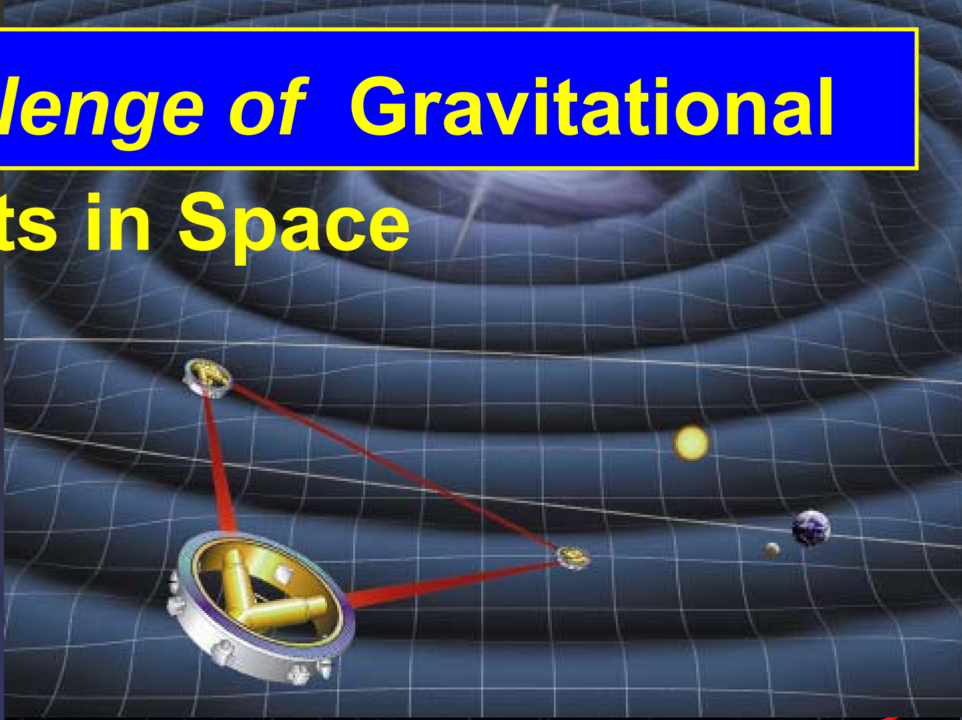
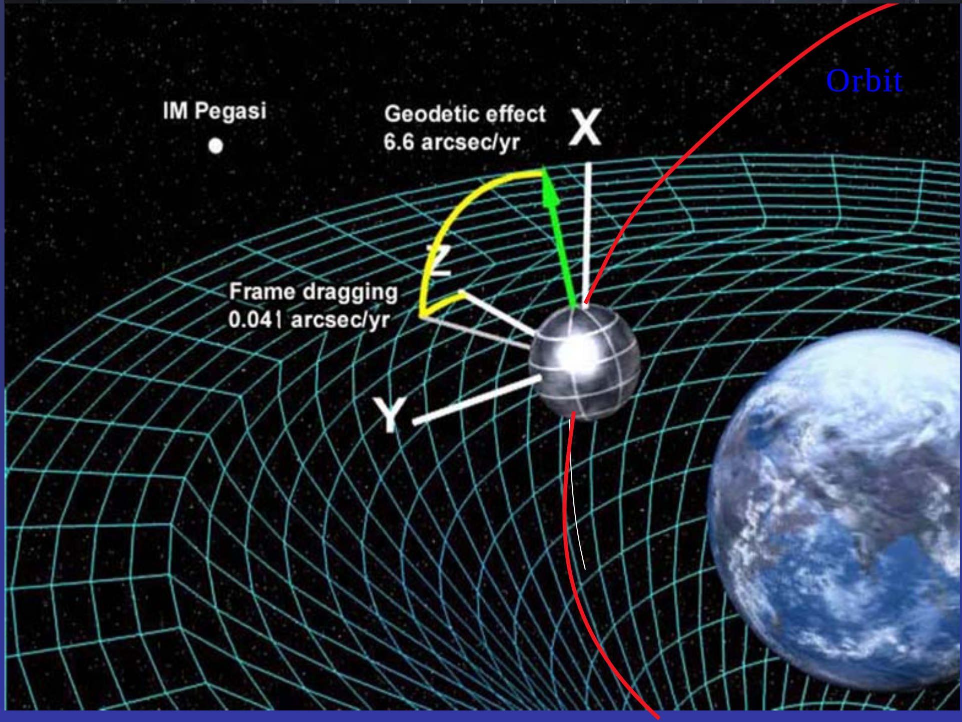
The Promise and Challenge of Gravitational Experiments in Space





GP-B

and Lessons for

LISA Technology

Sasha Buchman
Stanford University
Elba, May 2006

LIGO-G060315-00-Z

Summary

- Complex physics experiment do work in space, GP-B

- LISA and GP-B have significant technology overlap

- LISA requires for success
  - Simplified more robust design
  - Use of modern technology
  - Innovative operations methods

George Bernard Shaw
Toast at a banquet honoring Albert Einstein
1930

George Bernard Shaw 1930

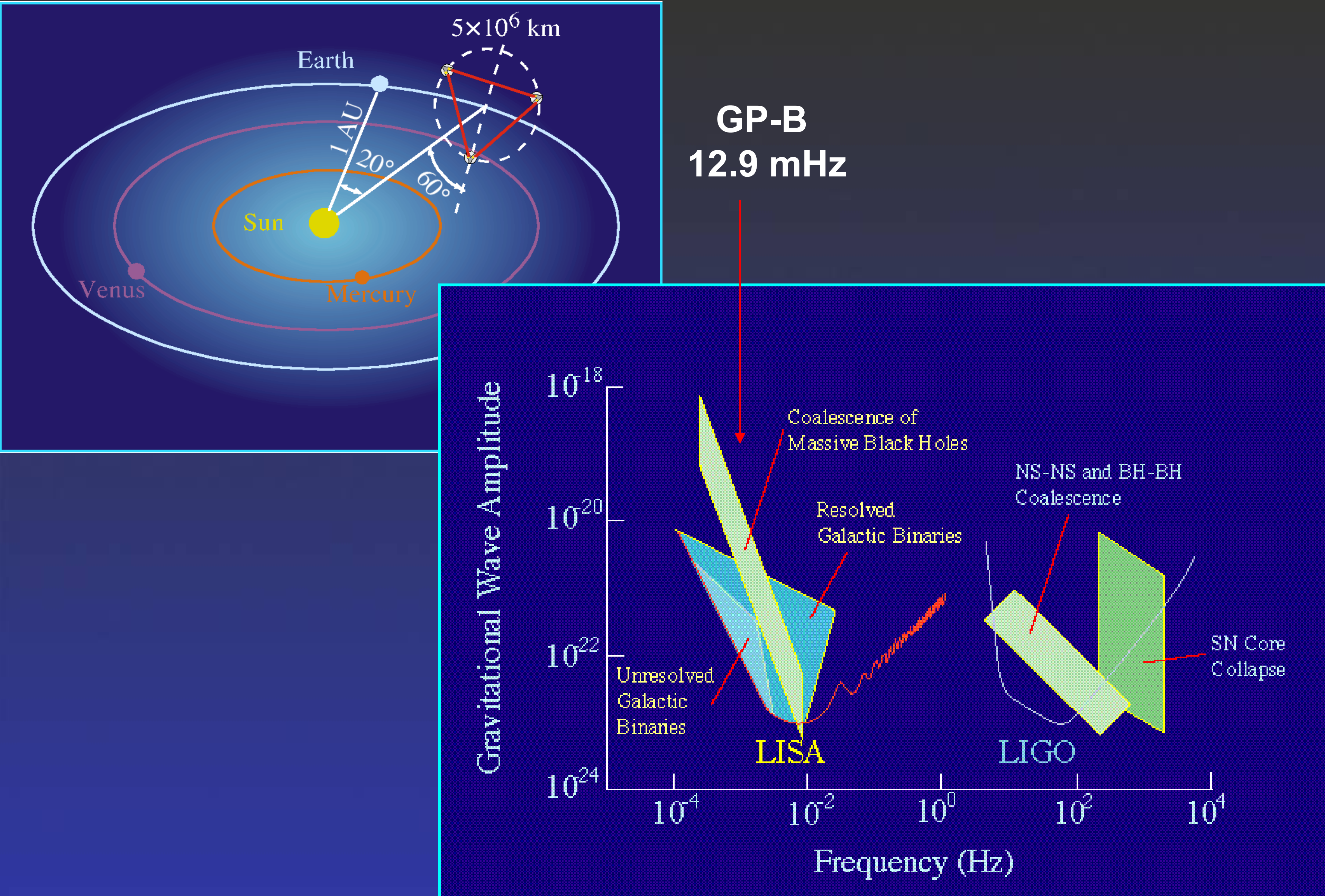
Why Space?

- 👍 Seismic Noise <10Hz
- 👍 Low gravity
- 👍 Long Baselines
- 👍 Long Measurement Times

- 👎 Launch Environment
- 👎 Cost and Duration
- 👎 Reliability; One Shot
- 👎 Communications

STANFORD UNIVERSITY

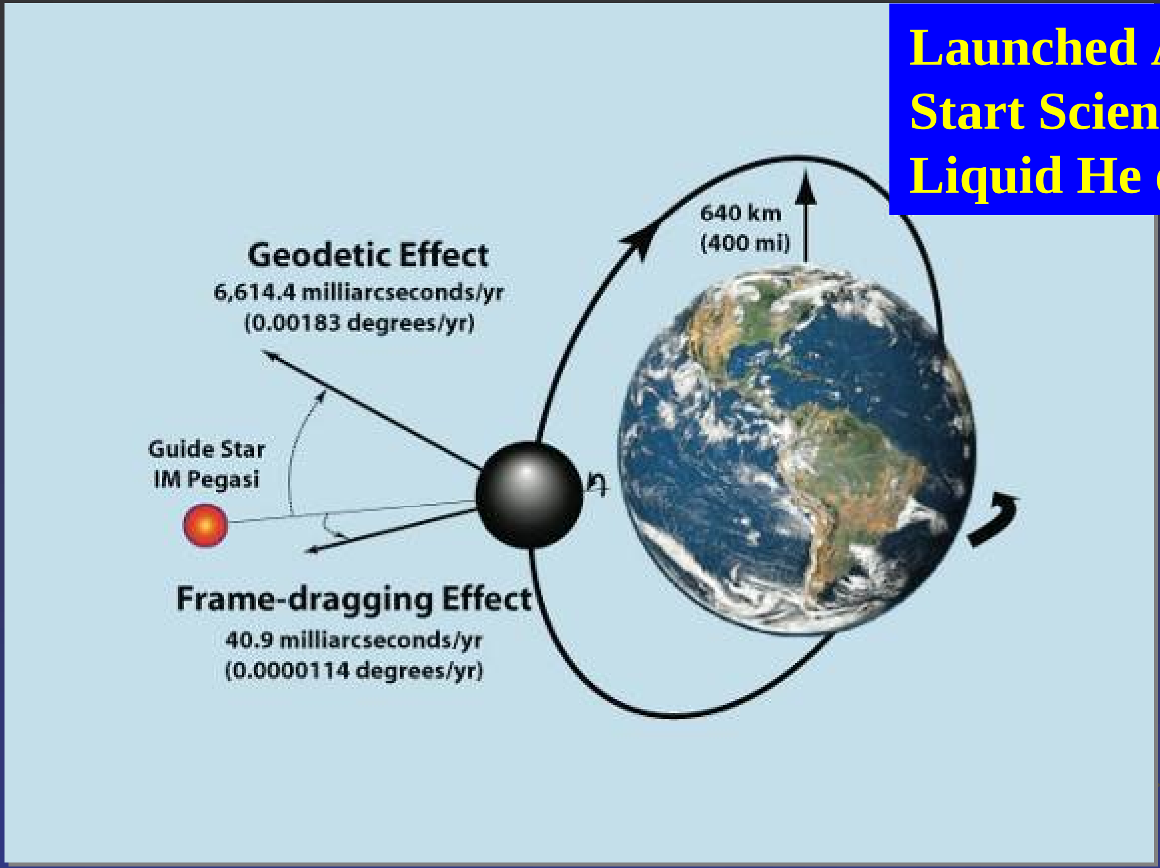
LISA the Laser Interferometer Space Antenna



