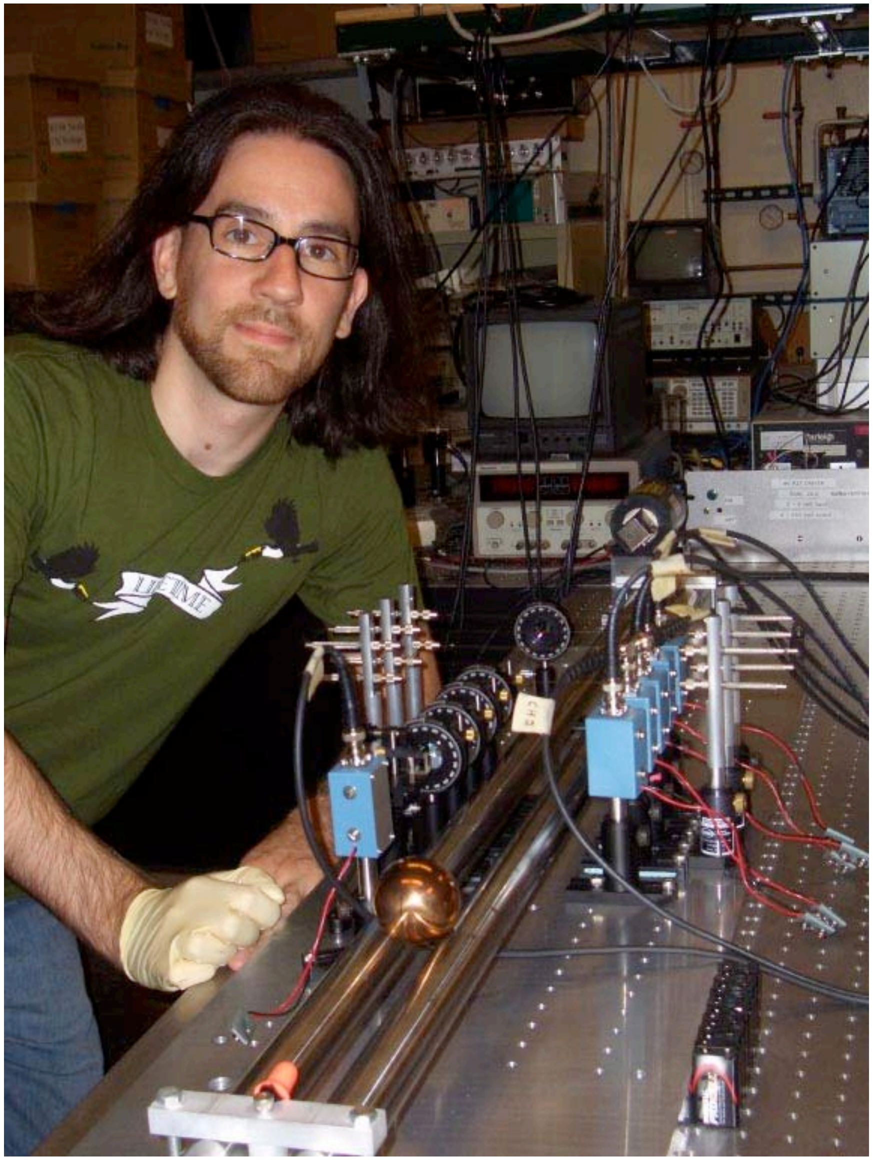
- Goal:
  - Combine fiber optics portability with bulk optics performance
- Fiber Coupled, Littrow Grating Cavity
  - Laser frequency serves as a reference
  - Unique reference surface
  - Fiber delivery
  - Low power



Use fiber coupled 10 microwatt optical source at 1.5 microns to measure distance to 3 pm

Measure Center of Mass of Sphere

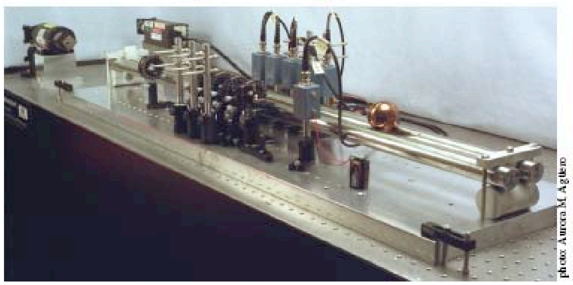
John Conklin - Aero-Astro GP-B/LISA



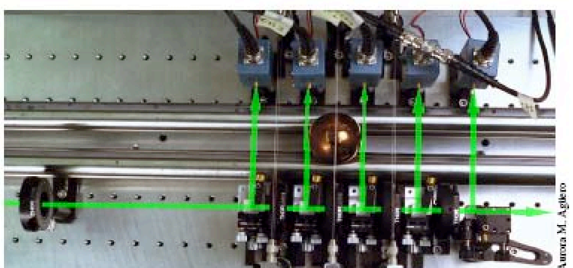
DOSS Measurement of Velocity Modulation
Determine Sphere Mass Center Offset to ~150 nm

Measuring Velocity Modulation

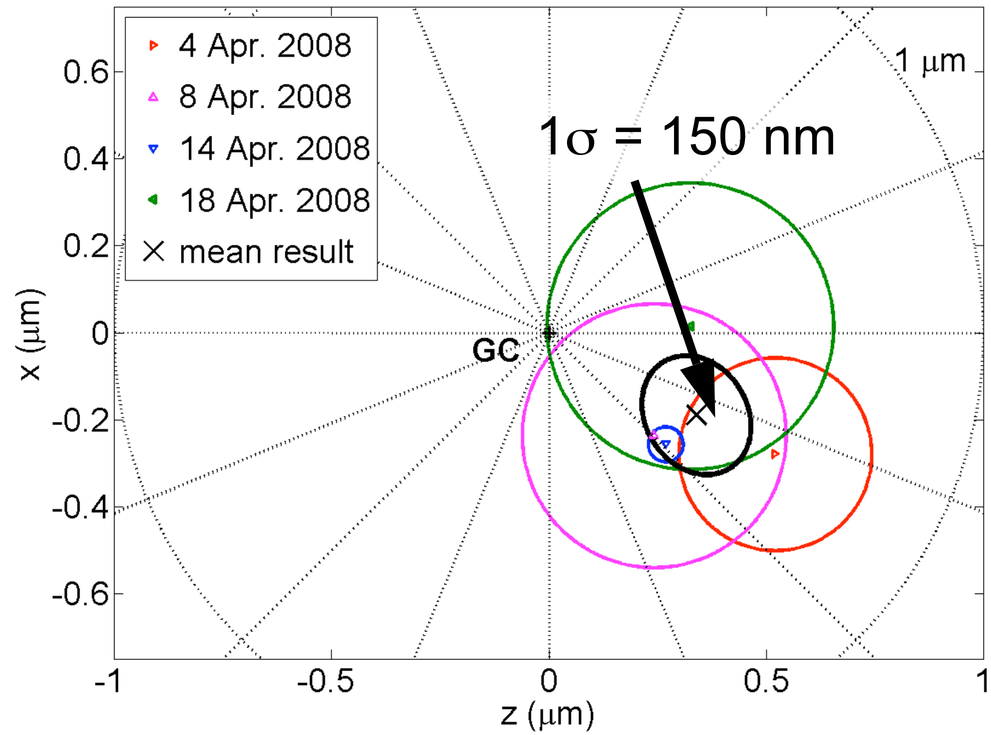
- Roll sphere down rails to spectrally shift CM information, avoid $1/f$ noise boundary
- Sense sphere trajectory optically (100 ns timing accuracy)



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



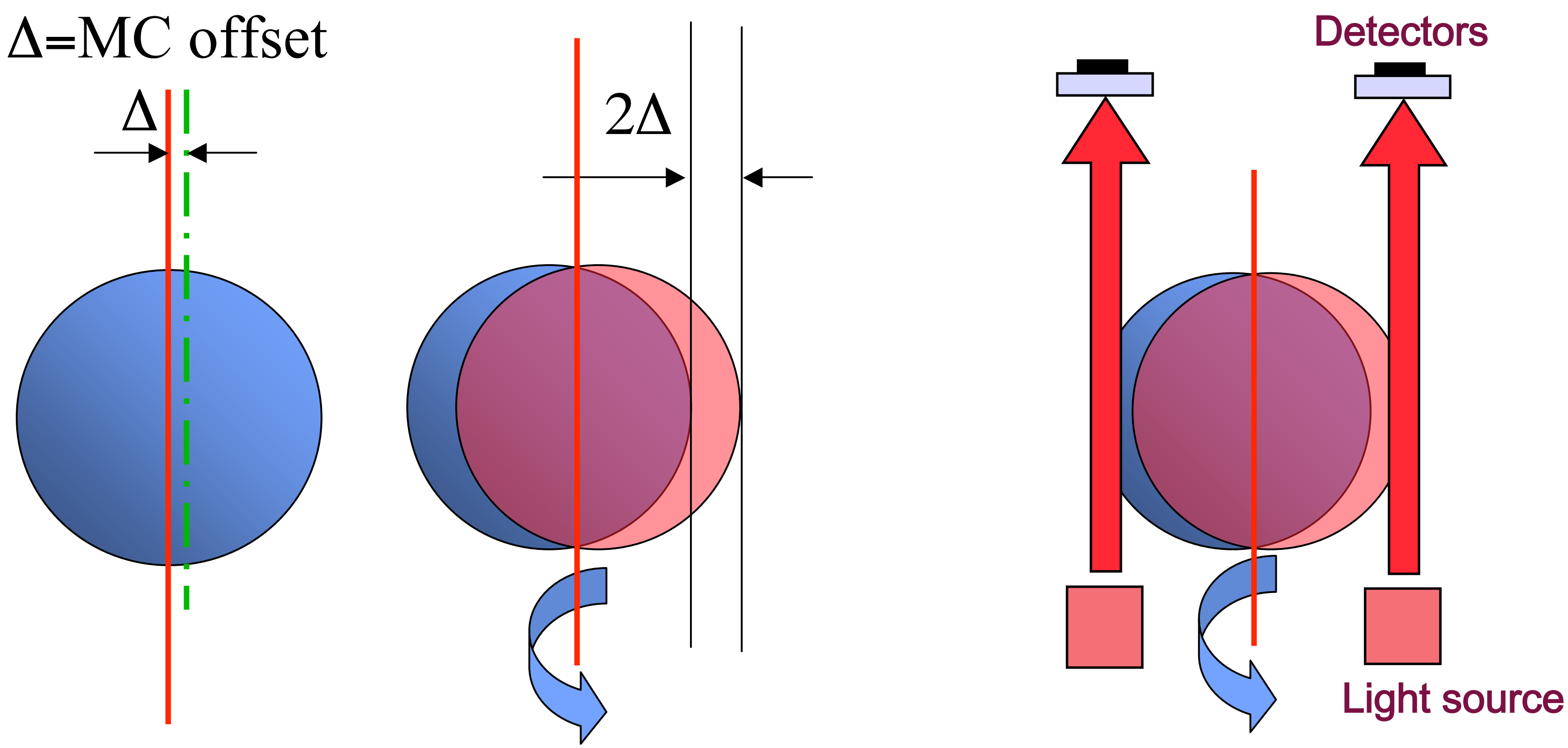
Experimental Results



Present measurement accuracy: 150 nm

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

Spinning Sphere Movement and Differential Optical Shadow Sensing (DOSS)



