Possible Space-Based Gravitational Wave Observatory Mission Design

Minimum Cost 3-arm/6-link LISA-like Mission

Jeff Livas
NASA Goddard Space Flight Center
30 June 2015
Outline

• Current US activity
• Rough Development Timeline
• Range of Mission Designs
  – Original NGO as proposed
  – SGO-Mid proposed alternative
  – LISA baseline
• Summary
Current US Activity

• Plan of record is a minority partnership for L3
• Monitoring ongoing ESA L3 planning activity: Gravitational-wave Observatory Advisory Team (GOAT)
  – Evaluate technology readiness/concepts for L3
    o Atom interferometry ruled out as not ready
  – Evaluate the success of the LISA Pathfinder mission
• LISA Pathfinder participation (Nov 2015 launch)
• Technology Development and Decadal Survey Preparation
• Many details of a US role remain undefined at this stage
  – Financial contribution
  – Specific technologies
### One possible timeline...

<table>
<thead>
<tr>
<th>Year</th>
<th>ESA Activity</th>
<th>NASA Activity</th>
<th>Other Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>LISA Pathfinder launch</td>
<td>Mid-Decadal Review</td>
<td>NANOGrav* Science Frontier Center</td>
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<tr>
<td>2016</td>
<td>L3 Call and selection</td>
<td>US L3 Technology Development</td>
<td>EPTA + PPTA = IPTA</td>
</tr>
<tr>
<td>2017</td>
<td>L3 Formulation Phase</td>
<td>US 2020 Decadal Survey</td>
<td>+</td>
</tr>
<tr>
<td>2018</td>
<td>TRL 5/6 delivery date to support the EM</td>
<td>JWST Launch</td>
<td>LIGO-India (planned)</td>
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<tr>
<td>2019</td>
<td>EM Development</td>
<td>Operations + upgrades</td>
<td></td>
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<tr>
<td>2020</td>
<td>SPC</td>
<td></td>
<td></td>
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<tr>
<td>2021</td>
<td>L3 Adoption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td>L2 Launch Mid 2028</td>
<td></td>
<td></td>
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<tr>
<td>2023</td>
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<td>2034</td>
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<tr>
<td>2035</td>
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<td></td>
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</tbody>
</table>

*See poster #31 J. Lazio for more information*

**Timeline Notes:***
- L3 Implementation Phase:
  - L3 Formulation Phase
  - L3 Call and selection
  - TRL 5/6 delivery date to support the EM
  - SPC
  - L3 Adoption
  - L2 Launch Mid 2028
  - L3 Launch Mid 2034
- NASA Activity:
  - US L3 Technology Development
  - JWST Launch
  - US 2020 Decadal Survey
- Other Activity:
  - LIGO C1, O2, O3
  - Operations + upgrades
  - VIRGO
  - iKAGRA, bKAGRA
  - NANOGrav*
  - EPTA + PPTA = IPTA

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Range of Mission Concepts

**NGO\(^1\) (L1 Proposal)**

- Two-arm version design

**SGO\(^2\) Mid**

- Minimum-cost three arm design with acceptable Decadal-survey science return.

**LISA/SGO High**

- LISA concept with single-agency costing and all know cost reductions.

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\(^1\)New GW Observatory
\(^2\)Space-based GW Obs

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Architecture Trades

• Trades that do affect the science performance
  – Two arms (NGO)
  – Measurement arm length (SGO Mid)
  – Duration of science operation*
  – Orbit: drift-away, or not
  – Telescope diameter
  – Laser power