GP-B
12.9 mHz

The Relativity Mission Concept

Launched April 20, 2004
Start Science August 27, 2004
Liquid He exhausted September 29, 2005



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

GP-B Space Vehicle

GP-B Launch; April 20, 2004

GP-B Timeline

I. **GP-B Launch:** Apr. 20, 2004

- *Initial orbit checkout - 4 months*
- *Plan was 40-60 days*

II. **Science Mission Start:** Aug. 20, 2004

- *Science Mission – 11.5 months*
- *Data segments*

III. **Science Mission End:** Aug. 5, 2005

- *Post Mission Calibrations – 1.5 months*

IV. **Helium Depleted:** Sep. 29, 2005

ALL MAJOR SYSTEM WORKED WELL

Surprises occurred at all stages

V. **Data Release:** Apr. 30, 2007

The Final Phase of the GP-B Mission

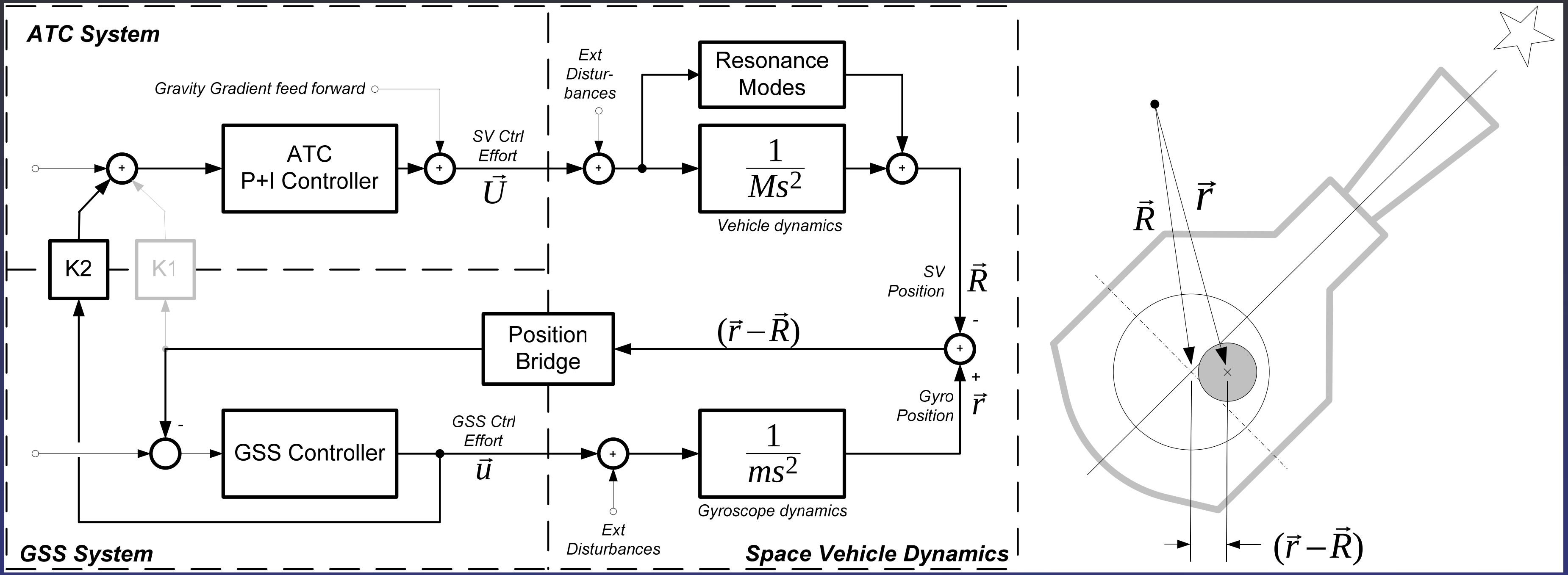
Data Ground Analysis

- Anticipated completion early 2007
- ~ 1.5 Terabytes of data
    - ~ 700 sensors
    - ~ 10,000 monitors
    - Nominal data rate: 0.1-10 Hz
    - Snapshots: 220-2200 Hz
- > 99.1% data recovery

- Data release on COBE/WMAP model
    - Drift data embargoed until analysis is complete
    - Data released to public coinciding with publication of refereed papers

GP-B Drag-Free & Attitude Control:

A 9 degree of freedom problem



Satellite actively controls 9 interacting DOF:

- 3 in attitude of spacecraft to track guide star & maintain roll phase
- 3 in translation: drag-free about geometric center of gyro housing
- 3 in translation of gyroscope with respect to housing

Dynamics coupling is complex

GP-B, STEP, LISA: *INERTIAL REFERENCES*
3 Ultra-Untypical Space Missions

What is different?

- Sophisticated drag-free & attitude control system
- Payload is space vehicle sensor in a single integrated unit

Human & management implications

- Integrated engineering/physics team ***for whole development phase***
- New approaches to requirement verification
- Co-located operations/science team essential for initial orbit set-up

Telescopes	GP-B	STEP	LPF	LISA
3 DOF Precision Control	**9 DOF Precision Control**	**18 DOF Precision Control**	**18 DOF Precision Control**	**57 DOF Precision Control**

Limited comm links for non LEO missions present serious challenges

GP-B Technical Lessons Learned

LISA Technology

- Data Analysis
- Ground Simulations

- **Operations and simulation**
  - Interacting multiple degrees of freedom and cross-coupling complicate operation concepts.
  - Significant data rates are to be expected for LISA
  - High fidelity simulation tools are needed to support operations planning and anomaly resolution for LISA.
  - LISA system must be designed for realistic operations.

- Surface Coatings

- **Surface physics of coatings**
  - 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

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

GP-B Communications, Commands, and Telemetry

GP-B at 12.9 mHz

- **TDRSS Network**
  - 20-40 minutes/contact
  - ~12 contacts per day
  - 1-2 Kbits/sec data rate
- **Ground Stations**
  - 10-12 minutes/contact
  - 4 contacts per day
  - 32 Kbits/sec data rate
- **1.5 Tbytes/year**

TDRSS Satellite

GP-B Satellite

Ground Station

- **LIGO/VIRGO/GEO600**
  - **~ 50 – 1000 Hz**
  - **~ 50Tbytes/year**
- **LISA**
  - **0.03mHz to 1 Hz**
  - **Deep Space Network**

The Instruments: GPB and LISA

12.9 mHz

- 4 Gyroscopes
- 1 Telescope
- 1 Spacecraft
- Thermally Controlled
- 4 SQUIDs
-
- 9 DOF Control

0.03 mHz - 1 Hz

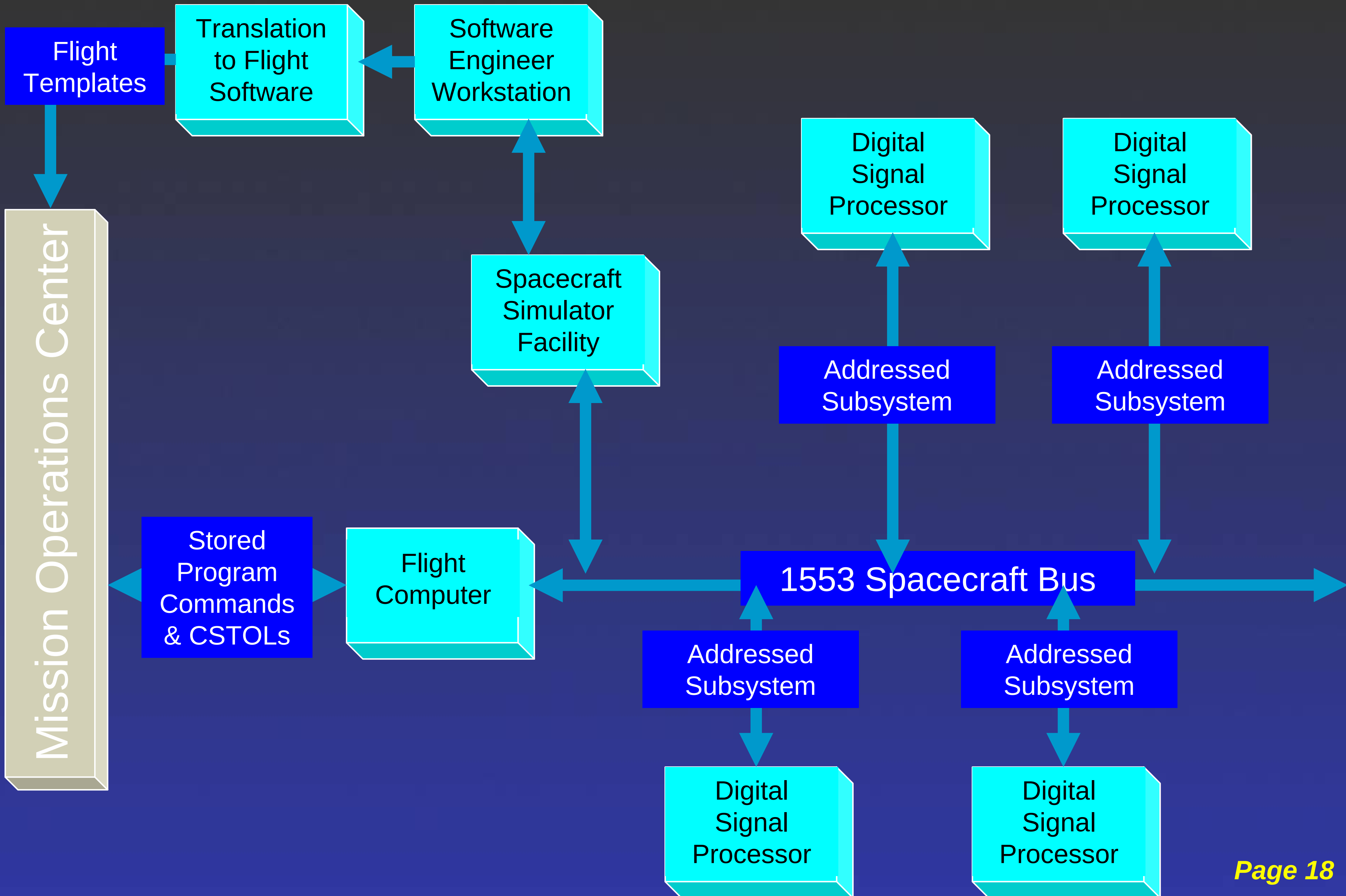
- 6 GRS (3)
- 6 Telescopes
- 3 Spacecraft
- Thermally Controlled
-
- 3 Interferometers
- 57 DOF Control (30)