Center of Mass Offset Δ ~ 10~ 300 nm

Spinning sphere: 2Δ variation

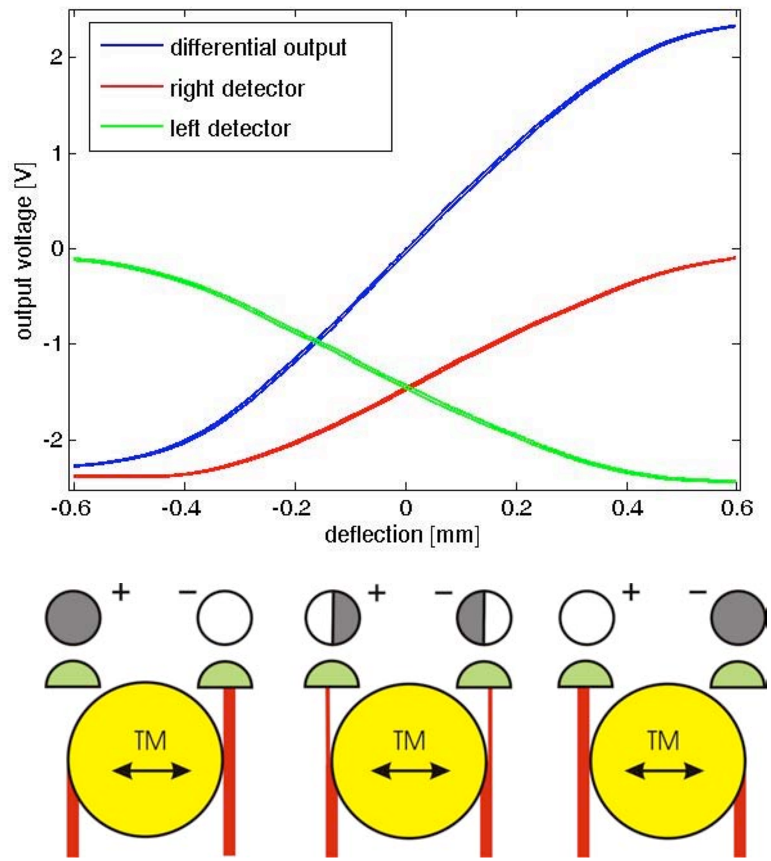
Other variations

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

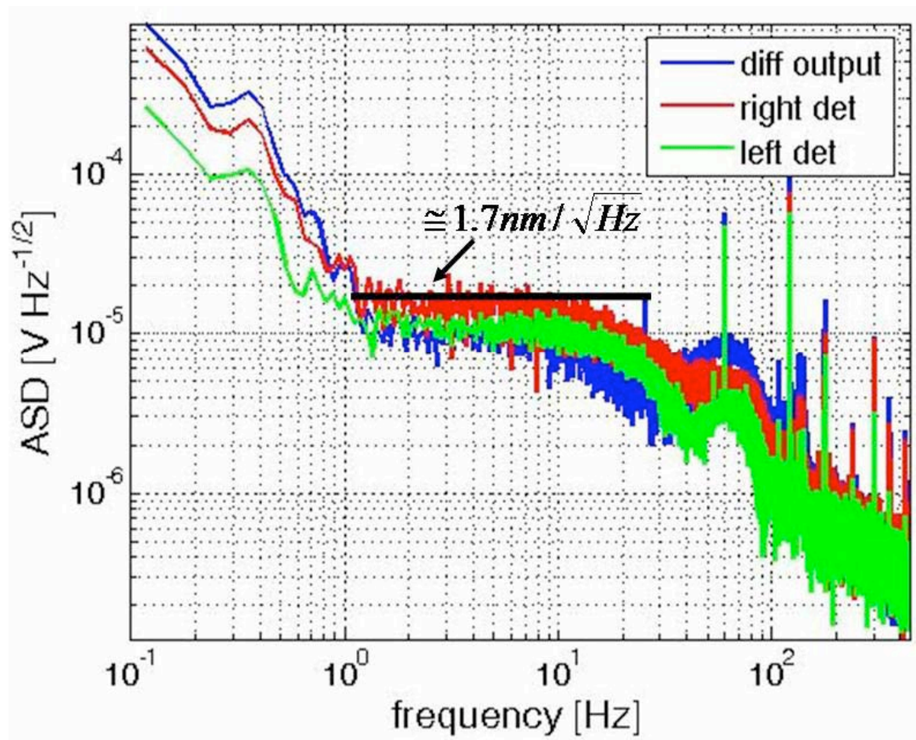
Optical shadow sensing is appropriate

- **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$^{1/2}$)



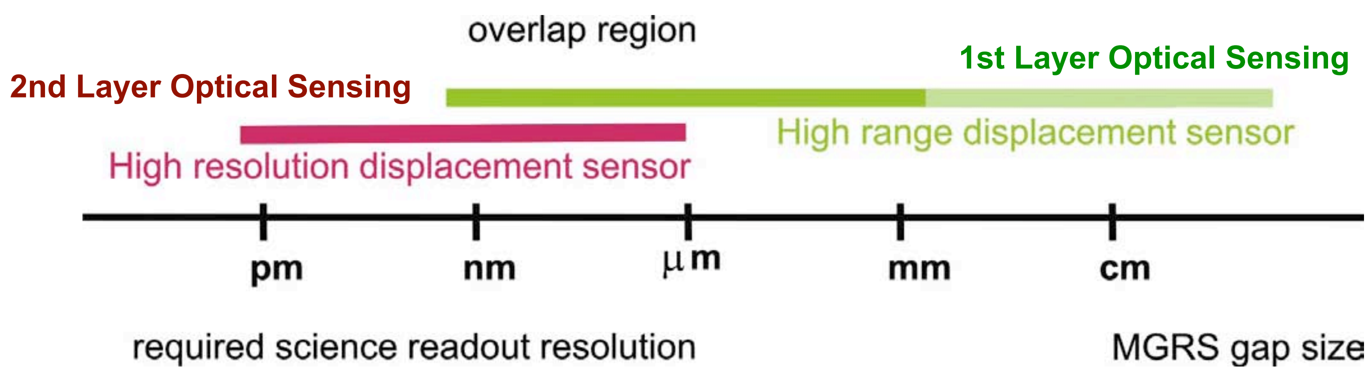
PSD of sensor noise for 10s of data

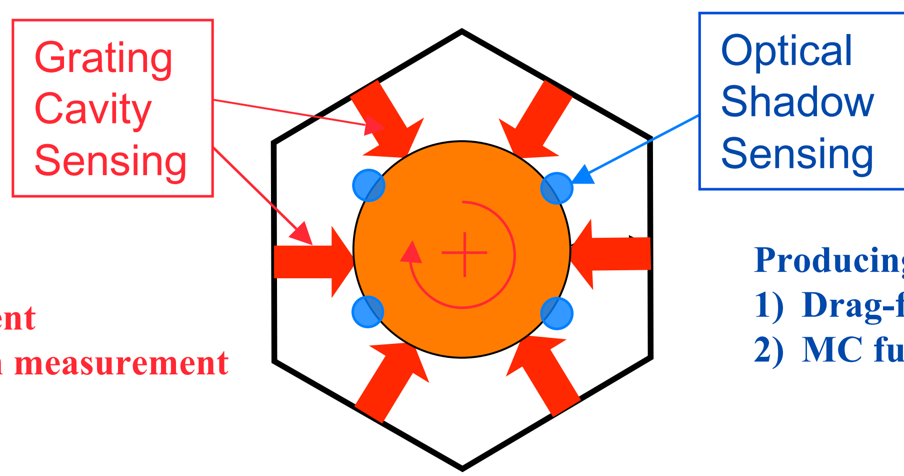


Sun, Trittler, Conklin, Byer, "Differential optical shadow sensing (DOSS) for LISA and MGRS applications", Poster on Wednesday

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 laser interferometry





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

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

Outline

- Introduction
  - LIGO and LISA
  - Gravitational Waves & Sources
  - Drag Free Concept

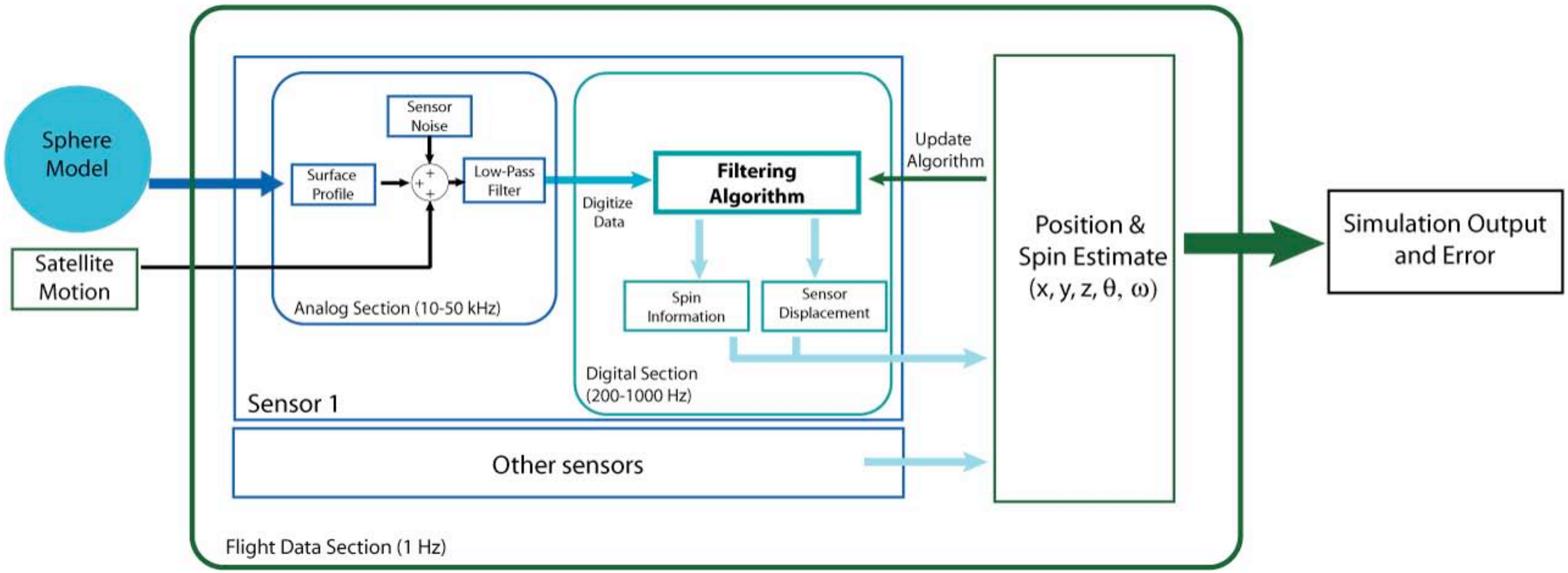
- LISA Technology
  - LTP/ST-7 Technology Mission
  - Cube vs Sphere study
  - Modular Gravitational Reference Sensor (MGRS)
  - Simulate the performance of the MGRS

- Future directions
  - Develop and Test LISA Technology
  - Small satellite missions for UV charge control/Gratings

Graham Allen, John Conklin, Dan DeBra

- **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



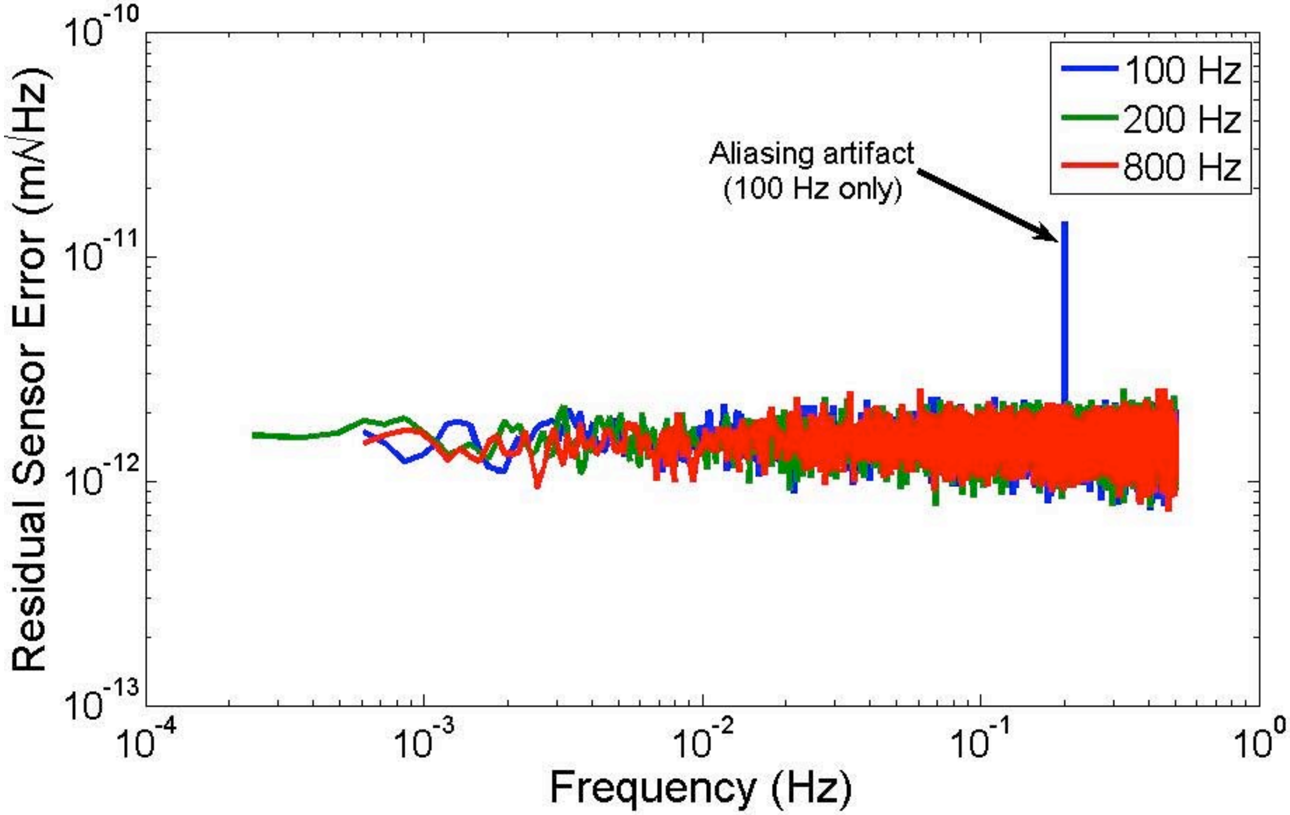
- **Model the analog and digital systems of the satellite**
- **Most simulation parameters are adjustable**
  - **Spin frequency, sample rates, non-linearity, noise levels**

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)

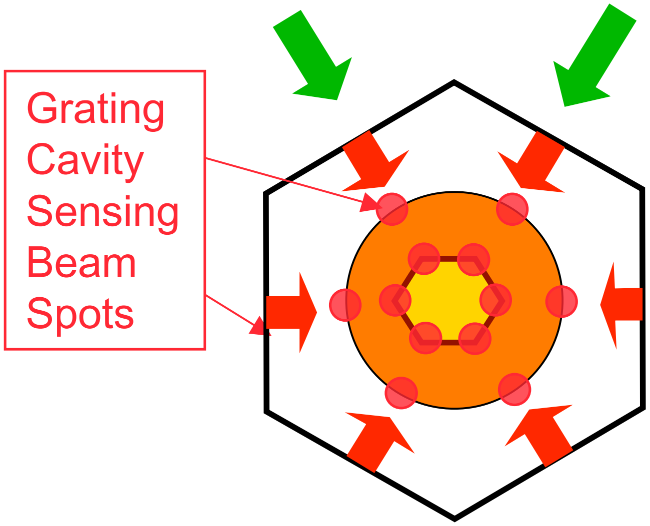
- **1 MHz CPU is sufficient for all algorithms**
  - **1 Hz Science Data Rate, 400 Hz sample rate**
- **Sine Fitting is preferred**
  - **Highest resolution**
  - **Polynomial fit → Easy interpolation for science data**
  - **Provides sphere phase automatically**

