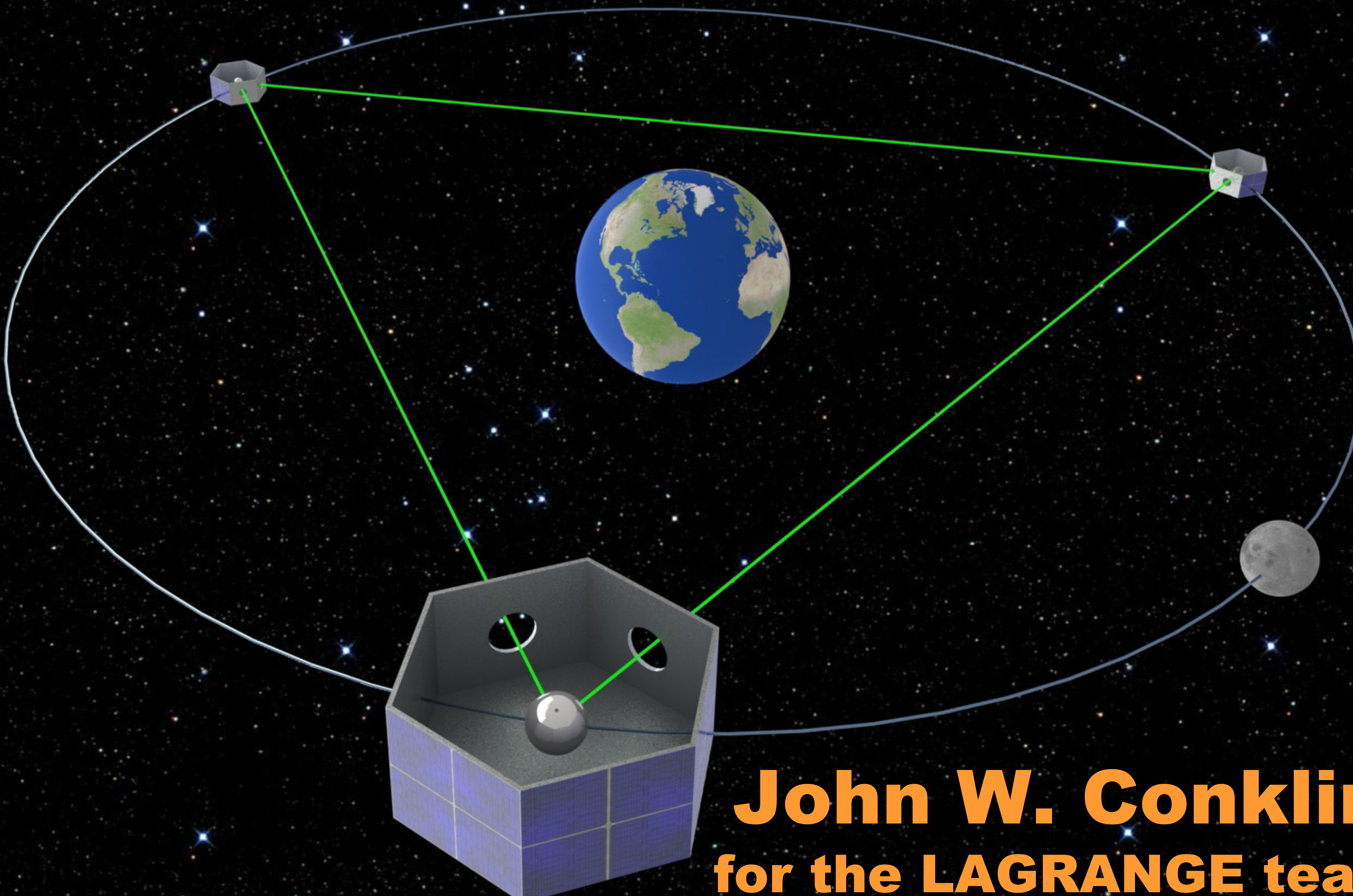
LAGRANGE

LAser GRavitational-wave ANtenna at GEo-lunar L3, L4 , L5



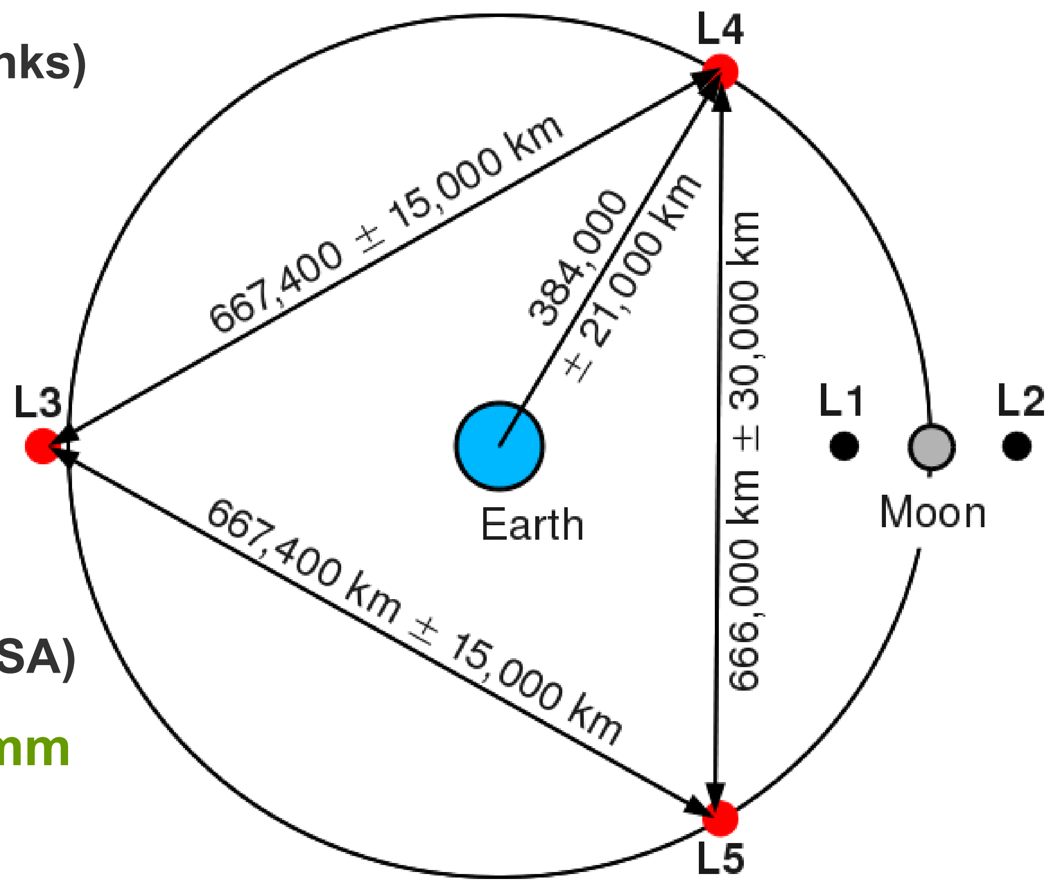
John W. Conklin
for the LAGRANGE team

The SALKS Collaboration

Stanford	NASA ARC	Lockheed Martin	KACST of Saudi Arabia	SRI International
science payload lead (GRS / IMS)	science orbit, orb. injection, prop. mod.	telescope, spacecraft	science payload, tech development	µN thrusters
John Conklin Karthik Balakrishnan Chin San Han	BJ Jaroux	Gopal Vasudevan		Victor Aguero

Design Overview

- 3 identical drag-free spacecraft & payloads
- Stable geocentric orbit (EM L3, L4, L5)
  - 670,000 km equilateral triangle (6 links)
- Minimum complexity
  - 1 spherical TM per S/C
  - 1 laser & bench per S/C
  - 2 telescopes, in-field pointing
  - 7 DoF control per spacecraft
  - Flight proven tech with high TRL (Honeywell gyro, DISCOS, GP-B, LISA)
- Continuous, simultaneous, fast comm
  - Fixed antennas on each S/C
  - Mbps through NASA GN (11 m class), ~1 hour data latency
  - Critical for mission success (GP-B, LIGO)
- 5 year mission lifetime



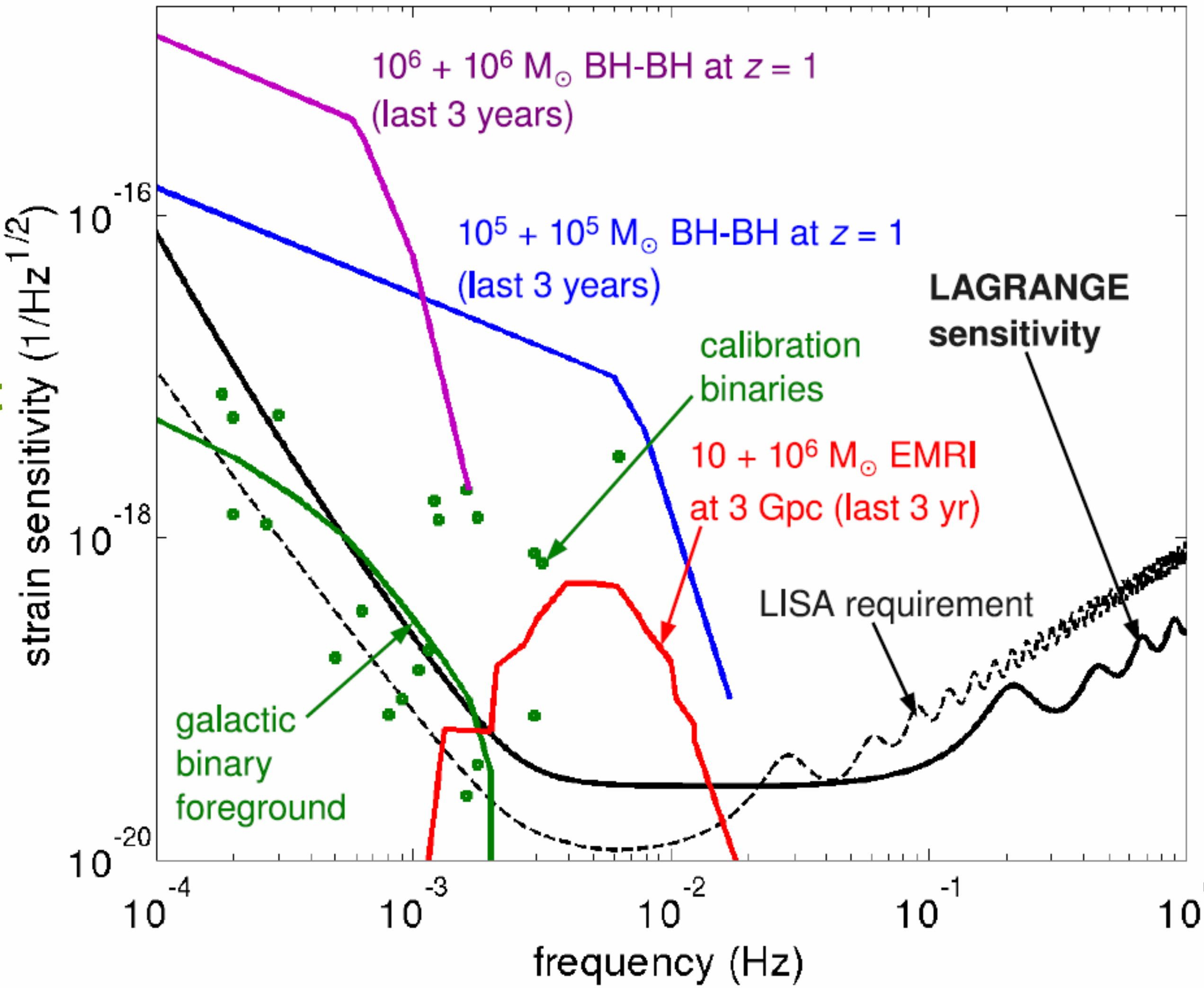
Principal Cost Savings Relative to LISA

1. **Reduced S/C mass from reduced payload components**
   - 1 GRS, 1 Laser, 1 optics bench, smaller (20 cm) telescopes
     - 2 Lasers budgeted for redundancy (4 in LISA)
     - No credible TM failure mechanism
     - TM sensing, charge control, spin-up, and drag-free have redundancy
   - Launch mass savings: ~ 150 kg × 3 spacecraft
2. **Orbit change: Geocentric, 667,000 km arm length**
   - Requires 1 small propulsion module instead of 3
   - Launch mass savings: ~ 2,500 kg
   - Reduced operations & communications complexity

- **LAGRANGE wet launch mass: ~2,000 kg (~5,000 kg for LISA)**
  - Historic trends show cost scales with mass
  - Save ~$150M in launch alone

LAGRANGE Strain Sensitivity

- **Arm length: 670,000 km**
- **Metrology: 8 pm/Hz$^{1/2}$ at 3 mHz (see APPENDIX D)**
- **Acceleration noise: 3×10^{-15} m/sec^2**
  - **Must be over-designed**
- **Sensitivity 2x less than LISA below 20 mHz**
- **Below 2 mHz galactic binary confusion sets limit**
- **LAGRANGE maintains most important science objectives of LISA**



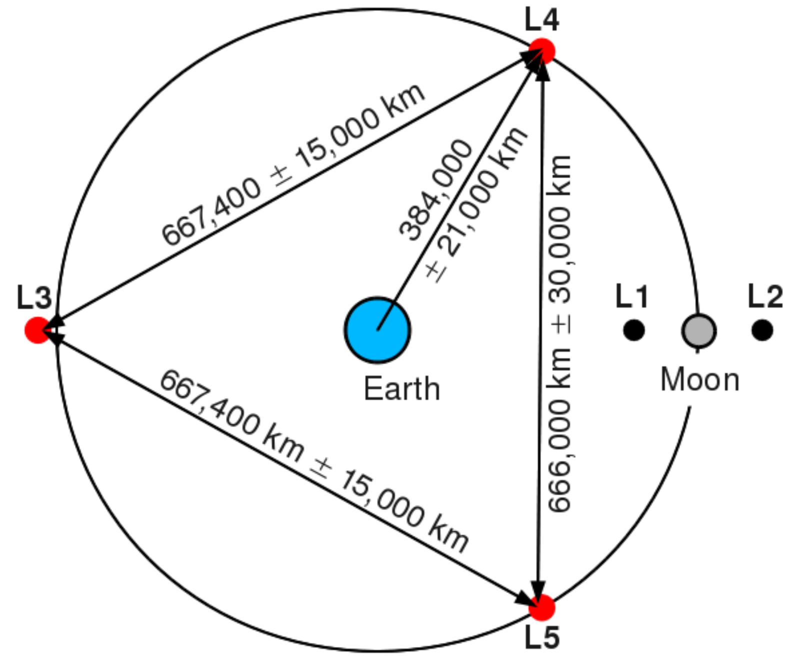
Orbit Selection

- **Communications (& cost) drives decision for geocentric orbit**
- **~ 3 stable, near-Earth orbits found**
  1. **High retrograde: ~600,000 km from Earth (Hellings, OMEGA 1998)**
  2. **Earth-moon L3, L4, L5: 384,000 km from Earth (LAGRANGE)**
  3. **Earth-Sun L2 circular Halo: ~1.5 Mkm from Earth (must be checked)**
- **1. & 2. have similar performance (range rate, breathing, etc.)**
- **EM L3, L4, L5 chosen because:**
  - **Closest to Earth**
  - **Minimum cruise time**
    - **Launch to Weak Stability Boundary: 4 months with Δv = 580 m/sec**
    - **Launch to Trans-Lunar Injection: 7 months with Δv = 475 m/sec**

Orbit Performance Summary

- Initial conditions maximize time each S/C remains at L-point
  - Station keeping every 6-12 months (L3)
  - Station keeping capability recommended for any orbit
- 3 S/C simultaneous optimization may improve performance
  - e.g. synchronous periodic orbits

	EM L3,L4,L5	LISA
Arm length	0.67 Gm	5 Gm
Δ arm length	≤ 5%	1%
Breathing angle	≤ ±5 deg	±0.5 deg
Range rate	≤ 150 m/sec	10 m/sec
Δ orbit plane	5 deg	60 deg