Initial Orbit Checkout

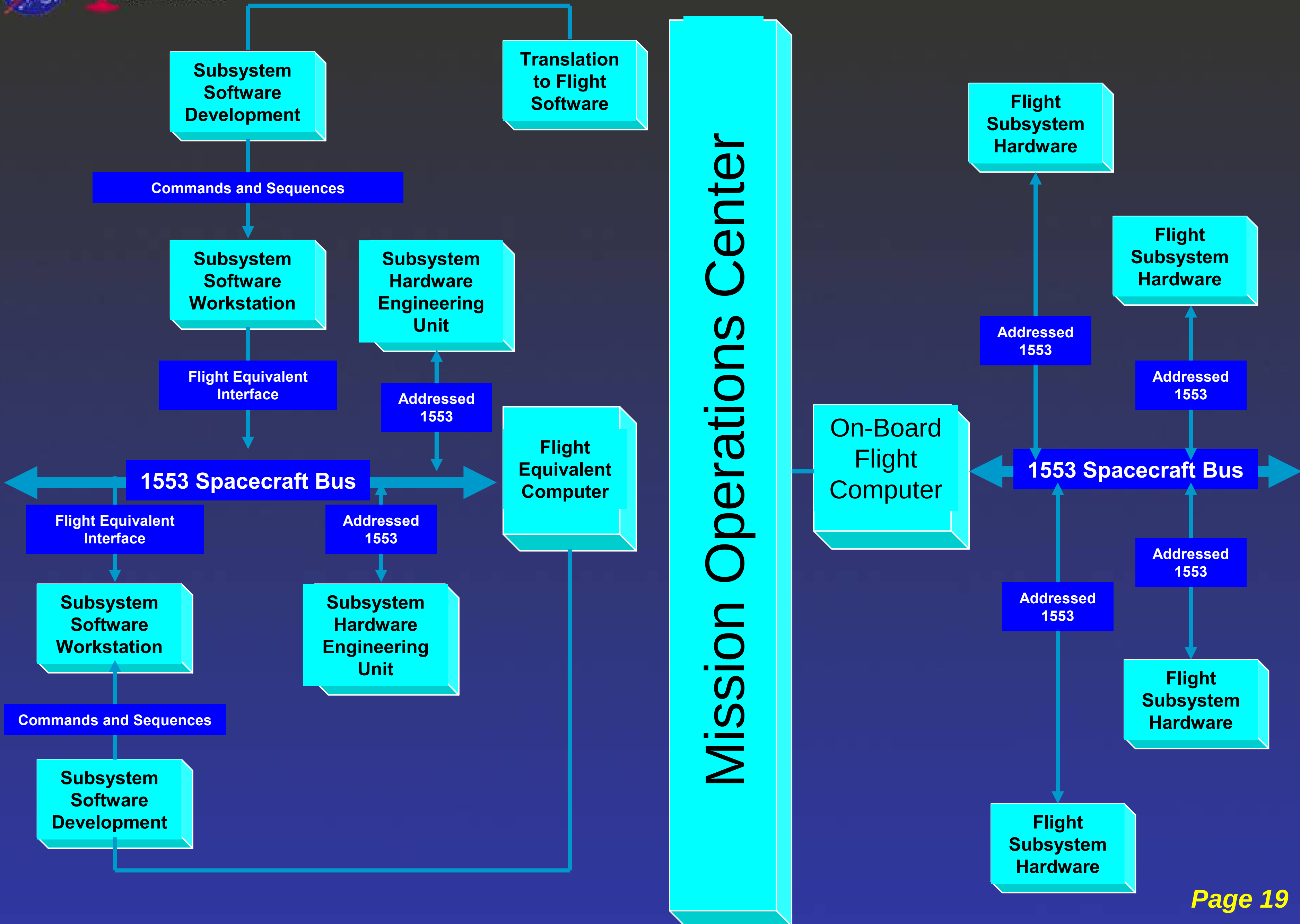
- Mission planning
  - Planned 6 weeks lasted 4 months
- The unexpected (> 100 anomalies)
  - Thruster failures
  - Rad induced MBEs (10 × expected rate)
  - Computer reboots
  - Forward antenna degraded
  - Star sensor software difficulties
- Spacecraft commanding
  - 10,000 commands to spacecraft during IOC

- LIGO/VIRGO/GEO600
  - Commissioning ~ 12 month
- LISA
  - Lower science band than LVG
  - Slower communications

Use During Mission Development Phase



Use During Flight Phase



Subsystem Software Development

Translation to Flight Software

Commands and Sequences

Subsystem Software Workstation

Subsystem Hardware Engineering Unit

Flight Equivalent Interface

Addressed 1553

1553 Spacecraft Bus

Flight Equivalent Computer

Flight Equivalent Interface

Addressed 1553

Subsystem Software Workstation

Subsystem Hardware Engineering Unit

Commands and Sequences

Subsystem Software Development

Mission Operations Center

On-Board Flight Computer

Flight Subsystem Hardware

Addressed 1553

Flight Subsystem Hardware

Addressed 1553

1553 Spacecraft Bus

Addressed 1553

Addressed 1553

Flight Subsystem Hardware

Flight Subsystem Hardware

Simulator Features

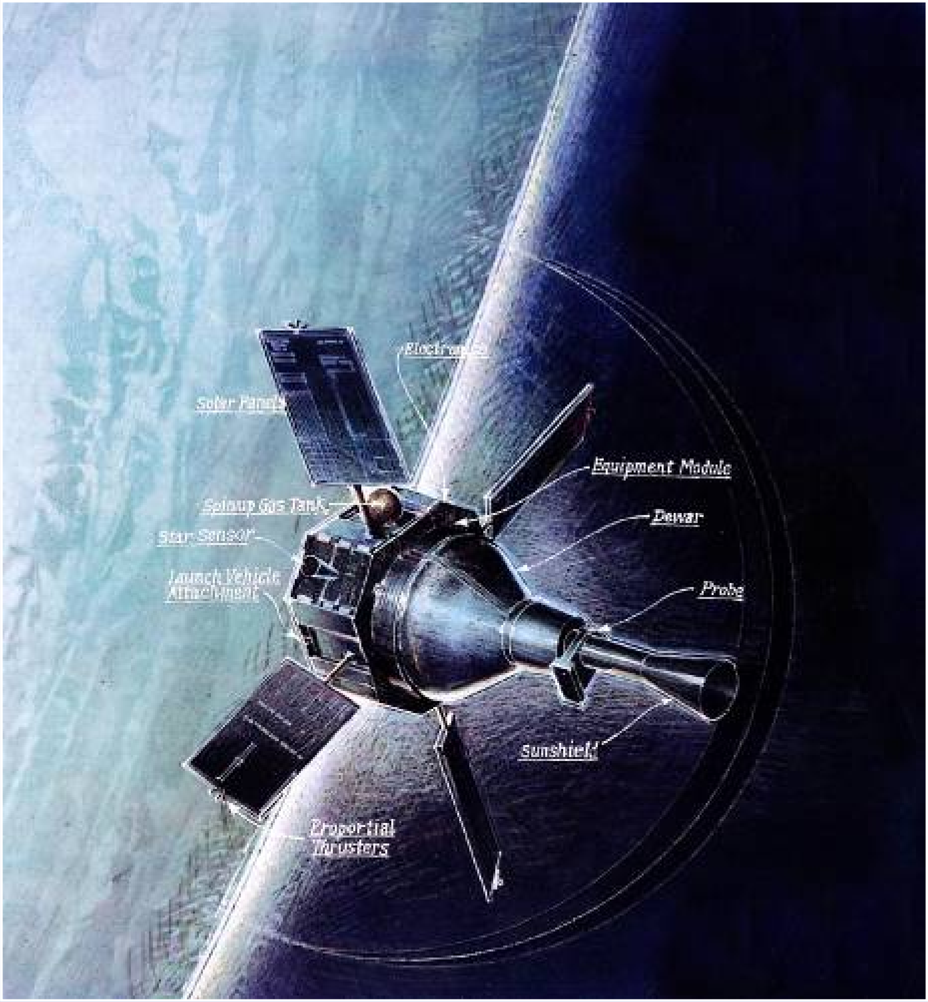
- **Hardware-in-the-loop verification**
  - Fully integrated sensor-control-actuator simulations, operating across payload/spacecraft interface
  - Modular architecture
- **Realistic simulation for ops training**
  - Common development environment
  - High fidelity spacecraft bus and CPU
  - Integrated MOC

Facility Status

- **Fully operational system**
    - Hardware/software integrated
    - Versatile interface for new mission development
    - Incremental upgrade capability

- **LISA Pathfinder drag-free control group ZARM Bremen, Germany, secured EU funding for collaboration**

- **Stanford submitting proposal to ROSES 2005 AISR AO for further development**

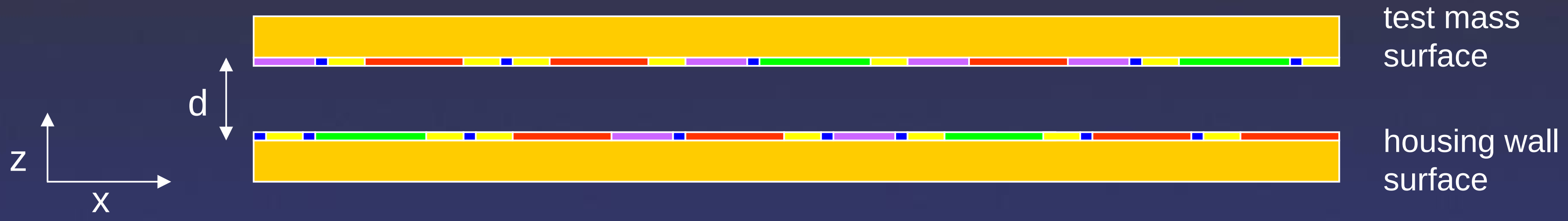


Recommendations

- Extensive ground simulator with hardware in the loop
- Full instrumentation of all systems
- Comprehensive periodical instrument calibrations
- Maximum instrumentation data to ground
- Fast data snapshots to ground
- Critical data processing on the ground

The Patch Effect

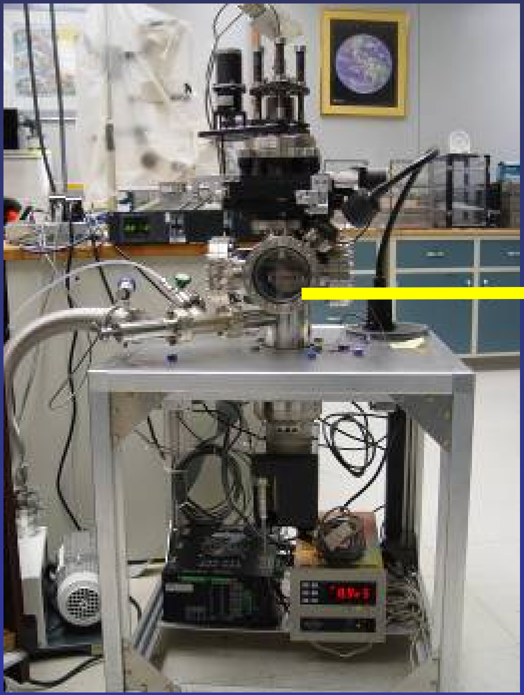
- The patch effect refers to spatial variations in surface potential
- It can arise due to polycrystalline structure
- It can be affected by presence of contaminants