Tested Sampling Rates

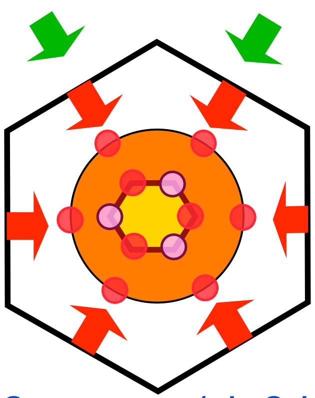


- **12-bit sampling at 200 Hz is sufficient**
  - **16 bit at 400 Hz is ideal**
  - **Mass center offset provides a reliable dither**

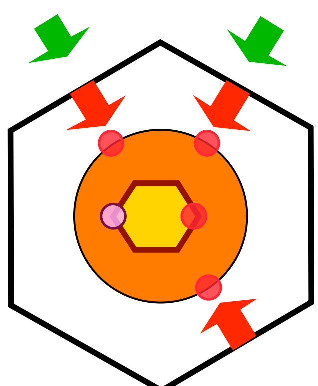
Robustness of Redundant Multi-Sensor Configuration Shown via Computer Simulation



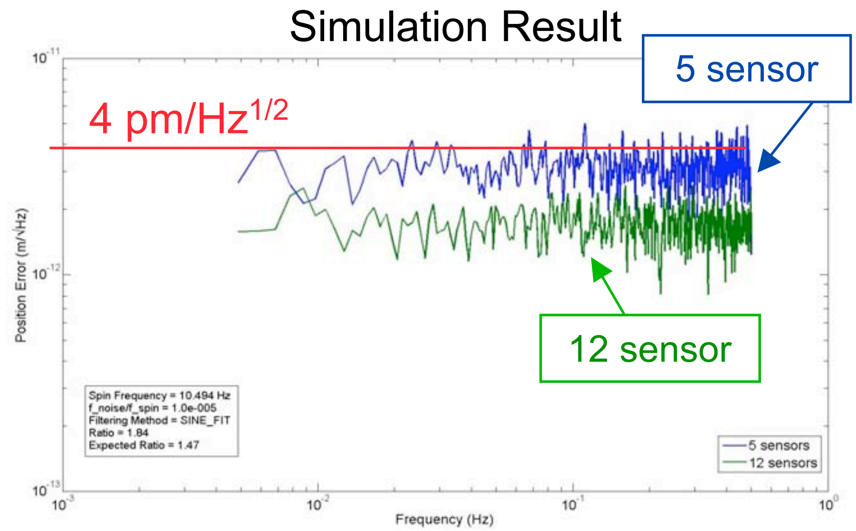
18 sensor, full 3d
6-6-6 Pattern



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

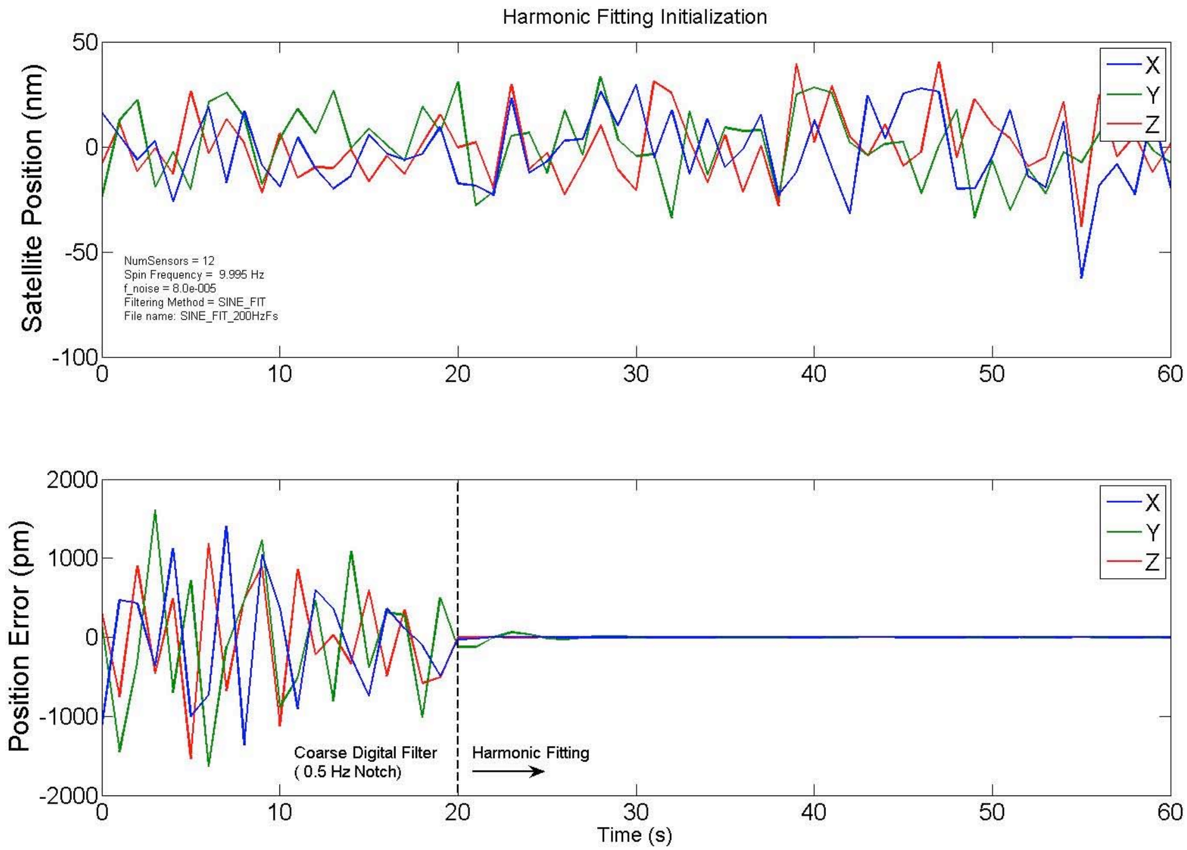


5 sensor, 1d+1d
3+1+1 Pattern



- 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

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

Outline

- Introduction
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  - Gravitational Waves & Sources
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- LISA Technology
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  - Cube vs Sphere study
  - Modular Gravitational Reference Sensor (MGRS)

- Future directions – testing in space environment
  - Develop and Test LISA Technology
  - Small satellite missions for UV charge control/Gratings
    - Charge Control
    - Grating Sensing and Control

A Sequential Roadmap for Small Satellites

Science and Technology Requirements for
Drag Free Gravitation Reference Sensors

Deep UV LED
Charge Management & Optical Calibration

Grating Angular Sensor
& Laser Stabilization

Grating Displacement
Sensor Combined with Angular Sensor

Laser Second Harmonic Generation,
Multiport Grating Interferometer

Spherical Prof Mass Caging Mechanism
(Initial Scaling)

MEMS Microthrusters
And Nanothrusters

Drag Free Control with Floating Proof
Mass and MEMS thruster

Miniature Modular Gravitational Reference Sensor
Combined System from Previous Flights

Small Satellite Formation, Multiple Small Satellites
Mini LISA, BBO Fleet

Stanford Professor Bob Twiggs

AMES GENESAT

MINISAT, The Mini Satellites
Gravitational Reference Sensor Technologies

The Program

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

The Benefits

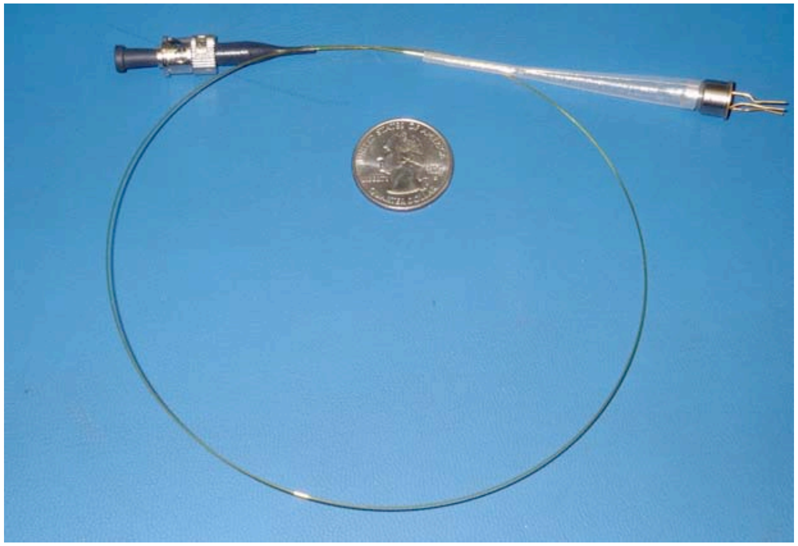
- New science: Physical, Life, Engineering
- Critical technology demonstrations
- Fast advance of NASA mission objectives
- Train engineers and scientists for the future

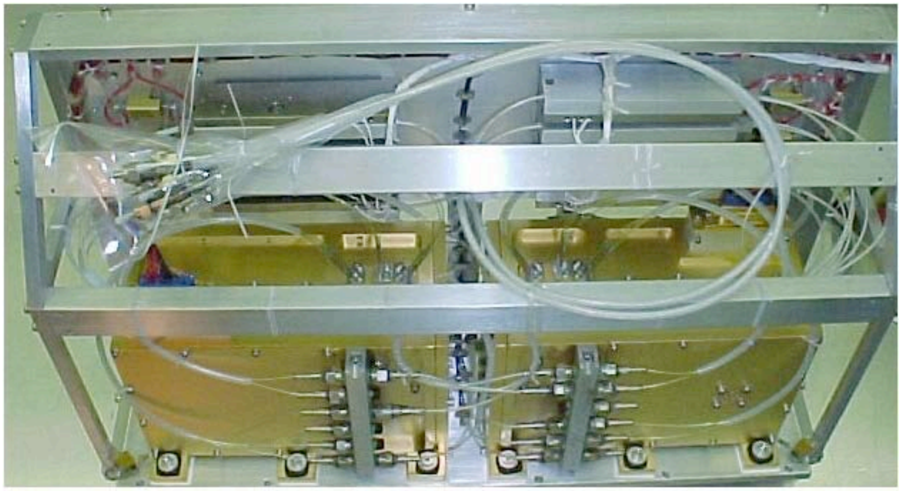
What is Needed for Program Start ?

- Collaboration: AMES, KACST, Stanford
- Continuity: 1 to 2 missions per year
- Total cost per mission: 5 million dollars

Charge Control: UV LED vs. Mercury Lamp

Ke-Xun Sun and Sasha Buchman





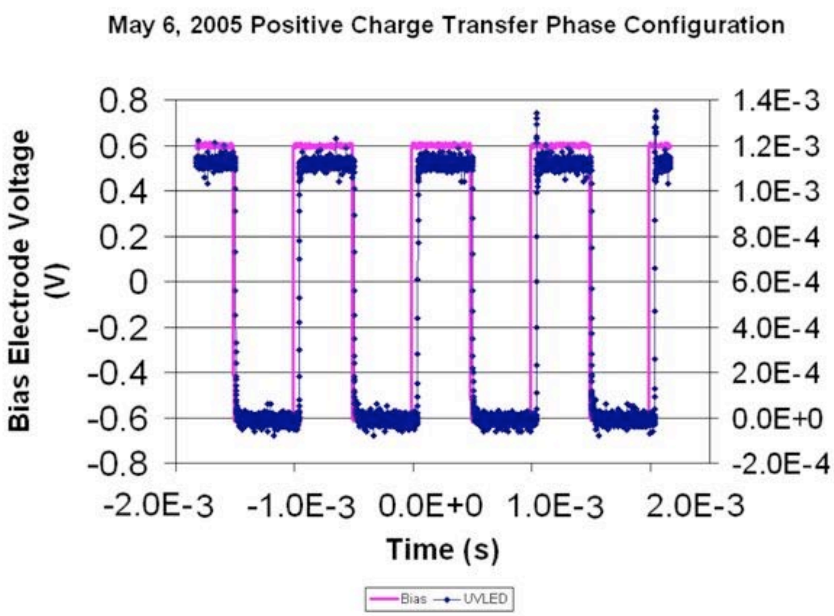
UV LED

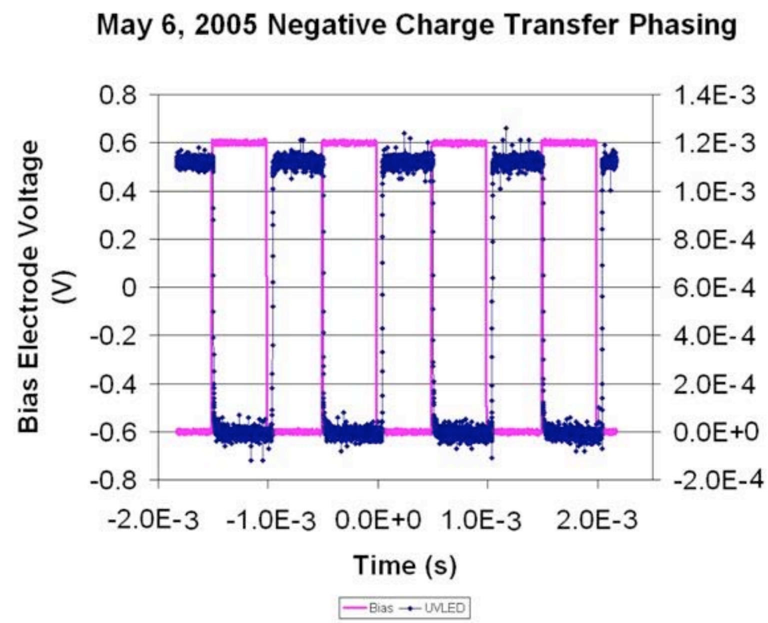
- TO-39 can packaging
- Fiber output with ST connector
- Reduced weight
- Power saving
- Reduced heat generation, easy thermal management near GRS

