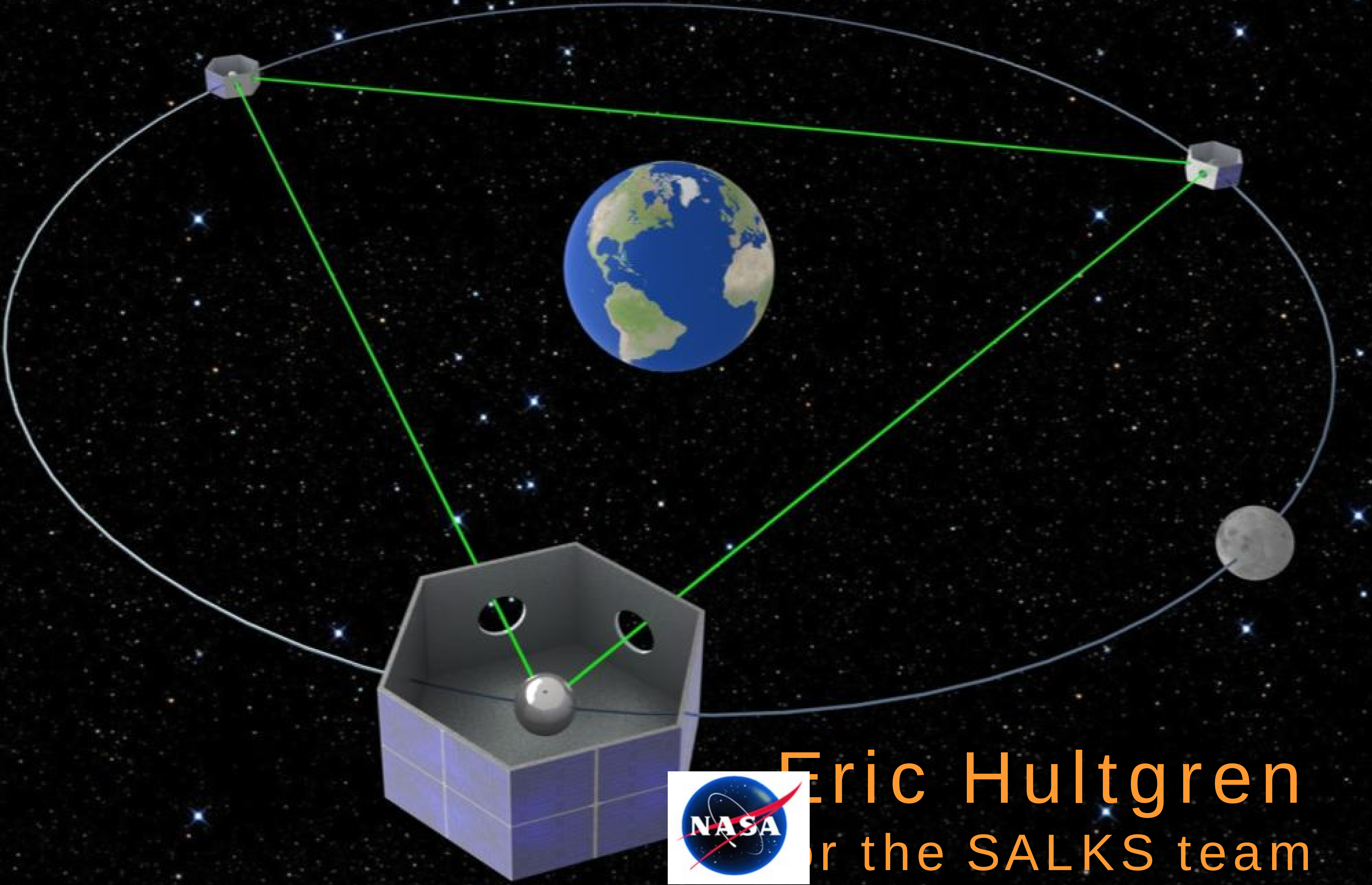
LAser GRavitational-wave ANtenna in GEocentric Orbit



Eric Hultgren

or the SALKS team

Background

- **LAser GRavitational-wave ANtenna in GEocentric Orbit was proposed originally as a response to NASA's Request for Information (RFI) titled "Concepts for the NASA Gravitational Wave Mission" NNH11ZDA019L**
  - **One of 17 submissions**
  - **One of two called "LAGRANGE"**