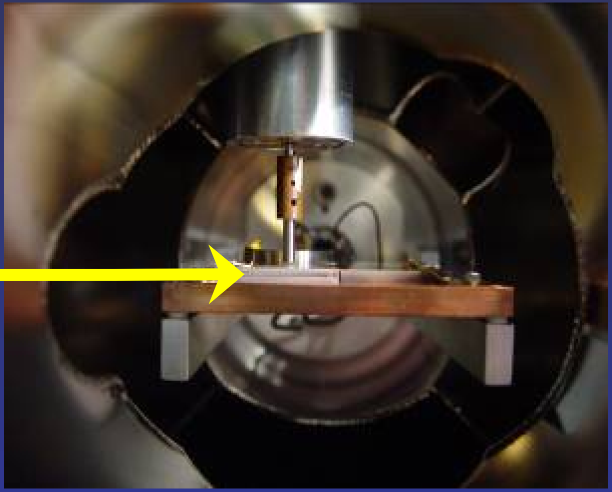


- Patch fields are present on test mass and housing wall surfaces
- Interactions between patch fields cause forces that change with position, both in x and z directions
- Temporal variations in surface potential produce acceleration, in conjunction with
  - an ambient DC voltage, or
  - net free charge on the test mass

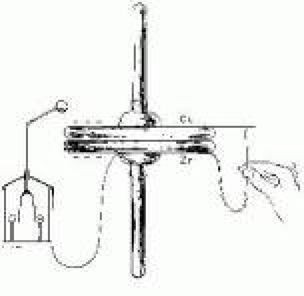
Kelvin Probe

- The Kelvin probe measures contact potential difference (Vc) between a conducting specimen and a vibrating probe tip
- It is a non-contact, non-destructive vibrating capacitor device
- A backing potential Vb electrically connects specimen and probe tip
- When Vb = -Vc, the circuit is balanced
- Null condition can be detected accurately
- The Goddard probe is a custom-built UHV system with scanning capability





View of probe (diameter 3mm) sitting above samples



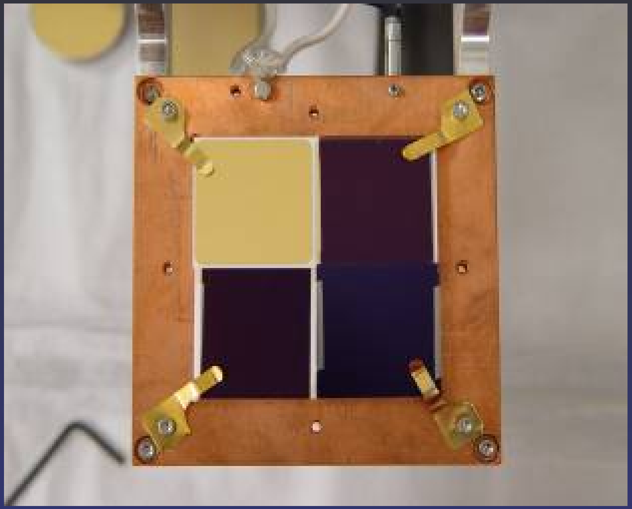
Kelvin's original apparatus

Materials Studied

- **Test mass:**
  - Au/Pt with gold coating

- **Housing walls:**
  - substrate:
    beryllia, alumina or titanium (for inserts)
  - coatings:
    gold, diamond-like carbon (DLC), indium tin oxide, titanium carbide

+ various underlying layers chosen for adhesion, conductivity and smoothness



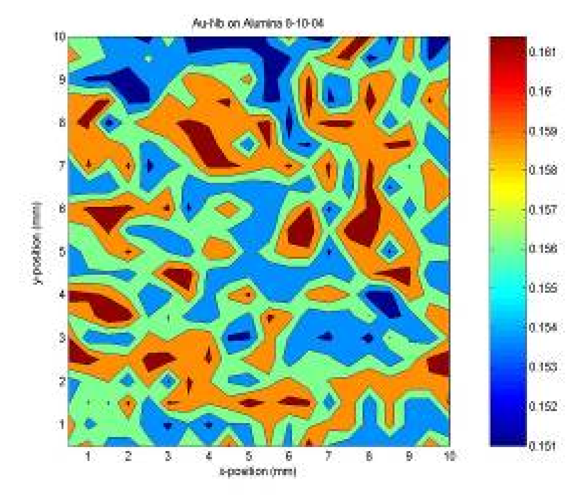
Example of samples ready for measurement in the Kelvin probe

Clockwise from top left:
AuNb on alumina,
DLC/Ti/Au/Nb on beryllia,
DLC/Ti/Au/Ti on titanium,
DLC/Ti/Au/Ti on alumina

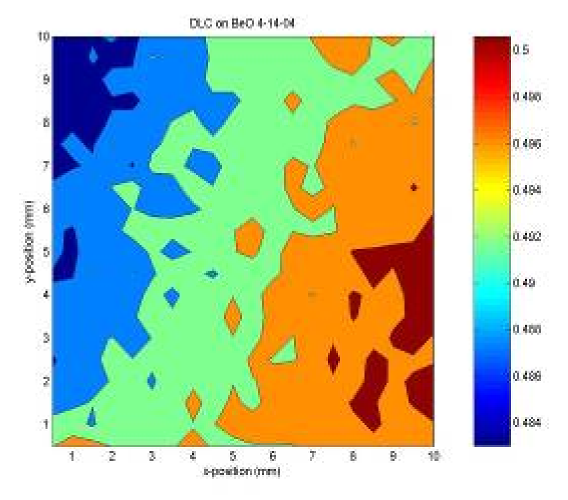
Note:
many of the samples were precision coated in-house at Stanford

Examples of Spatial Scans

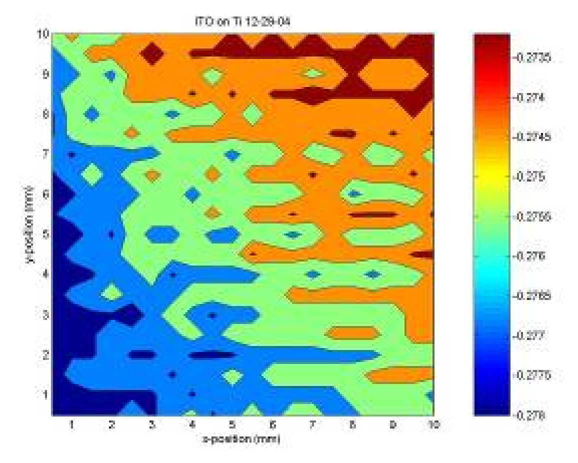
Gold-niobium on alumina (p-to-p 13 mV)



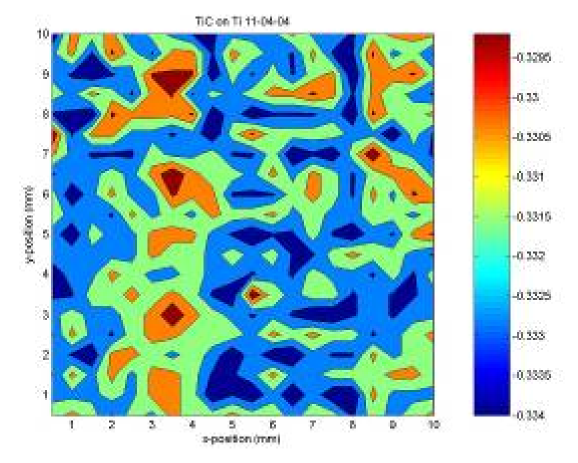
Diamond-like carbon on beryllia (p-to-p 22 mV)



Indium tin oxide on titanium (p-to-p 6 mV)



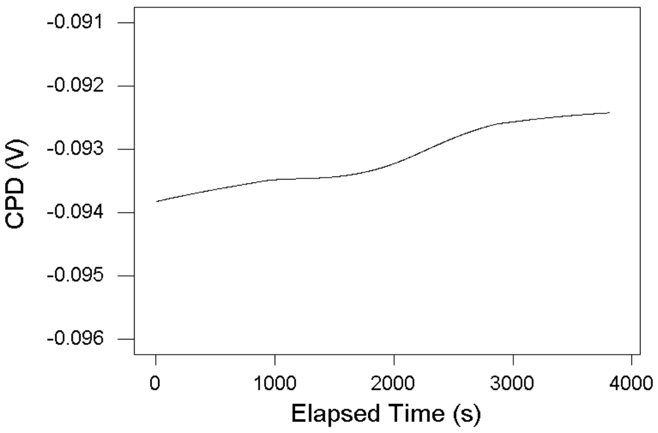
Titanium carbide on titanium (p-to-p 6 mV)



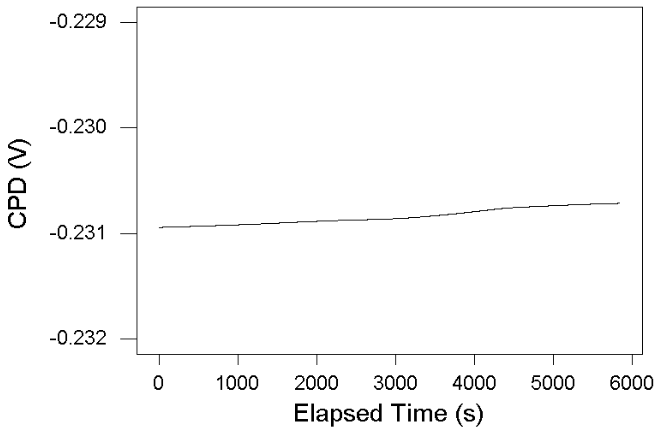
Contact potential difference in volts over 10 mm by 10 mm area (400 data points).