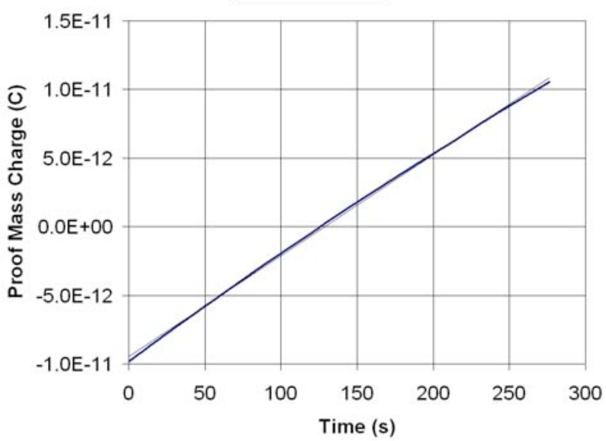
GP-B CMS in Flight

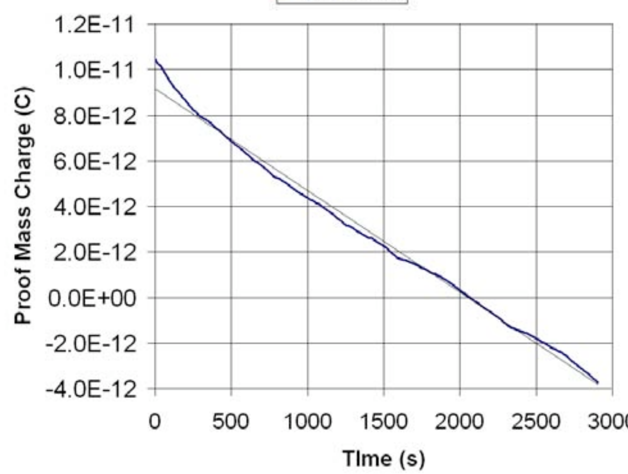
- 2 Hg Lamps
- Weight: 3.5 kg
- Electrical Power 7~12 W
  (1 lamp on, 5 W for lamp, 5 W TEC cooler)

Positive and Negative AC Charge Transfer
UV LED and bias voltage modulated at 1 kHz –



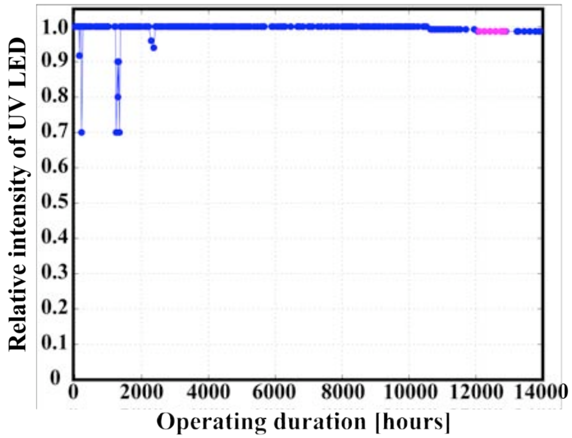


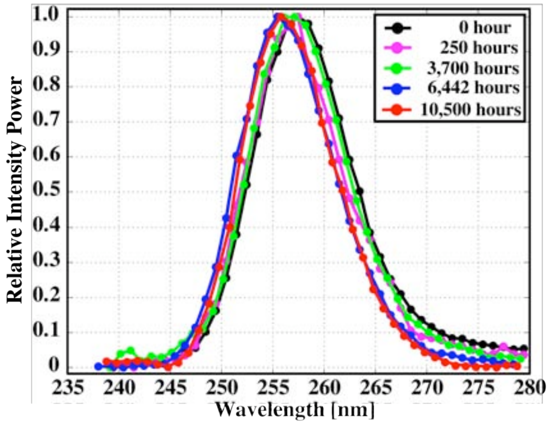




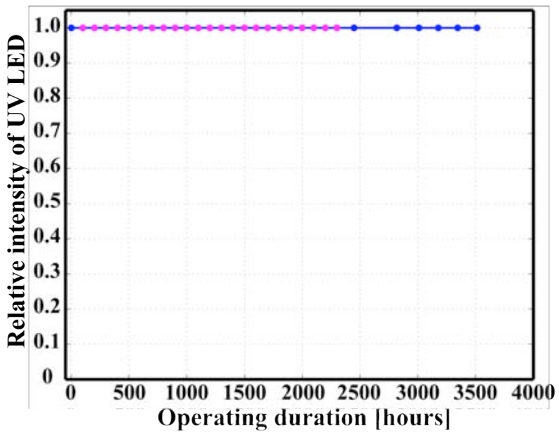
UV LED Power and Spectral Stability
The LED Reported at LISA 6th Symposium

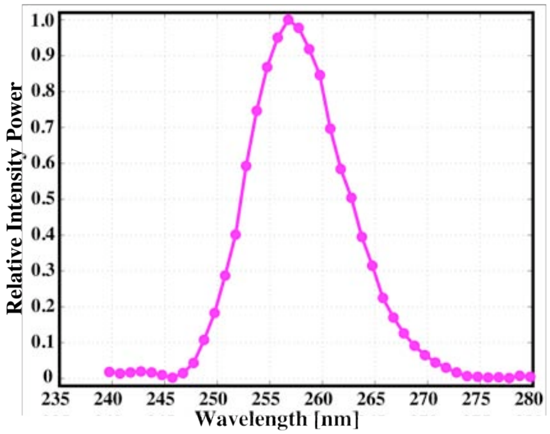
Operation Lifetime in Nitrogen > 14,000 hours





Operation Lifetime in Vacuum > 3,500 hours



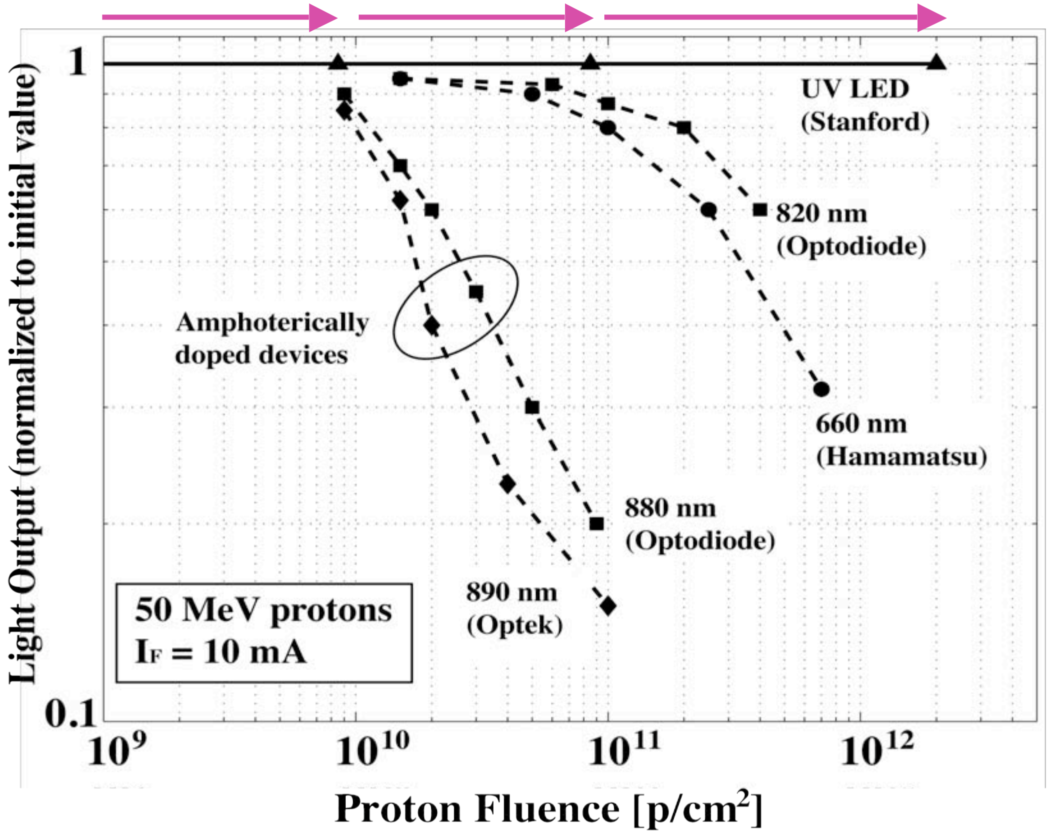


UV LED Lifetime Using Proton Irradiation

80 pA Run Proton Fluence $1x10^{10}$ p/cm^2

500 pA Run Proton Fluence $6.3x10^{10}$ p/cm^2

15,000 pA Run Proton Fluence $2x10^{12}$ p/cm^2



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",

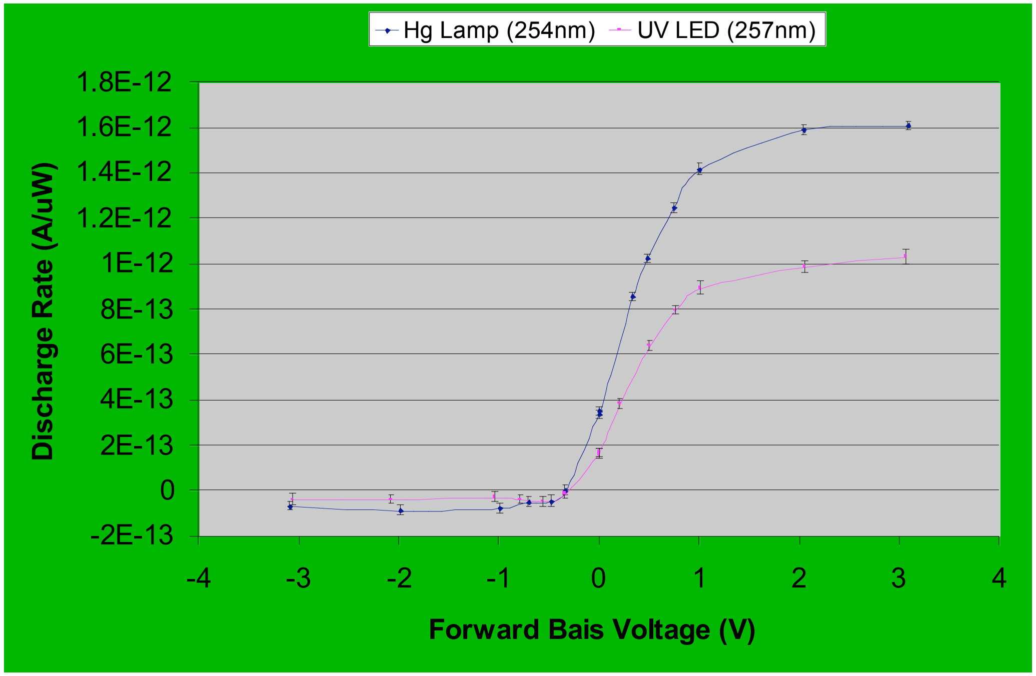
.

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

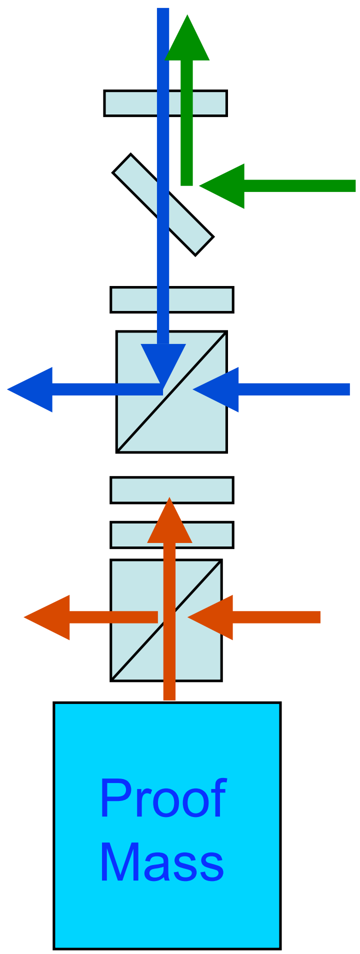
- The power can be used to increase laser power by 2x--
  - Enhance sensitivity by 41%,
  - Increase event rate and detection volume by a factor of 282%.
  - Significant astrophysical observational pay off



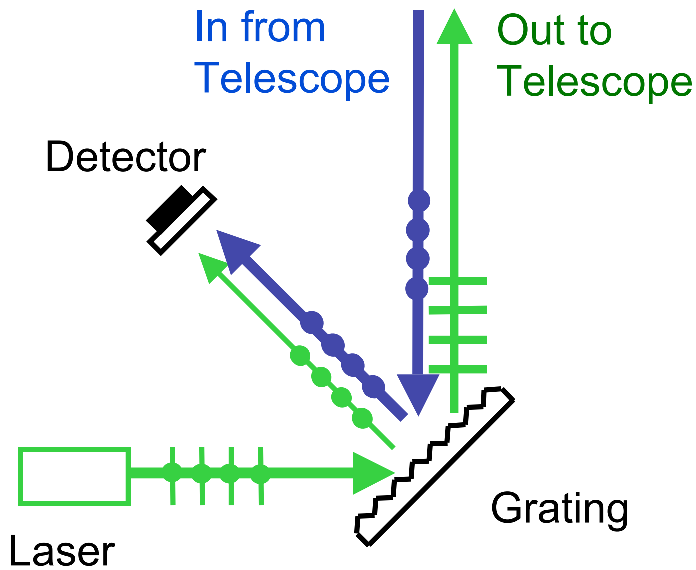
Comparable Discharge Rates
For First UV LED Experiment