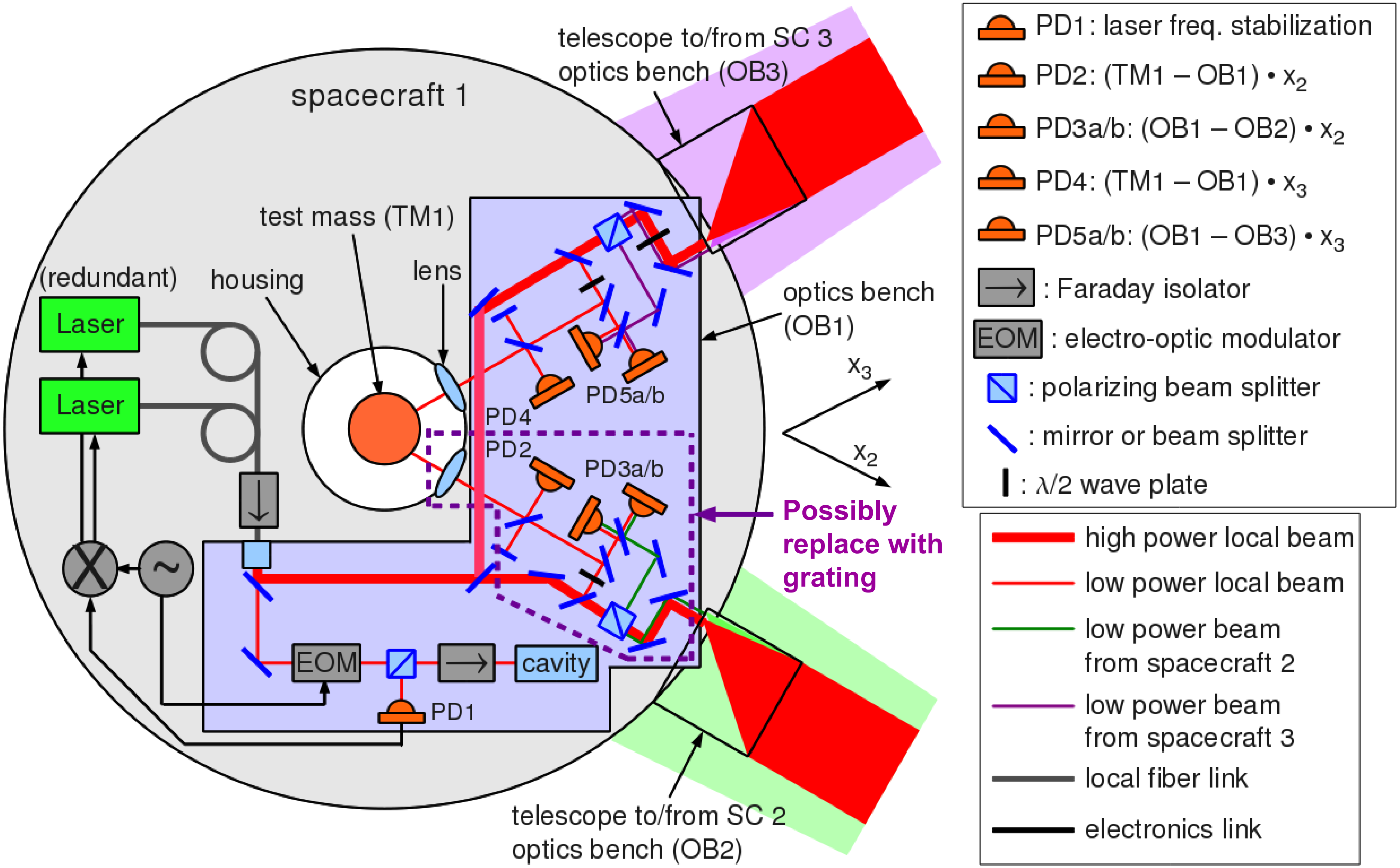


(see APPENDIX B)

Interferometric Measurement System

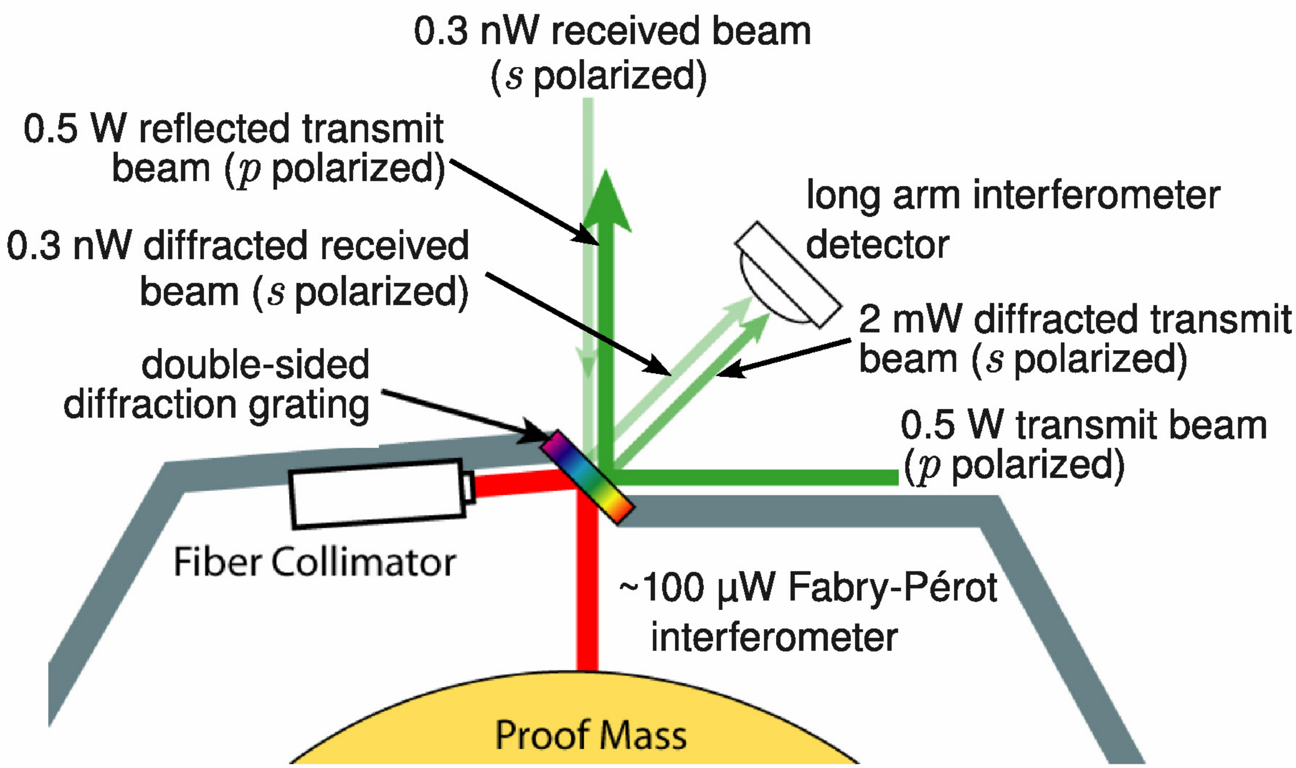
- IMS follows LISA scheme with some differences
- 1 W Nd:YAG (1064 nm), split to feed both arms
- Split interferometry: long-arm / short-arm interferometers
  - Short-arm (TM to optics bench): Michelson or gravity Fabry-Pérot cavity
  - Long-arm (optics bench to remote optics bench): local & received laser phase difference (PBS or diffraction grating)
- Laser pre-stabilization by optical cavity or iodine cell
- Single TM requires no back-link → 4 phase measurements (6 for LISA)
- 150 MHz Doppler frequency
  - Requires modified LISA phasemeter
  - Alternate: frequency shift low-power local beam with AOM (or EOM)
    - Requires clock with ~10^{-14} accuracy (e.g. space qualified H maser)
- 6 μrad point-ahead angle: LISA PAAM (TRL 4)

LISA-like Optical Bench



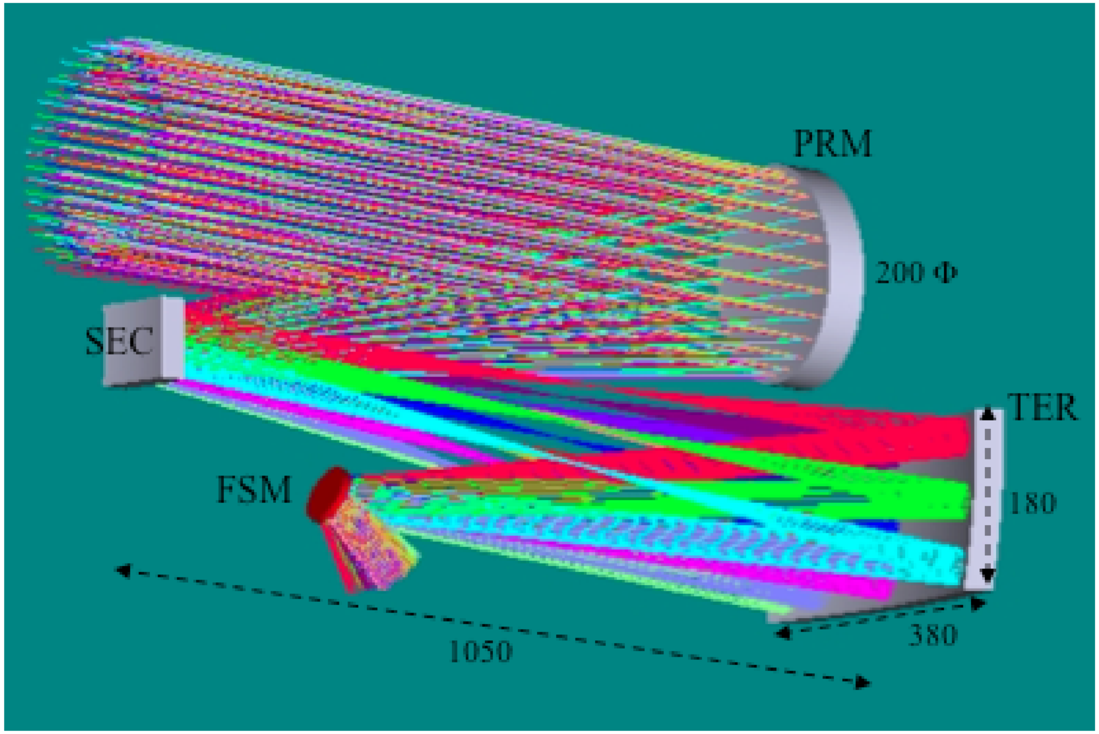
Interferometry with a Diffraction Grating

- **Double sided diffraction grating on low CTE material**
  - **Small, ~ mm relay region between long & short arm interferometers**
  - **CTE < *dn*/*dT***
  - **Fewer components → smaller optics bench**
- **Sensitivity to grating motion: 1 µcycle/pm (similar to LISA req.)**



Telescope Design

- 20 cm aperture
- ±2.5 deg beam steering
- 5 pm path-length stability
- Composite metering structure
- Off-axis, 2-stage design
- Stage one is 6:1 3-mirror Anastigmat
  - Leads to ±15 deg steering mirror near exit pupil
- mK temperature control
- Off-axis TMA TRL9
  - mK temp control, low CTE composite, pm path length combo TRL 4

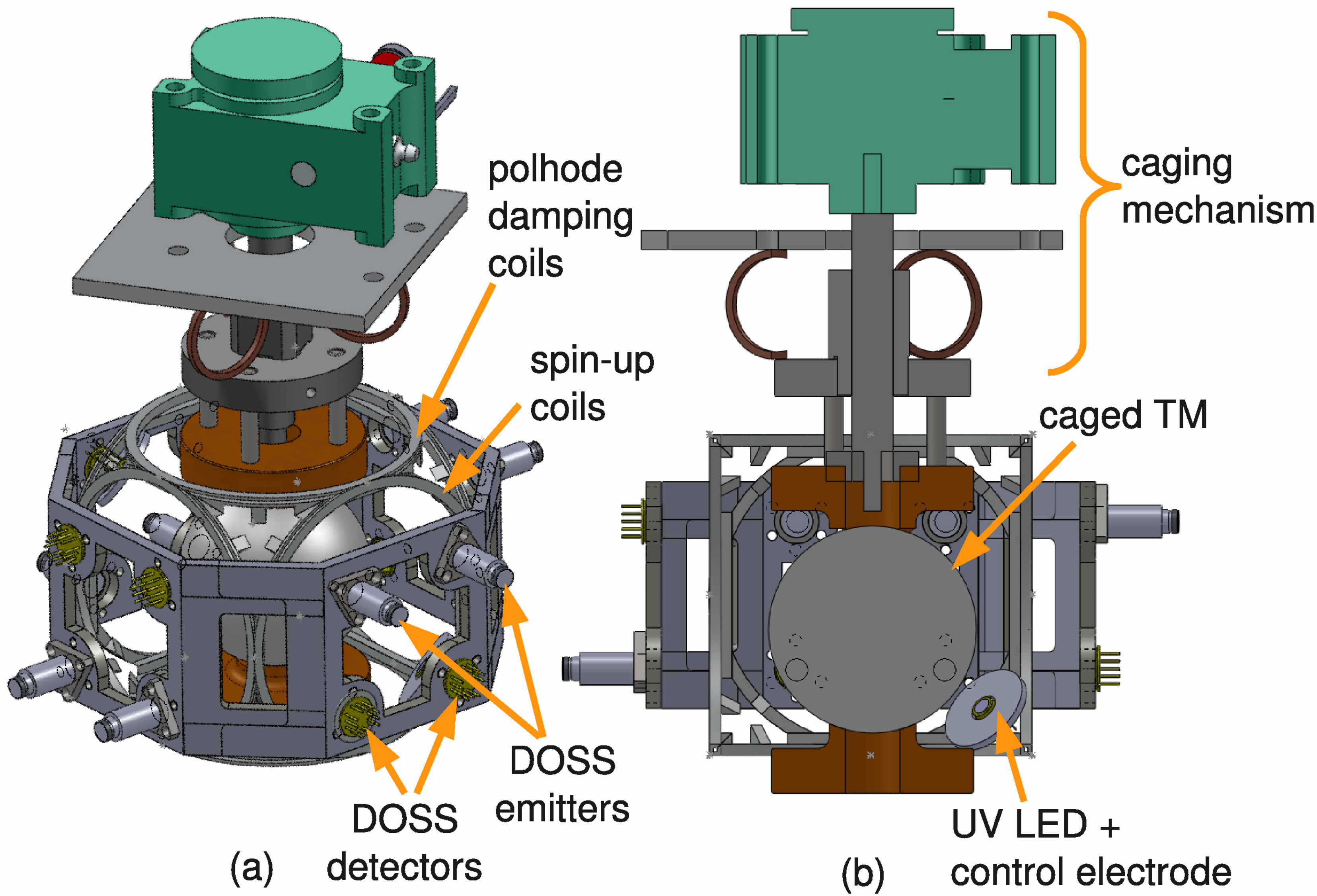


Stage One Design

Advantages of a Spherical GRS

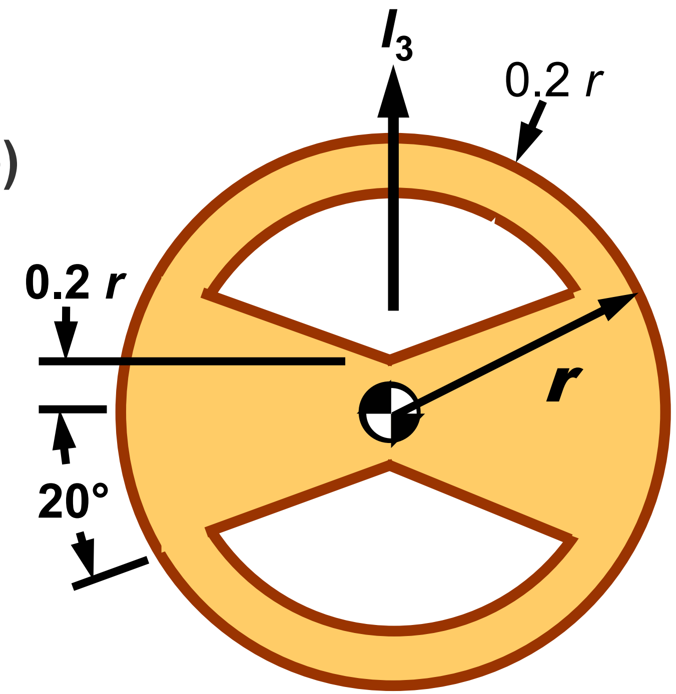
1. **No TM forcing or torquing**
   - Neither electrostatic support nor capacitive sensing required, reducing disturbances & complexity
2. **Large gap (35 mm)**
   - Disturbances reduced and/or spacecraft requirements relaxed
3. **A long flight heritage**
   - Honeywell gyros, Triad I (5×10^{-11} m/sec^2), GP-B (4×10^{-11} m/sec^2 Hz$^{1/2}$)
4. **Scalability**
   - Performance can be scaled up or down by adjusting TM and gap size
5. **Simplicity**
   - No cross coupling of degrees of freedom
6. **Simple flight-proven caging mechanism (DISCOS)**

Modular Gravitational Reference Sensor



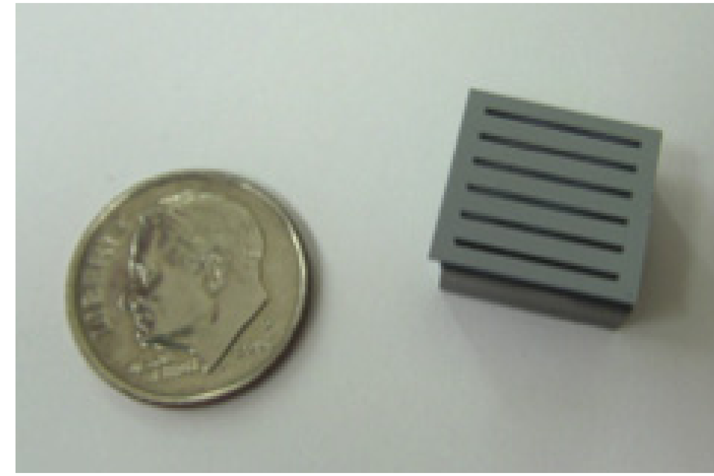
LAGRANGE Test Mass

- Test mass: 70%/30% Au/Pt (LISA)
  - Alternate: Berglide (2%/97.5%/0.5% Be/Cu/Co)
- Spinning (3-10 Hz) average all but axisymmetric irregularities
  - Out-of-plane motion → patch length changes 1 pm/Hz$^{1/2}$ at 1 mHz (see APPENDIX E)
- Hollowed out sections ($\Delta I/I = 0.1$) shift polhode to 0.3-1 Hz (APPENDIX E)
- MC determined to IFO limit by notching spin + harmonics
- Carbide coated (e.g. SiC, ZrC)
  - Hard (no sticking), reflective, conductive, allows UV charge control, measured patches consistent or better than gold (APPENDIX E)