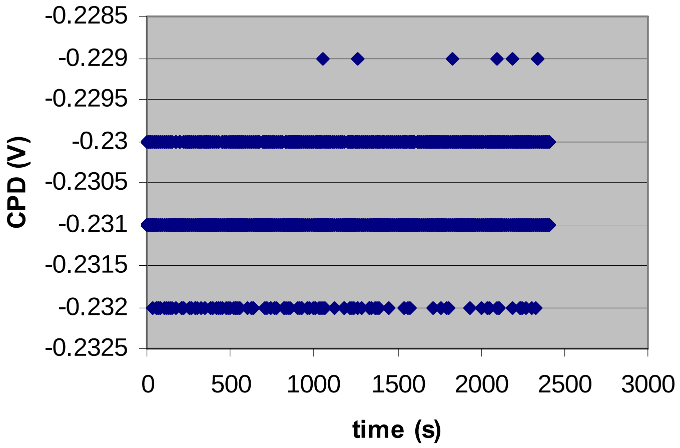
Time variations of contact potential differences

Au on Au/Pt

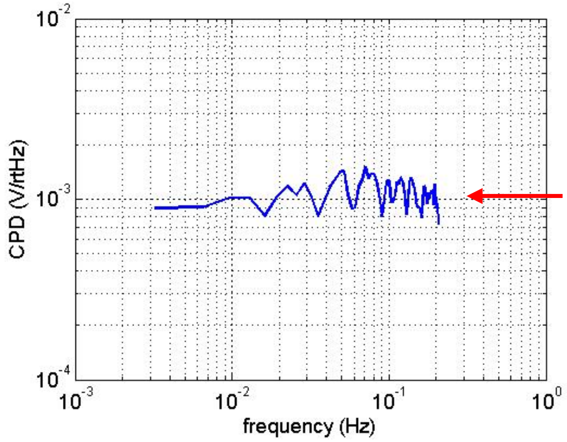


Au/ITO on Alumina





Raw data for first 2400 seconds of graph top right



1mV/√ Hz

Amplitude spectral density of data shown at bottom left

General Recommendations

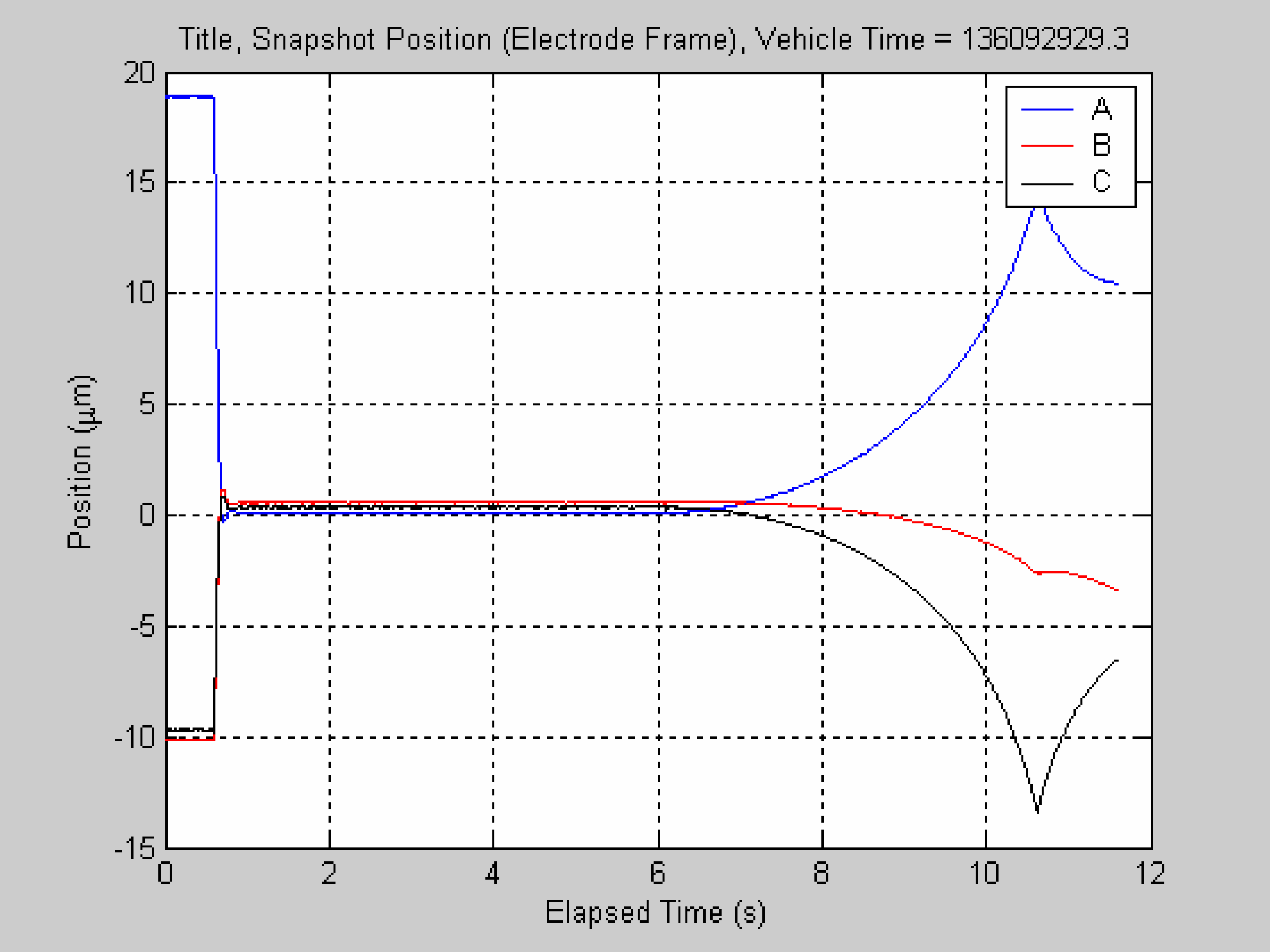
The patch effect is a noise source which is not well characterized.

An integrated effort is required to:

- achieve reliable reproducible coatings with acceptable properties
- establish magnitude of spatial and temporal effects
- characterize the properties of the patch effects under flight-like environmental conditions:
  pressure, temperature, presence of contaminants..
- relate patch effects to noise requirements:
  update noise tree analysis and reassess parameters/requirements

GP-B Gyroscope Suspension

Gyro #4 Analog Backup Levitation and De-levitation



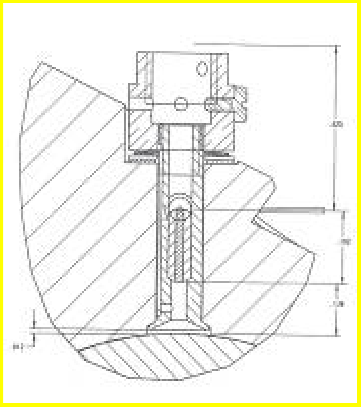
Gyroscope charge on levitation is 200 - 400 mV

Requires discharge to < 10 mV

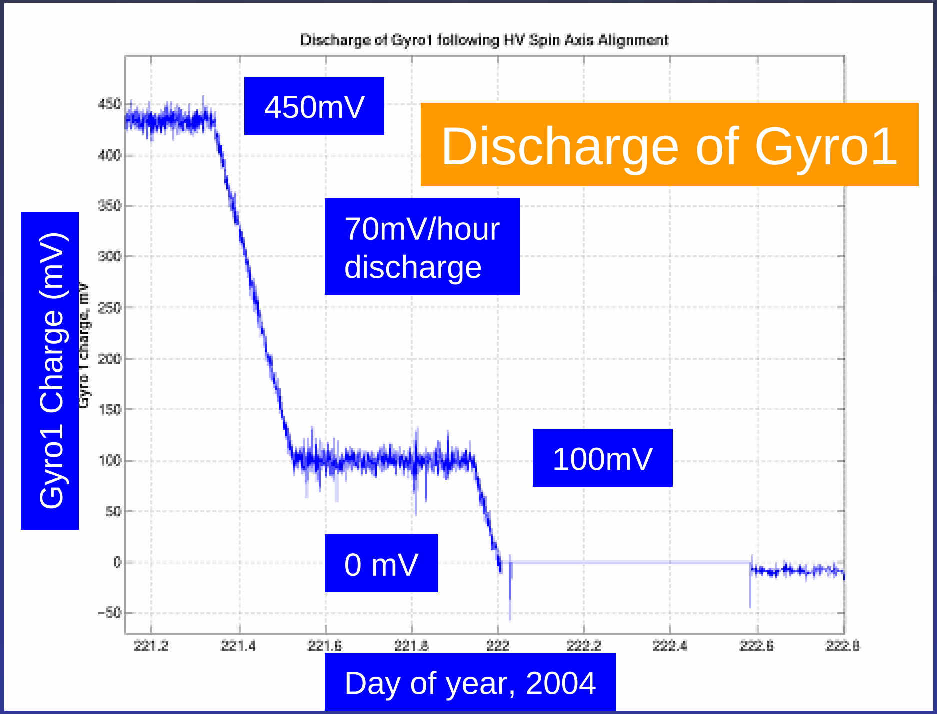
Expected de-levitation time at 10^{-6} m/s^2 is 10 s

Charge Management

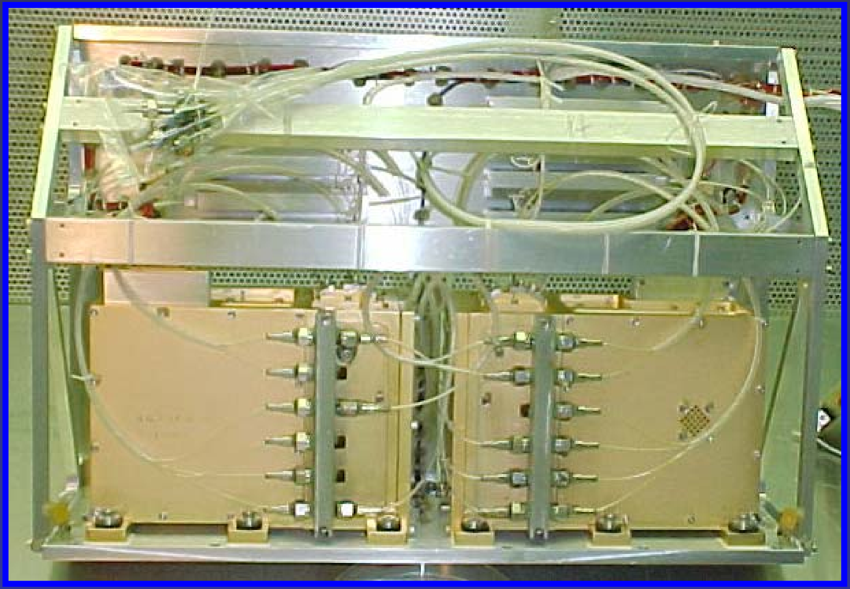
- Rotor charge controlled via UV excited electrons
- Charge rates ~ 0.1 mV/day
- Continuous measurement at the 0.1 mV level
- Control requirement: 15 mV