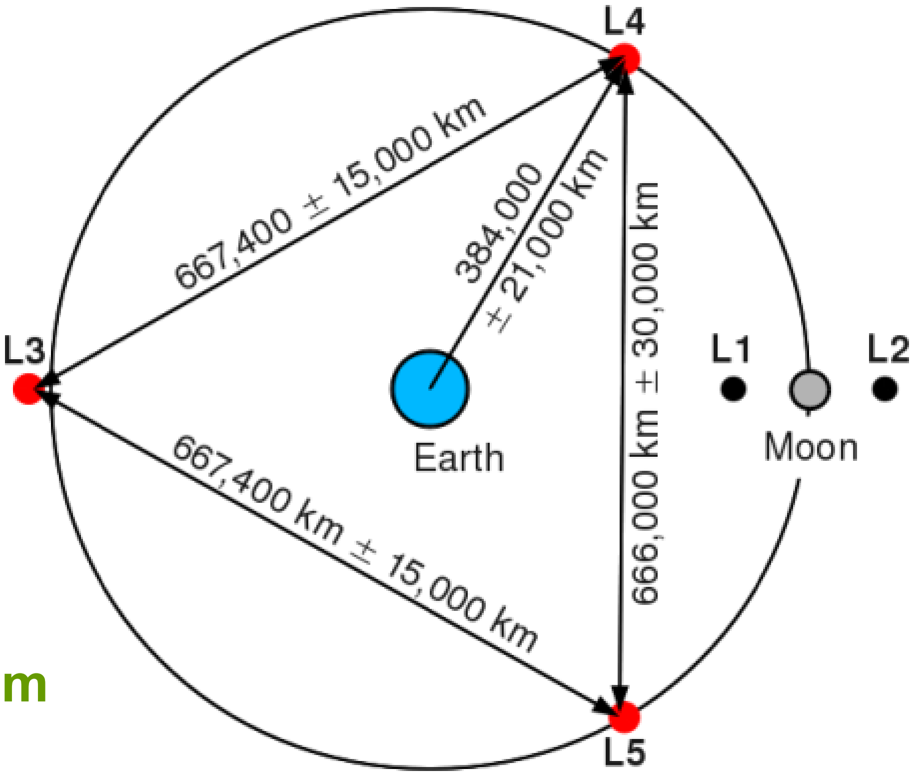
- **Reference:**
  - **Conklin, et. al. "LAGRANGE: LAser GRavitational-wave Antenna at GEo-lunar Lagrange points" arXiv:1111.5264v2 [astro-ph.IM] 5 Dec 2011**

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

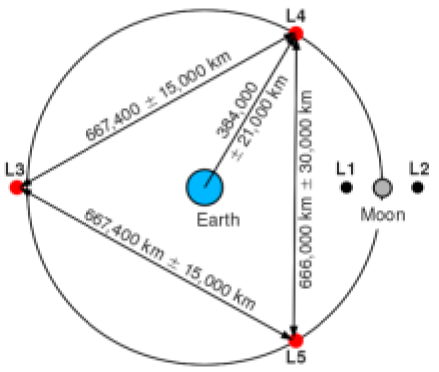
Design Overview

- **3 identical drag-free spacecraft & payloads**
- **Communications & cost drives decision for geocentric orbit**
- **Minimum complexity**
  - **1 spherical TM per S/C**
  - **1 laser (+1 spare) & bench per S/C**
  - **2 telescopes, in-field pointing**
  - **7 DoF control per spacecraft**
    - **Translation**
    - **Rotation**
    - **Breathing angle**
- **Continuous, simultaneous, fast comm**
  - **Fixed antennas on each S/C**
  - **Mbps through NASA GN (11 m class), ~1 hour data latency**
- **5 year mission lifetime**