• Trades that don’t affect the science performance
  – In-field guiding/backlink fiber
  – Single optical bench
  – Single proof mass
  – Spherical proof mass
## Mission Concept Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NGO</th>
<th>SGO Mid</th>
<th>LISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement arm length</td>
<td>$1 \times 10^6$ km</td>
<td>$1 \times 10^6$ km</td>
<td>$5 \times 10^6$ km</td>
</tr>
<tr>
<td>Number &amp; type of spacecraft</td>
<td>1 corner (2 optical assemblies, 2 end (single optical assembly)</td>
<td>3 corner (2 optical assemblies)</td>
<td>3 corner (2 optical assemblies)</td>
</tr>
<tr>
<td>Number of measurement arms, one-way links</td>
<td>2 arms, 4 links</td>
<td>3 arms, 6 links</td>
<td>3 arms, 6 links</td>
</tr>
<tr>
<td>Constellation</td>
<td>Vee</td>
<td>Triangle</td>
<td>Triangle</td>
</tr>
<tr>
<td>Gravitational-wave polarization measurement</td>
<td>Single instantaneous polarization, second polarization by orbital evolution</td>
<td>Two simultaneous polarizations continuously</td>
<td>Two simultaneous polarizations continuously</td>
</tr>
<tr>
<td>Orbit</td>
<td>Heliocentric, earth-trailing, drifting-away 9° - 21°</td>
<td>Heliocentric, earth-trailing, drifting-away 9° - 21°</td>
<td>22° heliocentric, earth-trailing</td>
</tr>
<tr>
<td>Trajectory</td>
<td>Launch to Geosynchronous Transfer Orbit, transfer to escape, 14 months</td>
<td>Direct injection to escape, 18 months</td>
<td>Direct injection to escape, 14 months</td>
</tr>
<tr>
<td>Duration of science observations</td>
<td>2 years</td>
<td>2 years</td>
<td>5 years</td>
</tr>
<tr>
<td>Launch vehicle</td>
<td>Two Soyuz-Fregat</td>
<td>Single Medium EELV (e.g., Falcon 9 Block 3)</td>
<td>Single Medium EELV (e.g., Atlas V 551)</td>
</tr>
<tr>
<td>Optical bench</td>
<td>Low-CTE material, hydroxy-catalysis construction</td>
<td>Low-CTE material, hydroxy-catalysis construction</td>
<td>Low-CTE material, hydroxy-catalysis construction</td>
</tr>
<tr>
<td>Laser</td>
<td>2 W, 1064 nm, frequency and power stabilized</td>
<td>1 W, 1064 nm, frequency and power stabilized</td>
<td>2 W, 1064 nm, frequency and power stabilized</td>
</tr>
<tr>
<td>Telescope</td>
<td>20 cm diameter, off-axis</td>
<td>25 cm diameter, on-axis</td>
<td>40 cm diameter, on-axis</td>
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<tr>
<td>Gravitational Reference Sensor</td>
<td>46 mm cube Au:Pt, electrostatically controlled, optical readout</td>
<td>46 mm cube Au:Pt, electrostatically controlled, optical readout</td>
<td>46 mm cube Au:Pt, electrostatically controlled, optical readout</td>
</tr>
</tbody>
</table>
Science Comparison

(Working observatory doing precision parameter estimation: not just detection.)

<table>
<thead>
<tr>
<th></th>
<th>NGO</th>
<th>SGO Mid</th>
<th>LISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive Black Hole Binary Totals</td>
<td>40-47</td>
<td>41-52</td>
<td>108-220</td>
</tr>
<tr>
<td>Detected z &gt; 10</td>
<td>1-3</td>
<td>1-4</td>
<td>3-57</td>
</tr>
<tr>
<td>Both mass errors &lt; 1%</td>
<td>13-30</td>
<td>18-42</td>
<td>67-171</td>
</tr>
<tr>
<td>One spin error &lt; 1%</td>
<td>3-10</td>
<td>11-27</td>
<td>49-130</td>
</tr>
<tr>
<td>Both spin errors &lt; 1%</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1-17</td>
</tr>
<tr>
<td>Distance error &lt; 3%</td>
<td>3-5</td>
<td>12-22</td>
<td>81-108</td>
</tr>
<tr>
<td>Sky location &lt; 1 deg^2</td>
<td>1-3</td>
<td>14-21</td>
<td>71-112</td>
</tr>
<tr>
<td>Sky location &lt; 0.1 deg^2</td>
<td>&lt;1</td>
<td>4-8</td>
<td>22-51</td>
</tr>
<tr>
<td>Extreme Mass-Ratio Inspirals</td>
<td>12</td>
<td>35</td>
<td>800</td>
</tr>
<tr>
<td>Resolved Compact WD Binaries</td>
<td>3,889</td>
<td>7,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Interacting</td>
<td>50</td>
<td>100</td>
<td>1,300</td>
</tr>
<tr>
<td>Detached</td>
<td>5,000</td>
<td>8,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Sky location &lt; 1 deg^2</td>
<td>1,053</td>
<td>2,000</td>
<td>13,000</td>
</tr>
<tr>
<td>Sky location &lt; 1 deg^2, distance error &lt; 10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stochastic Background (normalized)</td>
<td>0</td>
<td>0.2</td>
<td>1</td>
</tr>
</tbody>
</table>