UV Electrode

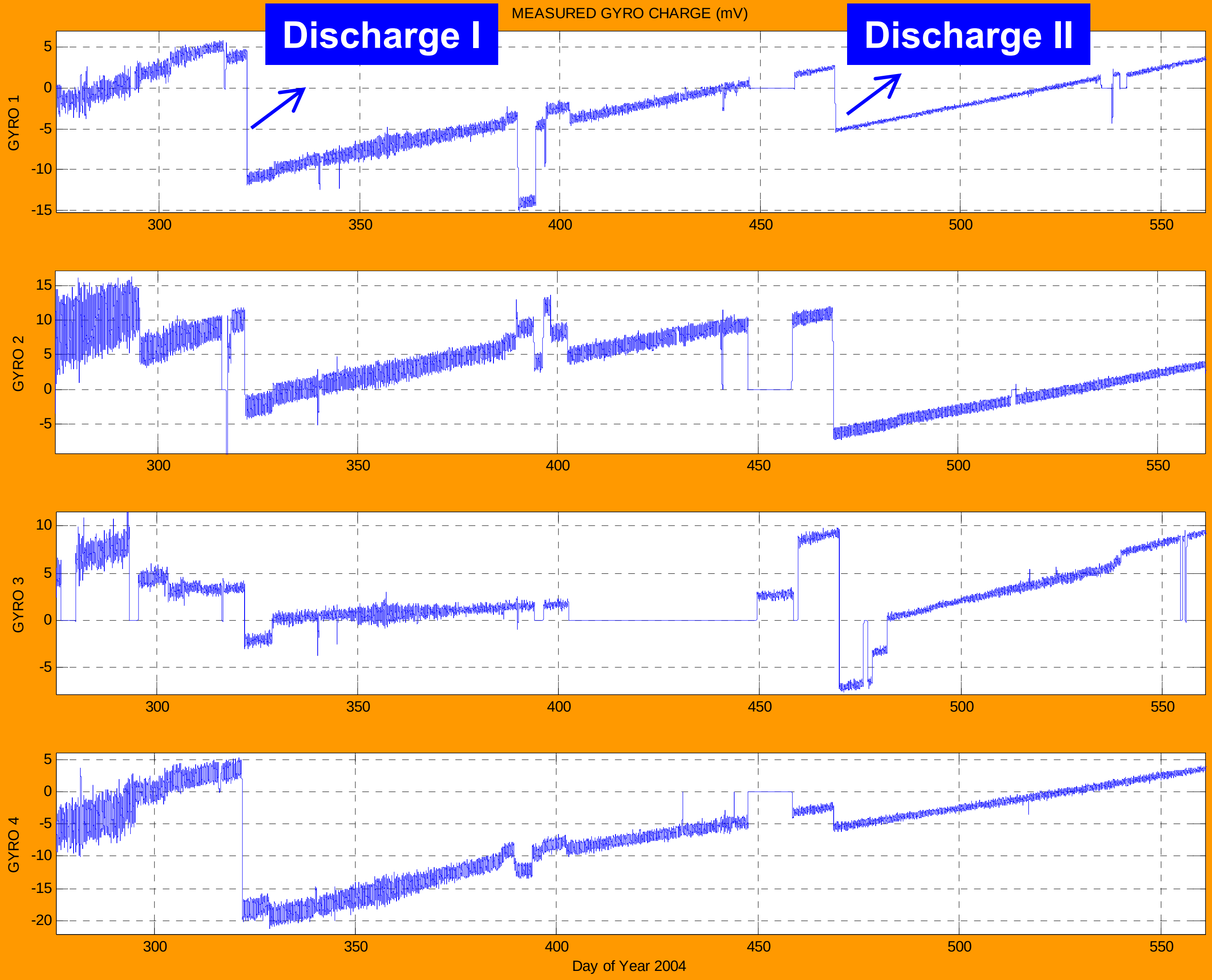


Charge controlled to < 5 mV



UV Lamp Assembly

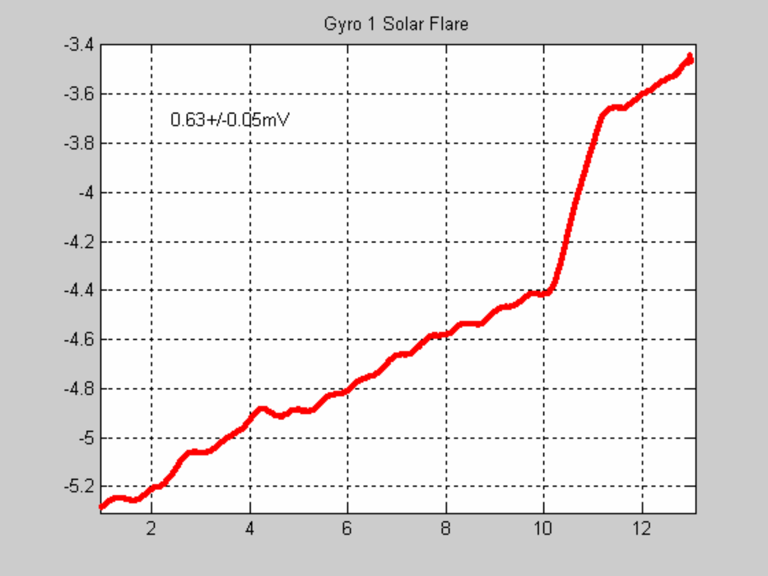
Gyro Charge for Science Mission

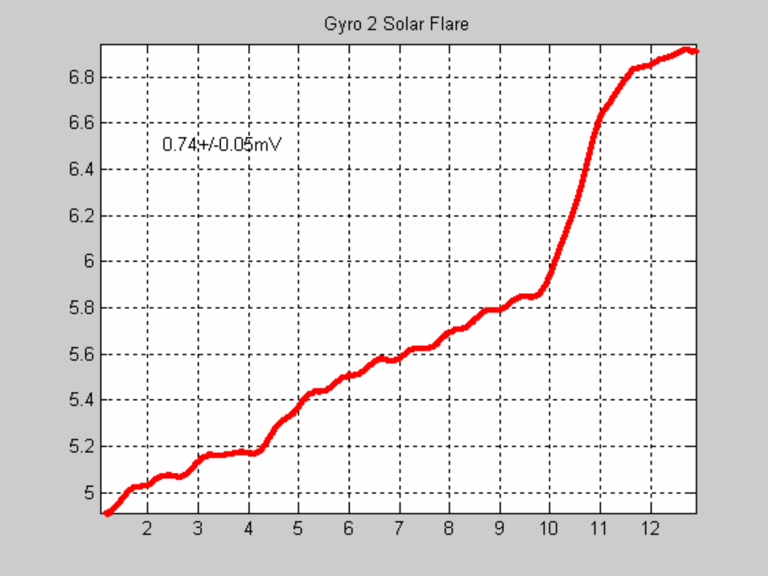


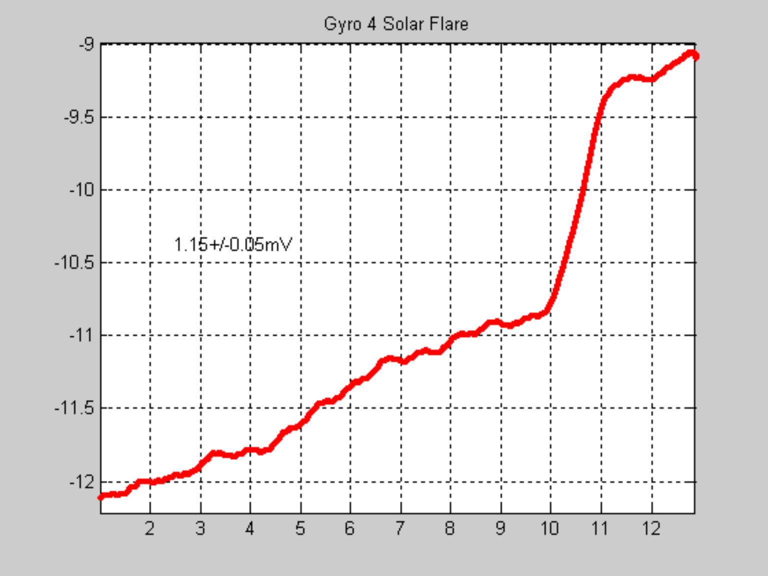
Measured Gyro Charge (mV) vs Day of Year 2004

Solar Flare 720

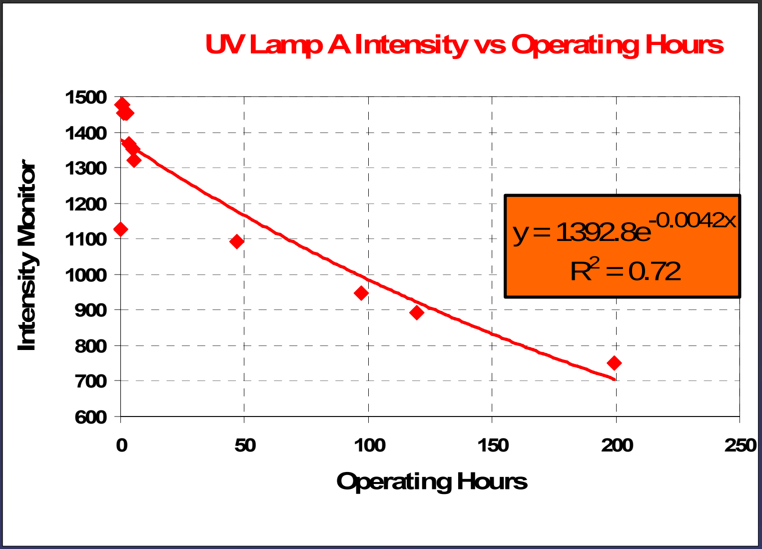
Charging rates to day 390		
	Average Charging Rate	Sun Spot 720
	mV/day	mV
Gyro 1	0.098+/-0.003	0.63+/-0.05
Gyro 2	0.114+/-0.003	0.74+/-0.05
Gyro 4	0.152+/-0.003	1.15+/-0.05