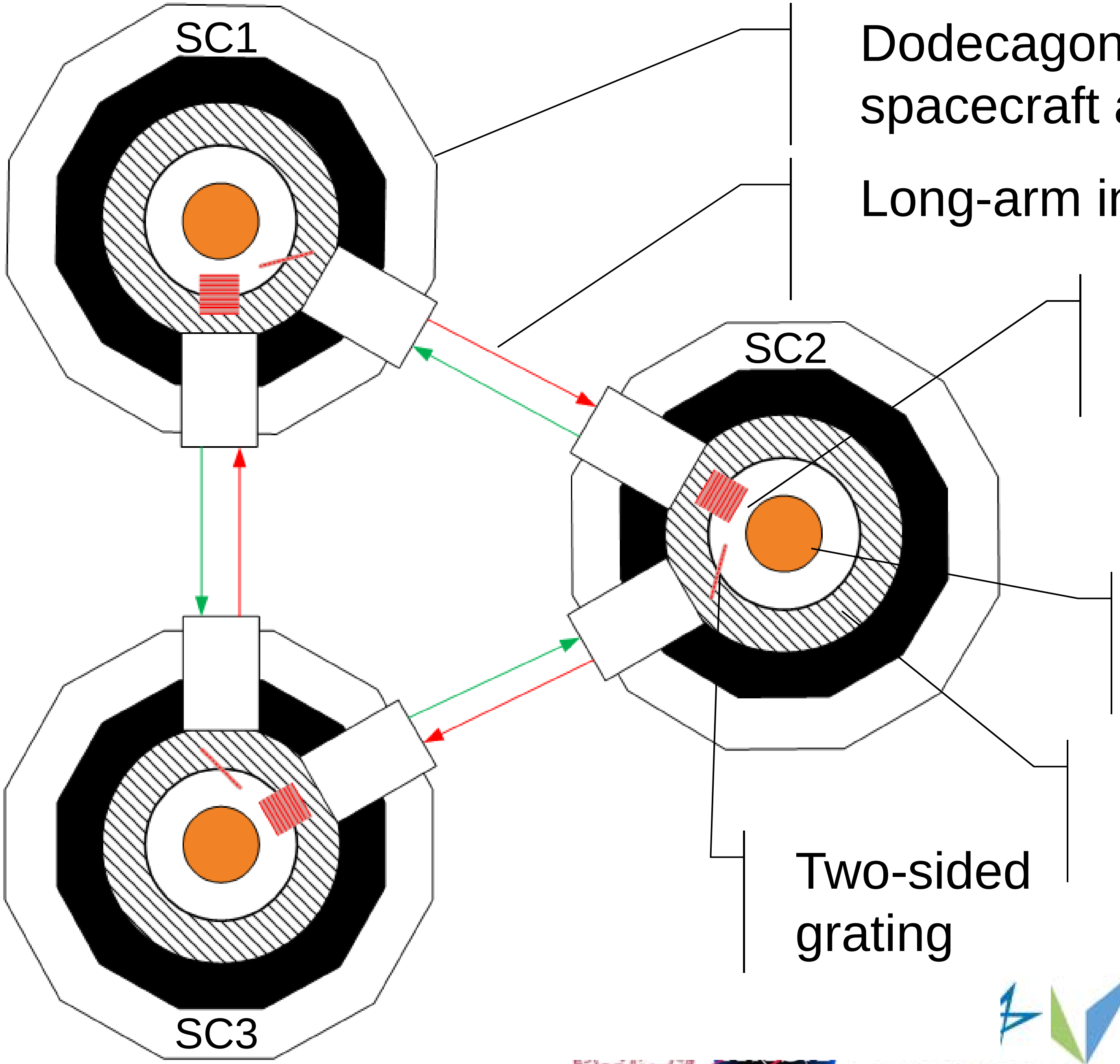
Orbit Selection

- **~ 3 stable, near-Earth orbits considered**
  1. **High retrograde: ~600,000 km from Earth (Hellings, OMEGA 1998)**
  2. **Earth-moon L3, L4, L5: 384,000 km from Earth**
  3. **Earth-Sun L2 circular Halo: ~1.5 Mkm from Earth (must be checked)**
- **EM L3, L4, L5 chosen for detailed study, 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**



	EM L3,L4,L5	LISA
Arm length	670 000 km	5 000 000 km
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