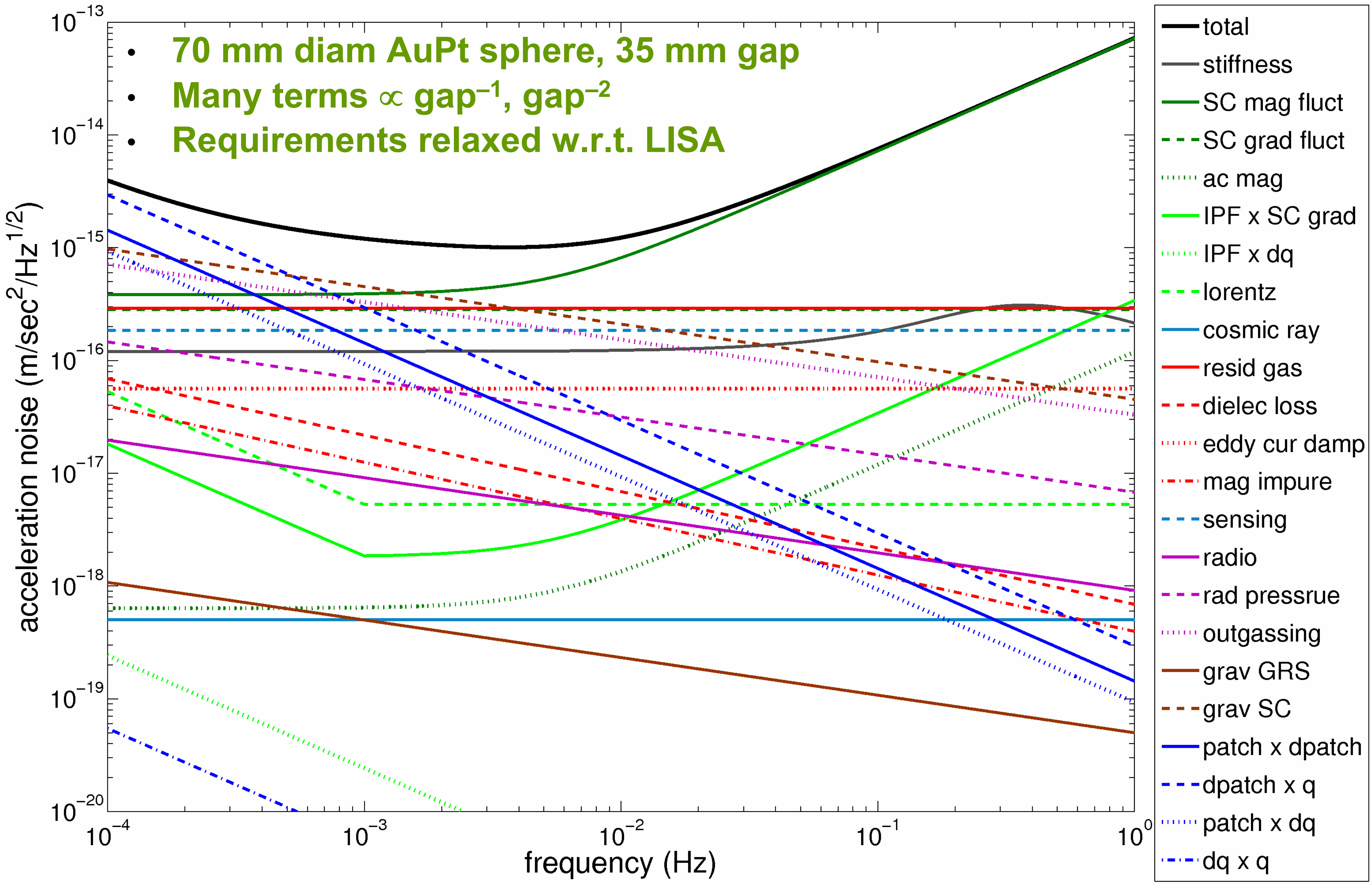
Optimal geometry

Micronewton Thrusters



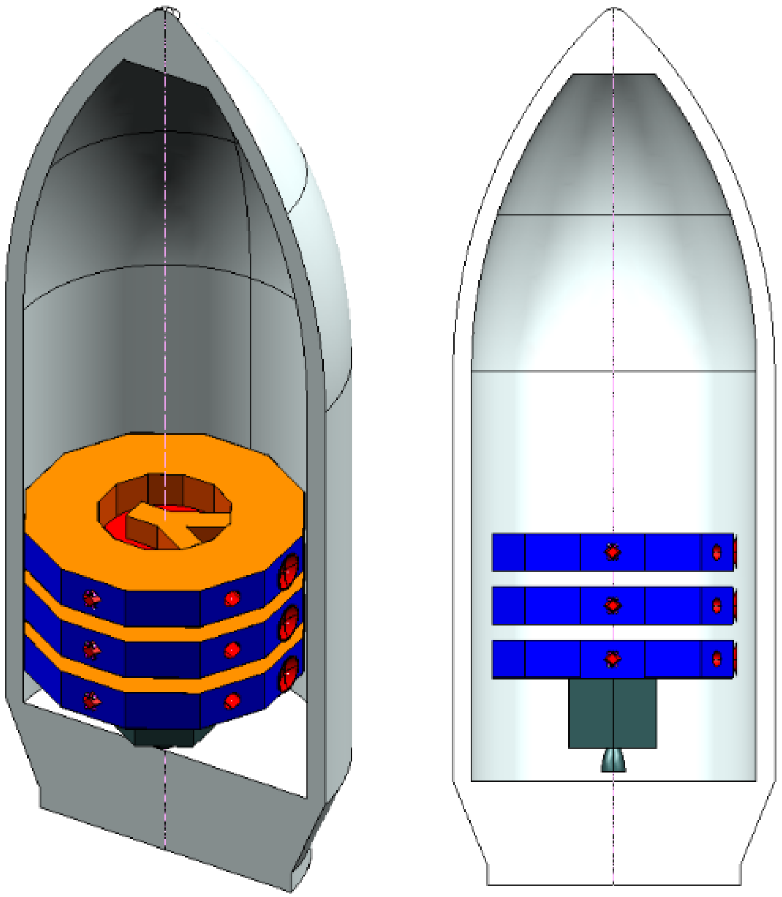
- Drag-free & attitude via μN thrusters
- No existing thruster meets LISA noise, max thrust and lifetime requirements
  - NGO evaluating alternates to FEEPs
- SRI micro-fabricated ion thruster attractive alternate to Busek CMNT or Italian/Austrian FEEPs
  - Micro-fabricated emission sites produce ions & electrons
  - "Digital propulsion": 100's – 1,000's of independent emitters / cm^2
    - Single unit can produce forces + torques
  - Huge dynamic range: ion production physics unchanged over 10^{-9} to 1 N
  - Up to 10,000 sec Isp
  - Prototype: 1 nN to 5 μN thruster ion source tested to 40 hr of operation
  - Can be demonstrated on a 1U CubeSat

Acceleration Noise Budget



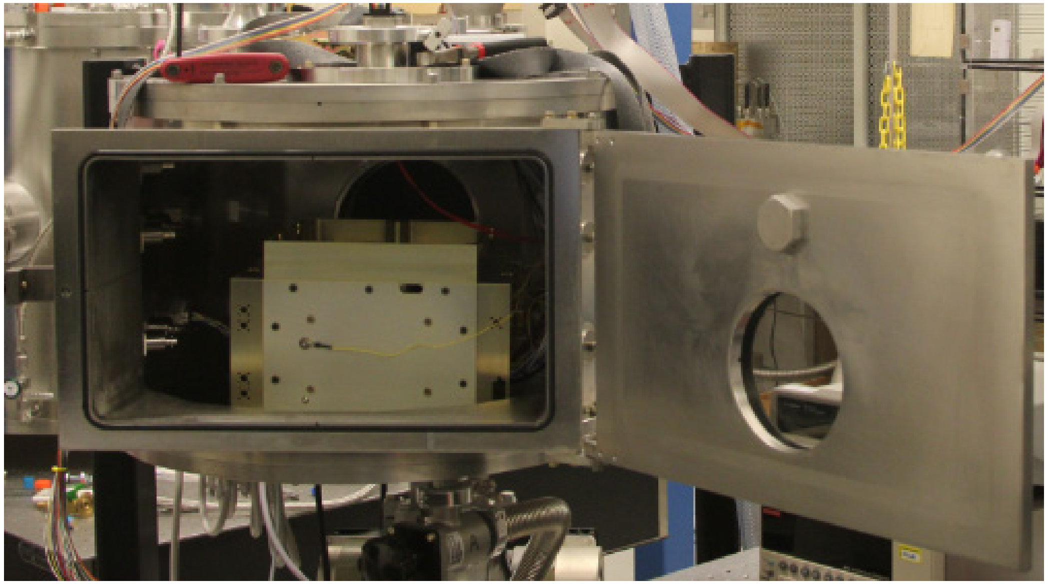
Spacecraft & Mission Design

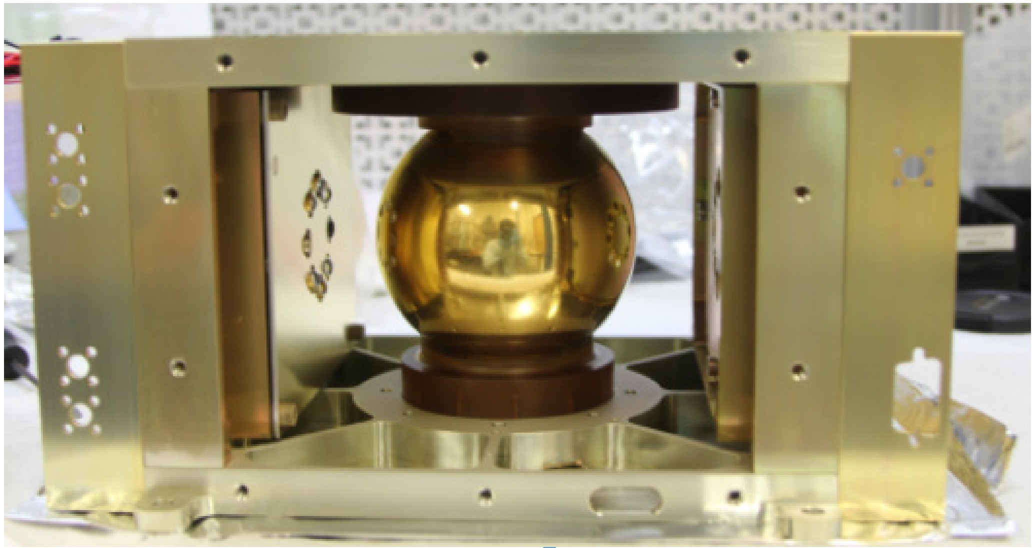
- **S/C based on existing LM S/C, TRL >6**
  - **~3 m × 0.7 m, 300 kg, 500 W**
  - **Fixed 10 W antenna between telescopes**
- **Thermal design: GRS 10 μK at 1 mHz**
  - **±50 K at exterior at 27.3 period**
  - **Thermal load radiated top/bottom**
  - **Payload at center**
- **Launch mass: 2,070 kg**
- **4-7 month cruise**
- **5 year lifetime**
- **$950M FY12**



1st Tech Demo on nano/micro Sats: UV LED Sat

- **Stanford: Payload**
  - 16 UV LEDs (4 different types)
  - Electrometer
  - Bias plates
  - Active ac charge control
- **NASA ARC:**
  - Systems engineering, integration & testing
- **KACST:**
  - S/C bus, launch, ops
- **Flight payload: Mar. 2012**
- **Launch: 2013**





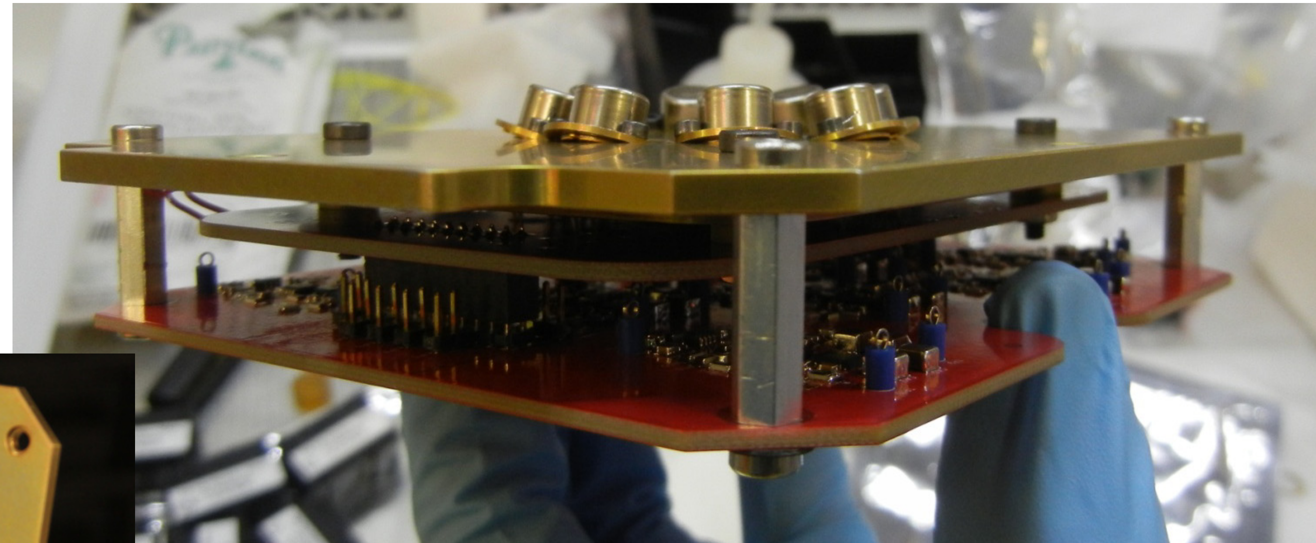
Low cost, ~2 yr → TRL 9

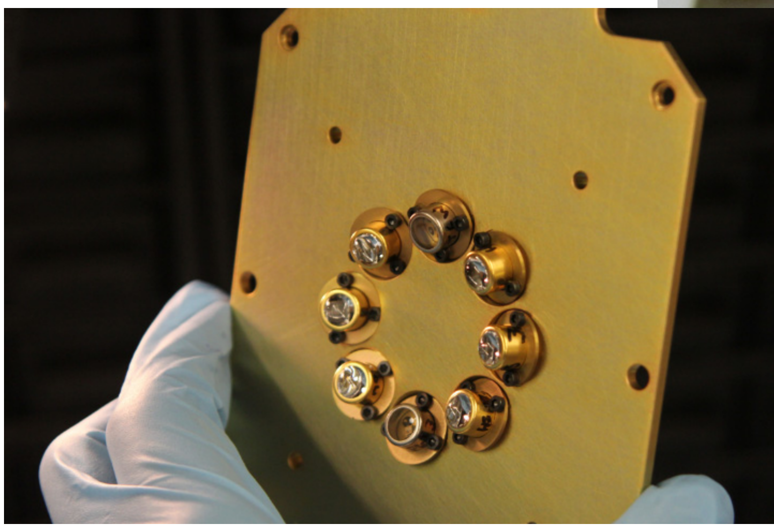
LOCKHEED MARTIN

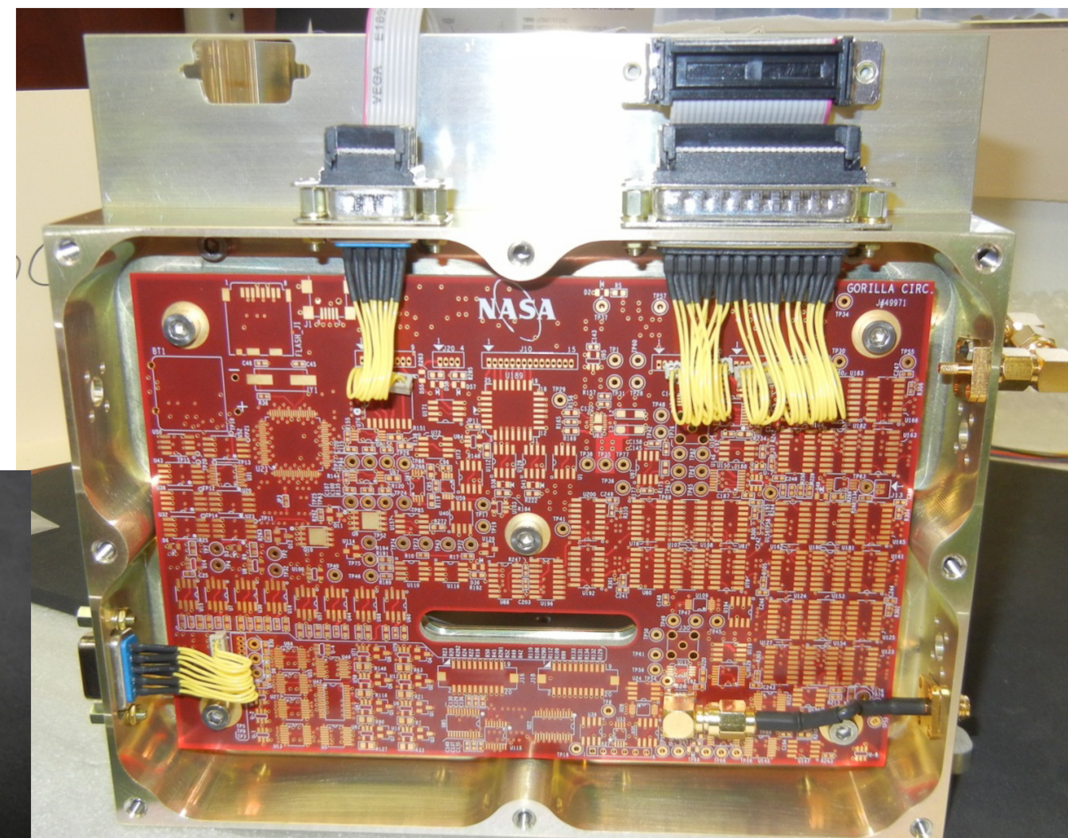
مدينة الملك عبد العزيز للعلوم و التقنية KACST