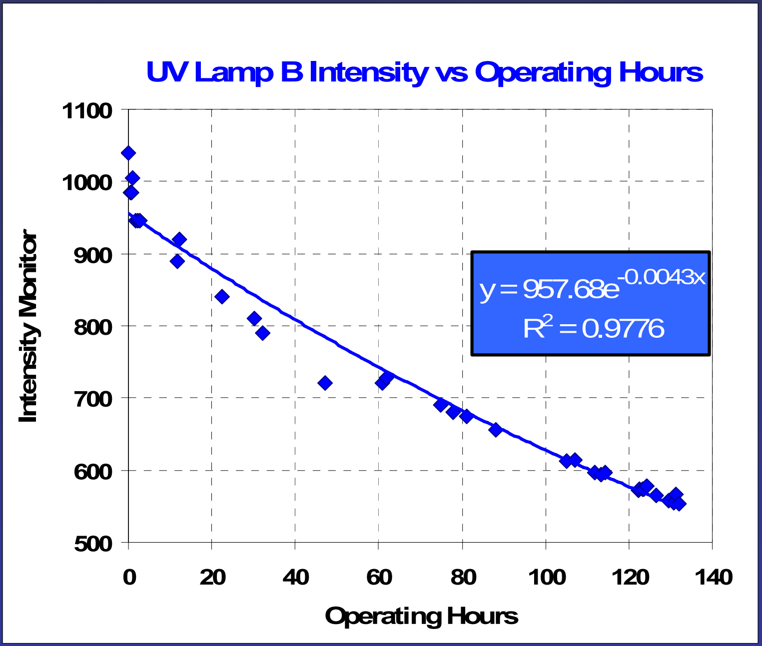




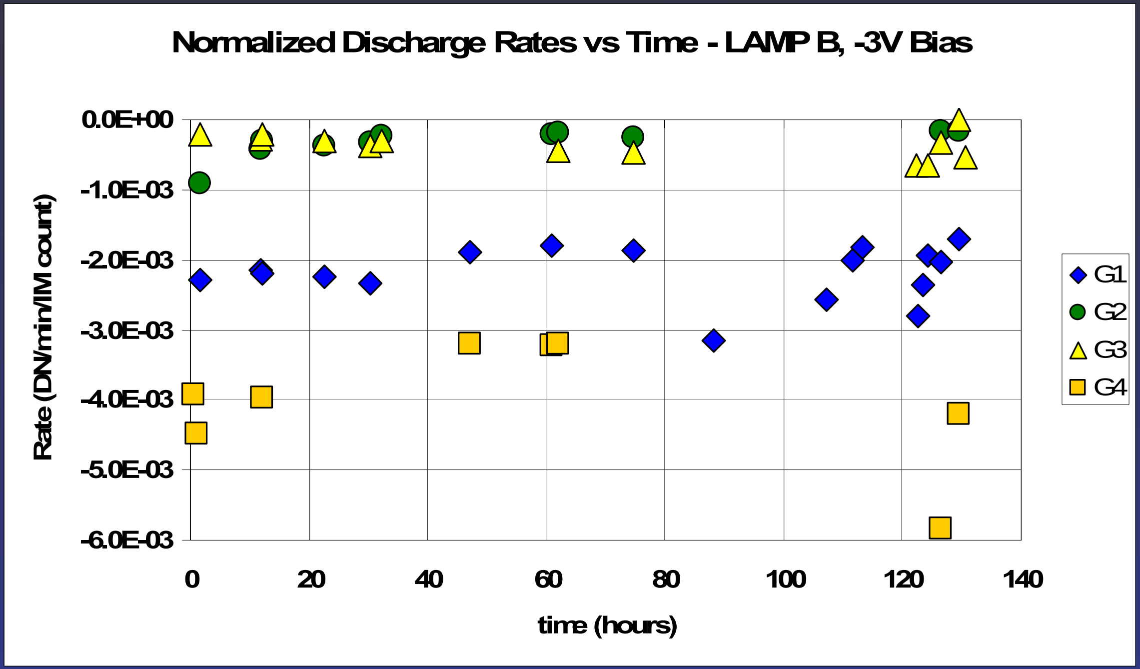
UV Lamps Lifetime


UV Lamp A Intensity vs Operating Hours

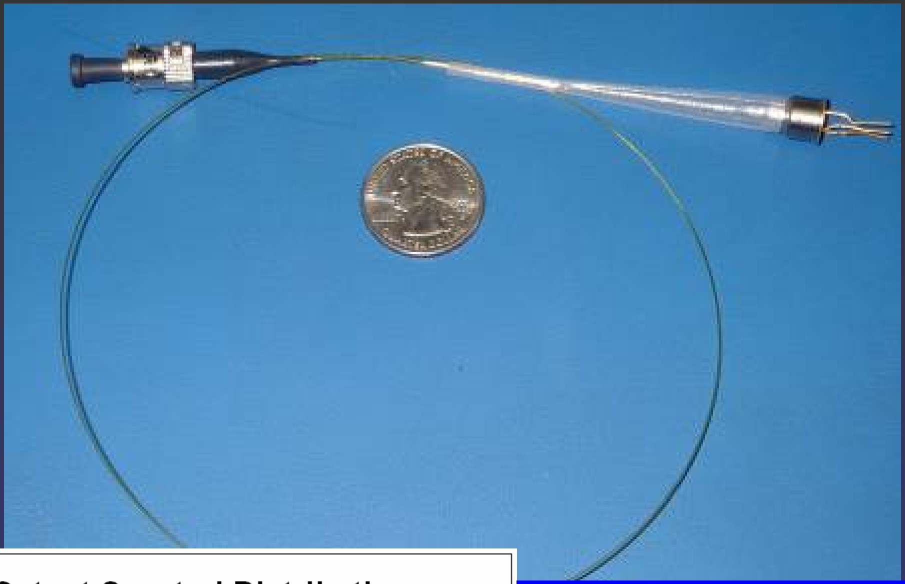
$y = 1392.8e^{-0.0042x}$
$R^2 = 0.72$

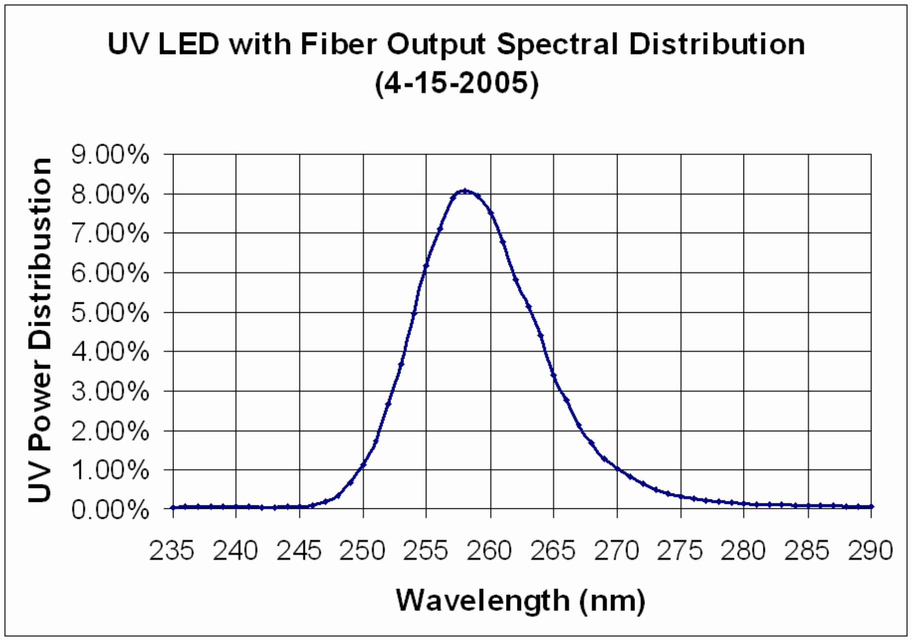

UV Lamp B Intensity vs Operating Hours

$y = 957.68e^{-0.0043x}$
$R^2 = 0.9776$


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

LED Deep UV Source for Charge Management





Peak wavelength:

257.2 nm, comparable to Hg line 254 nm

FWHM:

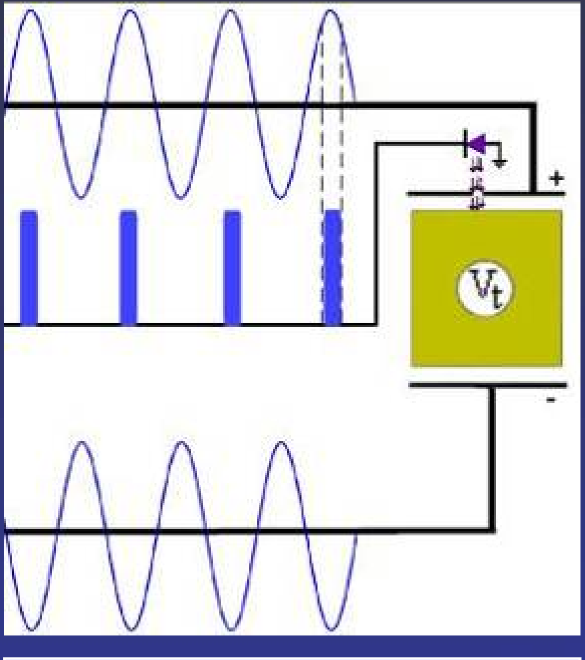
12.5 nm, good photoemission for Au coatings

Total UV power:

0.144 mW, sufficient for charge management

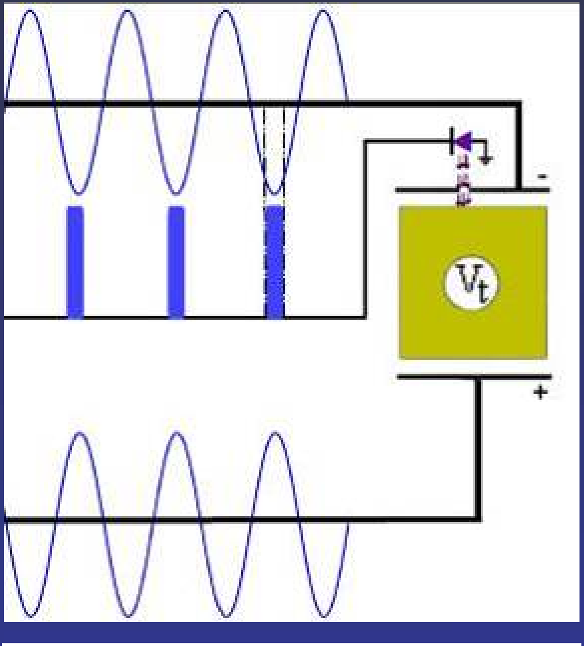
AC Charge Management

- No need for dedicated DC bias
- AC electrical field can be used for control
- UV LED modulation is high frequency



UV modulation is phased in *positive* AC ½ cycle:

Photoelectrons to housing electrodes

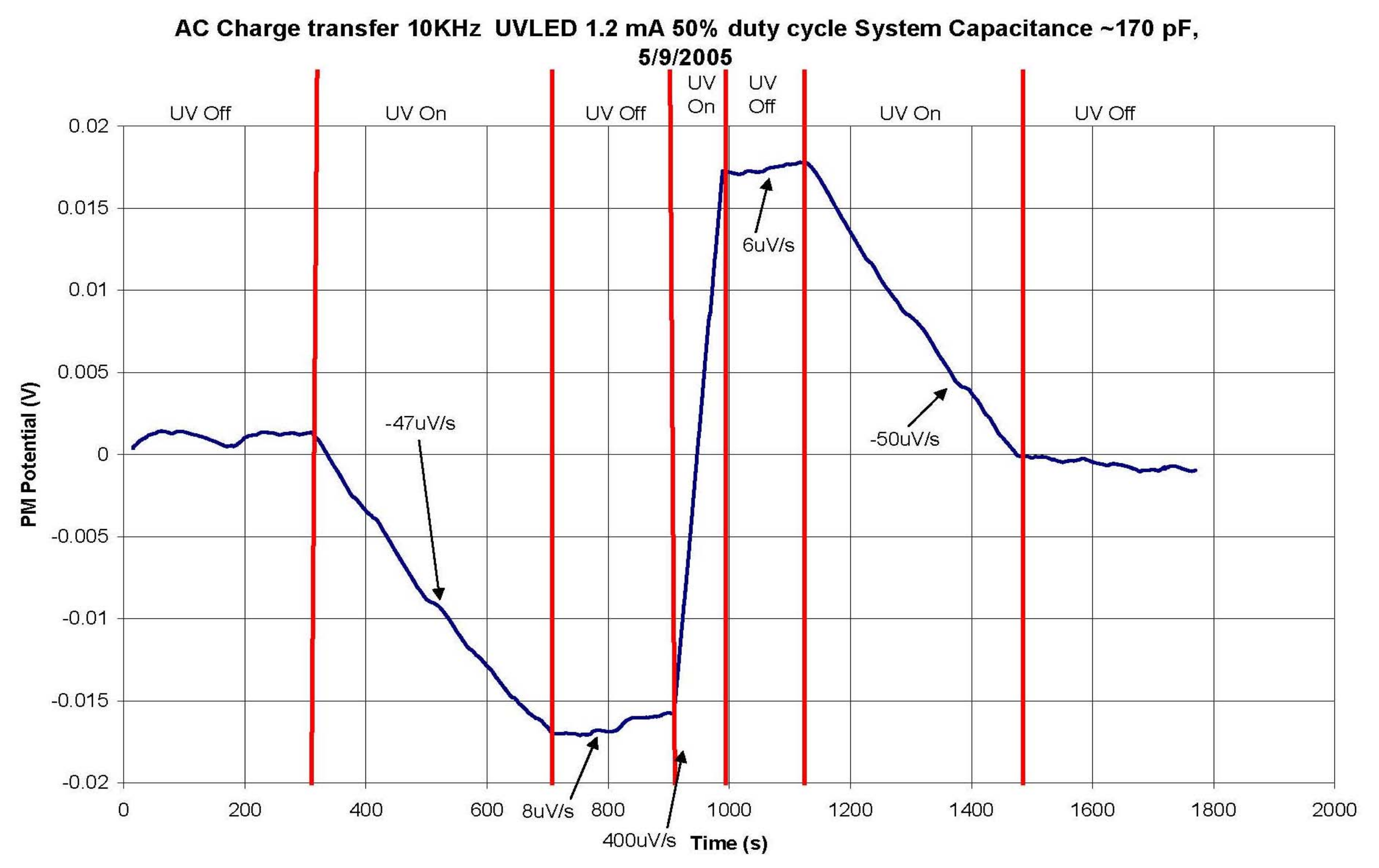


UV modulation is phased in *negative* AC ½ Cycle:

Photoelectrons to test mass

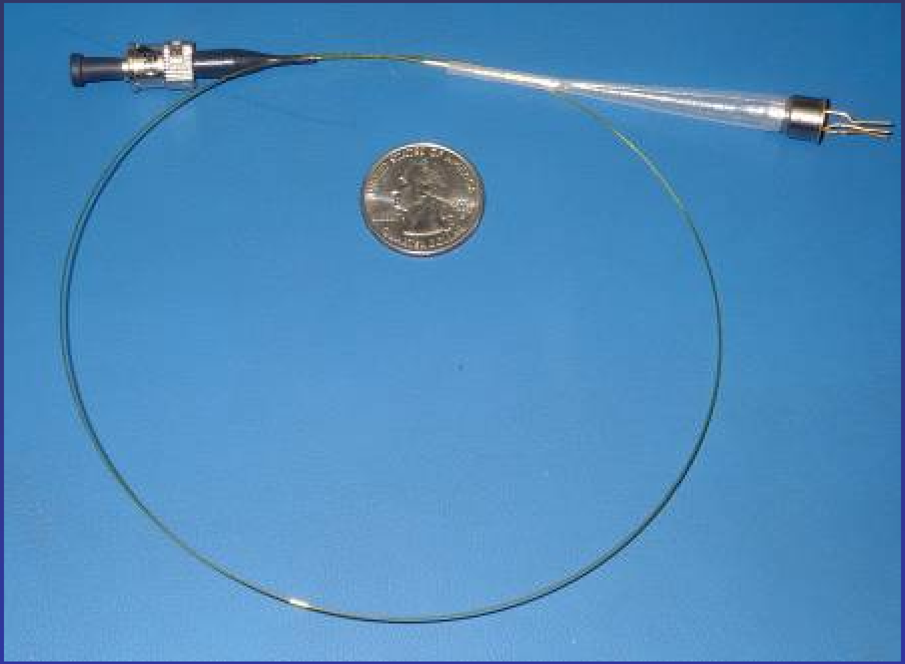
AC Charge Management Shows Promising Characteristics

UV LED and bias voltage modulated at 10 kHz



Recommendations for UV Charge Management

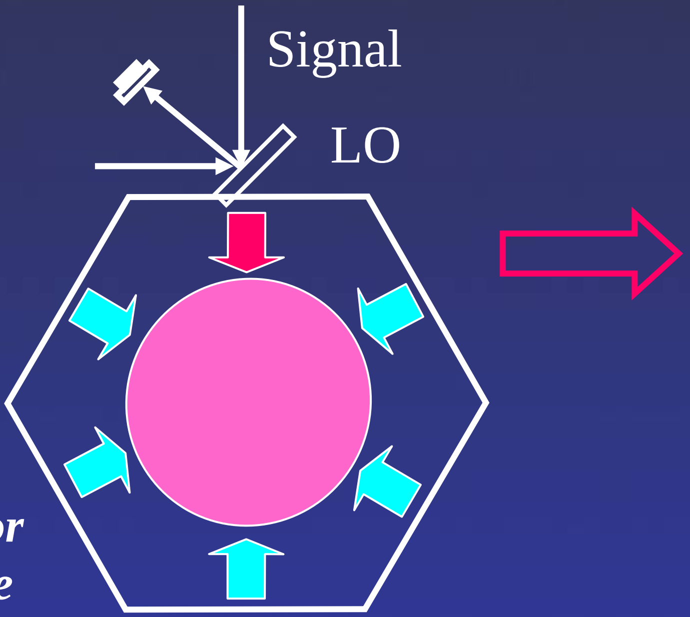
- **Use UV LED as the UV source**
  - **Light weight**
  - **Low electrical power**
  - **Compact, robust**
  - **Fast modulation**



Advanced LISA Concepts – Stanford (2004)

Autonomous Gravitational Sensor

  - Separation from S/C Interferometry
  - Measure PM position in housing
  - Use housing for interferometry
- Single proof mass (PM) per S/C
- Non constraint GRS
- Large gap



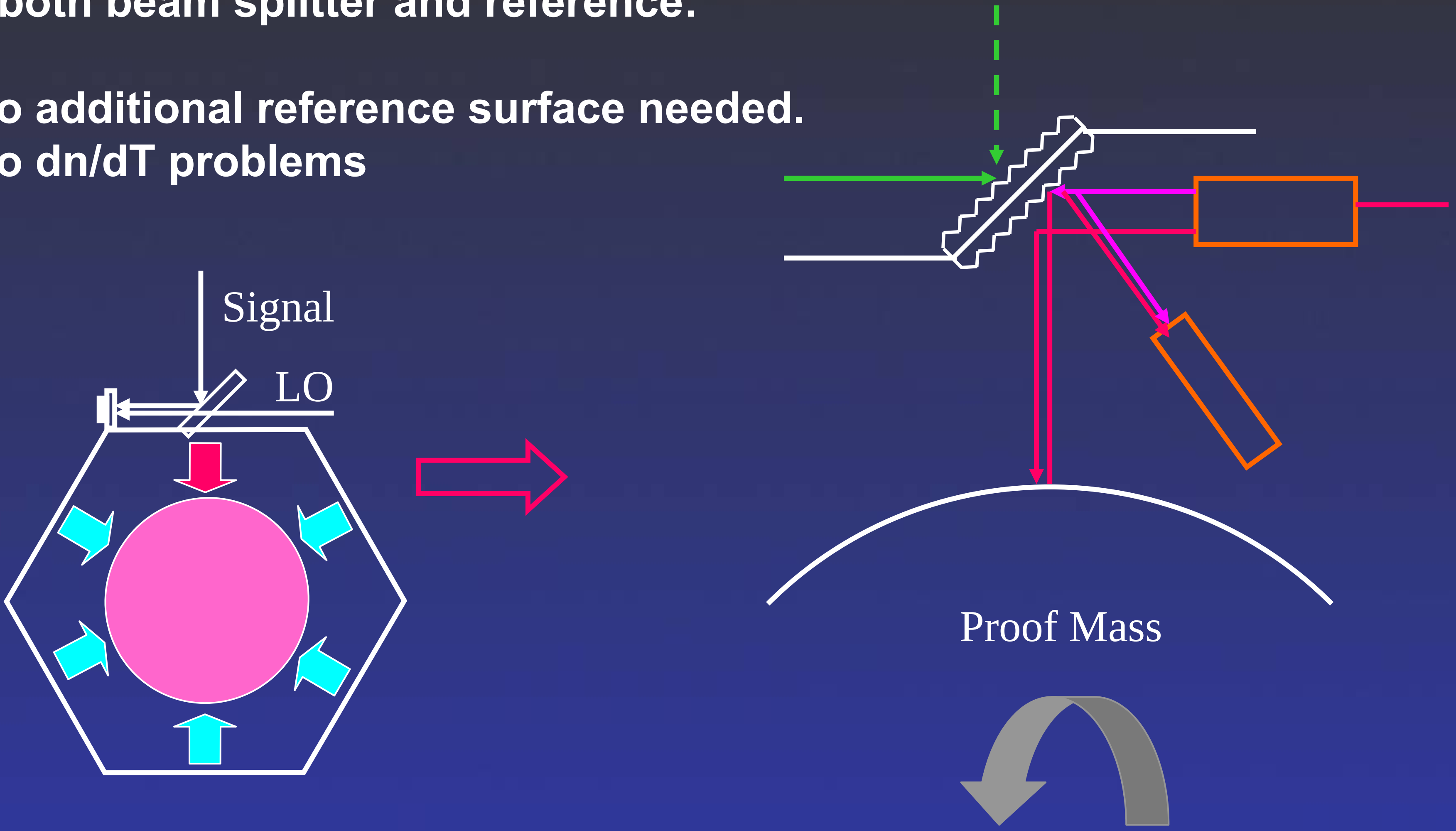
GRS with double sided grating for PM and interferometer reference

GRS Interferometer Configuration

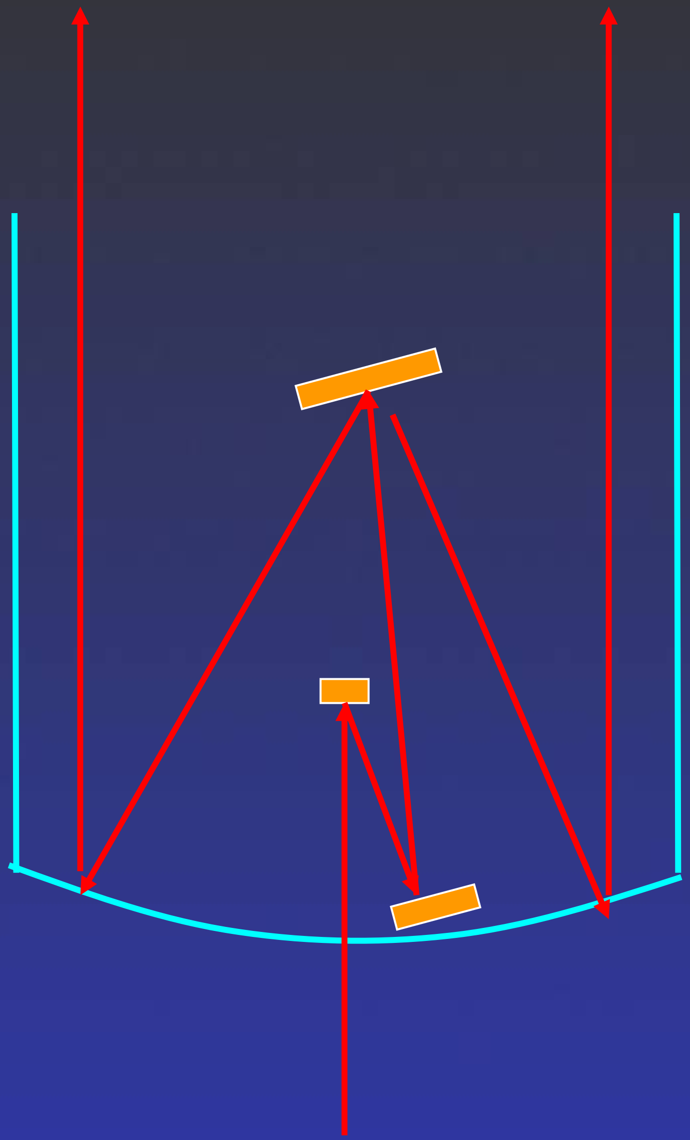
(Example 2: Reflective Diffraction Optics)

One reflective dielectric grating functions as both beam splitter and reference:

- **No additional reference surface needed.**
- **No dn/dT problems**



Multiple Mirror Scheme for Telescope



- “The trend” (Ternary design was for next Hubble)
- Move lighter parts only
- Optical bench does not move
- Assign coarse and fine adjustments to different mirrors (numbers are OK)

Conclusions

- Complex physics experiment do work in space, GP-B
- LISA and GP-B have significant technology overlap
- LISA requires for success
  - Simplified more robust design
  - Use of modern technology
  - Innovative operations methods