System Overview



Dodecagon ring with spacecraft avionics

Long-arm interferometer

Short-arm interferometer, 35mm gap size

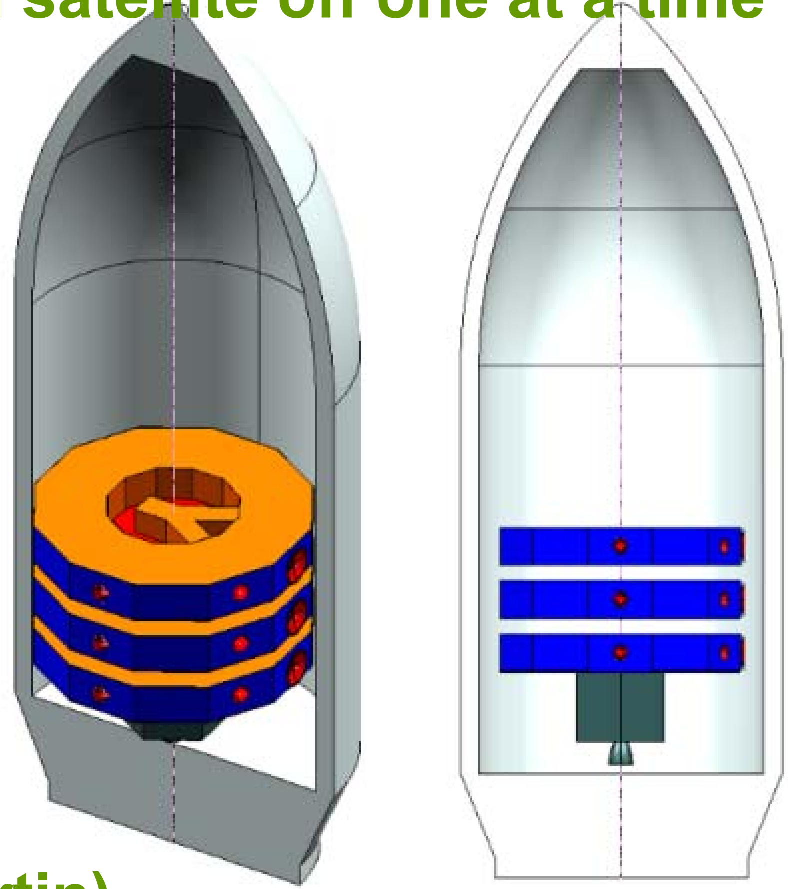
AuPt Test Mass 2.9kg

Optics Bench

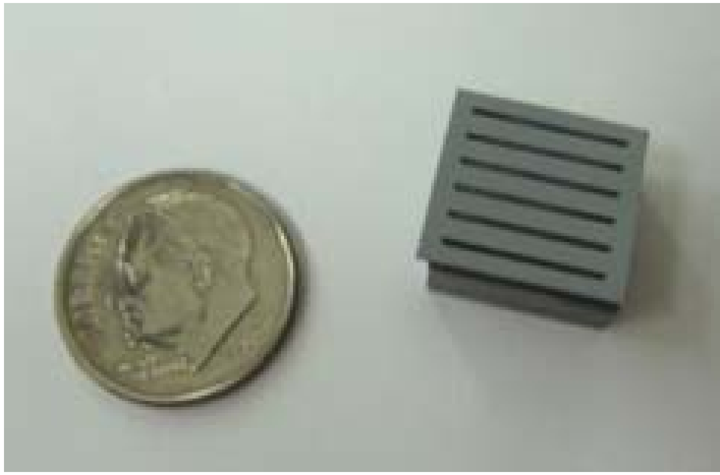
Two-sided grating

Spacecraft & Mission Design

- S/C based on existing LM S/C, TRL >6
  - ~3 m × 0.7 m, 300 kg, 500 W
- Single propulsion module drops each satellite off one at a time
- 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
- ROM cost $950M FY12 (Lockheed Martin)
  - Includes 30% reserve



Spacecraft Propulsion

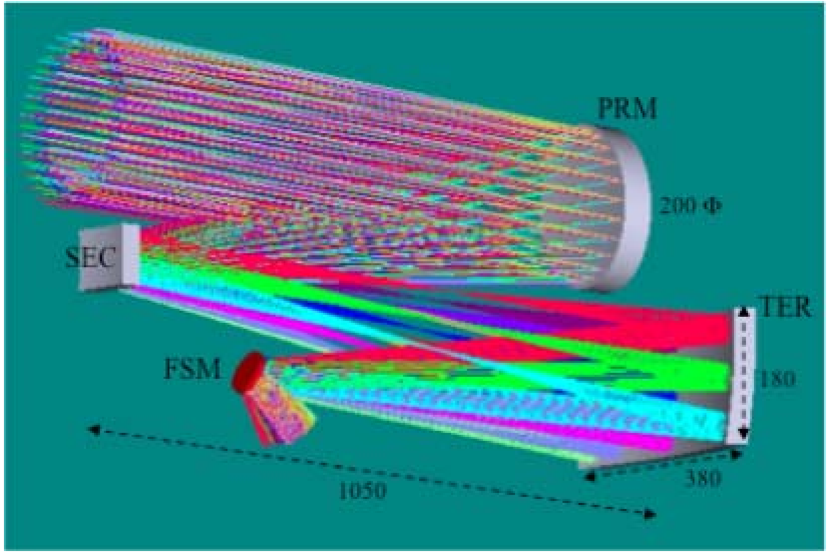


- Initial conditions maximize time each S/C remains at L-point
  - Station keeping every 6-12 months (L3)
  - Station keeping capability recommended for any orbit
- Drag-free & attitude via μN ion thrusters
- NGO evaluating alternates to FEEPs
- SRI micro-fabricated ion thruster attractive alternate 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

Telescope Design

- **Two-stage design required for**
  - **5 degree Field or Regard due to constellation geometry changes**
  - **1mm beam size on optical bench**
- **20 cm aperture**
- **±2.5 deg beam steering**
- **5 pm path-length stability**
- **Low CTE composite metering structure**
- **Stage one is 6:1 3-mirror Anastigmat (TMA)**
  - **Leads to ±15 deg steering mirror near exit pupil**
- **mK temperature control**