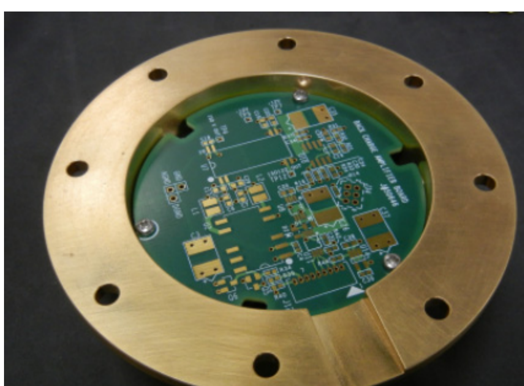
SRI International

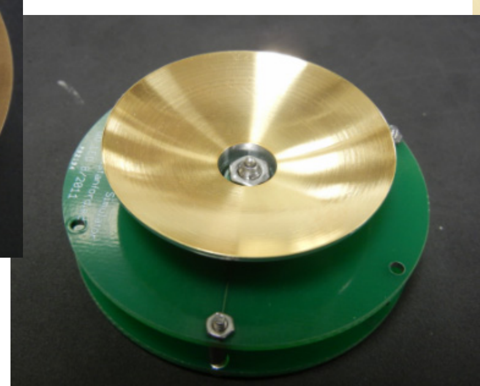
Engineering Unit











Responses to Questions (1/5)

1.	The maximum one-way Doppler is ~150 MHz, making the round trip ~300 MHz. How do you plan to handle this?	Phase at remote S/C not necessarily re-transmitted. Heterodyne on both S/C ~ 150 MHz. Phasemeter mod or frequency shift local laser.
2.	LISA requires a fairly sophisticated clock noise correction system. To meet your length sensing requirements with these Doppler frequencies, this would have to be rescaled. Did you look into this?	Yes, it is in our budget. Residual clock noise $\propto$ Doppler frequency. LAGRANGE Doppler is 10x LISA. Reduced shot noise helps a bit. LAGRANGE clock noise = 3 pm/Hz$^{-1/2}$ at 3 mHz (LISA ~ 0.4 pm/Hz$^{-1/2}$)
3.	Have you looked at path length stability of the telescope?	Yes, LM analyzed path length stability w.r.t. temperature change & steering.
4.	Does the telescope need a focus mechanism to compensate for de-watering of the composite metering structure?	Yes.

Responses to Questions (2/5)

5.	The angular variations are +/- 5 deg between S/C. The telescope reduces the beam size by a factor of 6 but also increases the angular variations by a factor of 6, requiring +/- 30 deg of angular actuation. Are you proposing to use 2 mirrors actuating by +/- 15 deg to correct for this?	Telescope range is ±2.5 deg, and steering is handled by a single mirror. (see Chart 11)
6.	Do the telescope and in-field guiding system require an additional interferometer to read out their length changes?	Metering structure temperature controlled to mK level, and OPD calibrated as a function of field, allowing one to operate without actively tracking OPD at pm level. Internal monitoring system could be used, but at the cost of additional power, weight, cost, complexity.

Responses to Questions (3/5)

7.	Typically a measurement telescope is somewhat different from an imaging telescope. You've identified a Three Mirror Anastigmat with flight heritage, but do you have tests to show that it meets the optical pathlength requirements and all other performance and environmental requirements at TRL 9?	Off-axis TMA is TRL 9. mK temp control, low CTE composite telescope, pm path length monitoring have flight qualification test heritage. Combination of all three is new and is considered TRL 4. (see APPENDIX A)
8.	Can you comment how you envision that the typical milliradian steering range of AOMs and EOMs can be increased to the required levels? Reference 55 states that maximum deflection angles of 0.1° are possible using 375V in an 11cm long and 2mm wide crystal.	Not baseline design. Commercially available products have larger range, but may still need magnificaiton.

Responses to Questions (4/5)

9.	The grating readout will be very sensitive to angular motion and lateral displacement of the grating. See PRL 95, 013901 (2005) for a measurement of how the interferometric signal in a Michelson interferometer changes when the grating is translated. Did you consider this in your analysis?	Sensitivity to spot motion over grating surface is 1 μcycle/pm, equivalent to LISA optical bench deformation requirements. Affect of sphere's motion w.r.t. Littrow cavity must be analyzed in detail.
10.	A spherical metallic proof mass has had figure/CG issues in the past. Have these been resolved?	Path-length changes due to sphere form/MC ~ 1 pm. See chart 14, APPENDIX E.
11.	Are the proposed carbide coatings consistent with the expected surface and patch field requirements?	Yes, 40% better than gold when clean. However, measurements show patches dominated by contamination. See chart 14, APPENDIX E.

Responses to Questions (5/5)

12.	The kinetic energy of the proof mass is taken out by bouncing the proof mass inside the housing with initially mm/s velocities. What tests have been done that show that this does not dent the surfaces creating patches? The shadow sensors, the grating, and the sources for the UV light will have to be protected from impact?	Once released S/C 'catches up' to TM. Bounces need not be inelastic. mm/sec bounces similar to careful handling of TM pre-launch. Elastic limit of sphere's material is not exceeded. Any residual marks averaged by spin. Patch voltages of 100 mV in error budget, bounding any possible patches produced on-orbit.
13.	How long will the damping take?	Capture time only function of release velocity and max thrust. Capture in ~1,000 sec, DISCOS ~100 sec
14.	Have you looked at other constellation concerns, like point-ahead variations? If so, how will they be addressed?	Yes, see APPENDIX B
15.	Explain the cruise phase steps in more detail.	See APPENDIX C

APPENDIX A: Mission Concept Details

LAGRANGE / LISA Comparison

Table 1. Top-level LISA / LAGRANGE comparison.

	LISA	LAGRANGE
Number of spacecraft	3	3
Orbit	heliocentric, 20° Earth trailing	Earth-Moon L3, L4, L5
Wet launch mass	~5,000 kg	2,070 kg
Arm length	5 Gm	0.67 Gm
IMS sensitivity	18 pm $Hz^{-1/2}$	5 pm $Hz^{-1/2}$
DRS accel. noise	3 fm/s^2 $Hz^{-1/2}$	3 fm/s^2 $Hz^{-1/2}$
Observation period	5 yr	5 yr
Telescopes / spacecraft	2 × 40 cm	2 × 20 cm
GRSs / spacecraft	2	1
Optics benches/spacecraft	2	1
Laser power/spacecraft	2 × 1.2 W	1 × 1 W
Controlled degrees of freedom / spacecraft	19	7
Beam steering	articulated optics & GRS	in-field pointing

Technology Readiness

Component	Heritage	TRL
Spacecraft	Lockheed	>6
Laser system	LISA Pathfinder [27]	6
Charge control	UV-LED Sat [40]	6
GRS	DISCOS [1], GP-B [2], LISA [27]	5
Laser freq. system	LISA [27], STAR	5
Phasemeter	GPS, LISA [14]	5
Caging mechanism	DISCOS [37]	5
μN thrusters	SRI [48] (CMNT[44]), In FEEP[47])	4(6)
Telescope	QuickBird [16], MTI [17]	4
PAAM	LISA [15]	4
Shadow sensor	SALKS small sat. [34]	4

Spacecraft & Payload Mass & Power

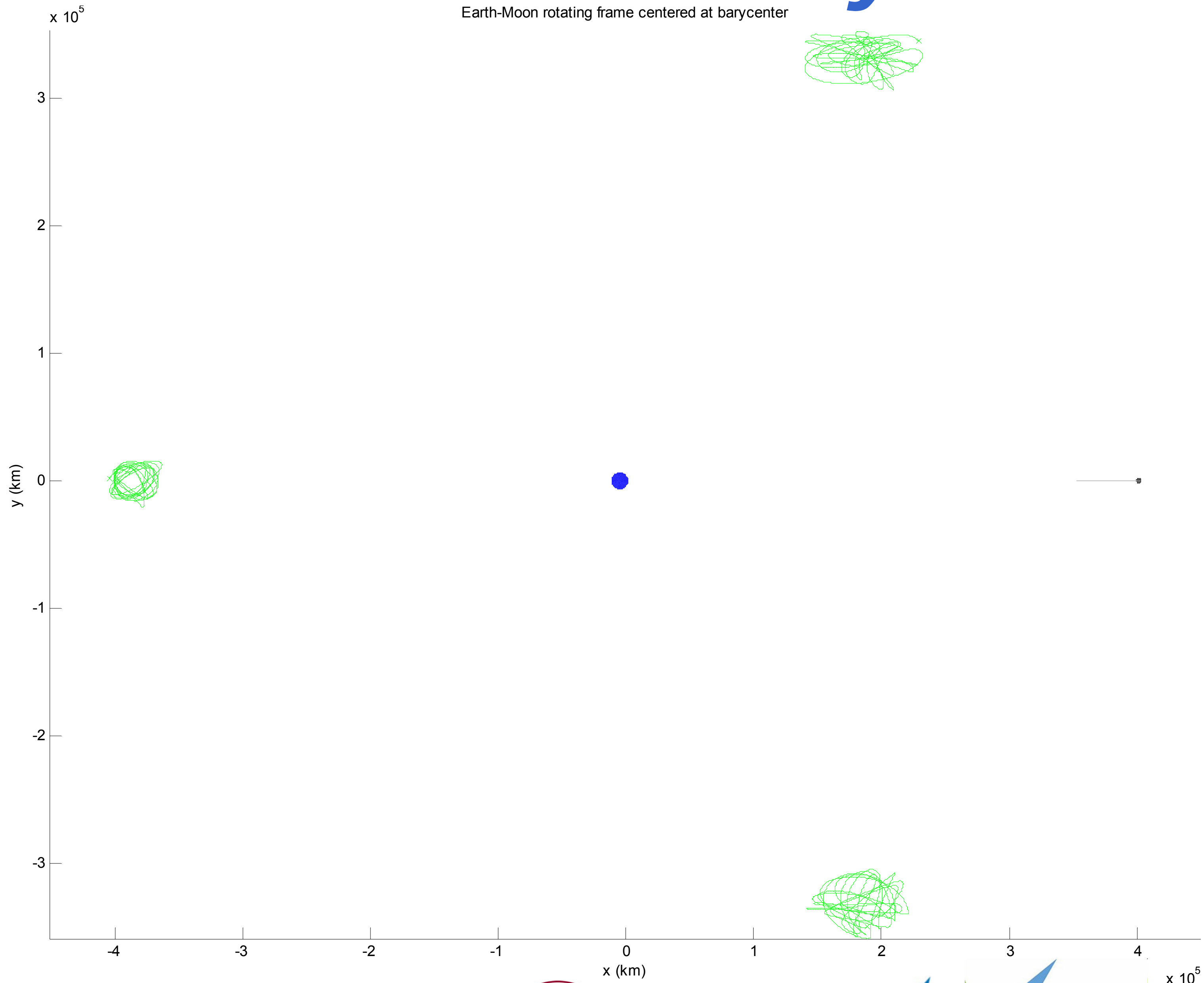
	Mass* (kg)	Power** (W)
Spacecraft (× 3)		
Payload	170	175
Spacecraft	300	325
Total spacecraft + payload	470	500
Propulsion module (× 1)		
dry propulsion module	330	
propellant	230	
Launch adapter (× 1)	100	
TOTAL	< **2,070**	

* including 30% margin for payload and propulsion module, 14% margin for > TRL 6 Lockheed spacecraft

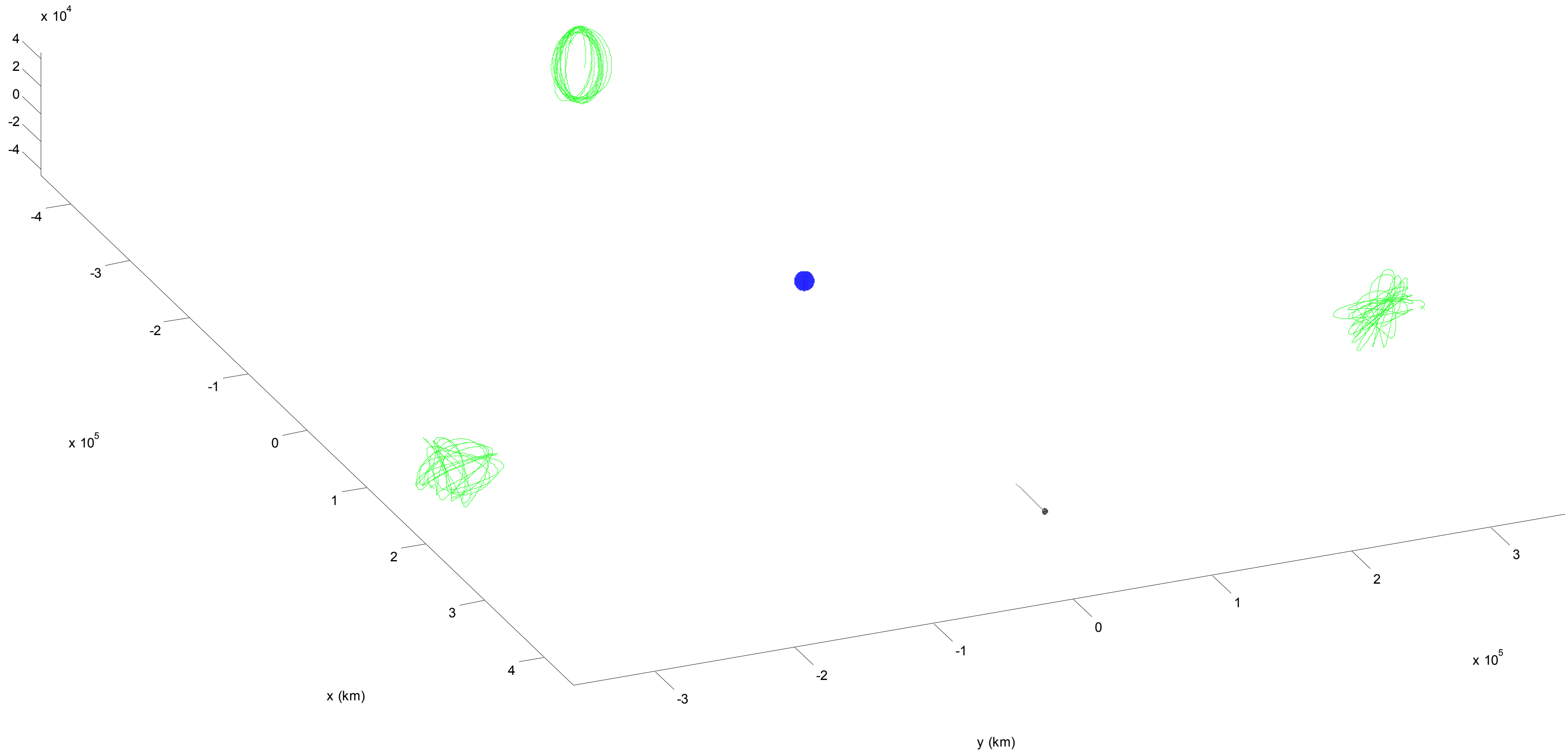
** including 30% margin for payload, 8% margin for spacecraft, while transmitting