Special acknowledgement to Ryan Lang (Univ. of Florida) and Neil Cornish (Montana State Univ.)
NGO Mission Summary

- **Mission Design**
  - $10^6$ km arm-length, 2 arms, 60 deg “V”
  - Mother + 2 x daughter S/C configuration
  - LISA-like payload
    - 20 cm telescope/2W laser
  - 10-degree drift away heliocentric orbit
  - Launch to sub-GTO, separate from LV
    - Two Soyuz-FRG or
    - shared Ariane V
  - Baseline 2 year lifetime + 2 years
    - Limited by communications bandwidth

Figures from K. Danzmann ESA presentation

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SGO-Mid Mission Summary

• Mission Design
  – 10^6 km arm-length, 3 arms, 60 deg triangle
  – 3 identical spacecraft
  – LISA-like payload
    o 25 cm telescope/1 W laser
  – 9-21 degree drift away heliocentric orbit
  – Direct injection to escape, 18 mo transfer
    o Single EELV (e.g. Falcon 9 Block 3)
  – Baseline 2 year lifetime + 2 years
    o Limited by communications bandwidth

“Sciencecraft”
Payload Integrated with Bus

Payload systems
- Interferometer Measurement System (IMS)
  - Laser
  - Telescope
  - Optical bench
- Disturbance Reduction System (DRS)
  - Gravitational Reference Sensor (GRS)
  - µN thrusters
  - Control laws

(Refer to diagrams for visual representation)

(Note: solar array not shown)
Prop Module/Cruise Configuration

Propulsion Module:
- Bi-prop design
- $\Delta v \sim 200$ m/sec capability
- 6 coarse sun sensors
- 2 star tracker heads
- 2 omni antennas
Mission Timeline

Falcon Heavy EELV

Cruise Trajectories

Science Orbits

Doppler/Arm length changes

Mission Timeline

24 months science operations: orbits optimized for 48 months

Pre-Launch 18 month cruise Science Operations
Considerations for a Mission

• Need one that does the science, and gets selected

• To get “adopted” by ESA
  – Fit within the available cost cap
  – Allows assignment of responsibilities, including US
  – Recognizes European investments (LPF)

• To get “started” by NASA
  – Acceptable and affordable role for NASA
  – Suitable endorsement by 2020 decadal review
  – Acceptable to the “stakeholders” (e.g. ESA, NASA, member states)
Costs

• Estimate of contributions that could be available for L3
  – ESA cap is 1B€, ~$1.2B
  – Member states contribution is ~250-300M€, ~$360M
  – 20% NASA contribution is $316M
  – Total: $1.9B

• Cost estimates from 2012 Study
  – SGO Mid: $1.4B (study team), $1.9B (Team X)
  – LISA: $1.7B (study team), $2.1B (Team X)

• A NASA contribution of $500M would cover all options.
Summary

• Space-based gravitational-wave work continues
  – Spectacular science receives top ratings in reviews
  – Science return can be calculated from the design
  – Issue is funding, not technology

• Current opportunity is partnership with ESA on an L3 mission for 2034 launch
  – 20+ year scientific collaboration on both sides of the Atlantic
  – Requires successful LISA Pathfinder technology demo on track for a Nov 2015 launch
  – NASA role remains to be well defined

• US technology development targeted at TRL-5/6 level for ~2019 for key technologies
  – Includes hardware, astrophysics, and data analysis work

• Full LISA design returns best science for cost, risk
  – SGO-Mid carried as a de-scope