Progress Towards a Space-based Gravitational-Wave Observatory Since 2010

Robin Stebbins, GSFC
Midterm Assessment Committee
Washington, DC, 9 October 2015
Outline

- State of Play in August 2010
- 2010-2015
  - The LISA Project and Subsequent Studies
  - LISA Pathfinder
  - Technology Development
  - ESA’s Cosmic Visions Programme
  - Gravitational Wave Science
- The Plan Forward: 2016-2020
STATE OF PLAY IN AUGUST 2010
**LISA in August 2010**

Laser Interferometer Space Antenna (LISA)  
- Focus of all work since 1993  
- Unchanged since 1997  
- Project in Phase A since 2004  
- Extensive formulation work and products  
- Reviewed and recommended in many major reviews:  
  - AANM (NRC, 2001)  
  - TRIP (HQ, 2003)  
  - Connecting Cosmos to Quarks (NRC, 2003)  
  - AETD (GSFC, 2005)  
  - Beyond Einstein Program (NRC, 2007)  
  - NWNH (NRC, 2010)  
  - Second in ‘large’ space projects after WFIRST.  
  - Recommended for a new start  
  - Contingent on Pathfinder success and a roughly 50/50 European partnership.
ST7 in August 2010

- 2001: New Millennium Program selected the “Disturbance Reduction System” as Space Technology 7 (ST7)
- U.S. contribution to ESA’s LISA Pathfinder mission
- Original idea: NASA and ESA payloads, each with
  - 2 Gravitational Reference Sensors (GRSes)
  - Metrology interferometer
  - Microthrusters
  - Drag-free controller
- 2005: Descoped interferometer and GRSes
- 2010: Remaining U.S. hardware nearing completion.
THE LISA PROJECT AND SUBSEQUENT STUDIES: 2010-2015
The LISA Project

• March 2011: NASA withdrew from ESA’s L1 proposals because of increased program demands and decreased budget projections.

• April 2011: Joint NASA/ESA LISA Project ended

• Science team disbanded
  • Working groups stopped working.
  • Mock LISA Data Challenge stopped.

• Project team at GSFC and JPL largely disbanded.

• Technology support transitioned to SAT grants
Probe Mission Concept Study

2011-2012: Study of probe class concepts ($\leq$1B)

• Design trade-offs explored for impact on science, risk and cost.

• No viable concepts near or below $1B

• No technology dramatically reduces cost

• LISA architecture can be scaled down (SGO Mid), still compelling science.

• Science performance decreases far more rapidly than cost. Risk increases to an unacceptable level.

Final report and (many) other documents at http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php
Technology Development Roadmap

2012-2013: prepared ‘technology roadmap’ for a future GW mission

• The eLISA and SGO Mid concepts require the same technology.
• U.S.-centric plan to develop technologies for a LISA-like mission in the 2030’s.
• *Predates* the selection of L3.
• Links to final document and annual program technology reports at [http://pcos.gsfc.nasa.gov/technology/](http://pcos.gsfc.nasa.gov/technology/)
LISA PATHFINDER
LPF Objectives

• Drag-free flight demonstration
  • Residual acceleration on the test mass <3×10^{-14} m/sec^2/√Hz at 1 mHz
  • Multi-degree-of-freedom control system

• Microthruster demonstration
  • Thrust noise
  • Controllability

• Error budget validation
  • Programmable environment disturbances (magnetic, thermal, charging)
  • Measure the transfer function
  • Extrapolate to LISA
LPF – The Basic Idea

- Drag-free control system
  - One test mass as a sensor
  - Microthruster as a forcer.
  - Controller
- Second test mass as a “witness.”
- Measure the relative motions of the two test masses with picometer interferometer
LPF – Status

• 2012: ST7 delivered to ESA, integrated later in the year
• ESA thrusters changed to GAIA cold gas thrusters
• Final ground testing met or exceeded all requirements.
• September 3: spacecraft, propulsion module and launch I&T complete, ready for shipping
• Numerous operations exercises have been carried out.
• October 8: Flown to Kourou.
• December 1, 11:15 pm EST: scheduled launch on Vega 6
• L+74 d: LTP operations start
• L+186 d: ST7 operations start
• L+288 d: Nominal mission ends.
• Extended mission under consideration.
Fig. 3. Prototype telescope.

Left: drawing of the telescope with the central, or “gut” ray’s path through the telescope indicated by the solid brown line. The secondary is in the light blue mount to the left of the primary.

Right: photo of the telescope as aligned in the vendor’s cleanroom.

Both the telescope and the scattered-light test-bed are installed in the Laser Communication Relay Demonstration (LCRD) cleanroom, where we have arranged to share the space through the end of the calendar year. This arrangement allows us access to the clean room environment, which helps postpone the degradation we expect from particulate contamination. It also enables access to a key piece of test equipment (an interferometer).