APPENDIX B: Science Orbit Details

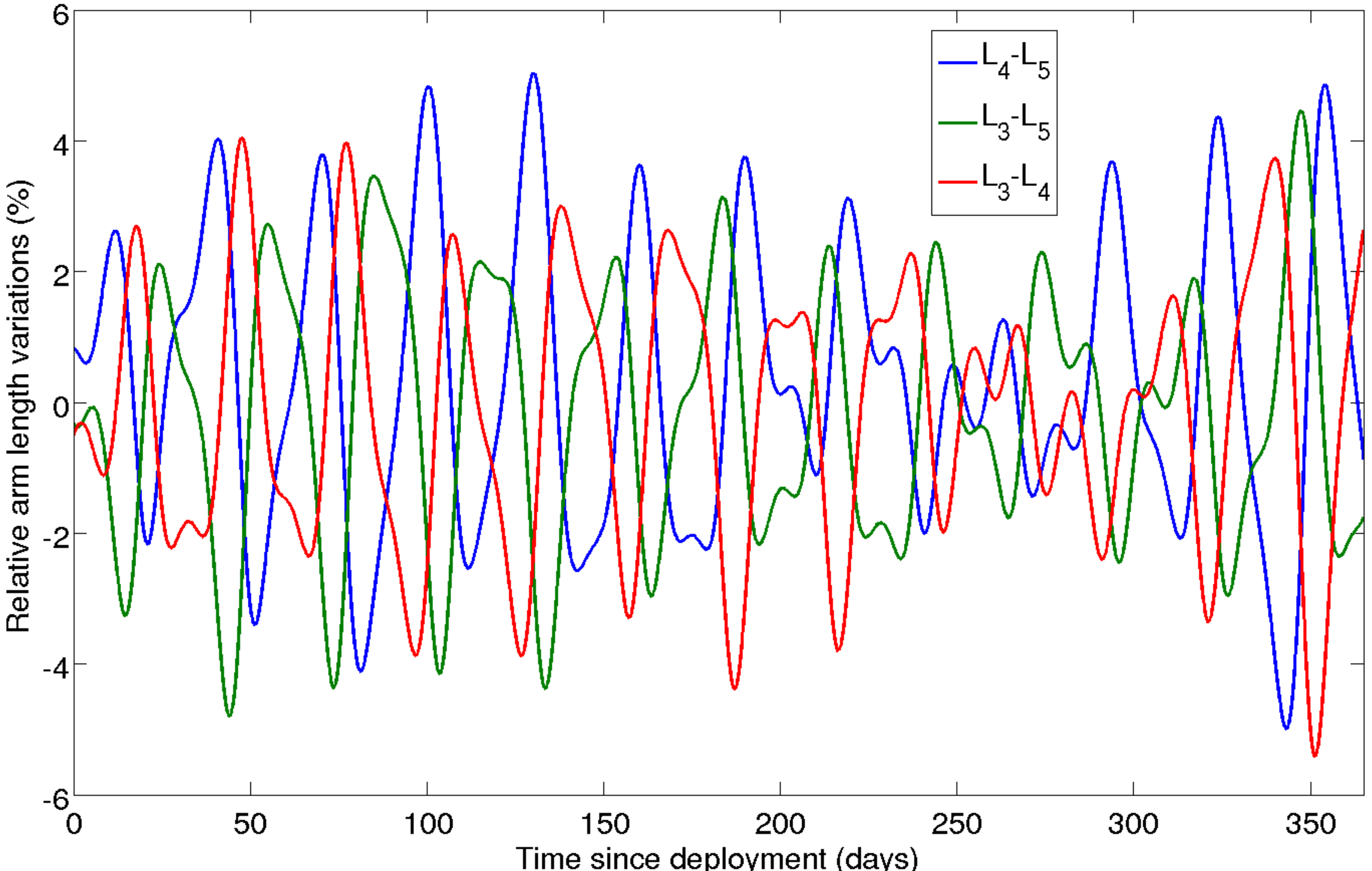
Science Orbit: 365 day solution



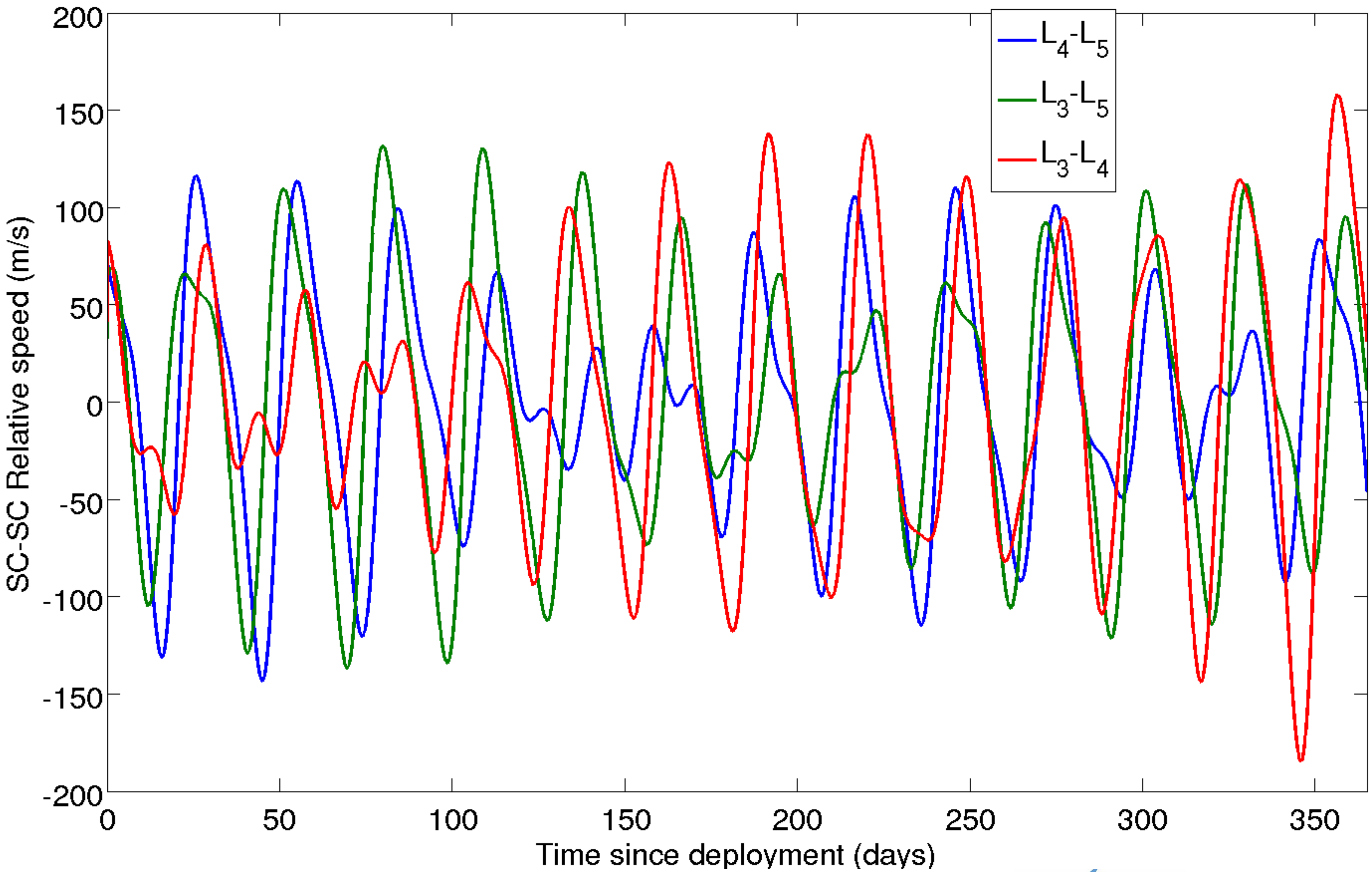
Science Orbit: 365 day solution



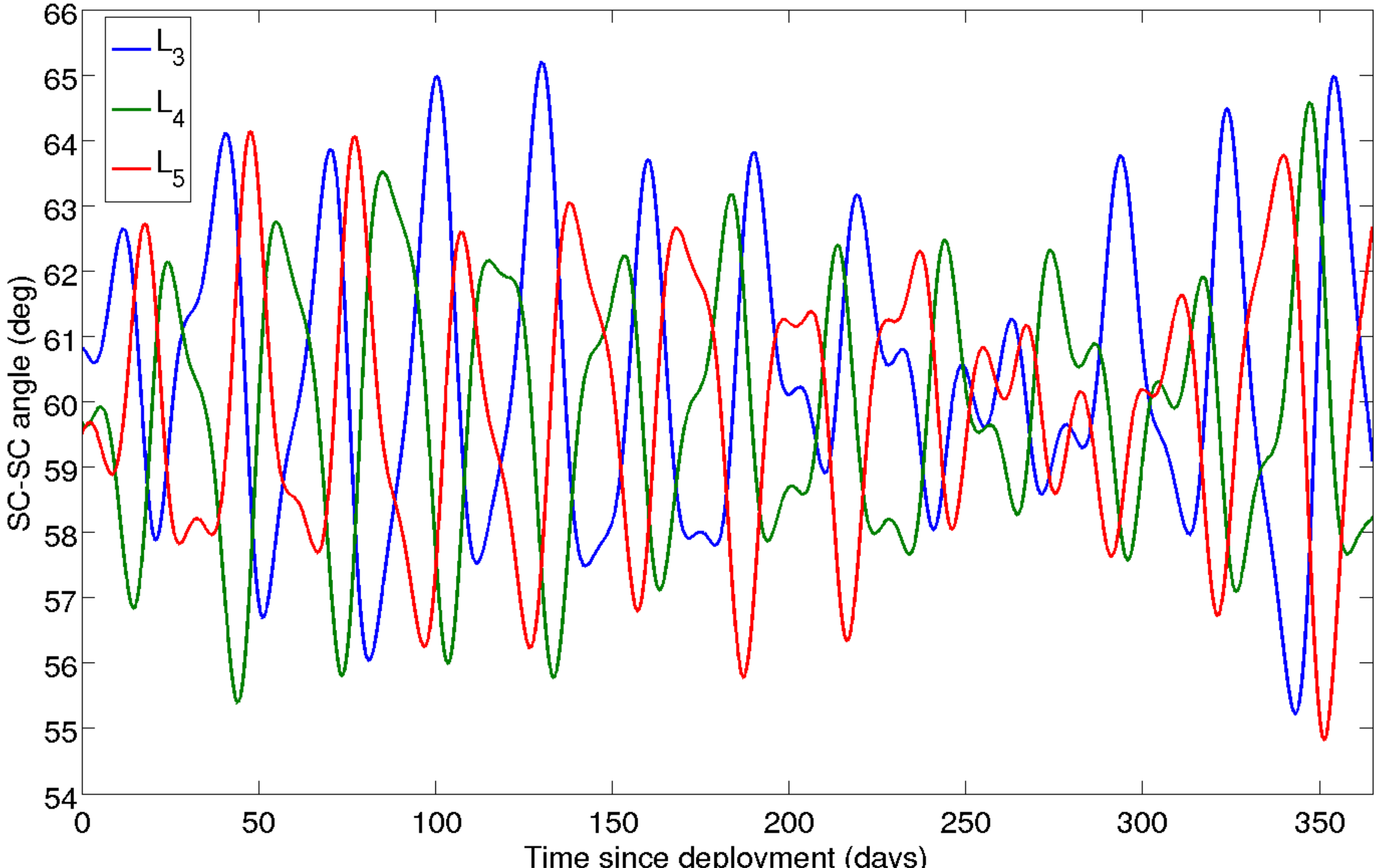
Relative Arm Length Changes



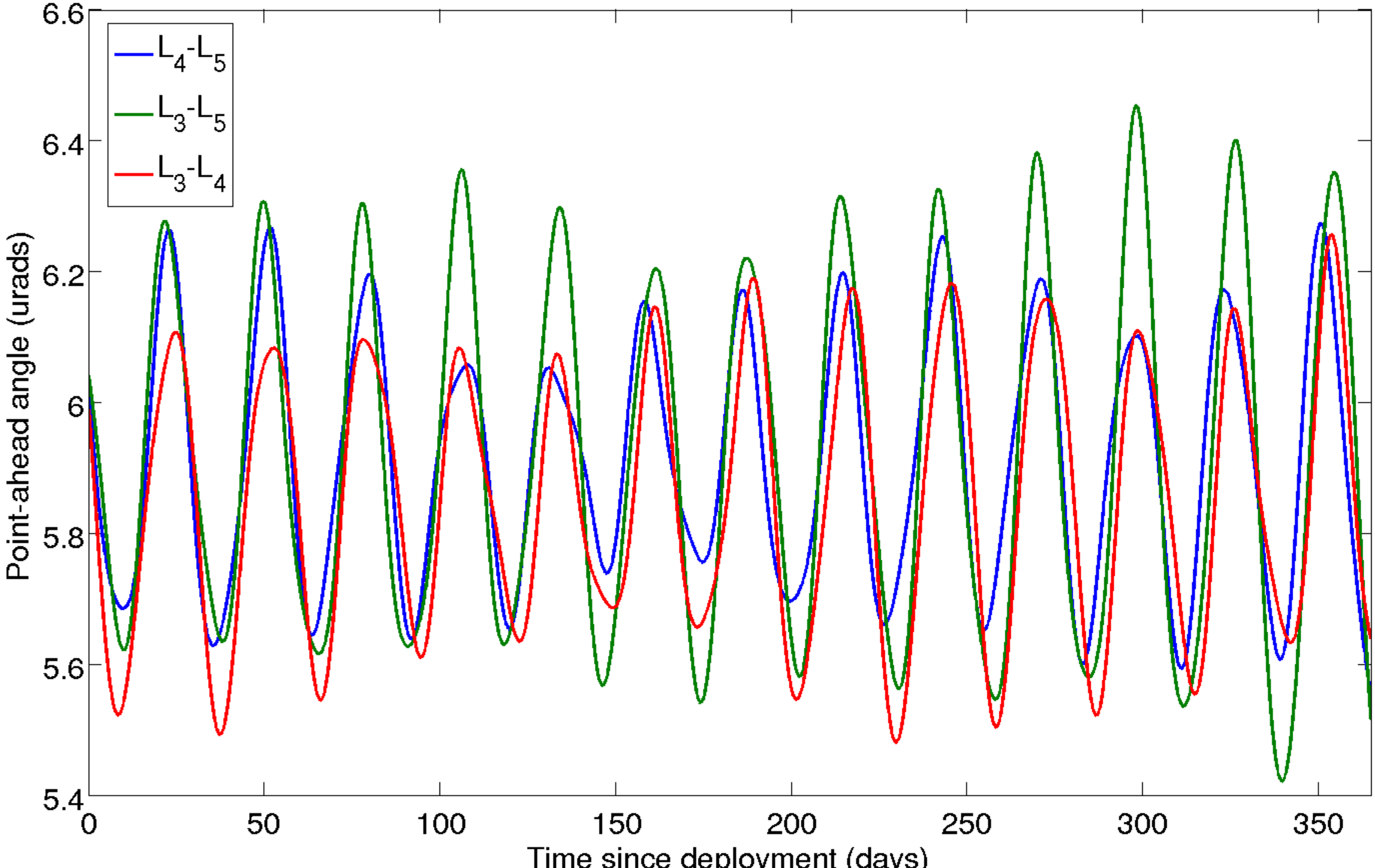
Spacecraft-to-Spacecraft Range Rates



Breathing Angle



Point-ahead Angle



Solar & Lunar Eclipses

- Eclipses over 365 days
  - Maximum Earth eclipse length: 4 hours
  - Maximum Lunar (partial) eclipse length: 3 hours

Number of Eclipses		L3	L4	L5
Earth Eclipse	Partial Eclipse	2	0	2
	Total Eclipse	3	2	4
Lunar Eclipse	Partial Eclipse	2	2	0
	Total Eclipse	0	0	0

APPENDIX C: Orbit Injection Details

Orbit Injection Scenario 1: Weak Stability Boundary

A. **Day 0:** Launch → WSB (C3 = 0 km^2/sec^2)

B. **Day 41:** WSB → Lunar swingby
(ΔV = 95 m/s)

C. **Day 81:** Lunar swingby → phasing orbit
(ΔV = 83 m/sec)

D. **Day 100:** phasing orbit → EM L5
(ΔV = 42 m/sec)

E. **Day 118:** Rendezvous EM L5
(ΔV = 51 m/sec)

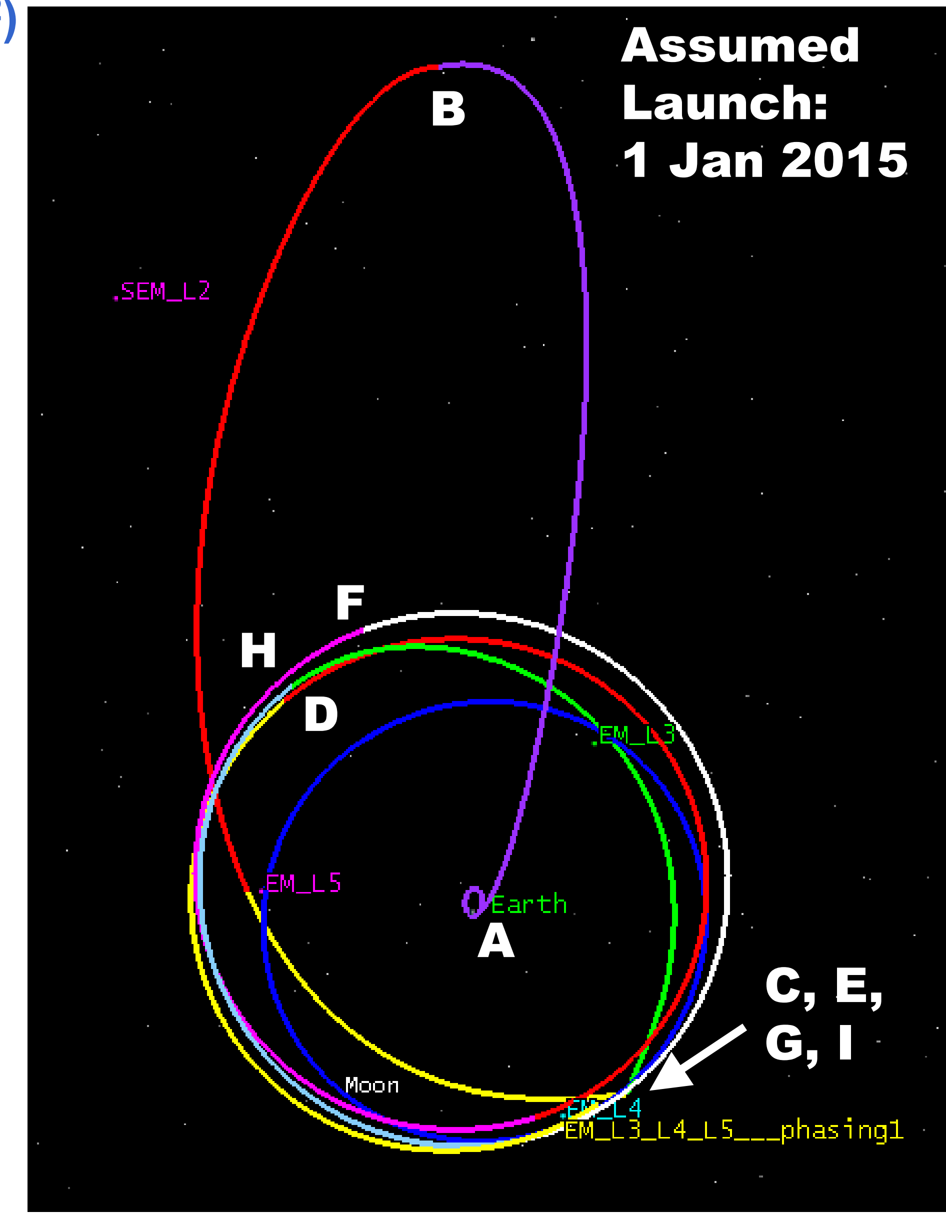
F. **Day 137:** phasing orbit → EM L3
(ΔV = 70 m/sec)