Next Step: Test Charge Control in space using small satellite
(Collaboration with KACST in Saudi Arabia)

Diffractive Optics for External Interferometry



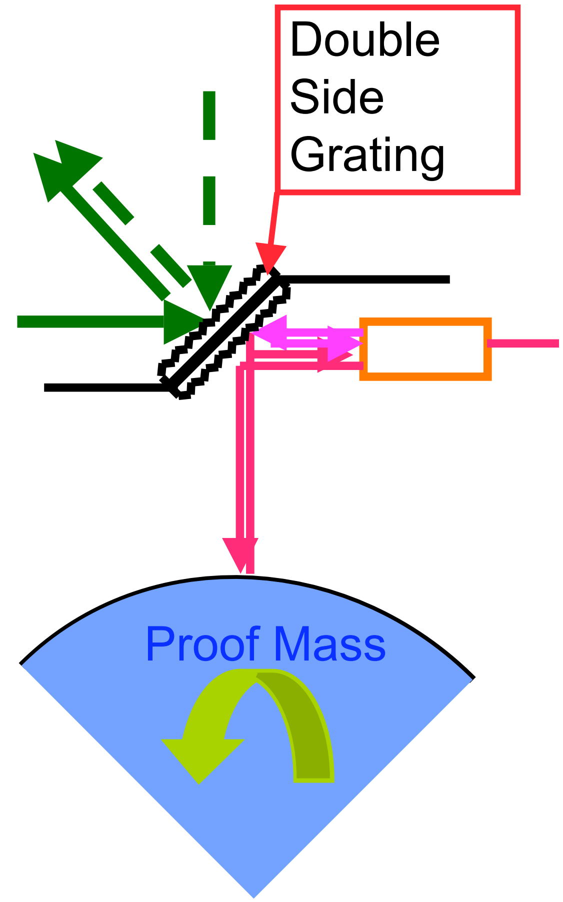
Transmissive Optics



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

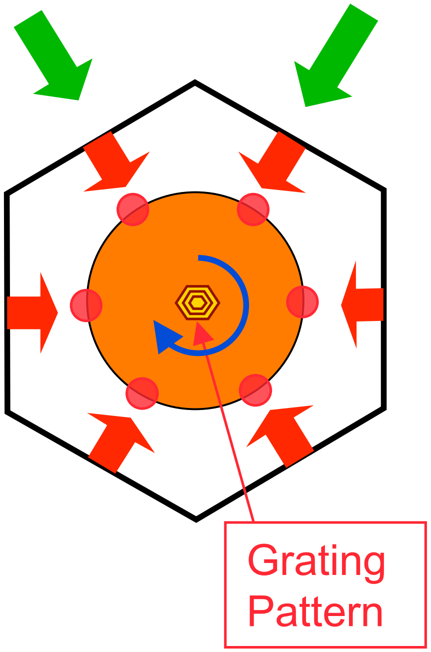
Reflective grating interferometry

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



Reflection Diffractive Optics

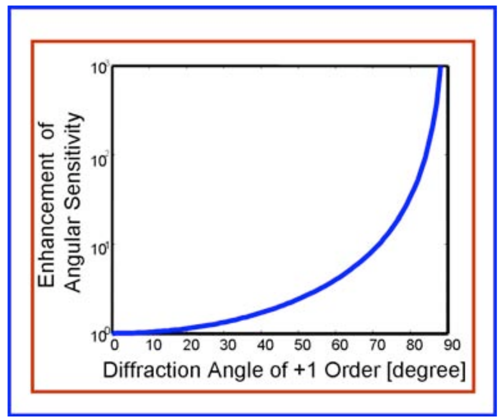
Grating Angular Sensor in LISA and MGRS

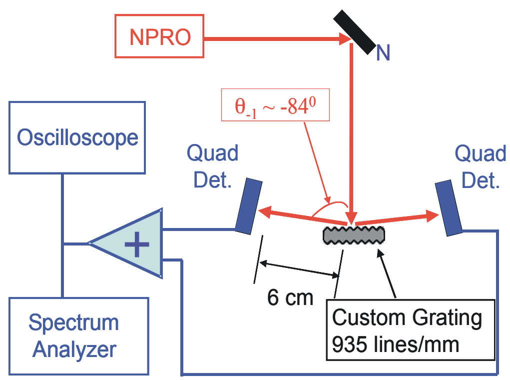


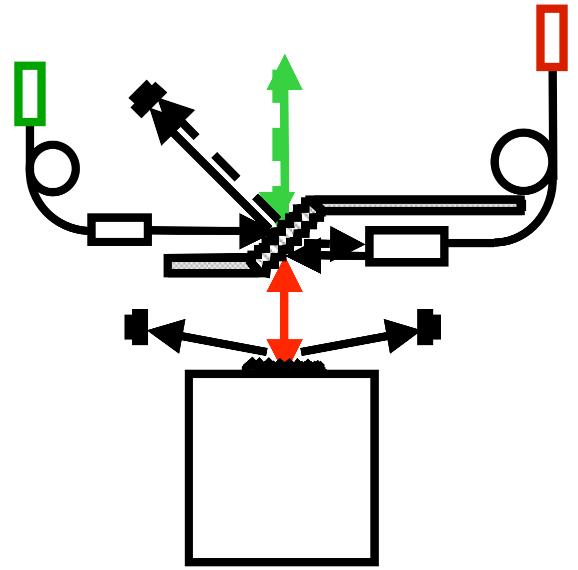
Grating pattern on a sphere:

1) Sphere orientation determination
2) Spin rage determination
3) Facilitate sphere mapping

Grating Angular Sensor





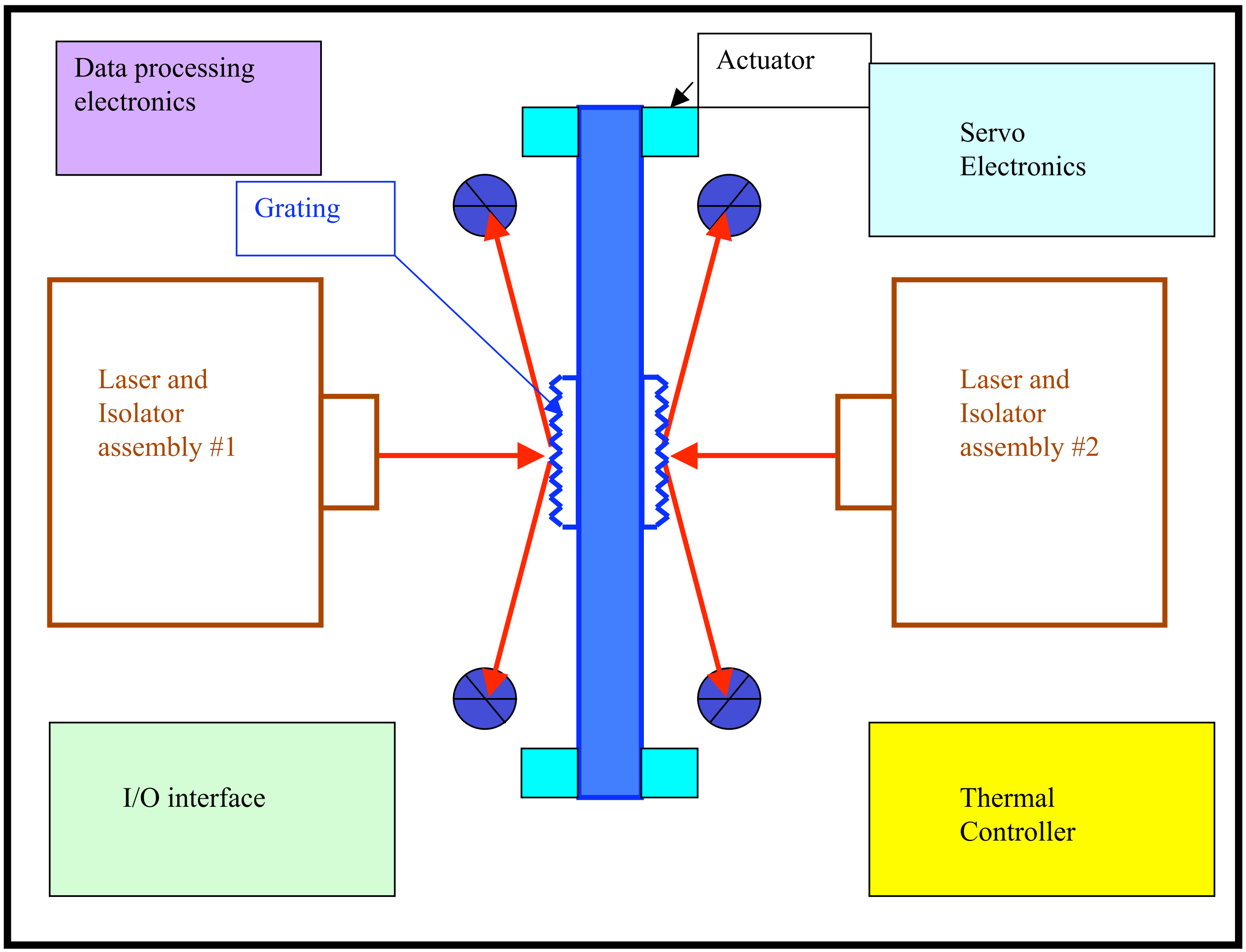


Grating pattern on a cube

1) Cube orientation determination
2) Decouple cube orientation from displacement data

Next Step: Test Gratings in space environment
(Collaboration with KACST in Saudi Arabia)

System design concept



Summary

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

- 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

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

Thank you

Stanford LISA Team

Robert Byer, Saps Buchman,
Dan DeBra, Ke-Xun Sun

Graham Allen	Optical Sensing
John Conklin	Mass Center Determination
Sei Higuchi	Thermal Control
Patrick Lu	Diffractive Grating Design
Aaron Swank	Mass Attraction

Stanford LISA MGRS Team

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Patrick Lu


Aaron Swank


Edgar Torres

Staff


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Dan DeBra


Ke-Xun Sun

International Visiting Researchers


Martin Trittler


Domenico Gerardi

Stanford Presentations at 7th LISA Symposium

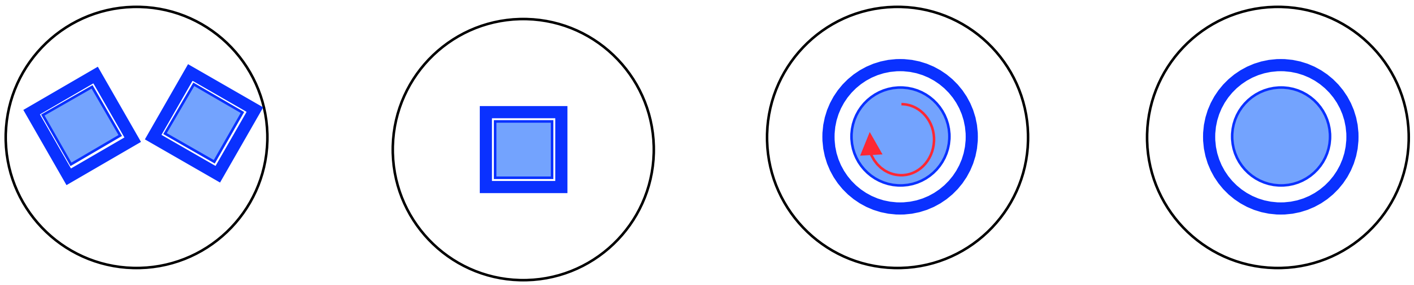
1. Stanford Modular Gravitational Reference Sensor Program (MGRS)
   Technology Overview (This talk)
2. Advanced concepts for future space gravitational wave detectors
   GRS trade-Off studies. (Presentation Tuesday afternoon)
3. Reflective gratings for inter spacecraft interferometry
   Highly polarization 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)

References and talk available at web site LISA.Stanford.edu

- **BACK UP SLIDES**

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**



2 cube | 1 cube | 1 Sphere (spinning)** | 1 Sphere (non-spinning)

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)

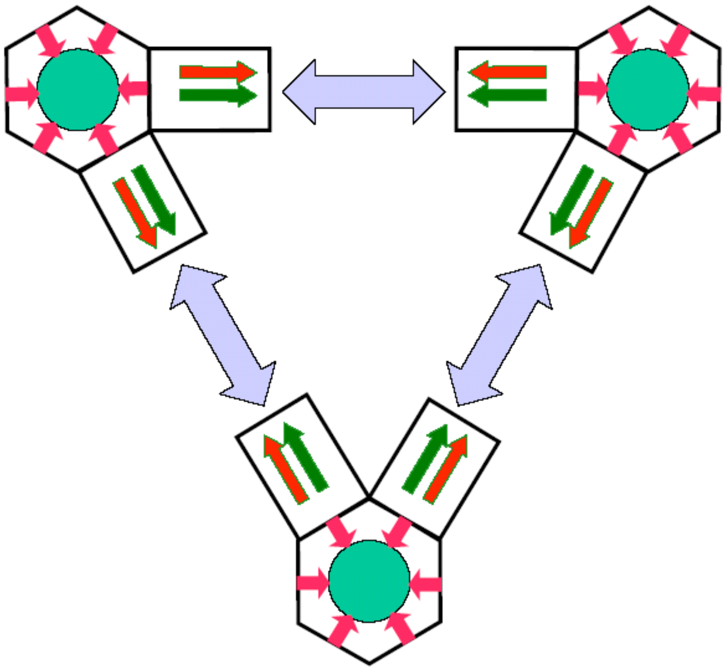
- GRS configuration trade off studies
  - Investigate performance in the presence of disturbance and stiffness related noises
  - Spinning spherical proof mass shows lowest noises due to:
    - > Reduced stiffness
    - > Intrinsic signal averaging process