In return, LCRD has access to a key piece of our test equipment, a point-source microscope.

The immediate next step is to re-assemble and re-align the telescope. We expect alignment to take approximately three weeks, and then we will begin stray-light testing. The goal is to complete these measurements, and measurements with the scattered-light test-bed, by September 2015 (see Fig. 2). The desired result is a validation of the scattered-light model we have developed, not necessarily to achieve a specific level of performance. Understanding the model will allow us to better design a follow-on telescope to meet the required level of performance. In some cases this may result in a reduction in risk and cost as we understand which aspects of the design, particularly the mirror design, are essential and which are not.

Scattered-light suppression work was augmented with funding received by Ron Shiri through the GSFC Internal Research and Development (IRAD) program for development of partially transparent petalled masks. This funding enabled Ron to engage with the University of Delaware for fabrication of partially transparent masks.

Experimental efforts continue with Shannon Sankar making transmission measurements of the petalled masks designed by Ron. The goal is to understand the challenges and limitations of the different steps that must be followed to progress from a theoretical design to a working mask.

A number of fabrication methods have been tested, and we are in the process of a quantitative comparison between theory and experiment for a circular mask for which we can calculate the expected response analytically. A publication is in preparation.

Successful implementation of these masks may allow us to adopt an on-axis telescope design, which may be less expensive to build and better suited to the application’s environmental requirements compared to an off-axis design.
Technology Development

• Telescope Subsystem – Jeff Livas (GSFC)
  • Demonstrate pathlength stability, stray light and manufacturability
  • SAT renewed FY16
• Phase Measurement System – Bill Klipstein (JPL)
  • Key measurement functions demonstrated
  • Incorporate full flight functionality
  • SAT expired
• Laser Subsystem – Jordan Camp (GSFC)
  • 1064 nm ECL master oscillator
  • Phase noise of fiber power amplifier
  • Demonstrate end-to-end performance in integrated system
  • Lifetime
  • SAT expires May ‘16
• Micronewton Thrusters – John Ziemer (JPL)
  • Propellant storage and distribution for long duration
  • Improve system robustness
  • Improve manufacturing yield
  • Lifetime
  • SAT expired
Technology Development

- Arm-locking Demonstration – Kirk McKenzie (JPL)
  - Studying a demonstration of laser frequency stabilization with GRACE Follow-On
  - Expiring APRA
- Torsion Pendulum – John Conklin (UF)
  - Develop U.S. capability with GRS and torsion pendulum test bed
  - Nancy Grace Roman Fellowship FY15-16
- Multi-axis Heterodyne Interferometry – Ira Thorpe (GSFC)
  - Investigate test mass/optical bench interface
  - APRA starting FY16
- UV LEDs – John Conklin+ (UF)
  - Flight qualify UV LEDs to replace mercury lamps in discharging system
  - Non-NASA support
- Optical Bench – Guido Mueller (UF)
  - Investigate alternate designs and fabrication processes to ease manufacturability
  - APRA starting FY16

LISA researchers at JPL are leading the Laser Ranging Interferometer instrument on the GRACE Follow-On mission.
ESA’S COSMIC VISION PROGRAMME 2015-2025
Cosmic Visions 2015-2025

- Next “planning horizon” for ESA science
- NASA withdrew from initial L1 competition in 2011.
- Next Gravitational Observatory (NGO) concept proposed to second L1 competition in 2012.
  - Descoped LISA-like mission to meet ESA cost cap without US participation
  - *Two arms, 1 million Km baselines, 2 year science operations, 2 launches, mother-daughter configuration.*
  - JUICE selected
- “Gravitational Universe” proposed for L2/L3 Competition in 2013
  - NGO the “notional” mission concept.
  - Senior Selection Committee selected Athena for L2 and the Gravitational Universe as the “science theme” for L3, on account that LPF had not yet flown.
ESA’s L3 Mission

• Only ‘science theme’ selected, not a mission concept
• Planned launch date is 2034.
• Cost cap is 1B€ to ESA.
• Member states typically contribute an additional 30-35%.
• International partners limited to 20% of total European contribution (about $300M).
• NASA interested at the $100-150M level
• ESA included three U.S. members and one NASA observer on the Gravitational Observatory Advisory Team (GOAT)
GRAVITATIONAL WAVE SCIENCE
LISA and Cosmological Structure Formation
Advances in LISA Science

• Improvements in MBHB parameter estimation
  • Added merger and ring-down phases to waveforms
  • Added higher harmonics to waveforms
  • Improved understanding of sky localization, especially from merger phase
  • Orbital eccentricity explored
  • Improved understanding of the interaction between SMBHs and their host galaxies, including effects of eccentricity and spin alignments
  • Kicks explored
  • Improved cosmological modeling of structure formation
  • Better understanding of final parsec problem and its resolution