G. **Day 156:** Rendezvous EM L3
(ΔV = 67 m/sec)

H. **Day 175:** phasing orbit → EM L4
(ΔV = 57 m/sec)

I. **Day 193:** Rendezvous EM L4
(ΔV = 0 m/sec)

- **TOTAL ΔV: 475 m/sec**
(including 10 m/s course corrections)
  - Each LM spacecraft has 100 m/sec prop. system for insertion / tip-off



Requires 230 kg biprop fuel

Orbit Injection Scenario 2: Trans-Lunar Injection

A. **Day 0:** Launch → TLI
(C3 = –1.7 km^2/sec^2)

B. **Day 3:** Lunar swingby → phasing orbit
(ΔV = 283 m/sec)

C. **Day 25:** phasing orbit → EM L5
(ΔV = 42 m/sec)

D. **Day 40:** Rendezvous EM L5
(ΔV = 51 m/sec)

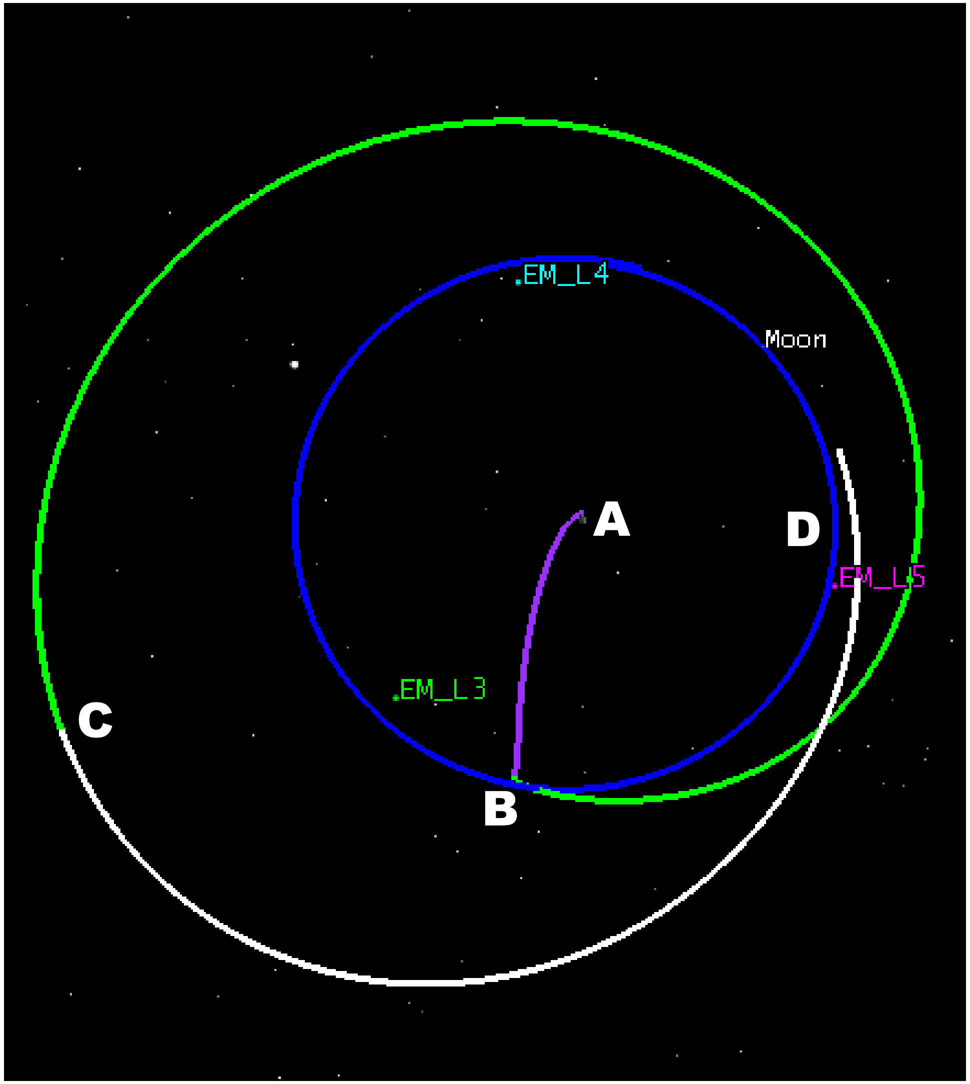
E. **Day 59:** phasing orbit → EM L3
(ΔV = 70 m/sec)

F. **Day 78:** Rendezvous EM L3
(ΔV = 67 m/sec)

G. **Day 97:** phasing orbit → EM L4
(ΔV = 57 m/sec)

H. **Day 115:** Rendezvous EM L4
(ΔV = 0 m/sec)

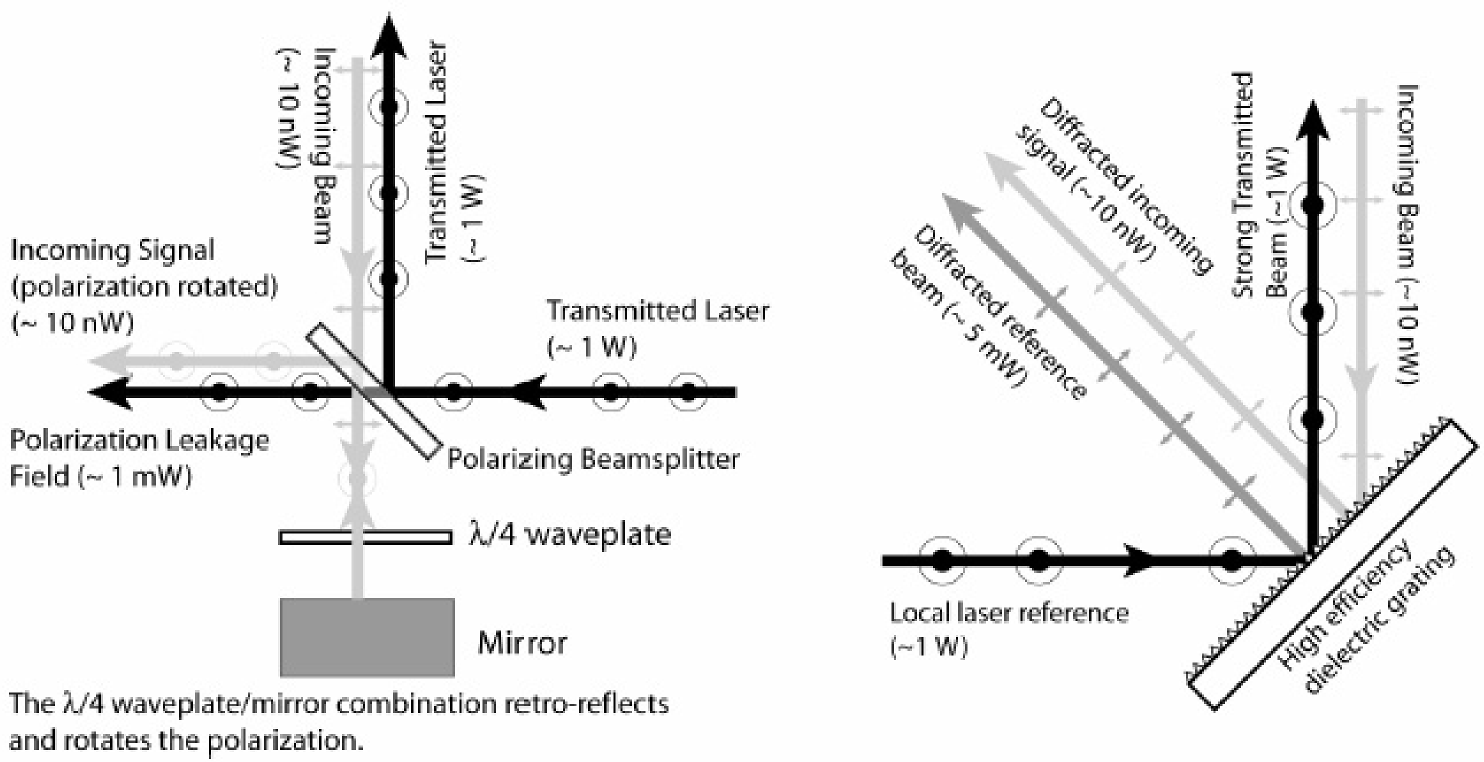
- **TOTAL ΔV: 580 m/sec**
(including 10 m/s course corrections)
  - Each LM spacecraft has 100 m/sec prop. system for insertion / tip-off



Requires 297 kg biprop fuel

APPENDIX D: IMS Details

Grating as a Beam Splitter

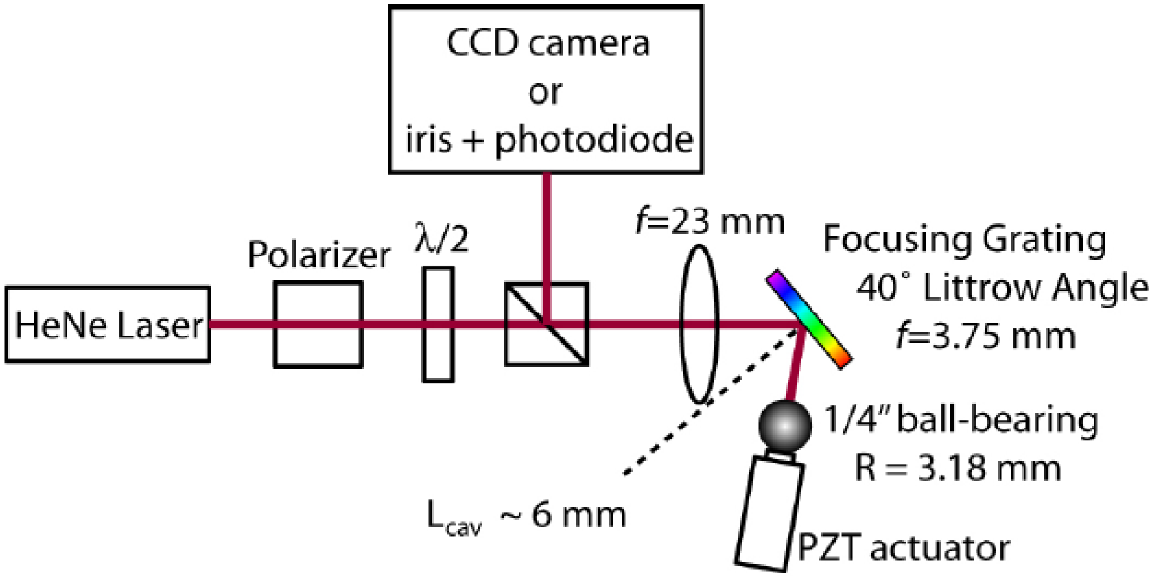


(a) Standard polarizing beam splitter (b) Diffraction grating as a PBS

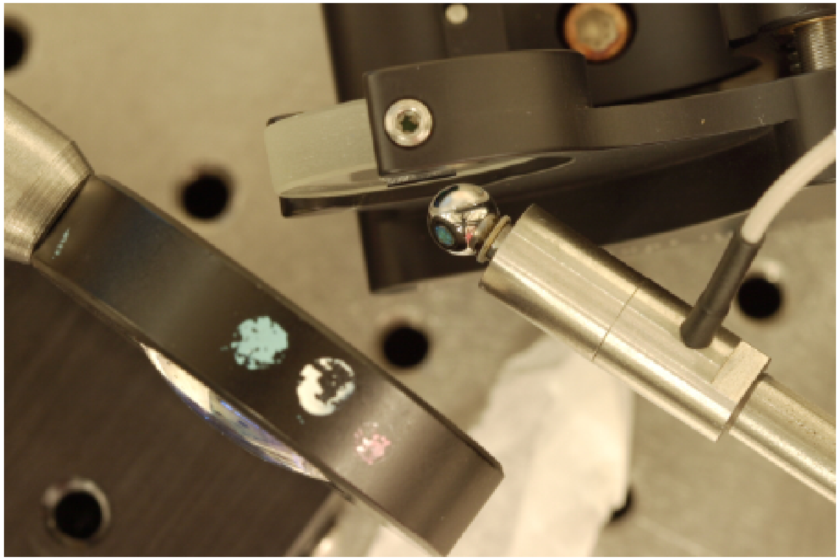
Figure 2.5: Illustration showing how the polarization selectivity of a high-efficiency diffraction grating can replace a conventional polarizing beamsplitter (PBS).

Grating-Sphere Cavity

- **Mode matching and stable low finesse cavity demonstrated**



(a) Layout of the spherical grating cavity



(b) Picture of the cavity

Figure A.1: Schematic and photograph of focusing grating cavity used to demonstrate successful mode-matching using a spherical end-mirror.

Phasemeter

- JPL Phasemeter, based on GPS tech (TRL 5)
  - Accommodate 150 MHz heterodyne frequency if possible
  - Alternate: frequency shift local laser pick-off to reduce heterodyne freq.
    - AOM or EOM with accurate synthesizer
    - ~150 MHz range, μcycle accuracy → requires H-maser or equivalent clock

Point-ahead Angle

- One-way light travel time: 2.25 sec
- Point-ahead angle: 6 ± 0.5 μrad (see APPENDIX B)
- LISA Point-Ahead Angle Mechanism sufficient (TRL 4)
  - Piezo-actuated flex pivot mirror
    - 800 μrad range, 16 nrad/Hz$^{1/2}$ angular jitter, 2 pm/Hz$^{1/2}$ piston jitter

Metrology Error Budget

Noise source	Noise at 3 mHz (pm/Hz$^{1/2}$)
Shot noise	4
Optical path-length changes*	5
Residual clock noise	3
Residual laser phase noise	3
Total (RSS)	8

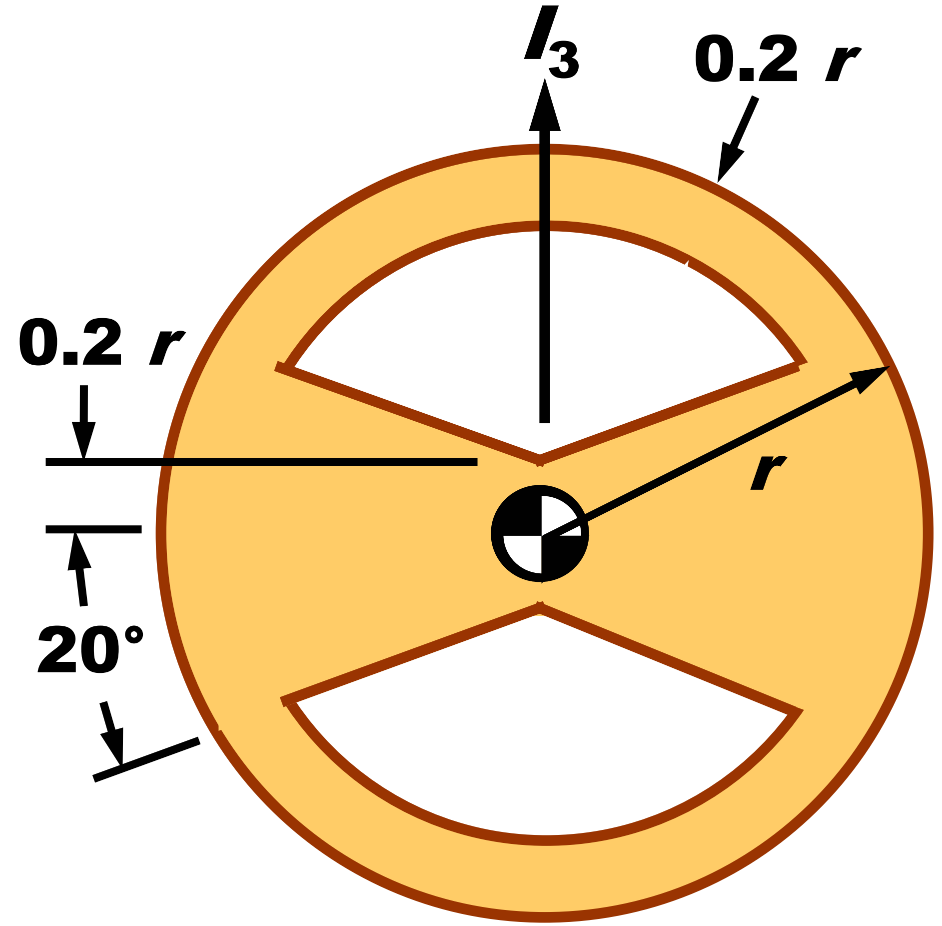
*Dominated by telescope

- Noise is flat above 3 mHz & 1/f^2 below
- Shot noise reduced w.r.t. LISA due to shorter arm (20 cm tel.)
- Residual clock noise ~10 larger due to larger Doppler rate