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	$k^m + k^{sg} + k^e \sim 4 \cdot 10^{-7} s^{-2}$ [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)	$k^m + k^{sg} + k^e \sim 4 \cdot 10^{-7} s^{-2}$ [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)	$k^m + k^{sg} + k^e \sim 5 \cdot 10^{-8} s^{-2}$ (**) 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)	$k^m + k^{sg} + k^e \sim 5 \cdot 10^{-8} s^{-2}$ (**) 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)	$\delta x = 1.44 \mathrm{\ nm}/\sqrt{\mathrm{Hz}}$ at 1 mHz (electrostatic readout) $\delta x = 0.32 \mathrm{\ nm}/\sqrt{\mathrm{Hz}}$ at 1 mHz (optical readout) [47]	$\delta l = \sqrt{\left(\delta x \cos(\frac{\alpha}{2})\right)^2 + \left(\delta y \sin(\frac{\alpha}{2})\right)^2} =$ $= 0.29 \mathrm{\ nm}/\sqrt{\mathrm{Hz}}$ at 1 mHz (optical readout) [46]	$\delta l = \sqrt{\left(\delta x \cos(\frac{\alpha}{2})\right)^2 + \left(\delta y \sin(\frac{\alpha}{2})\right)^2} =$ $\approx 0.3 \mathrm{\ nm}/\sqrt{\mathrm{Hz}}$ 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"

Modular GRS Simplifies Control



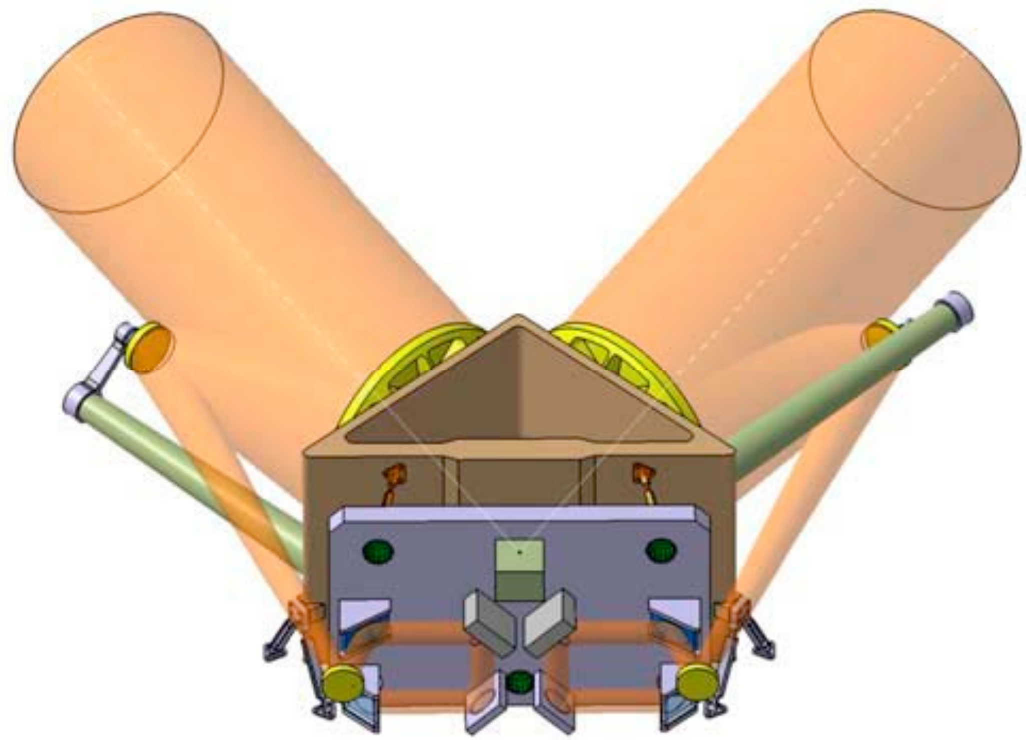
DOFs Comparison Table

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	

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

Previous Conceptual Design for LISA

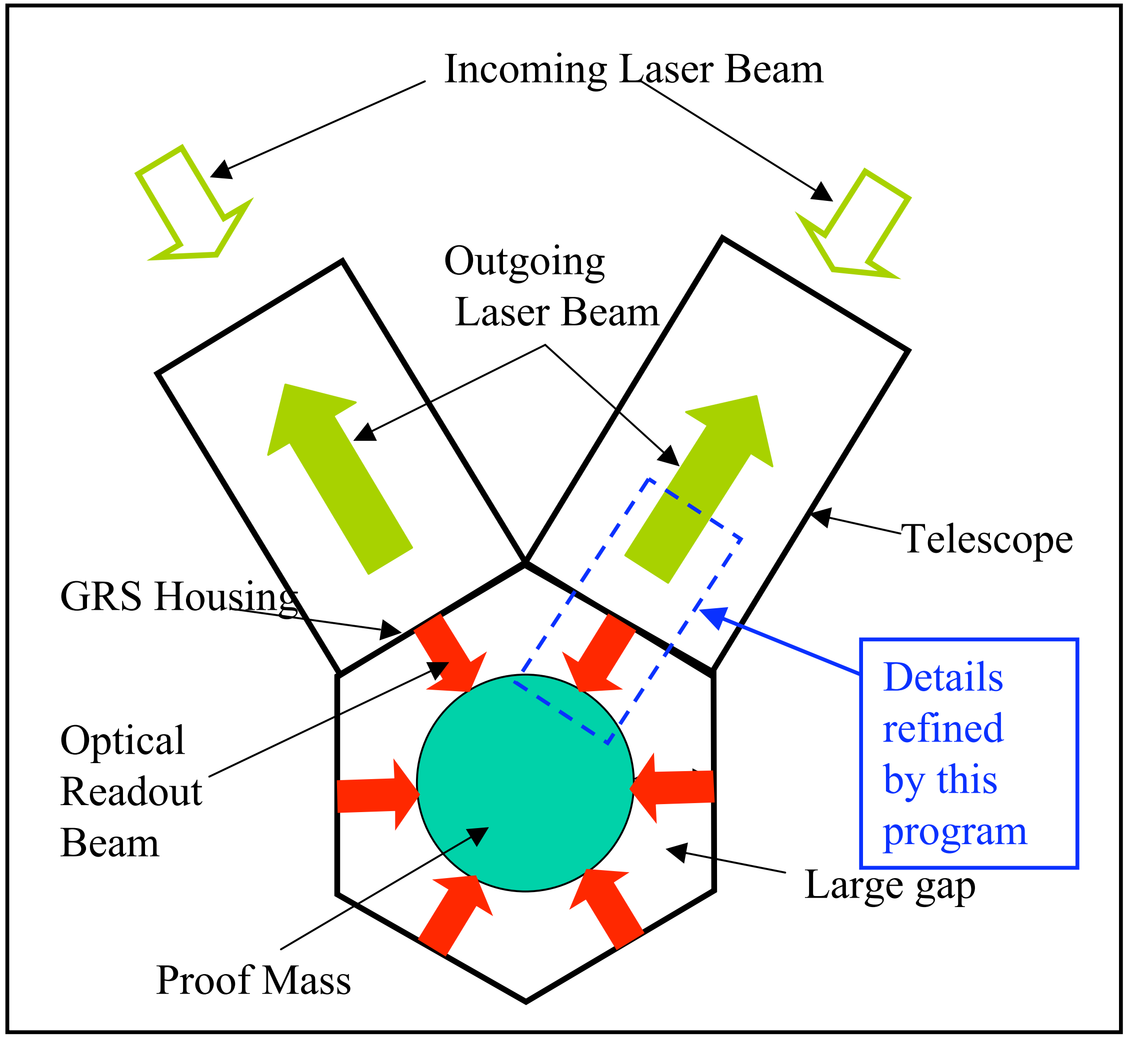
LISA spacecraft structure with
Two test masses



Proposal LISA Spacecraft with
Single proof mass and single GRS payload structure.

Modular GRS Architecture for Advanced Missions

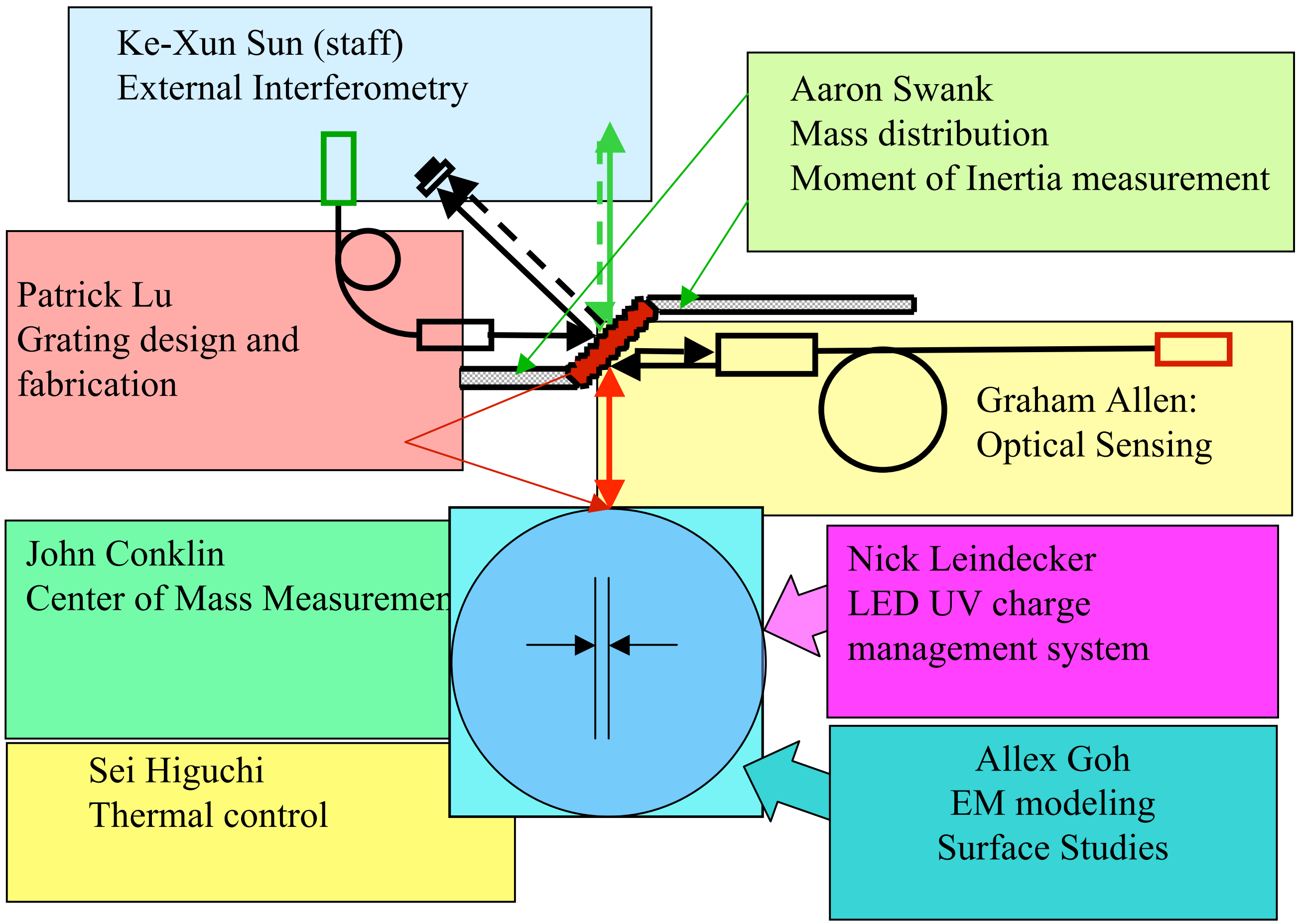
- Single proof mass
- Modularized, stand-alone GRS
- GW detection optics external to GRS
- External laser beam not directly shining on test mass
- Internal optical sensing for higher precision
-
- Large gap for better disturbance reduction
-
- True 3-dim drag-free architecture
- Determine the geometric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