• Emerging methods for quantifying GR tests
• Science performance calculations
  • ~50 mission concept variants analyzed
2010s – The GW Decade

Advanced LIGO/Virgo/KAGRA begin operations
• O1 observing run began September 18th for 3 months
• Reach 70 Mpc for NS-NS mergers, 3 times previous LIGO distance (27 times volume)
• Progressive sensitivity improvement in next few years
• First GW observations expected by ~2019

Pulsar Timing Arrays (PTAs)
• Several PTA efforts have published upper-limits on stochastic GW backgrounds from SMBH binary mergers (NANOGrav, EPTA, PPTA)
• A key astrophysical uncertainty is in the strength of SMBH binary interactions with their environments
• Recent (2015) results from Parkes (PPTA) are in conflict with models that assume modest rates of evolution passing through the nHz band.
• Models less sensitive to environmental effects at higher frequencies
THE PATH FORWARD: 2016-2020
Gravitational Observatory Advisory Team (GOAT)

• GOAT: an ad-hoc ESA advisory committee initiated in September 2014:
  “To evaluate and recommend on possible scientific and technical approaches for a gravitational wave observatory envisaged for a planned launch date in 2034.”

• 3 US members and 1 NASA observer out of 12 total, very active in the internal studies and debates

• Topics: technical feasibility, science goals, data analysis, system view, technology, partners, cost and schedule

• GOAT has been asked to assess LPF success, with addition of European and US experts. (cf. NWNH)

• GOAT Intermediate Report and other material at: http://www.cosmos.esa.int/web/goat/home
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Pre-decadal Study

• NASA participation in L3 needs a strong recommendation from Astro2020 to go forward.

• NASA needs to define its role, and understand the options
  • Starting point: $100-150M contribution
  • ESA’s limit: 20% of European contribution (~$300M)
  • Contributions: elements of the flight system
  • U.S. activities: science team, data analysis, data center, guest observer program
  • Cost and schedule estimates for collaboration, technology development, flight system contributions and U.S. activities

• Produce the basis for a proposal to Astro2020 by late 2018.
NASA activities 2015-2017

- Operations and data analysis on Pathfinder and ST7
- GW Science Interest Group/Physics of the Cosmos Program Analysis Group (POCs: John Conklin and Neil Cornish)
- Continued participation in ESA’s GOAT
- Participation in early ESA lead-in activities: mission concept proposal/selection, ESA’s Phase A starts 2017, ...
- Technology development to meet the L3 schedule (ISO TRL6 by Q4 2019)
- Rebuild a supporting GW community in the US
- Pre-decadal study in 2017-2018
- Preparations for next decadal
NASA activities 2018-2020

• GW Science Interest Group/Physics of the Cosmos Program Analysis Group
• Participation in early ESA lead-in activities: payload AO, payload engineering model, ...
• Technology development to meet the L3 schedule (ISO TRL6 by Q4 2019)
• Pre-decadal study in 2017-2018
• Continue rebuilding US research community
• Astro2020 decadal survey, a US role in L3 needs
  • A strong endorsement for science and feasibility.
  • Recommended financial commitment
Wrap-Up

• NASA’s strategic plan for a gravitational wave observatory is to participate in ESA’s L3 mission

• To carry out that plan, NASA has to
  • Participate in the successful execution of LPF and ST7, baseline and extended missions
  • Successfully negotiate a role with ESA
  • Refine its plan through a pre-decadal study
  • Develop appropriate technology and participate in pre-formulation studies on ESA’s schedule
  • Receive an endorsement for L3 participation from the 2020 decadal review
BACKUP
## Mission Concept Comparison

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<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>
</tr>
<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

<table>
<thead>
<tr>
<th></th>
<th>NGO</th>
<th>SGO Mid</th>
<th>LISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBH 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>EMRIs</td>
<td>12</td>
<td>35</td>
<td>800</td>
</tr>
<tr>
<td>Resolved CWDBs</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>533</td>
<td>800</td>
<td>8,000</td>
</tr>
<tr>
<td>Stochastic Background</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.)
What LPF does/doesn’t demonstrate

• Free flying test mass subject to very low parasitic forces:
  • Drag free control of spacecraft (non-contacting spacecraft)
  • Low noise micro-thruster to implement drag-free
  • Large gaps, heavy masses with caging mechanism
  • High stability electrical actuation on cross degrees of freedom
  • Non contacting discharging of test-masses
  • High thermo-mechanical stability of S/C
  • Gravitational field cancellation

• Precision interferometric, local ranging of test-mass and spacecraft:
  • pm resolution ranging, sub-mrad alignments
  • High stability monolithic optical assemblies

• Precision 1 Mo km spacecraft to spacecraft precision ranging:
  • High stability telescopes
  • High accuracy phase-meter
  • High accuracy frequency stabilization
  • Constellation acquisition
  • Precision attitude control of S/C