APPENDIX E: MGRS Details

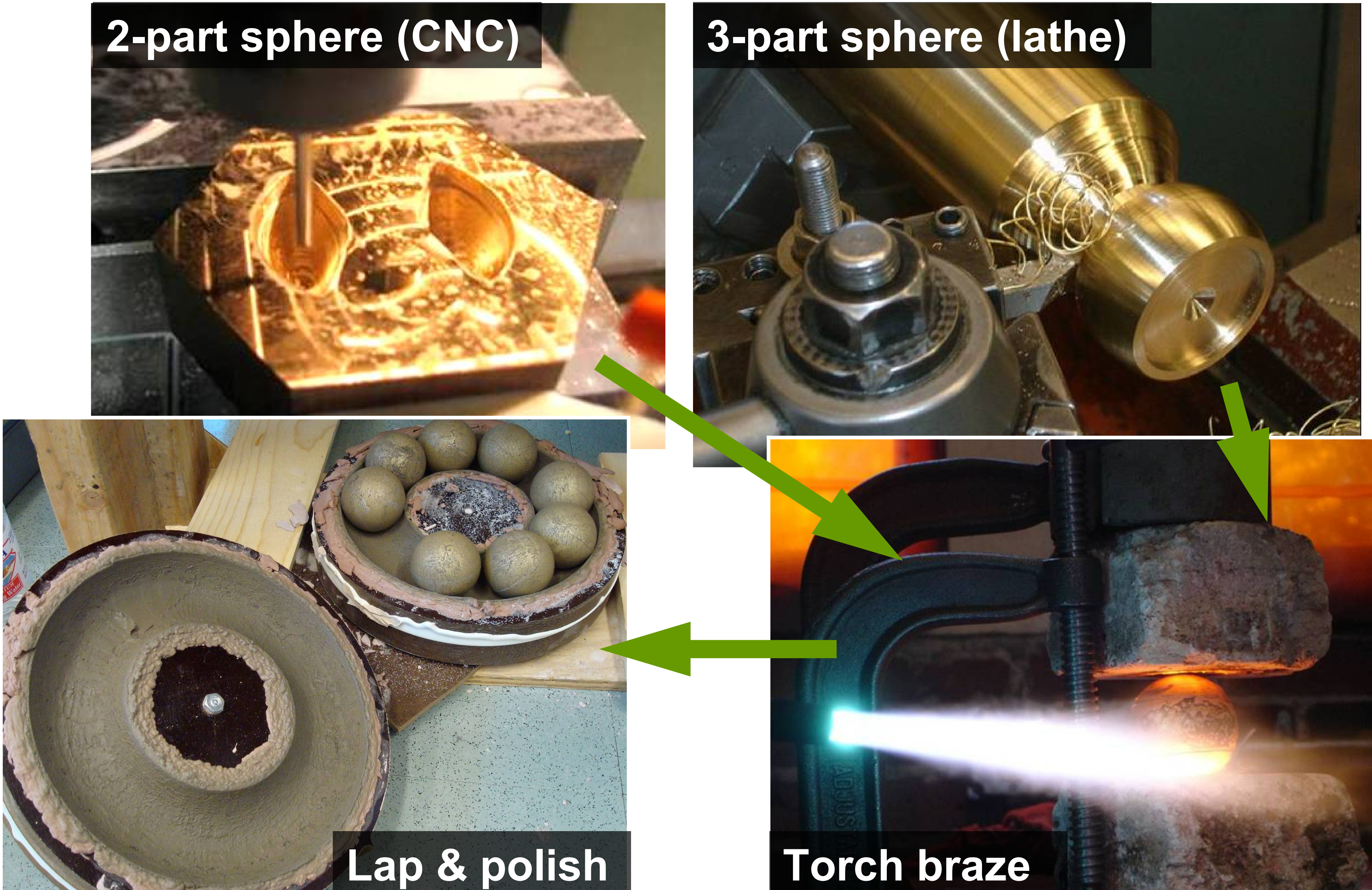
Test Mass Geometry

- **TM hollowed out**
  - $\Delta I / I > 0.1 \rightarrow$ polhode > 0.3 - 1 Hz for spin = 3 - 10 Hz
  - Density loss < 20%
  - Symmetric $\rightarrow$ IMS modulation is sinusoidal
- **External geometry requirements**
  - Spherical to < 30 nm
    - GP-B, Honeywell rotor ~ 10 nm
  - Mass unbalance < 300 nm
    - GP-B rotor ~ 10 nm



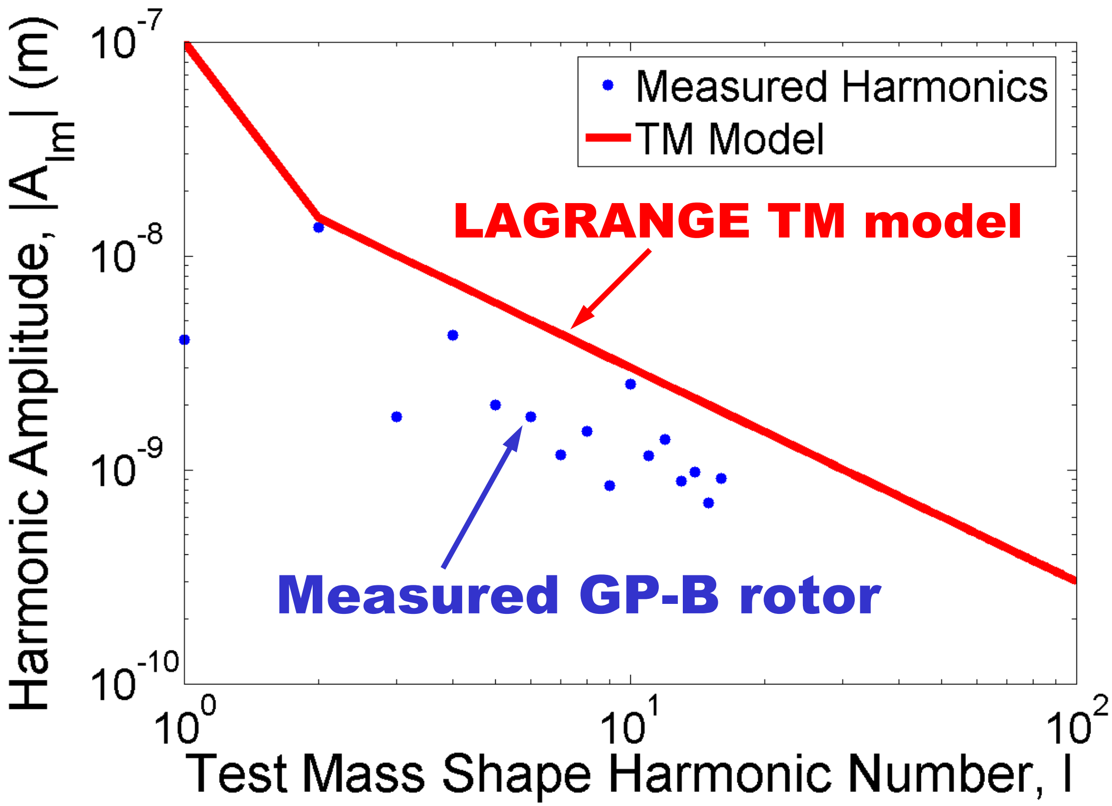
Optimal Geometry

Brass TM Fabrication Demo



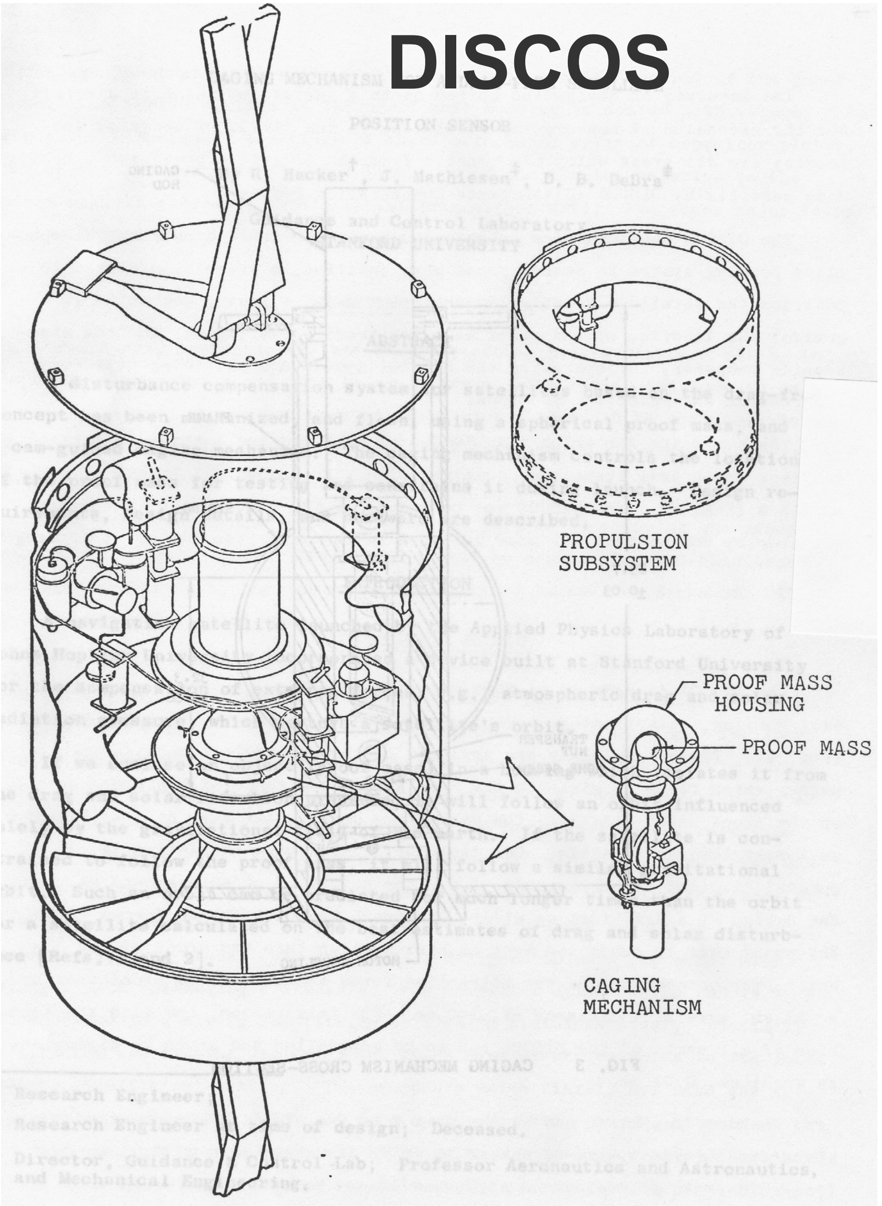
Path Length Changes due to Geometry

- **Lapping and polishing minimizes *slope* of surface**
  - **Amplitude of shape harmonics ∝ 1 / spatial size (l)**
- **Laser spot averages harmonics < 1 mm**
- **Spin averages all but axisymmetric harmonics**
  - **Out-of-plane motion → patch length changes**
  - **S/C jitter < 3 μrad/Hz$^{1/2}$ → < 1 pm/Hz$^{1/2}$**
  - **Orbit: 5°/27.3 days → 1 pm/Hz$^{1/2}$ at 1 mHz**
  - **LISA orbit: 60°/1 year → 10 pm/Hz$^{1/2}$ at 0.1 mHz**



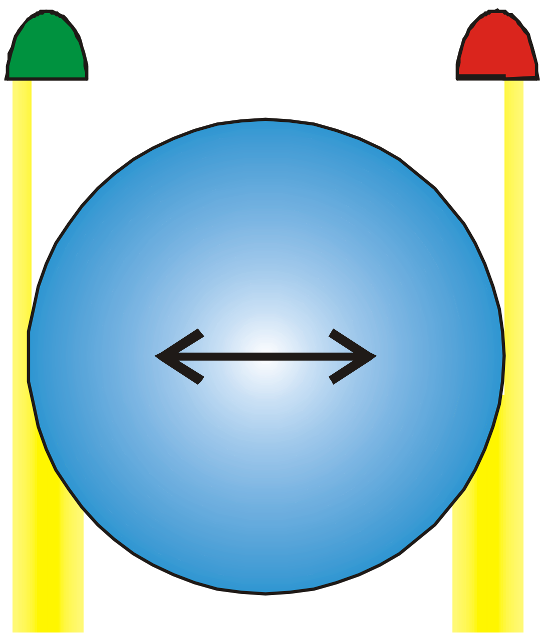
Test Mass Caging & Release

- DISCOS flight proven mechanism
  - Jack screw holds TM against housing
  - Successfully demonstrated twice on-orbit, 2nd time after 6 month caging
- After release, μN thrusters 'catch up' with inertial TM
- Capture time only function of residual velocity & max thrust
  - mm/sec bounces ~ handling on ground
  - Does not require inelastic collisions
  - DISCOS capture time: ~100 sec
    - On-orbit capture matched simulations
  - LAGRANGE: ~1000 sec

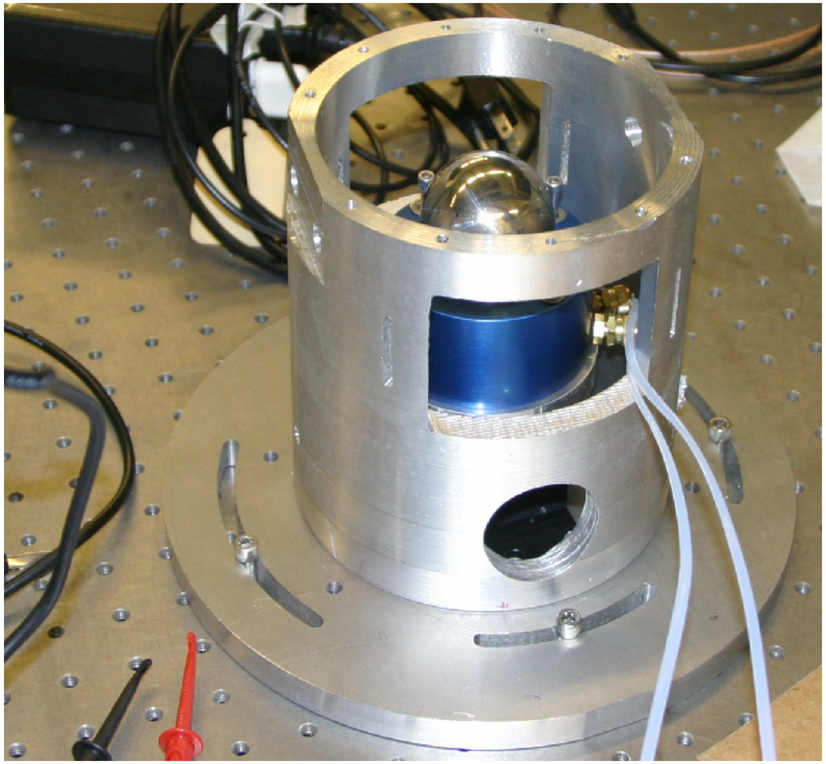


Differential Optical Shadow Sensor

- nm/Hz$^{1/2}$ accuracy over mHz-1Hz, ~mm dynamic range
- Demonstrated to 2 nm/Hz$^{1/2}$ at 1 Hz, 20 nm/Hz$^{1/2}$ at 1 mHz
  - Limited by environment, not the sensor



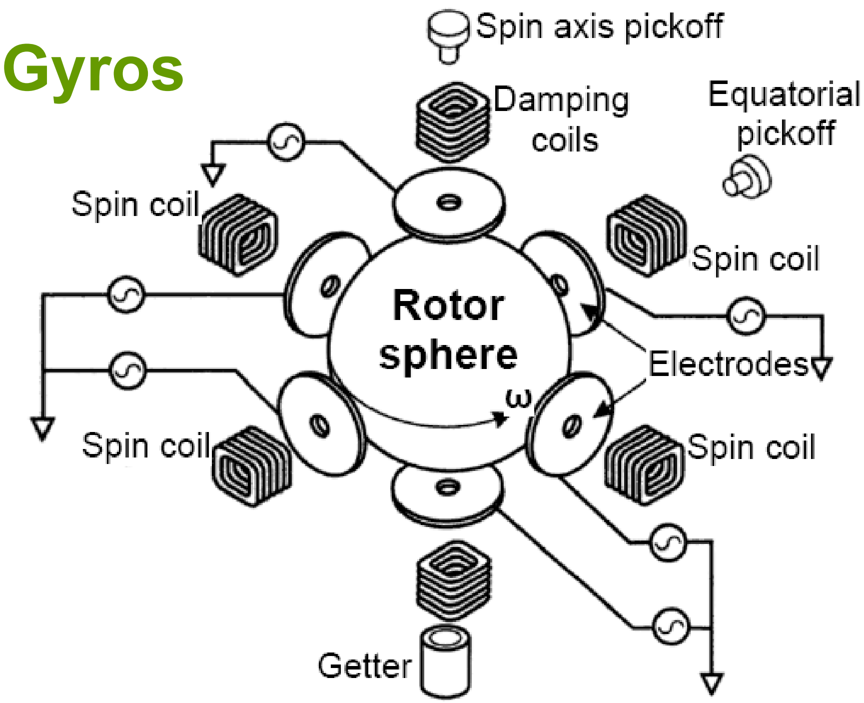
DOSS scheme



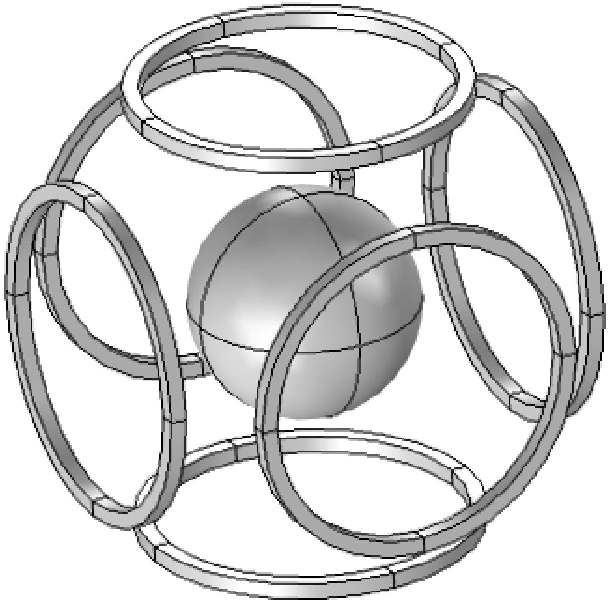
DOSS prototype at Stanford

Test Mass Spin-up Coils

- **Based on flight proven Honeywell Gyros**
  - **6 Helmholtz-like coils**
    - **4 in orbit-plane for spin-up (ac)**
    - **2 top/bottom for polhode damping & spin axis alignment (dc)**
  - **Open-loop system (on/off)**
  - **Spin-up to 10 Hz in few hours**



