Laser GRavitational-wave ANtenna in GEocentric Orbit

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**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:
**The SALKS Collaboration**

<table>
<thead>
<tr>
<th>Stanford</th>
<th>NASA ARC</th>
<th>Lockheed Martin</th>
<th>KACST of Saudi Arabia</th>
<th>SRI International</th>
</tr>
</thead>
<tbody>
<tr>
<td>science payload lead (GRS / IMS)</td>
<td>science orbit, orb. injection, prop. mod.</td>
<td>telescope, spacecraft</td>
<td>science payload, tech development</td>
<td>μN thrusters</td>
</tr>
</tbody>
</table>

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**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 $\Delta v = 580$ m/sec
    - Launch to Trans-Lunar Injection: 7 months with $\Delta v = 475$ m/sec

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**Table: Arm length and other criteria**

<table>
<thead>
<tr>
<th></th>
<th>EM L3, L4, L5</th>
<th>LISA</th>
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</thead>
<tbody>
<tr>
<td>Arm length</td>
<td>670 000 km</td>
<td>5 000 000 km</td>
</tr>
<tr>
<td>$\Delta$ arm length</td>
<td>$\leq 5%$</td>
<td>1%</td>
</tr>
<tr>
<td>Breathing angle</td>
<td>$\leq \pm 5$ deg</td>
<td>$\pm 0.5$ deg</td>
</tr>
<tr>
<td>Range rate</td>
<td>$\leq 150$ m/sec</td>
<td>10 m/sec</td>
</tr>
<tr>
<td>$\Delta$ orbit plane</td>
<td>5 deg</td>
<td>60 deg</td>
</tr>
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</table>
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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

SC1

SC2

SC3
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 FEEP**
- **SRI micro-fabricated ion thruster**
  - Attractive alternate to Busek CMNT or Italian/Austrian FEEP
- Micro-fabricated emission sites produce ions & electrons
- “Digital propulsion”: 100’s – 1,000’s of independent emitters / cm²
  - 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
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)
LISA-like Optical Bench

- PD1: laser freq. stabilization
- PD2: (TM1 − OB1) • x_2
- PD3a/b: (OB1 − OB2) • x_2
- PD4: (TM1 − OB1) • x_3
- PD5a/b: (OB1 − OB3) • x_3

- : Faraday isolator
- : electro-optic modulator
- : polarizing beam splitter
- : mirror or beam splitter
- : \( \lambda/2 \) wave plate

- high power local beam
- low power local beam
- low power beam from spacecraft 2
- low power beam from spacecraft 3
- local fiber link
- electronics link

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Interferometry with a Diffraction Grating

- Double sided diffraction grating on low CTE material
  - Small, ~ mm relay region between long & short arm interferometers
  - $\text{CTE} < \frac{dn}{dT}$
  - Fewer components compared to LISA $\rightarrow$ smaller optics bench
- Sensitivity to grating motion: $1 \, \mu\text{cycle/pm}$

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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
**Grating-Sphere Cavity**

- Mode matching and stable low finesse cavity demonstrated

![Diagram of Grating-Sphere Cavity](image)

(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 \((5\times10^{-11}\text{ m/sec}^2)\), GP-B \((4\times10^{-11}\text{ m/sec}^2\text{ Hz}^{1/2})\)

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/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
Charge Management

- 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, 2\textsuperscript{nd} time after 6 month caging

- **After release, \( \mu \)N 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: $3 \times 10^{-15}$ 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

![Graph showing strain sensitivity against frequency (Hz)]
The End