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

Technologies equally applicable to any LISA configurations

Ph. D Graduate Students heavily involved in LISA work and they like it



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."**

LISA Noise Sources

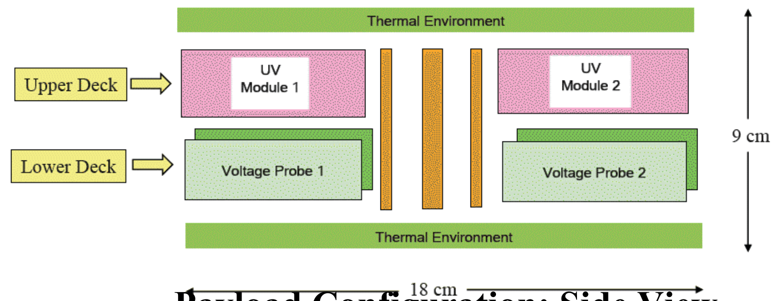
Source	Name	Formula	Value $[\mathrm{m\,s^{-3/2}}]$
Correlated readout noise	f_{corr}	$f_{corr} = \sqrt{2}\sqrt{f_{trip}^2 + f_{ampip}^2 + f_{act100}^2}$	6.36×10^{-18}
Uncorrelated readout noise	f_{unc}	$f_{unc} = \sqrt{2}\sqrt{f_{act0}{}^2 + f_{actth}{}^2}$	8.81×10^{-18}
Thermal effects	$f_{thermal}$	$f_{thermal} = 2\,(f_{rad} + f_{radpr} + f_{og} + f_{th} + f_{gravIS})$	4.97×10^{-15}
Brownian Noise	$f_{Brownian}$	$f_{Brownian} = \sqrt{2}\sqrt{f_{diel}^2 + f_{gas}^2 + f_{magdmp}^2 + f_{magimp}^2}$	9.36×10^{-16}
Magnetics S/C	f_{magnSC}	$f_{magnSC} = \sqrt{2}\,(f_B + f_{\Delta B} + f_{Bac})$	8.9×10^{-15}
Magnetics Interplanetary	f_{magnIP}	$f_{magnIP} = \sqrt{2}\,(f_{Bi} + f_{Lz})$	3.25×10^{-16}
Charging and voltage	f_{charge}	$f_{charge} = \sqrt{2}\sqrt{f_q{}^2 + f_{vs}{}^2}$	3.61×10^{-15}
Miscellanea	f_{misc}	$f_{misc} = 2\sqrt{f_{VAC}^2 + f_{laser}^2 + f_{grav}^2}$	6.04×10^{-15}
Cross – talk	$f_{cross-talk}$	$f_{cross-talk}$	1.01×10^{-14}
Readout noise	$f_{readout}$	$f_{readout} = \sqrt{f_{corr}{}^2 + f_{unc}{}^2}$	1.09×10^{-17}
Drag – free	$f_{dragfree}$	$f_{dragfree} = \mathrm{Abs}[\Delta\omega_x{}^2]\,x_{tot}$	1.57×10^{-15}
Total	f_{total}	$f_{total} = \sqrt{(f_{dragfree}^2 + f_{corr}^2 + f_{unc}^2 + f_{readout}^2 + f_{thermal}^2 + f_{Brownian}^2 + f_{cross-talk}^2 + f_{magnSC}^2 + f_{magnIP}^2 + f_{charge}^2 + f_{misc}^2)}$	1.61×10^{-14}
Measurement noise	f_{meas}	$f_{meas} = \sqrt{f_{act}{}^2 + f_{bl}{}^2 + f_{OM}{}^2}$	5.06×10^{-15}
Grand Total	f_{gtotal}	$f_{gtotal} = \sqrt{f_{total}{}^2 + f_{meas}{}^2}$	1.68×10^{-14}

Additional leading term: Voltage Reference Instability

HEPL Example

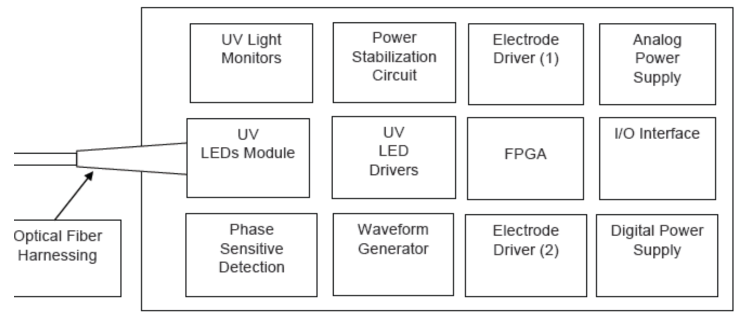
The First Planned Project: UV LED Space Demonstration - 2010

- 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



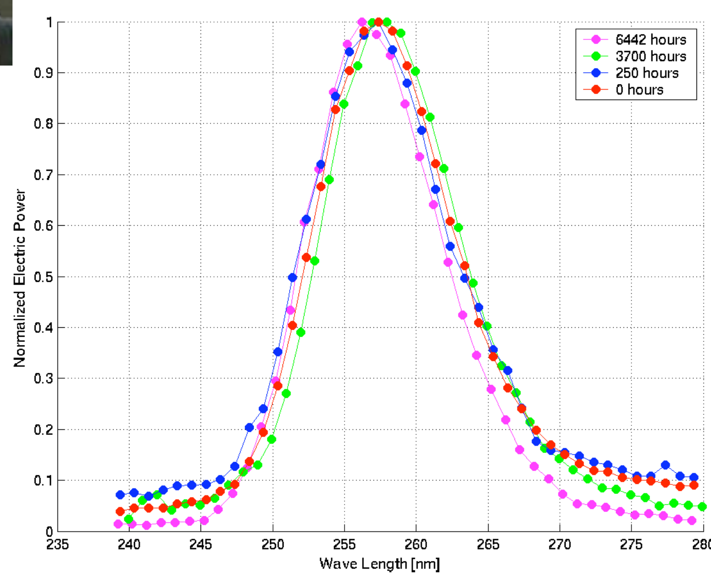
Payload Configuration: Side View

Nick Leindecker

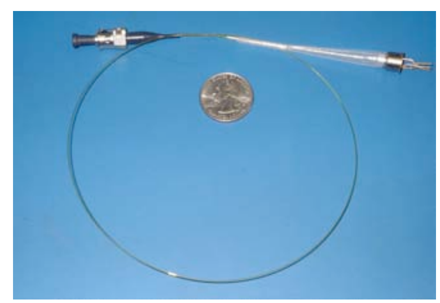


Payload Functional Components

GENESAT



UV LED Performance



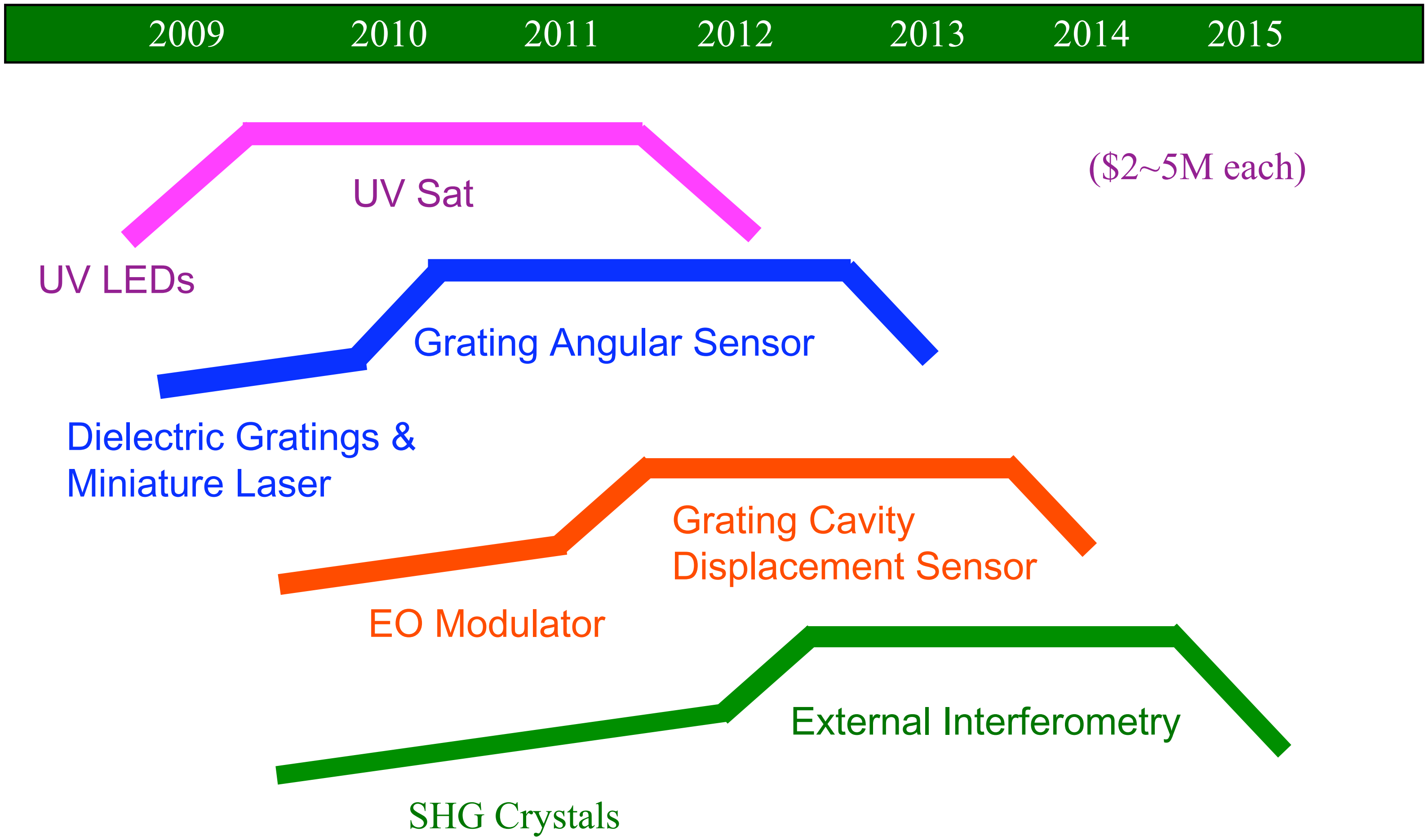
UV LED

Mission Goals

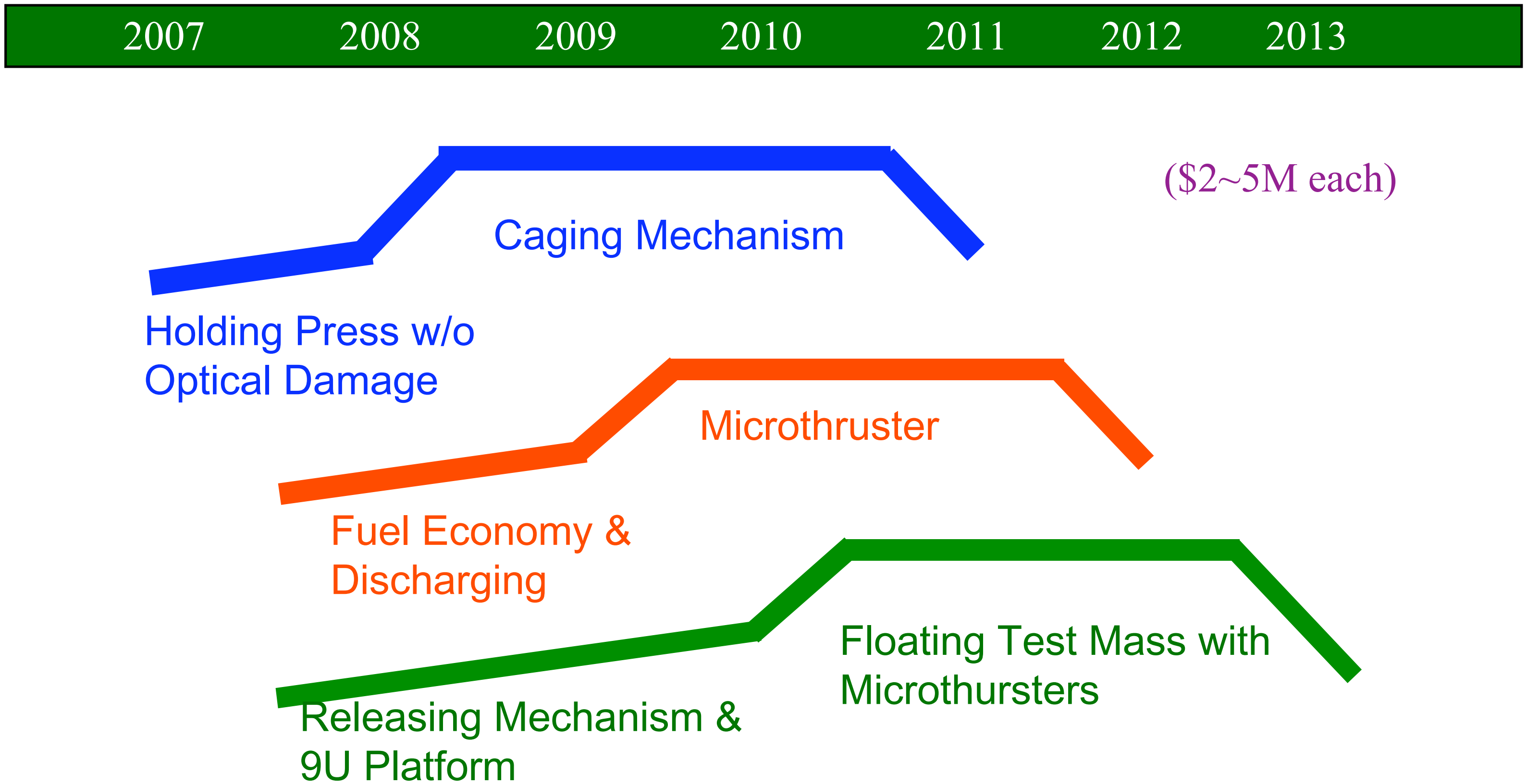
- **Space verification of deep UV LED as a promising light source for charge management of high precisions missions: GRACE II, STEP, LISA, BBO, ….**
  - Short wavelength
  - Light weight
  - Lower electrical power consumption, rendering higher power for science measurement
  - Compact, robust, …
  - Fast modulation

- **Space demonstration of AC charge management**
  - Out of signal band modulation at 1 kHz and 10 kHz, with higher frequencies in future
  - Linear response for proof mass potential, instead of RC decay curve in DC charge management