Honeywell ESG



← LAGRANGE Spin-up Coil

UV LED Charge Control

- Charge control by UV photoemission using 254 nm line of an rf mercury source successfully demonstrated on GP-B
- LAGRANGE: Newer commercial UV LEDs (240-255 nm)
  - Fast-switchable (> 100 MHz) allowing ac charge management through synchronization with bias electrode
  - 10 mW $\rightarrow$ 10 μW at 252 nm
- Passive charge management possible for LAGRANGE
  - Virtual wire between TM and S/C (~5 pF capacitance)
- Space qualification complete
  - Lifetime: >5 years
  - Radiation
  - Shake, bake, shock

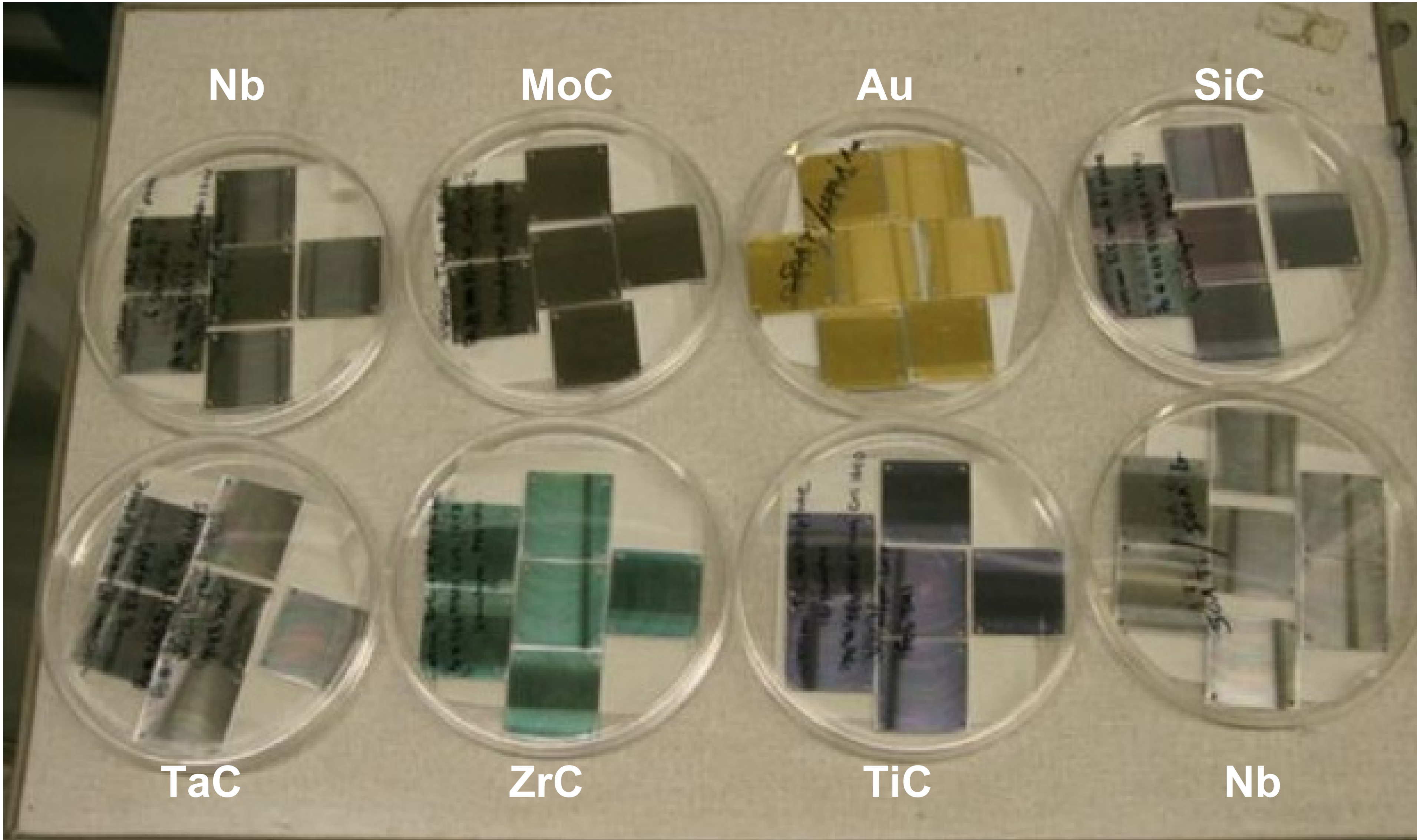
Test Mass Coating

- Carbide compond (e.g. SiC or ZrC)
  - Hard, conductive, reflective, permits UV charge control, measured patch potentials similar to gold (see APPENDIX E)

Property	Au	Carbides
Patch potentials in 10^{-7} Pa after bake-out, 3 mm tip	~ 10 mV	~ 6mV
Patch potentials in “regular environment” (from GP-B, LPF, Casimir force exp., etc)	20-80 mV	20-80 mV
Hardness	Low	High
“Sticktion”	Low	High
Optical reflectivity (measured)	High	High
UV Photoemission (electrons/photon at 252 nm)	3.4×10^{-7}	Au × (1.2-1.9)

- Carbides appear better choice for test mass coating
  - Patches dominated by contamination
  - Error budget: patches 100 mV dc, 100 μV/Hz$^{-1/2}$ (1 mHz / *f*) [GP-B, Trento]

Coatings Tested at Stanford



Kelvin Probe for Measurements of Patch Effects

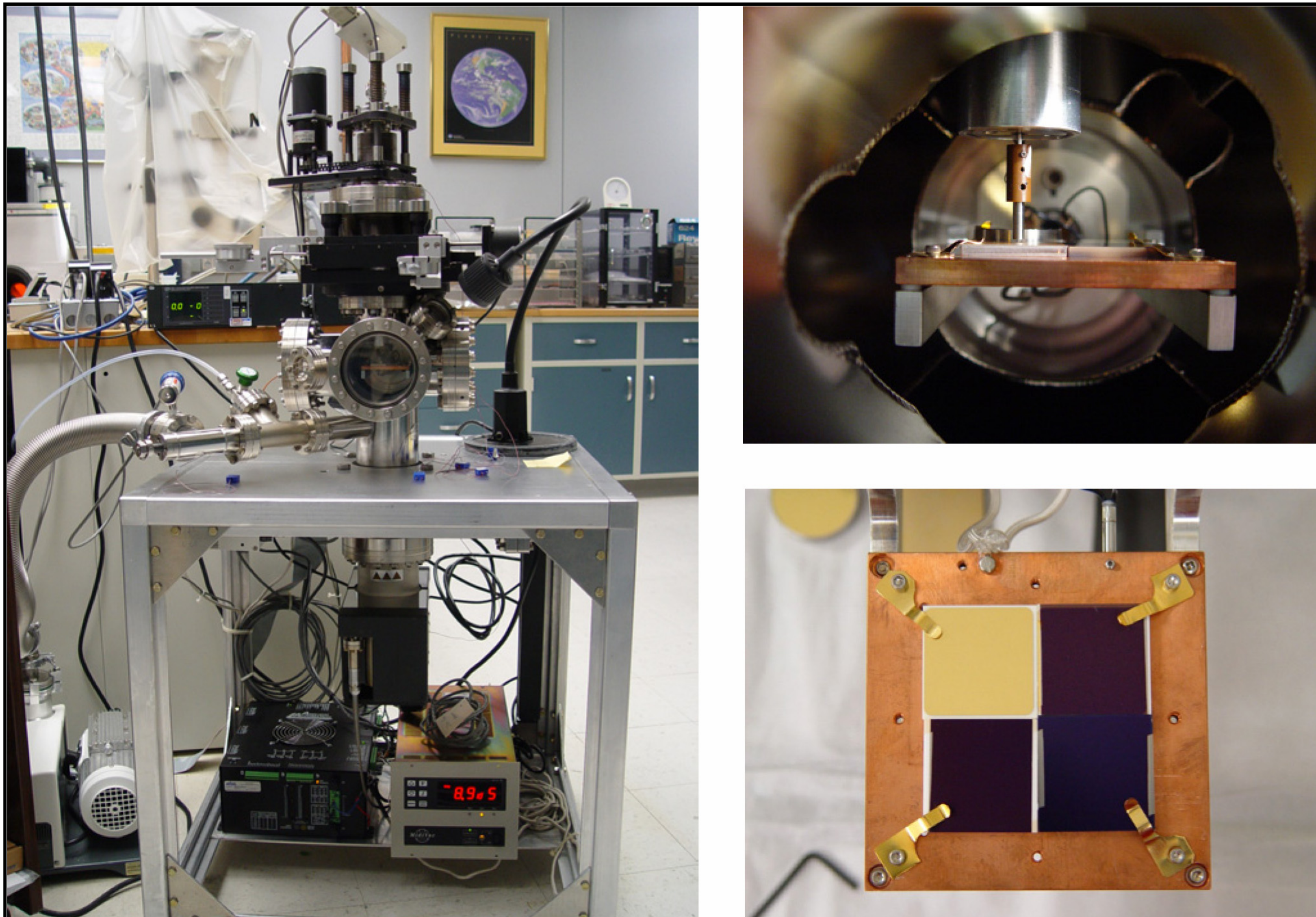
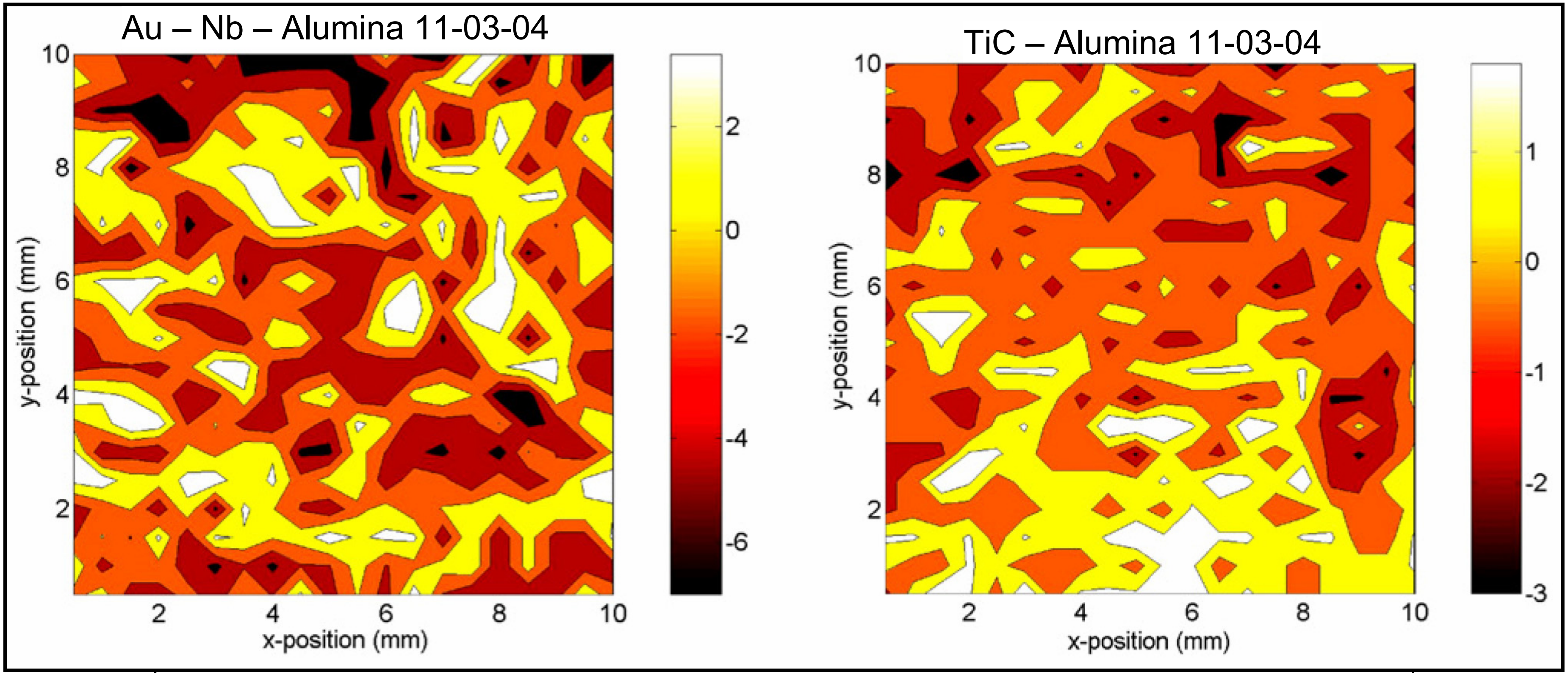


Figure 1. The Kelvin probe at GSFC is shown on the left. A view of the stainless steel probe (diameter 3 mm) positioned above the samples is shown upper right. An example of samples ready for measurements is shown lower right. The samples are (clockwise from upper left): AuNb on alumina, DLC on beryllia, DLCTiAuTi on titanium, DLC on alumina. More details of these coatings, including explanation of the abbreviations, are given in table 1.

Kelvin Probe for Measurements For Au and TiC



Sample name	Date (m/d/yr)	CPD peak to peak and range (mV)	Standard deviation σ_p (mV)
Data taken in November 2004			
AuNb on alumina	11-02-04	12 (−177 to −189)	2.1
AuNb on alumina	11-03-04	10 (−180 to −190)	1.4
TiC on alumina	11-03-04	6 (−325 to −331)	1.2
TiC on alumina	11-03-04(1)	6 (−325 to −331)	

Kelvin probe measurements: investigations of the patch effect with applications to ST-7 and LISA
N. A. Robertson *et al Class. Quantum Grav.* **23**(7) pp. 2665-2680 (2006) http://iopscience.iop.org/0264-9381/23/7/026

Photoemission efficiency of carbide films

Material	Current Source Drive Voltage (mV)	LED Current (mA)	Sphere Voltage	Sample Voltage	Sample Current (LED off)	Sample Current (LED on)	Vacuum Pressure (torr)	Sample current (net)	# electrons	# photons	QE mean	QE, relative to Au
Au	**53**	**10**	**5**	**-5**	**-4.50E-13**	**3.15E-12**	**2.1E-03**	**3.60E-12**	**2.25E+07**	**6.41E+13**		
	53	**10**	**5**	**-5**	**-1.50E-13**	**3.45E-12**	**6.5E-04**	**3.60E-12**	**2.25E+07**	**6.41E+13**	3.40E-07	1.00
Nb	**53**	**10**	**5**	**-5**	**-4.30E-13**	**4.71E-12**	**2.1E-03**	**5.14E-12**	**3.21E+07**	**6.41E+13**		
	53	**10**	**5**	**-5**	**-3.40E-13**	**5.80E-12**	**5.7E-04**	**6.14E-12**	**3.84E+07**	**6.41E+13**	5.64E-07	1.66
SiC	**53**	**10**	**5**	**-5**	**-4.40E-13**	**3.56E-12**	**1.8E-03**	**4.00E-12**	**2.50E+07**	**6.41E+13**		
	53	**10**	**5**	**-5**	**-3.50E-13**	**4.25E-12**	**5.8E-04**	**4.60E-12**	**2.88E+07**	**6.41E+13**	4.26E-07	1.25
TiC	**53**	**10**	**5**	**-5**	**-1.12E-12**	**3.60E-12**	**2.0E-03**	**4.72E-12**	**2.95E+07**	**6.41E+13**		
	53	**10**	**5**	**-5**	**-2.00E-13**	**4.70E-12**	**4.7E-04**	**4.90E-12**	**3.06E+07**	**6.41E+13**	4.51E-07	1.32
ZrC	**53**	**10**	**5**	**-5**	**-6.70E-13**	**3.65E-12**	**2.0E-03**	**4.32E-12**	**2.70E+07**	**6.41E+13**		
	53	**10**	**5**	**-5**	**-3.50E-13**	**3.52E-12**	**5.1E-04**	**3.87E-12**	**2.42E+07**	**6.41E+13**	3.92E-07	1.15
Mo_2C	**53**	**10**	**5**	**-5**	**5.00E-13**	**5.75E-12**	**2.0E-03**	**5.25E-12**	**3.28E+07**	**6.41E+13**		
	53	**10**	**5**	**-5**	**-2.50E-13**	**6.83E-12**	**5.5E-04**	**7.08E-12**	**4.43E+07**	**6.41E+13**	6.48E-07	1.90
TaC	**53**	**10**	**5**	**-5**	**-7.00E-13**	**5.42E-12**	**1.7E-03**	**6.12E-12**	**3.83E+07**	**6.41E+13**		
	53	**10**	**5**	**-5**	**1.00E-13**	**6.75E-12**	**5.2E-04**	**6.65E-12**	**4.16E+07**	**6.41E+13**	6.27E-07	1.84

Acceleration Noise Budget