Stage One Design: TMA



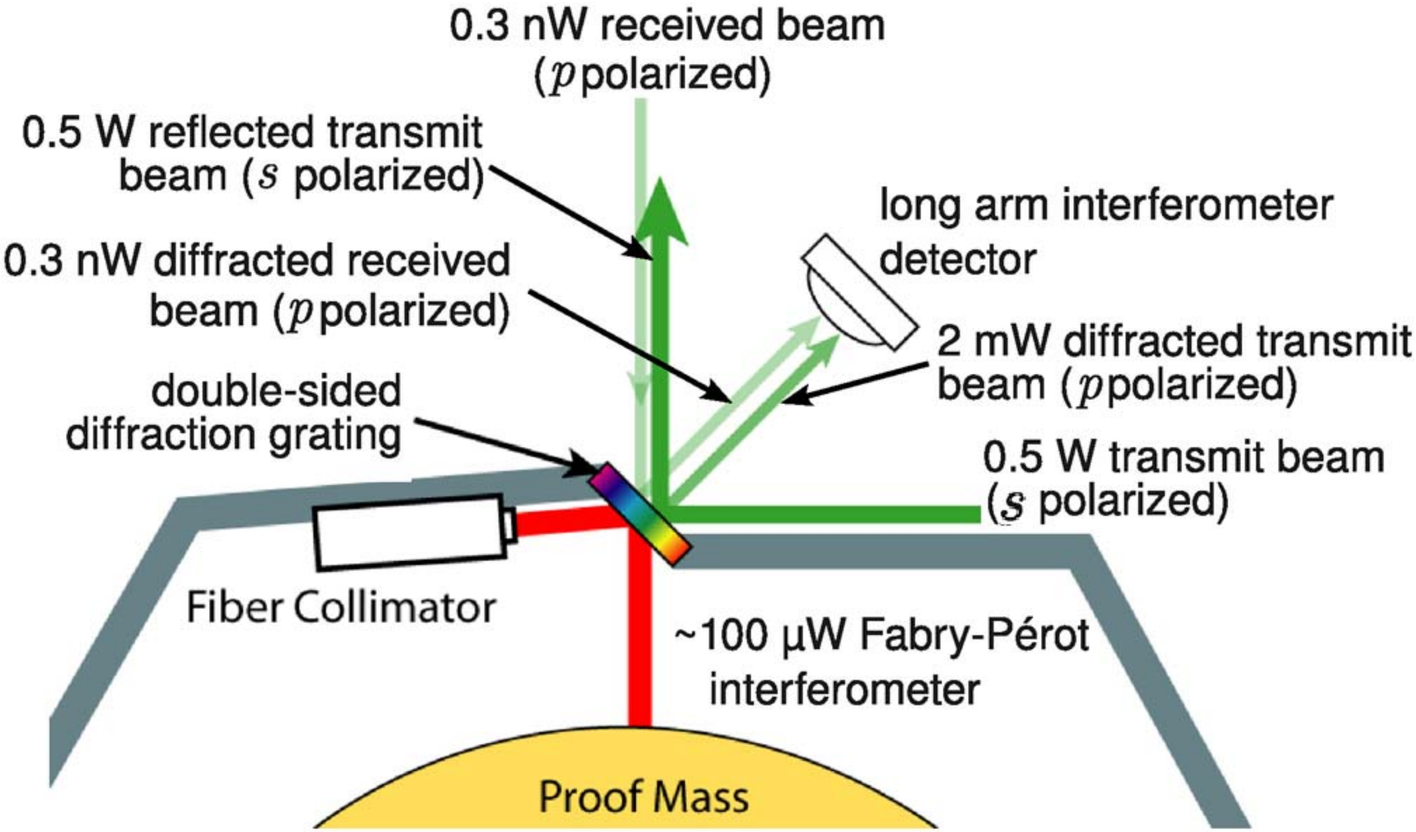
Stage Two gives additional 33x magnification

Interferometric Measurement System

- **IMS follows LISA scheme with some differences**
- **1 W Nd:YAG NPRO (1064 nm), split to feed both arms**
- **Split interferometry: long-arm / short-arm interferometers**
  - **Short-arm (TM to optics bench): grating 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**
- **150 MHz Doppler frequency**
  - **Use modified LISA phasemeter**
- **6 µrad point-ahead angle: LISA Point Ahead Angle Mirror (PAAM) by TNO (TRL 4)**