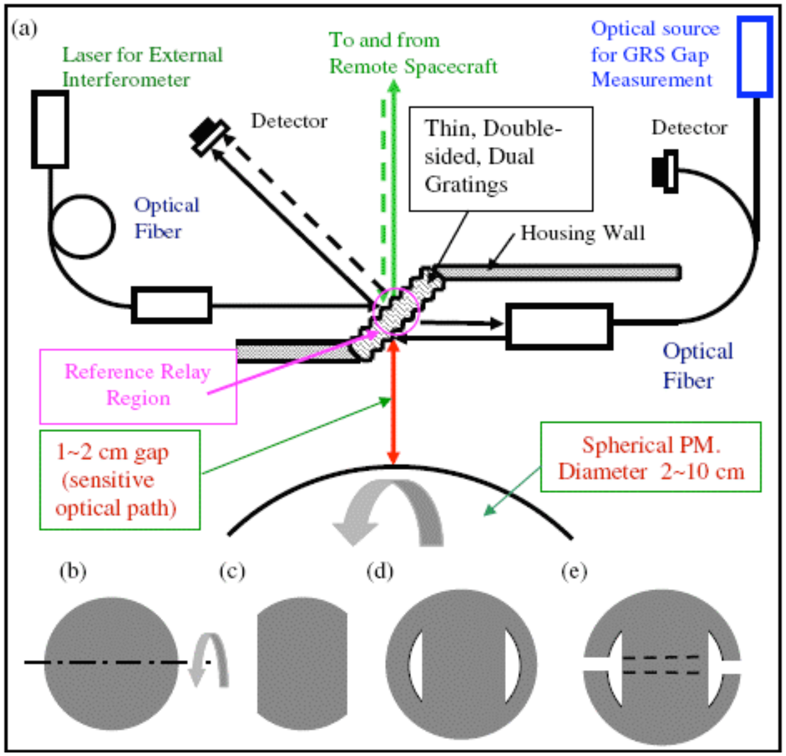
Parallel Efforts for Optical Small Sats



Parallel Efforts for Mechanical Small Sats



Modular Gravitational Reference Sensor Concept



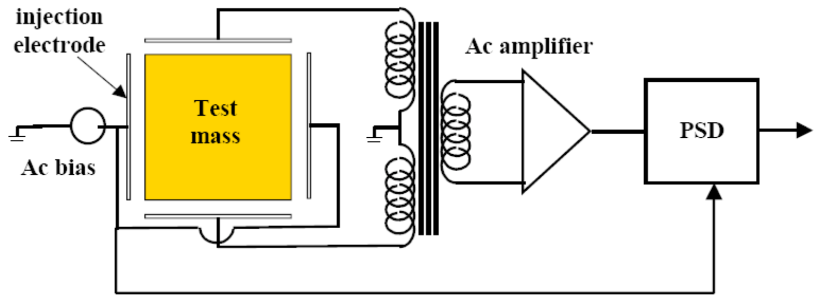
The details of modular GRS and some options for proof mass shape

(a) **Modular GRS structure for LISA. The only sensitive path is the red section between the thin grating and the Proof Mass. An interferometric measurement yields the center of mass information to picometer precision. Direct transfer of distance measurement through a double-sided grating made of well-characterized, low thermal expansion material, couples the internal measurement to the external measurement between platforms.**

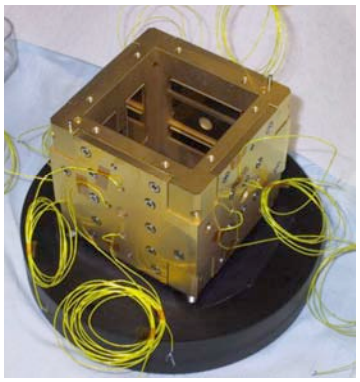
(b) **(b)-(e) Possible shapes for a Proof Mass.**

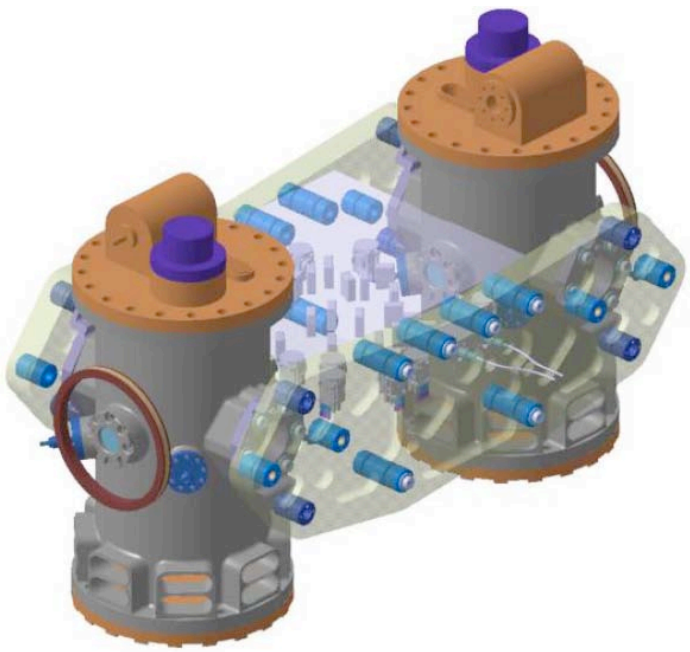
LTP Gravitational Reference Sensor

- GRS consists of:
  - A freely-floating proof mass within a housing,
  - Position measurement of the test mass w.r.t. housing
  - Control of test mass orientation
  - Charge control subsystem



- Disturbance reduction from:
  - Solar magnetic field
  - Solar radiation pressure
  - Residual gas pressure
  - Thermal radiation pressure
  - Charging by cosmic rays
  - Spacecraft self-gravity
  - Spacecraft magnetic fields
  - Spacecraft electric fields

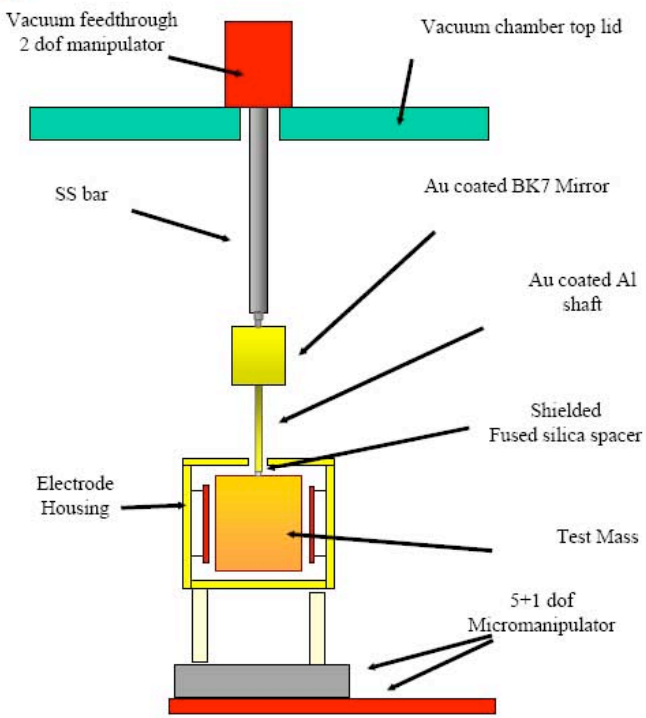


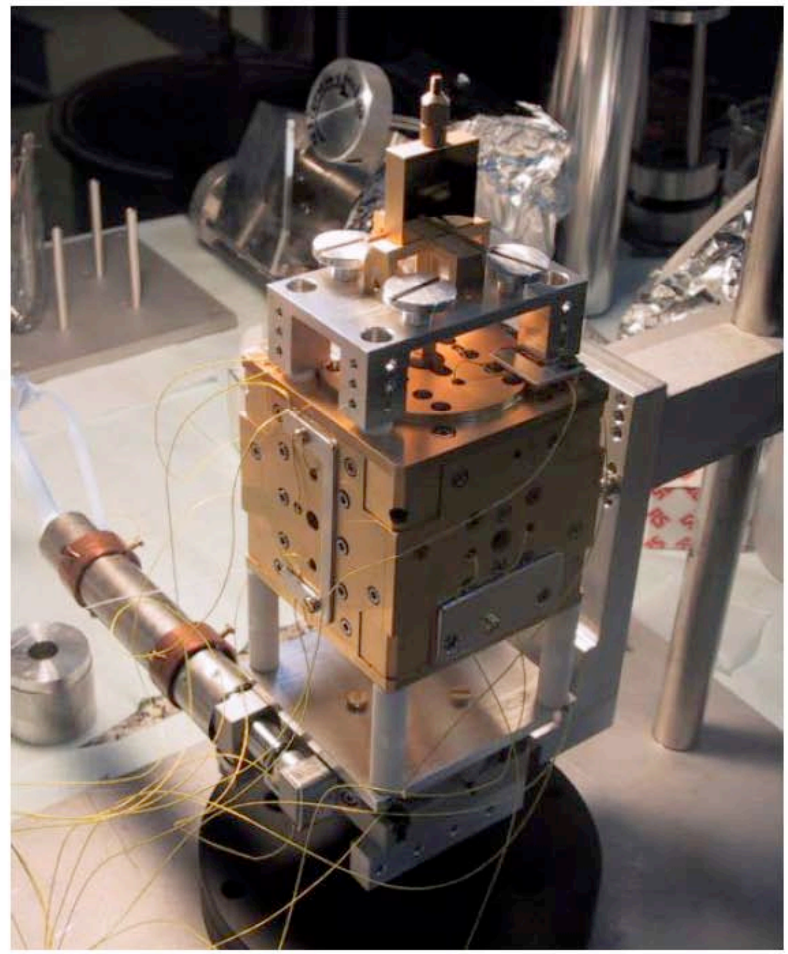


LTP Graphics courtesy of Stefan Vitale

LTP Engineering Model Testing

LTP





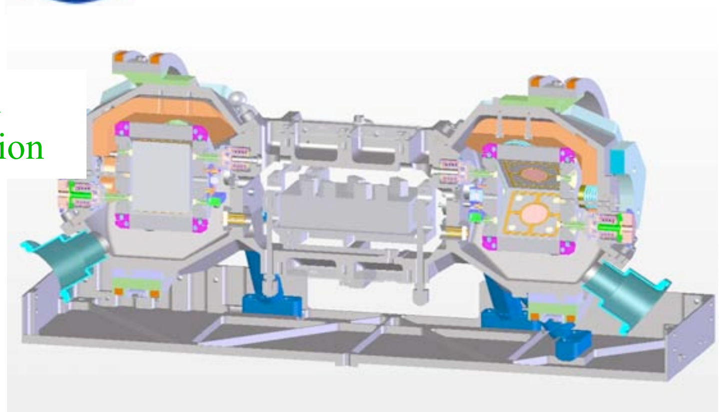
GSFC 22 06 2006

ST-7 Development at Stanford

GRS Configuration

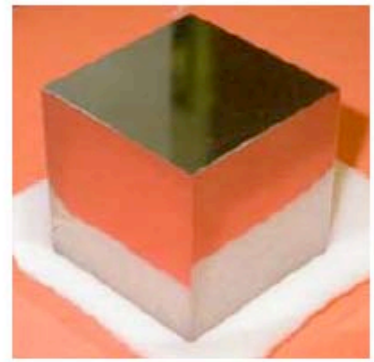
ST7 - DRS

Electronics and system integration



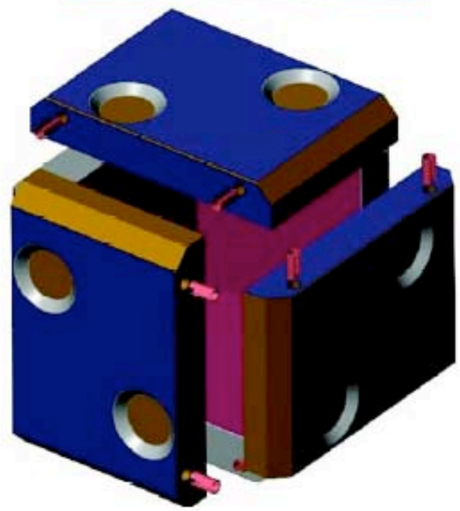
Vacuum system

Au/Pt PM



4 cm

Housing with compound material



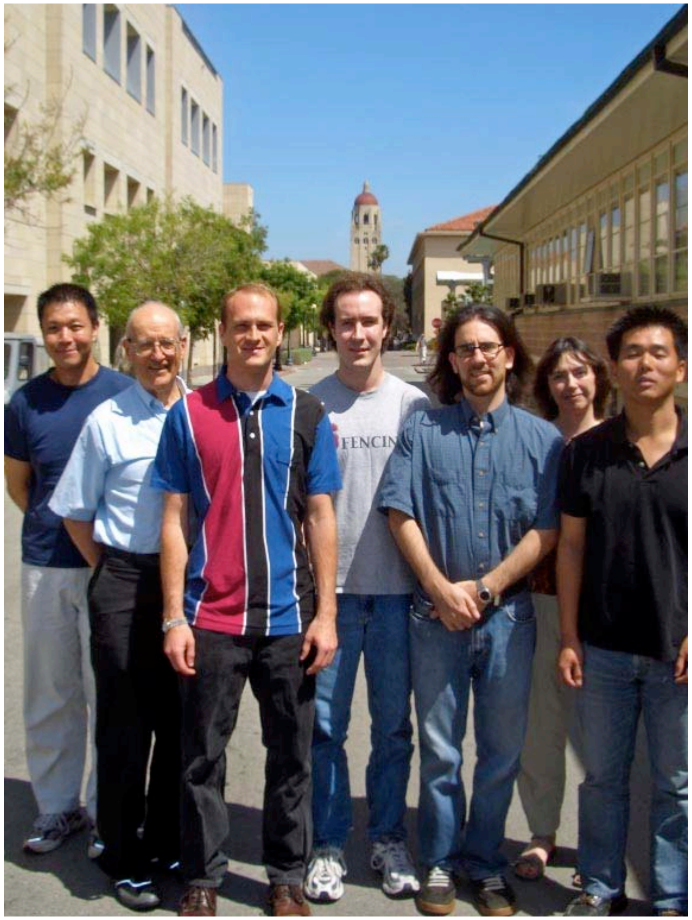
-4-

Stanford ST-7/GRS Team - April 2005

Descoped – May 2005

April 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.