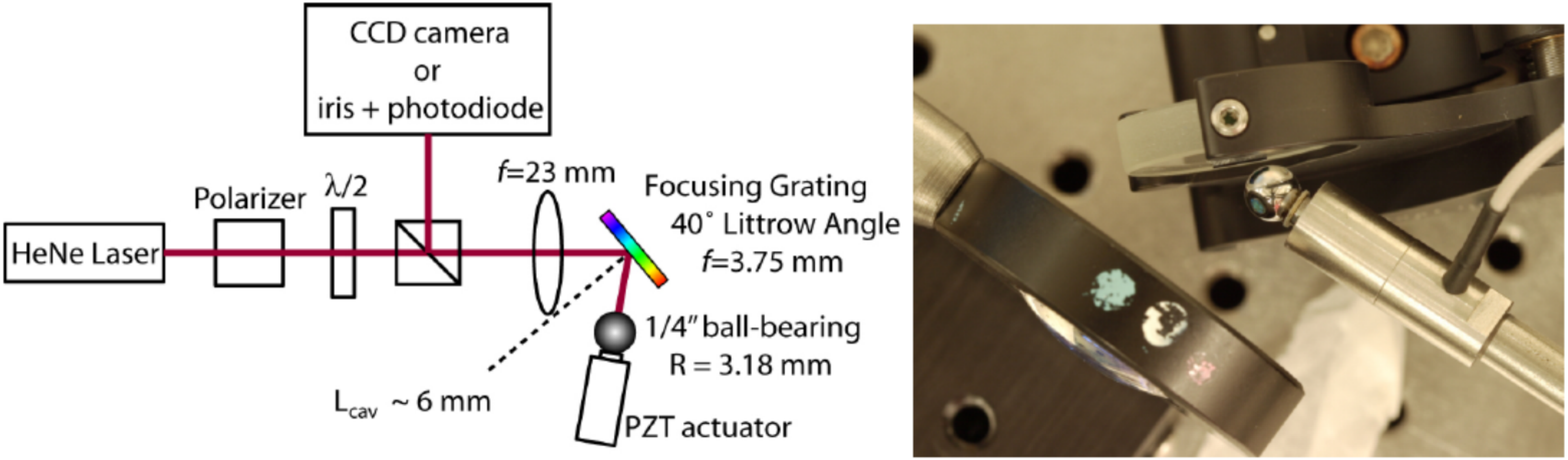
Interferometry with a Diffraction Grating

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



Grating-Sphere Cavity

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



(a) Layout of the spherical grating cavity

(b) Picture of the cavity

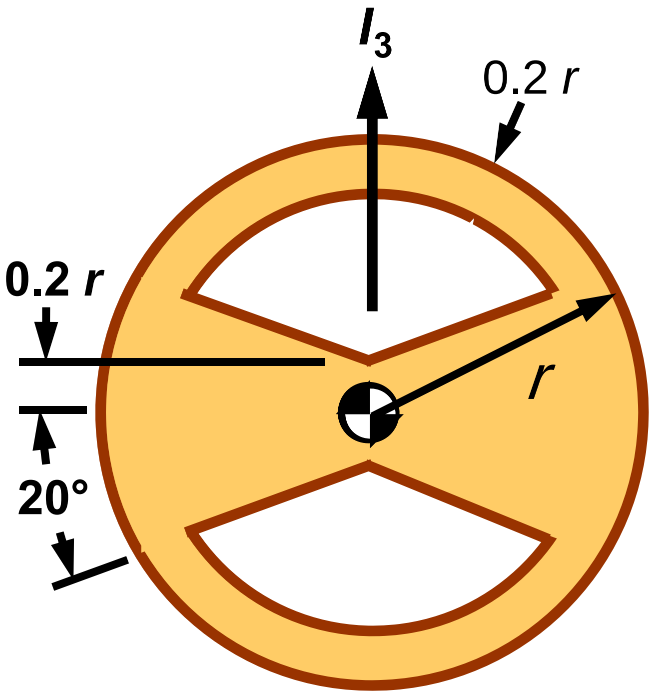
Figure A.1: Schematic and photograph of focusing grating cavity used to demonstrate successful mode-matching using a spherical end-mirror.

Advantages of a Spherical GRS

1. **No TM forcing or torquing**
   - Neither electrostatic support nor capacitive sensing required, reducing disturbances & complexity
2. **Optical readout enables 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)**

Test Mass

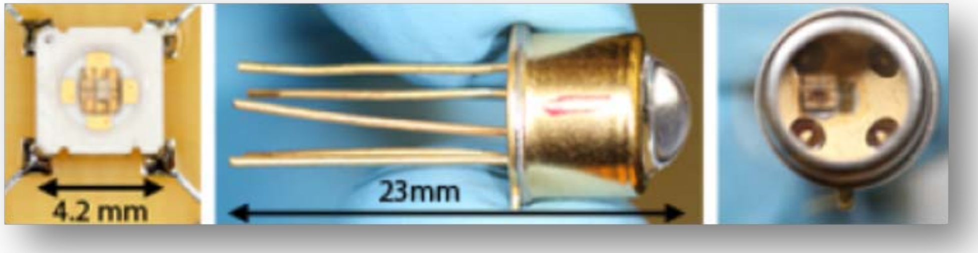
- **Test mass: 70%/30% Au/Pt (LISA)**
  - **Alternate: Berglide (2%/97.5%/0.5% Be/Cu/Co)**
- **Spinning (3-10 Hz) average all but axisymmetric irregularities**
  - **Out-of-plane motion → patch length changes 1 pm/$\text{Hz}^{1/2}$ at 1 mHz**
- **Hollowed out sections ($\Delta I/I = 0.1$) shift polhode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



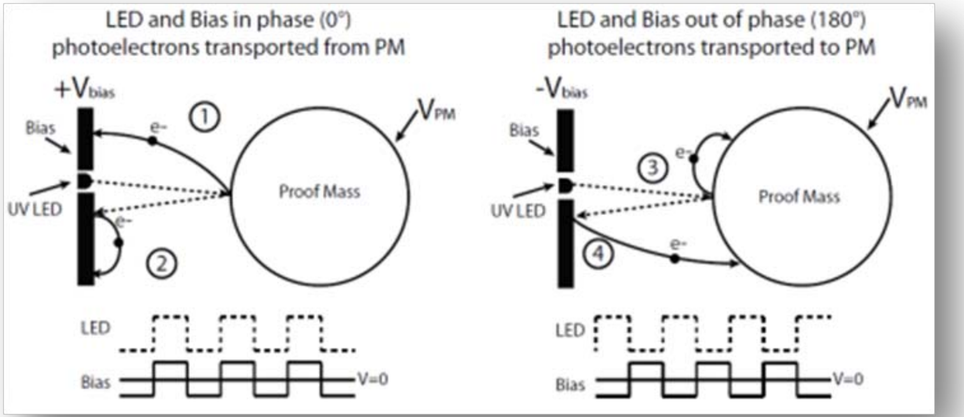
Optimal geometry

Insert Charge Management Here

- **Charge accumulation on proof mass: 50-200 e-/sec**
- **Charge control by UV photoemission using 254 nm line of an rf mercury source successfully demonstrated on GP-B**
- **Newer commercial UV LEDs (240-255 nm)**

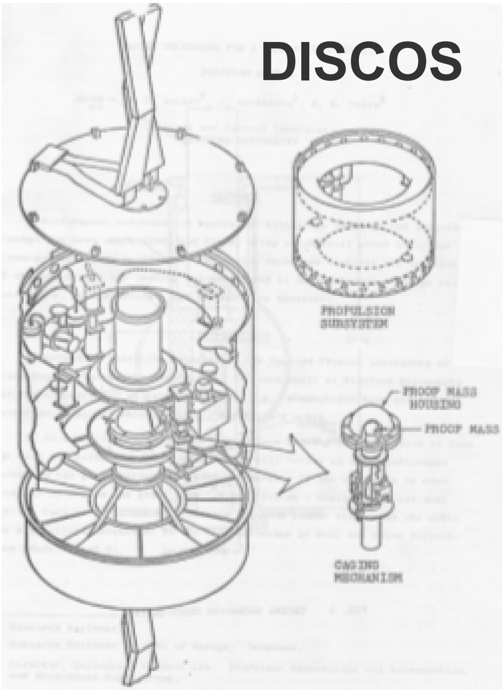


Fast-switchable (> 100 MHz) allowing ac charge management through synchronization with bias electrode



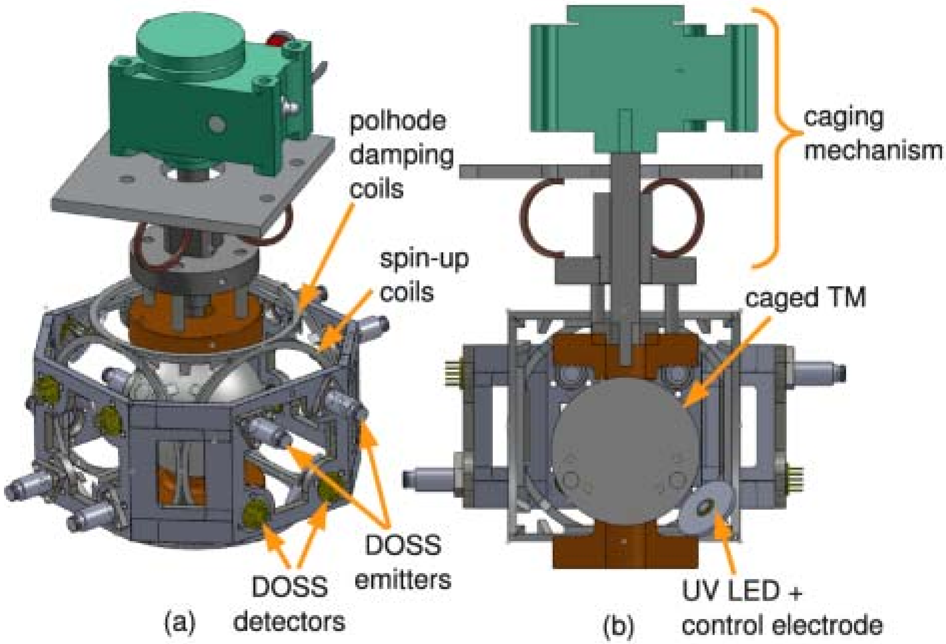
Test Mass Caging & Release

- **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**

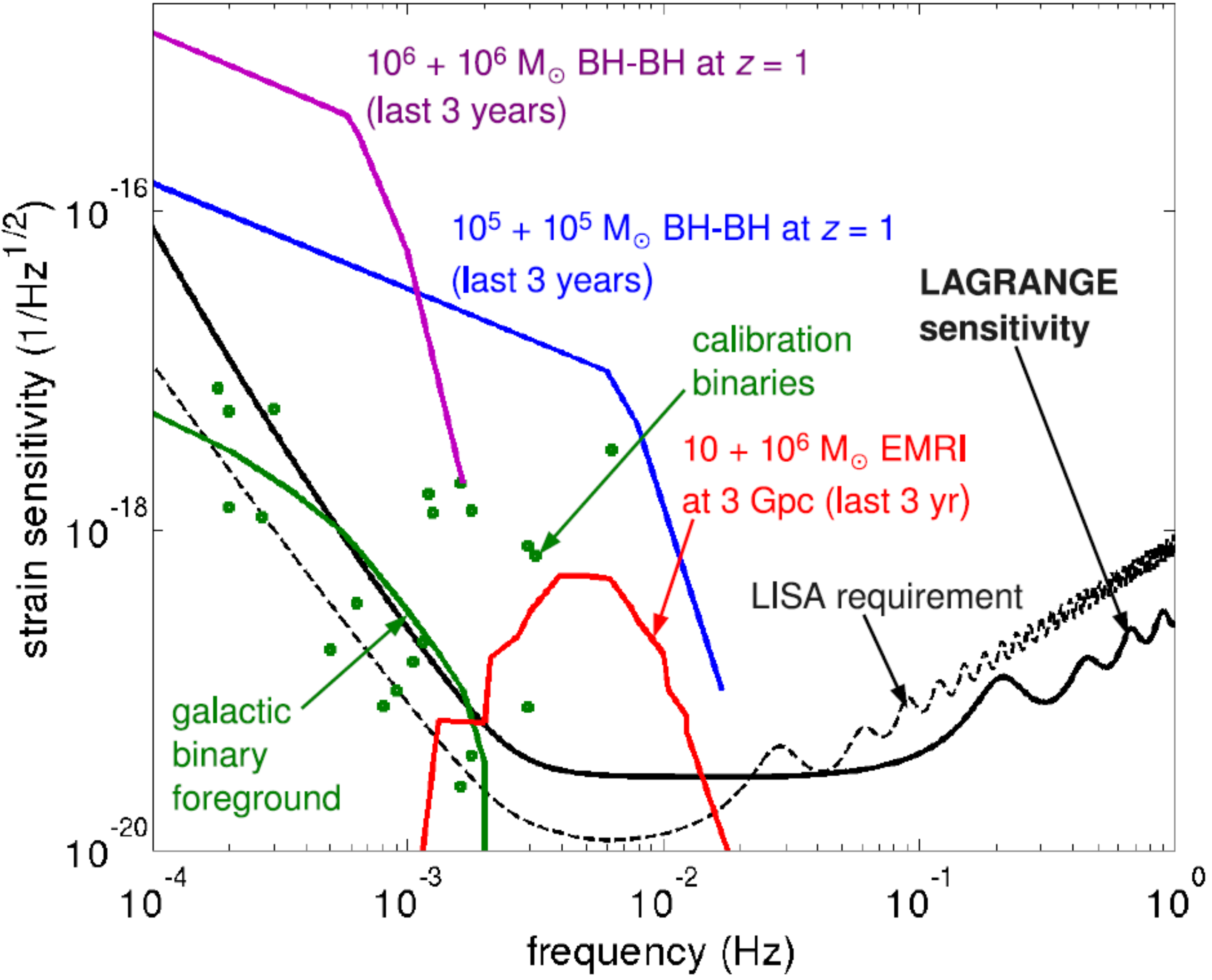
DISCOS capture time: ~100 sec
Proposed: ~1000 sec



Strain Sensitivity

- **Arm length: ~670,000 km**
- **Metrology: 8 pm/Hz$^{1/2}$ at 3 mHz**
- **Acceleration noise: 3×10^{-15} m/sec^2**
- **Sensitivity 2x less than LISA below 20 mHz**
- **Below 2 mHz galactic binary confusion sets limit**
- **Maintains most important science objectives of LISA**

Supermassive Black Hole Binaries
Extreme Mass Ratio Inspirals



The End